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ORIGINAL PAPER

Inter-basin water governance by transfer rules based on system dynamics

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Abstract

Inter-basin water transfers are implemented to counter the uneven geographical distribution of natural water sources. This paper's novelty consists of providing a system-dynamics framework to evaluate inter-basin water transfers based on integrated water governance. The Big Karun Basin, Iran, has long been of interest to water managers due to its discharge potential. It houses several water-transfer projects that are under operation or under study for possible future implementation. This study implements system dynamics modeling (SDM) in the Big Karun Basin considering existing inter-basin water transfers. This study's results estimate an average annual 8 to 10 billion cubic meters of water are transfered from the Karun River to the Persian Gulf. Part of this flow can be used to meet some of the water demands in Iran's central and eastern basins subject to social and environmental assessment of impacts. SDM modeling was also implemented accounting for the existing water transfers plus the under-study water transfers. This study's results indicate the firm energy from hydropower produced by the Big Karun Basin system would decrease by 28% relative to existing water transfer conditions. This issue raises concerns given the Big Karun Basin contribution to electricity production Iran. The water supply to several sectors would be marginally impacted by future water tranfers, yet water quality would be compromised in some instances. Therefore, the Big Karun Basin water system was simulated considering inter-basin water governance based on hedging rules for the under-study water transfers. Results indicate the minimum drinking and industrial demands could be met. In addition, the firm energy from hydropower produced by the Big Karun Basin system would decline by 12% relative to existing water-transfer conditions and the vulnerability of the water system would decline in terms of required quality for downstream demands and water users in comparison with the full-transfer water condition.

1 Introduction

Many regions of the world face serious water shortages (Bozorg-Haddad and Mariño 2011 and Bozorg-Haddad et al. 2016, Mani et al. (2018)). Water transfers have been built to provide water-scarce regions with needed water. Inter-basin water transfers have suppported socio-economic development in destination basins, although adverse impacts in the source and destination regions of transferred water have been documented. There are many water-transfer projects nowadays worldwide, a practice that was commonly used by the Roman Empire. Inter-basin water transfer is implemented to reduce shortage to support municipal and agricultural consumption, hydropower generation, navigation, water quality improvement, and other functions (Lund and Israel 1995), Yevjevich 2001)). Feng et al. (2007) assessed the impact of water transfer from the south to the north of China as an effective means of economic development. Several authors, such as Bahrami et al. (2018), Zhou et al.

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(2017), Akbari-Alashti et al. (2014), Sadegh et al. (2010), Kucukmehmetoglu (2009) and others applied evolutionary and fuzzy algorithms, Shapley fuzzy and fuzzy methods, game theory, and other optimization methods for the planning and design of inter-basin water allocations. A review of the pertinent literature documents positive and negative impacts of inter-basin water transfers with respect to various political, social, cultural, economic and environmental criteria. The positive impacts of inter-basin water transfers include flood control in source basins, restoration of natural landscapes and ecosystems, and improvement of biodiversity in destination basins, improvement of groundwater resources, wetlands, and various aquatic habitats receiving water imports (Bozorg-Haddad et al. 2015). On the other hand, the negative impacts of inter-basin water transfer disrupt river ecosystems in the source basins, dry springs and streams, reduce groundwater storage in source basins, cause or contribute to desertification, exacerbate pollution and the spread of infectious diseases (Davies et al. (1992), Larsona et al. (2001), Knapp et al. (2003), Chen (2004), Gupta and Van Der Zaag (2008), Ma and Wang (2011), Fallah-Mehdipour et al. (2011), Rivera Monroy et al. (2013), Karakaya et al. (2014), Sible et al. (2015), Bozorg-Haddad et al. (2017)). Some authors (e.g., Gibbins et al. (2000), Das (2006) and Changming and Zheng (2002)) have shown inter-basin water transfers may have adverse impacts concerning greenhouse gases emissions, water degradation, proliferation of metals disposal, erosion and sediment transport, and heighten temperature change, anaerobic aquatic conditions, and seawater intrusion.

Water scarcity can be eliminated due to inter-basin water transfers in the destination basin, yet, a lack of integrated water-resources governance in inter-basin water transfers may exacerbate adverse impacts in source and destination basins. Scholars in the water sector highlight the fact that enhancing water governance is the solution to many water crises (Araral and Yu (2013), Akhmouch (2012) and Biswas and Tortajada (2010)). Inter-basin water governance regulates which basins share water, when and how much water is transferred, and who receives water allocations. Equity and efficiency in water resource and services allocations may be achieved with proper governance (Beygi et al. 2014; Bozorg-Haddad and Mariño 2007, Bozorg-Haddad et al. 2009a, 2010a, b, Fallah-Mehdipour et al. 2013; Karimi-Hosseini et al. 2011; Orouji et al. 2014; Sabbaghpour et al. 2012).

Water resources in Iran are scarce, due to having an aridity index less than 0.2 and climate classification in the arid and hyper-arid classes (Soltanjalili et al. 2011 and Zomer et al. 2022). Population growth, urbanization, industrial development, and agricultural expansion have exacerbated the consumption of water resources, and, consequently, have raised the production of urban sewage, industrial waste, and agricultural drainage discharge (Bozorg-Haddad et al. 2009b). These pollutants impair the provision of high-quality water, especially in central Iran. Inter-basin water transfers from the Big Karun Basin to the central and eastern regions of Iran have been implemented to cope with water shortage in central Iran.

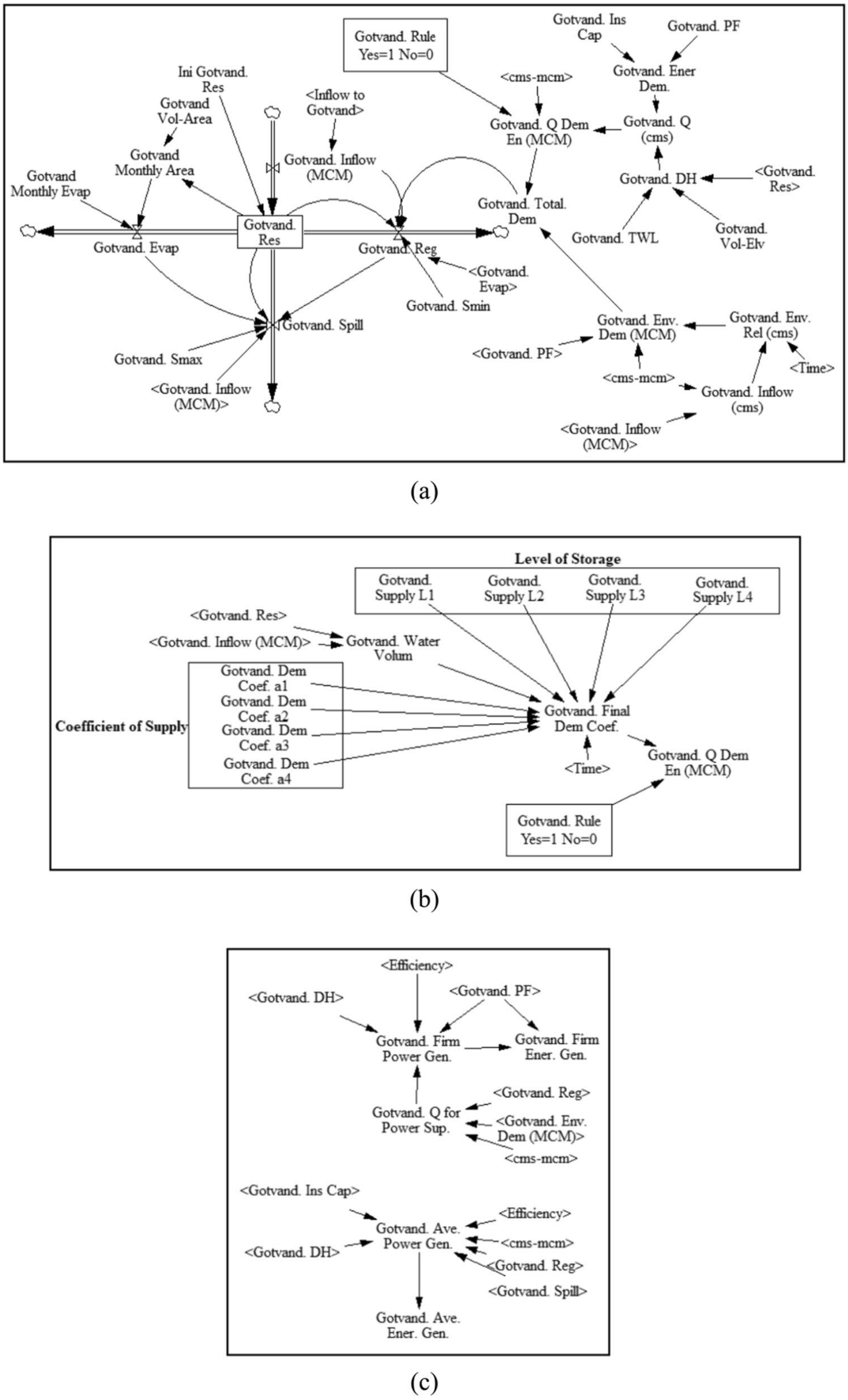
Several new water transfer projects are also under consideration in the Big Karun Basin. It is timely to assess the possible impacts of these projects on the regional water resources of the Big Karun Basin. This study assesses the water transfer from the Big Karun Basin to Iran's central basin relying of a comprehensive system dynamic modeling approach. Furthermore, inter-basin water governance based on the hedging approach is applied to meet water uses and hydropower demand. This paper's assessment of water transfer takes into account the fulfillment of equity among water users in the source and destination basins. In other words, this paper focuses on the need for a review of the inter-basin water transfers that are under study based on the water-governance concept. This paper's novelty consists of developing a system-dynamics framework to evaluate inter-basin water transfers based on integrated water governance.

2 Materials and methods

This section is divided into 2 sub-sections. The first and second sub-sections describe respectively the development of the quantitative simulation model and of the qualitative simulation model.

2.1 Development of the quantitative simulation model

The Big Karun Basin system consists of 7 dams, 12 drinking and industrial consumers, 7 fish farmers (aquaculture projects), 31 agricultural consumers, 5 present inter-basin water transfer projects, and 7 under-operation or under-study inter-basin water transfer projects. This system is simulated with the system dynamics modeling (SDM) (Forrester 1958). Water quality is assessed in Sect. 4. The dams on the Karun and Dez rivers generate hydropower and supply water to meet drinking, industrial, fish farming and agricultural water uses in the Khuzestan plain. This paper's application of SDM simulates (i) water quantity for hydropower generation and for meeting water demands, and (ii) water quality in the Big Karum Basin. The SDM simulates the operation of the Big Karun Basin components: (1) hydropower dams, (2) inter-basin water transfer, (3) drinking, industry, fish farming and agricultural water uses, and (4) downstream environmental requirements for each dam calculated with the Montana method (Orth and Maughan 1981). Figure 1 shows the SDM applied in the simulation of the Gotvand dam operation. Similar simulations were performed for the



(a)

(b)

(c)

Fig. 1 Simulation diagrams of the Gotvand Dam (**a**) with the goal of hydropower generation, (**b**) Rule Curve, and (**c**) Hydropower energy generation

other dams in the Big Karun Basin in this work. Modeling of the Big Karun Basin system was coded with Vensim DSS (5.9b).

The simulation of each reservoir's operation was based on the Standard Operation Policy (SOP) (Cancelliere et al. 1998; Bozorg-Haddad 2014). This operation rule seeks to meet all the water demands. The available water for release from a reservoir in period t is calculated as follows:

$$A_t = S_t + Q_t - E_t - L_t - R_t - SP_t \tag{1}$$

The volume of evaporated water in period t is calculated as follows:

$$E_t = \left[\frac{Ar_t + Ar_{t+1}}{2}\right] Ev_t \tag{2}$$

The reservoir surface water areas at the beginning of periods t and $t+1$ are calculated by Eqs. (3) and (4), respectively:

$$Ar_t = f(S_t) \tag{3}$$

$$Ar_{t+1} = f(S_{t+1}) \tag{4}$$

The constraint on reservoir storage in period t is given by Eq. (5):

$$0 \le S^{Min} \le S_t \le S^{Max} \tag{5}$$

The constraint on reservoir (water) release in period t is given by Eq. (6):

$$0 \le R^{Min} \le R_t \le R^{Max} \tag{6}$$

The constraint on reservoir (water) spill in period t is given by Eq. (7):

$$0 \le Sp^{Min} \le Sp_t \le Sp^{Max} \tag{7}$$

in which: A_t = available water for release in period t; S_t = reservoir storage at the beginning of period t; E_t = the volume of water loss or gain due to the difference between reservoir evaporation and precipitation in period t; Ar_t = the reservoir water surface area at the beginning of period t; R_t = the volume of water released from the reservoir except the spill in period t; Q_t = reservoir inflow in period t; Sp_t = the volume of water spilled from the reservoir in period t; S^{Min} = the minimum operating volume; S^{Max} = the maximum operating volume; R^{Min} = the minimum allowable release volume; R^{Max} = the maximum allowable release volume; Sp^{Min} = the minimum allowable spill volume; Sp^{Maz} = the maximum allowable spill volume; Ev_t = the difference between the evaporation depth and the precipitation depth in period t; t = index denoting the period number, $t \ge 1$.

The SOP prescribes that the volume of regulated water releases from a reservoir during the period $t\left(\text{Reg}_t\right)$ is calculated based on water demand $\left(D_t\right)$. If the available water is less than water demand ($A_t < D_t$) all the available water is released from the reservoir. In this case, $\text{Reg}_t = A_t$. The release equals the water demand $\left(\text{Reg}_t = D_t\right)$ when there is no water shortage ($A_t > D_t$), and surplus flow is stored in the reservoir. There is overflow when the storage capacity of the reservoir exceeds the maximum storage volume. Figure 2a displays a schematic of the SOP.

The SOP is adjusted based on the hedging concept to better account for system complexities that are not well captured by the SOP. Hedging estipulates that reservoir operation be based on rules that consider present conditions (as done by the SOP) and future conditions. With hedging part of the reservoir storage volume and inflow to the reservoir meet water demands in future periods. There are different types of hedging rules. The discrete hedging rule is employed in this study (Neelakantan and Pundarikanthan 1999). Discrete hedging is well suited for real-time reservoir operation during dry periods. The discrete hedging rule calculates reservoir release according to a series of conditional formulas given by Eqs. (8) through (17). A schematic of the discrete hedging rule is depicted in Fig. 2b.

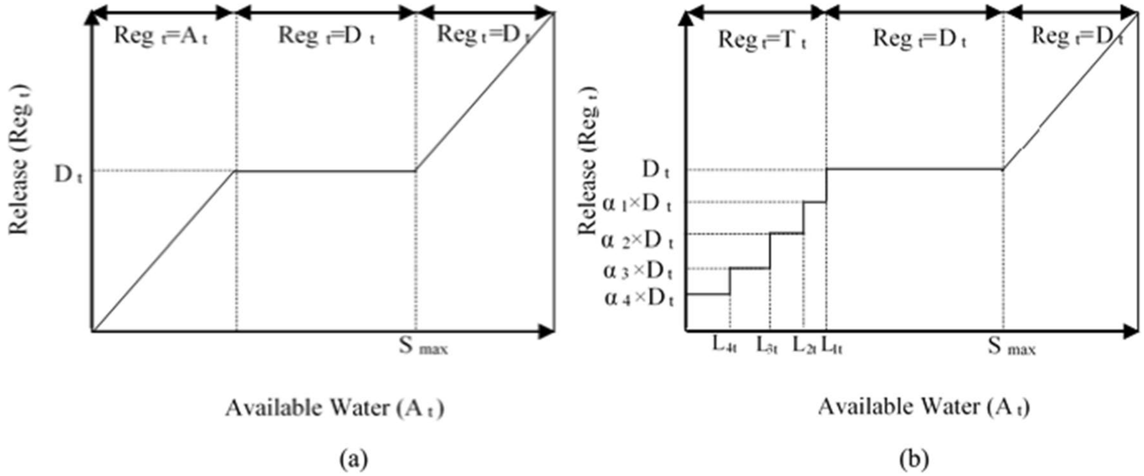


Fig. 2 **a** The SOP rule and (**b**) Discrete hedging rule

$$T_t = D_t \text{ if } S_{t-1} \geq L_{1t} \tag{8}$$

$$T_t = \alpha_1 \times D_t \text{ if } L_{2t} \leq S_{t-1} \prec L_{1t} \tag{9}$$

$$T_t = \alpha_2 \times D_t \text{ if } L_{3t} \leq S_{t-1} \prec L_{2t} \tag{10}$$

$$T_t = \alpha_3 \times D_t \text{ if } L_{4t} \leq S_{t-1} \prec L_{3t} \tag{11}$$

$$T_t = \alpha_4 \times D_t \text{ if } S_{t-1} \geq L_{4t} \tag{12}$$

$$\text{Reg}_t = S_{t-1} + I_t - L_t - S_{\max} \text{ if } S_{t-1} + I_t - L_t - T_t \geq S_{\max} \tag{13}$$

$$\text{Reg}_t = T_t \text{ if } 0 \leq S_{t-1} + I_t - L_t - T_t \prec S_{\max} \tag{14}$$

$$\text{Reg}_t = S_{t-1} + I_t - L_t \text{ if } S_{t-1} + I_t - L_t - T_t \leq 0 \tag{15}$$

$$0 \leq L_{4t} \leq L_{3t} \leq L_{2t} \leq_{1t} \leq S_{\max} \tag{16}$$

$$0 \leq \alpha_4 \leq \alpha_3 \leq \alpha_2 \leq \alpha_1 \leq 1 \tag{17}$$

where $T_t =$ target water release during period t, $\alpha_1, \alpha_2, \alpha_3, \alpha_4 =$ hedging coefficients, L_{1t}, L_{2t}, L_{3t}, $L_{4t} =$ threshold's levels of reservoir storage volume in period t and $S_{\max}$ = maximum reservoir storage. The discrete hedging rule equals the SOP whenever $\alpha_4 = 1$ or $L_{1t} = 0$.

The operation of hydropower plants is herein based on system reliability (Sharifi 2008): the water release from the reservoir is such that the amount of generated energy in a monthly time period exceeds the firm energy. Firm energy is the minimum amount of monthly generated energy with a specified reliability. The generated hydropower and energy are calculated respectively with Eqs. (18) and (19):

$$P_t = \frac{9.81 \times e_p \times \left(\text{Reg}_t / pf\right) \times \Delta H_t}{1000} \tag{18}$$

$$E_t = \frac{P_t \times pf \times nh_t}{1000} \tag{19}$$

where P_t = power generated in time t (MW), e_p = total efficiency of turbine and generator, Reg_t = release from the powerhouse in period t $\left(m^3/s\right)$, pf = the powerhouse coefficient which indicates the operating hours of the powerhouse during 24 h, ΔH_t = the water level difference between the reservoir level and the power houses's downstream water level in period t (i.e., the tailwater, m), nh_t = number of operational hours in month t,and E_t = generated energy in period t (GWh/month). Reservoir water elevation is calculated from elevation-volume formulas for the reservoirs.

In each time period (one month long each) the reservoir storage capacity must be within the minimum and maximum storage limits. In addition, the reservoir storage at the end and beginning of the operation period are set equal to each other (this is the so-called periodicity constraint). In each operation period hydropower generation increases whenever the reservoir storage exceeds the maximum storage because of surplus flow for hydropower generation. Accordingly, firm energy is calculated based on Eqs. (18) and (19). The average energy is determined based on the total regulated release from the powerhouse that generates hydropower. The power generated by a powerhouse cannot exceed its installed capacity.

All the reservoir system dams are simulated in this study based on the discrete hedging rule with the main goal of hydropower generation (which is their main function). Subsequently, the operational or under study inter-basin water transfer projects were added to the water-resources system to assess the performance of the Karun River Basin system based on system reliability and vulnerability to meet hydropower and water quantity and quality requirements (Bozorg-Haddad 2014).

2.2 Development of the qualitative simulation model

Water quality simulation was carried out with SDM based on mass-balance equations [Eqs. (20) through (24)] and considering the TDS (total dissolved solids) in water.

$$S.V._{ext(t)} = Sup_t \times TDS_{up(t)} \tag{20}$$

$$S.V._{ret(t)} = Sup_t \times Co._{Sup} \times TDS_{up(t)} \times Co._{TDS} \tag{21}$$

$$S.V._{d(t)} = S.V._{up(t)} - S.V._{ext(t)} + S.V._{ret(t)} \tag{22}$$

$$Inf._{d(t)} = Inf._{up(t)} + Sup_t(1 - Co._{Sup}) \tag{23}$$

$$TDS_{d(t)} = \frac{S.V._{d(t)}}{Inf._{d(t)}} \tag{24}$$

in which $S.V._{ext(t)}$ and $S.V._{ret(t)}$ = the amounts of output and return TDS in output and return flows in period t, respectively, Sup_t = the flow delivered to meet water demands in period t, $TDS_{up(t)}$ and $TDS_{d(t)}$ = TDS of flow upstream and downstream specific location, respectively, in period t, $Co._{Sup}$ = the percentage of return flow which varies based on the type of water users, $Co._{TDS}$ = the coefficient of variation of TDS which varies based on the type of user, $S.V._{up(t)}$ and $S.V._{d(t)}$ = The TDS volume upstream and downstream of specific location, respectively, in period t, $Inf._{up(t)}$, and $Inf._{d(t)}$ = flow upstream and downstream of specific location, respectively, in period t.

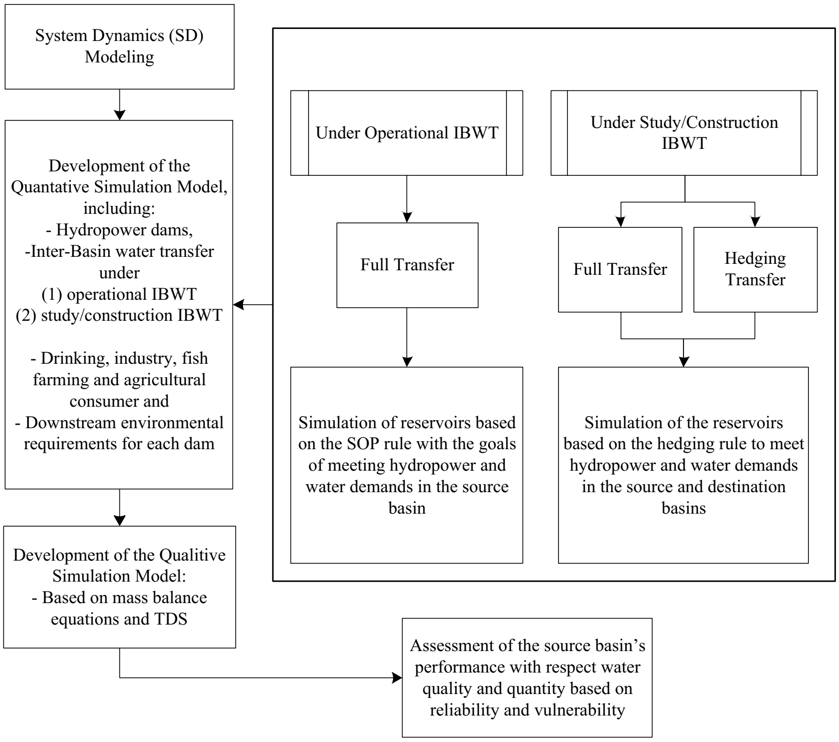
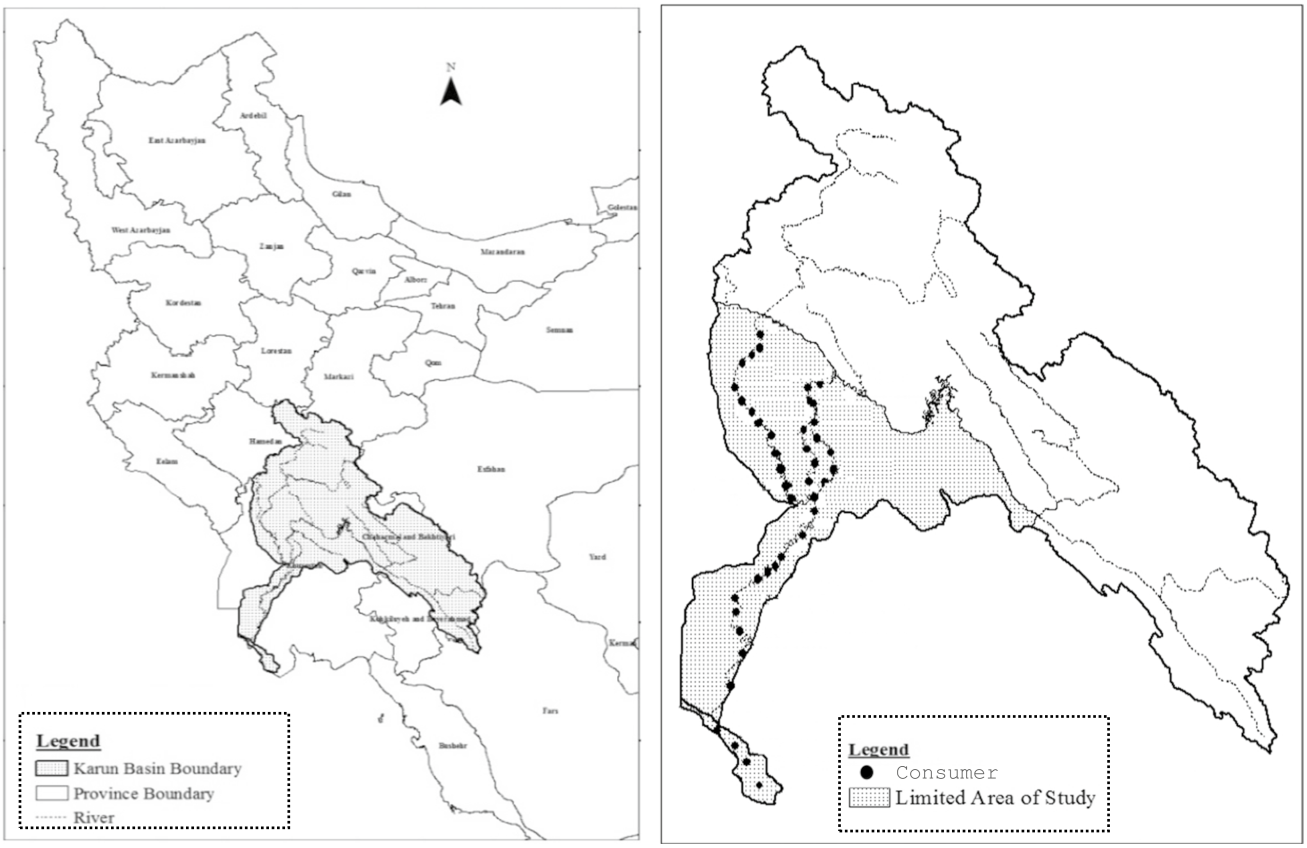
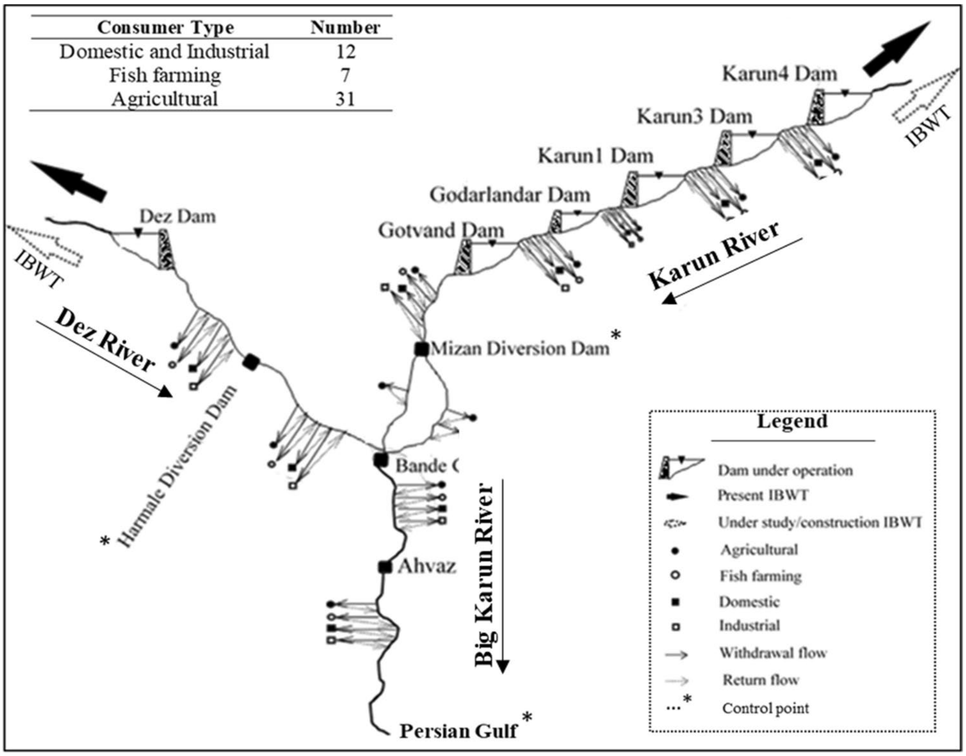


Fig. 3 Flowchart of of this work's methodology



(a) (b)

Fig. 4 The schematic of the location of the Big Karun Basin showing the distribution of users, (**a**) the Karun Basin, (**b**) the study area within the Karun Basin



Consumer Type	Number
Domestic and Industrial	12
Fish farming	7
Agricultural	31

Fig. 5 A schematic of the Big Karun Basin with its components. Not drawn to scale

Table 1 General and technical characteristics of the operating dams in the Big Karun Basin

Parameters	Unit	Karun-4	Karun-3	Karun-1	Godarlandar	Gotvand	Dez
Area of upstream basin	Km^2	12,813	24,260	26,838	27,632	32,425	17,430
Average annual discharge	m^3/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
Normal elevation	m	1,025	845	532	372	230	352
Minimum reservoir storage	$10^6m^3/s$	1,266	1,141	1,095	181	117	1,126
Reservoir storage	$10^6m^3/s$	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

Table 2 Monthly water requirement by users in the Big Karun Basin (m^3/s)

Consumer Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Domestic and industrial	64.4	64.4	63.4	70.4	70.5	70.7	57.4	57.4	57.4	72.3	64.9	64.5	64.8
Agricultural	42.4	154.9	657.8	648.6	414.6	346.1	427.9	744.9	505.9	315.2	161.7	29.1	370.8
Fish farming	23.9	42.3	61.1	61.1	61.1	39.8	39.8	39.8	39.8	39.8	39.3	31.6	43.4

Water quality was simulated from the Gotvond dam on the Karun River and the Dez dam on the Dez River to the Persian Gulf. TDS is a key water quality parameter within the simulation region because of its use as an indicator variable, and, also, because of existing data availabity.

2.3 Methodology

This work's methodology is depicted in Fig. 3.

Table 3 Monthly water requirement for operational water transfer projects in the Karun and Dez basins (m^3/s)

Basin	Name	Jan	Jan	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Dez	Dez to Qomrud	4.9	4.9	8.6	13.1	11.6	5.5	3.1	2.6	2.0	2.4	3.9	5.1	5.7
	CheshmehLangan Tunnel	1.5	1.5	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	0.7	2.6	8.2	9.0	4.5	2.0	0.9	0.5	0.5	0.7	1.1	2.6
Karun	Kuhrang-1	4.5	4.5	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	4.8	9.4	18.4	25.3	21.0	14.2	7.2	4.1	3.2	4.4	4.8	10.2

Table 4 Monthly water requirements for water transfer projects under study in the Karun and Dez basins (m^3/s)

Basin	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Nov	Annual
Dez	GukanTunel and Dam	2.4	4.9	9.1	19.9	19.6	9.9	4.0	1.5	0.6	0.5	1.0	1.0	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	2.2	2.1
Karun	Kuhrang-3	4.4	5.0	9.0	16.4	19.3	12.2	7.5	5.0	3.5	3.1	4.4	4.4	7.9
	Beheshtabad	24.3	31.3	56.3	87.7	84.0	39.9	20.9	14.6	10.8	10.4	17.0	17.0	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	4.6	7.9
	Shahid Dam	0.7	0.9	1.7	2.9	3.9	4.6	2.9	1.7	1.2	0.7	0.8	0.8	1.9
	Bideh Dam	7.4	7.4	7.6	7.2	7.2	7.2	7.2	7.2	7.2	7.4	7.4	7.4	7.3

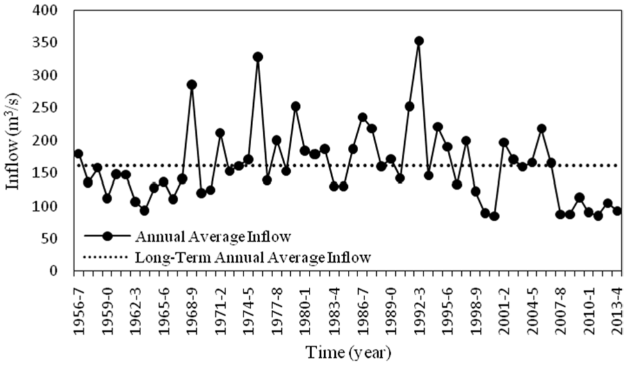


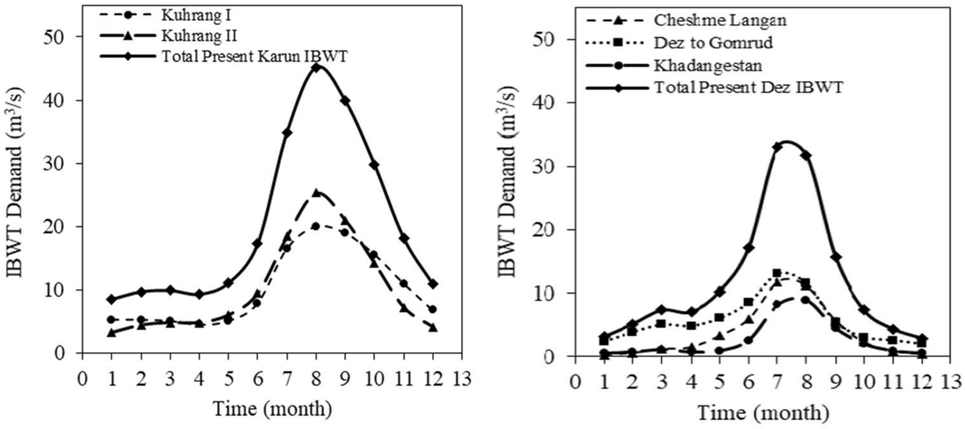
Fig. 6 Chart of inflows to the Karun-4 dam's lake and comparison to the long-term average inflow

3 The case study

The Big Karun Basin encompasses the Dez and Karun rivers, and contains most of the water resources in Iran. This basin is located in the middle Zagros Mountains between eastern longitudes 48.00 and 30.52 degrees and northern latitudes 30.00 and 34.05 degrees. This basin plays an important role in hydropower generation and in meeting drinking, industrial and agricultural water demands in the provinces of Khuzestan, Chahar Mahal and Bakhtiari, Kohgiluyeh and Boyer Ahmad, and Lorestan. Figure 4 displays the location of the basin and the distribution of various water users.

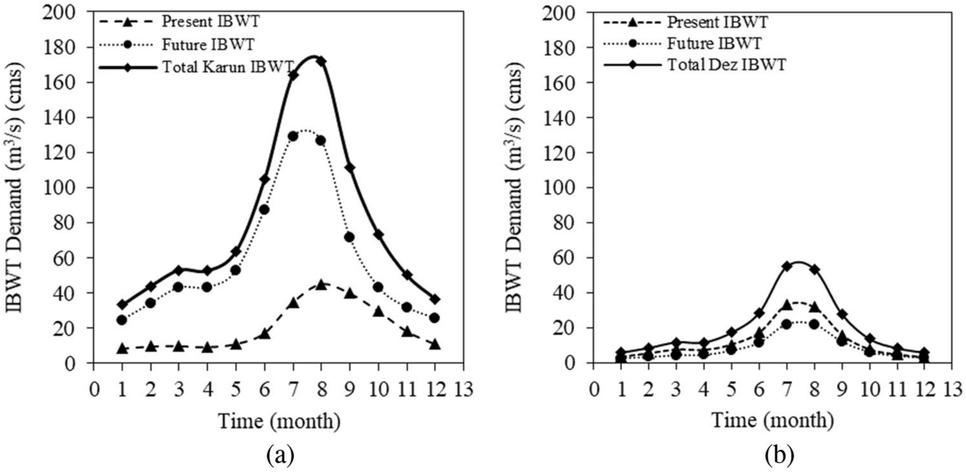
The Big Karun Basin houses various water projects. Those projects include the Dez Dam on the Dez river, and

Fig. 7 Charts of water demands met through present inter-basin water transfer projects in the (**a**) Karun and (**b**) Dez River Basins under present condition (IBWT: inter-basin water transfer)



(a)

(b)

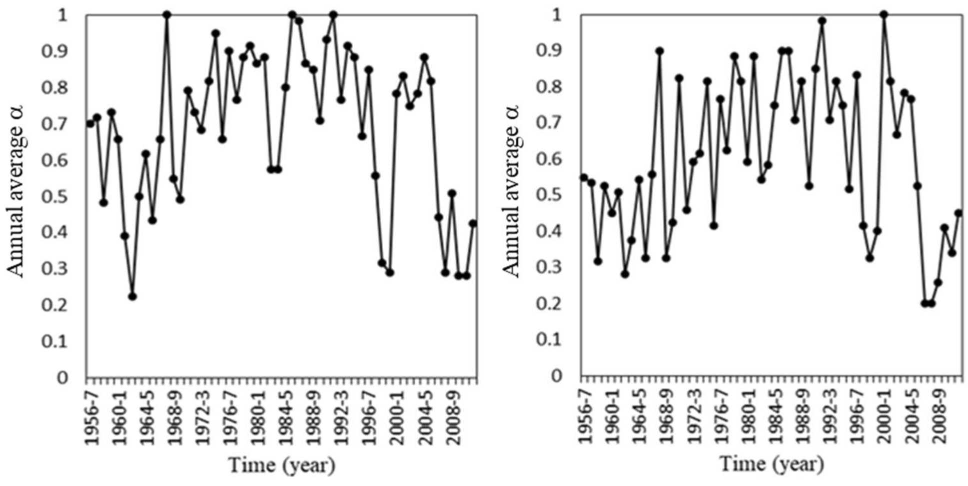


(a) (b)

Fig. 8 Charts of water demand met through present and under study inter-basin water transfer in (**a**) Karun and (**b**) Dez River Basins under full transfer conditions (IBWT: inter-basin water transfer)

Table 5 Threshold levels L_{1t}, L_{2t}, L_{3t}, L_{4t}, and L_{5t} in each month of the year in the Karun and Dez rivers (m^3/s)

Basin	Threshold	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Dez	L_{5t}	9.4	9.4	10.5	13.3	16.1	24.5	37.5	36.1	26.2	17.5	12.8	10.3
	L_{4t}	10.2	10.5	12.4	15.7	21.0	31.7	45.3	44.7	30.4	20.7	14.6	11.5
	L_{3t}	11.0	11.1	14.6	17.8	26.8	40.0	56.8	52.1	33.8	23.6	16.4	12.4
	L_{2t}	12.9	14.9	23.9	23.6	35.1	49.7	82.8	74.7	43.2	29.1	19.8	14.8
	L_{1t}	14.3	18.3	33.7	32.4	52.6	67.6	100.1	91.5	59.0	37.8	25.6	17.9
Karun	L_{5t}	46.8	57.6	72.4	80.5	97.6	165.8	248.2	211.2	129.3	82.8	57.7	46.5
	L_{4t}	51.4	61.9	76.1	84.2	108.8	185.1	283.8	232.0	146.3	88.7	67.3	55.9
	L_{3t}	55.0	64.0	86.8	89.5	123.5	198.6	312.5	260.7	161.2	95.8	68.9	58.1
	L_{2t}	63.4	71.7	102.4	109.4	142.6	245.6	369.6	332.7	187.4	115.1	79.8	65.7
	L_{1t}	74.3	93.3	140.0	158.9	206.1	325.8	510.7	420.6	235.1	135.1	94.4	75.3



(a) (b)

Fig. 9 Average annual hedging coefficients of inter-basin water transfer in the (**a**) Karun and (**b**) Dez river basins under water governance based on hedging transfer conditions

the Karun-4, Karun-3, Karun-1 (ShahidAbbaspur), Godarland (MasjedSoleyman), and Gotvand dams on the Karun River. Other projects are the Lorestan's Roudbar and Bakhtiari Dam in the Dez river basin, and the Bazoft, Khersan-1, Khersan-2 and Khersan-3 dams in the Karun River Basin, which are in the planning stages or under construction. The functions of these dams are hydropower generation and water supply for the agricultural, drinking, and industrial sectors in the Khuzestan plain. A schematic of the Big Karun Basin and its water resources system, including 6 dams under operation, 5 existing inter-basin water transfer projects, 12 drinking and industrial consumers, 7 fish farmers,

Table 6 The values of the efficiency coefficient, firm energy, and generated energy for each dam

Dam	pf			Average Annual Firm Energy (GWh/year)			Average Annual Average Energy (GWh/year)		
	Present Condition	Full Transfer	Hedging Transfer	Present Condition	Full Transfer	Hedging Transfer	Present Condition	Full Transfer	Hedging Transfer
Karun-4	0.135	0.061	0.106	0.106	510.1	510.1	2,148.7	1,367.8	1,594.5
Karun-3	0.112	0.075	0.096	0.096	1,264.9	1,264.9	3,650.1	2,886.5	3,121.1
Karun-1	0.121	0.088	0.106	0.106	1,508.7	1,508.7	3,991.8	3,270.8	3,493.0
Godarladar	0.108	0.080	0.095	0.095	1,379.5	1,379.5	3,759.9	3,107.6	3,391.1
Gotvand	0.111	0.086	0.100	0.100	1,474.3	1,474.3	3,961.7	3,337.4	3,541.1
Dez	0.405	0.395	0.398	0.398	1,693.6	1,693.6	2,449.2	2,381.1	2,405.1
Total					7,831	7,831	19,961.4	16,351.2	17,473.9

31 agricultural consumers and 7 under-study/construction inter-basin water transfer projects is depicted in Fig. 5.

The technical characterisitics of operating hydropower dams on the Karun and Dez rivers are listed in Table 1. The hydropower dams supply electricity during peak hours of electricity consumption in the national Iranian network. New dams and power plants are intended to enhance electricity supply to the national network.

Table 2 lists the monthly water requirements for drinking, industry, agriculture, and fish farming in the Big Karun Basin. Inter-basin water transfer projects are a key component of the Big Karun Basin, which transfers part of the Karun and Dez rivers' inflows to meet water demands in the central plain of Iran, in spite of conflicting goals of the water transfer project pitting hydropower generation against downstream water supply. These projects are key components of the regional water and electric supplies.

Currently, there are other inter-basin water transfer projects in the Big Karun Basin as follows: the Kuhrang-1 and 2 tunnels in the Karun basin, and the Cheshmehlangan, Dez to Qomroud, and Khadangestan tunnels in the Dez Basin are also operational. Similar projects include the Kuhrang-3, Beheshtabad, Solakan, Shahid, and Bideh dams in the Karun River basin and the Gukan and Kamal Saleh dams in the Dez basin are under study. Tables 3 and 4 list the monthly water requirements for existing water transfer projects and for projects under study in the Karun and Dez rivers. Numerous water projects on the Karun and Dez rivers with conflicting goals create complex operational and benefits/cost issues.

Figure 6 displays the river inflow to the Karun-4 reservoir. The flow pattern is typical and similar for inflows to other reservoirs in the study area. It is seen in Fig. 6 that inflow to the Karun-4 reservoir is smaller than the long-term average inflow from 2006 through 2013, equivalent to a drought. This dry period continues until 2018, and it affirms the need for careful water resources management in the Big Karun Basin.

The water gavernance for inter-basin water transfers which is applied in this paper transcends water management. This study develops a simulation model of the Big Karun Basin water resources system based on system dynamics. The model includes all the operating dams located on the Karun and Dez rivers, all the drinking, industry, fish farming, and agricultural water uses, water withdrawals from the Karun and Dez rivers, return flows from each user sector to rivers, existing inter-basin water transfer projects, and under-study inter-basin water transfers.

4 Results

The SDM of the Big Karun Basin was applied from 1956 through 2013. This period includes wet, dry, and normal precipitation years. Figures 7 and 8 display the water demands met by inter-basin water transfers under present and under full transfer conditions, respectively. It is evident that only the demand of present inter-basin transfer projects can be met. Under full transfer conditions projects under study are added to existing projects and their combined water demand must be fully met. Figures 7 and 8 indicate larger water-transfer flows would be required in the Karun River Basin than in the Dez River Basin.

Five levels of water-supply thresholds set equal to 80%, 60%, 40%, 30% and 20% were considered based on hedging transfer rules. In other words, the values of the hedging coefficients α_1, α_2, α_3, α_4, α_5 equal 0.2, 0.3, 0.4, 0.6 and 0.8, respectively. These coefficient values were determined based on experts' opinions. When the threshold level is 20% drinking and industrial demands are fully met and no shortage would occur. The threshold values L_{1t}, L_{2t}, L_{3t}, L_{4t}, and L_{5t} were calculated based on long-term inflow data for the Karun-4 dam on the Karun River and the Dez dam on the Dez River (Table 5).

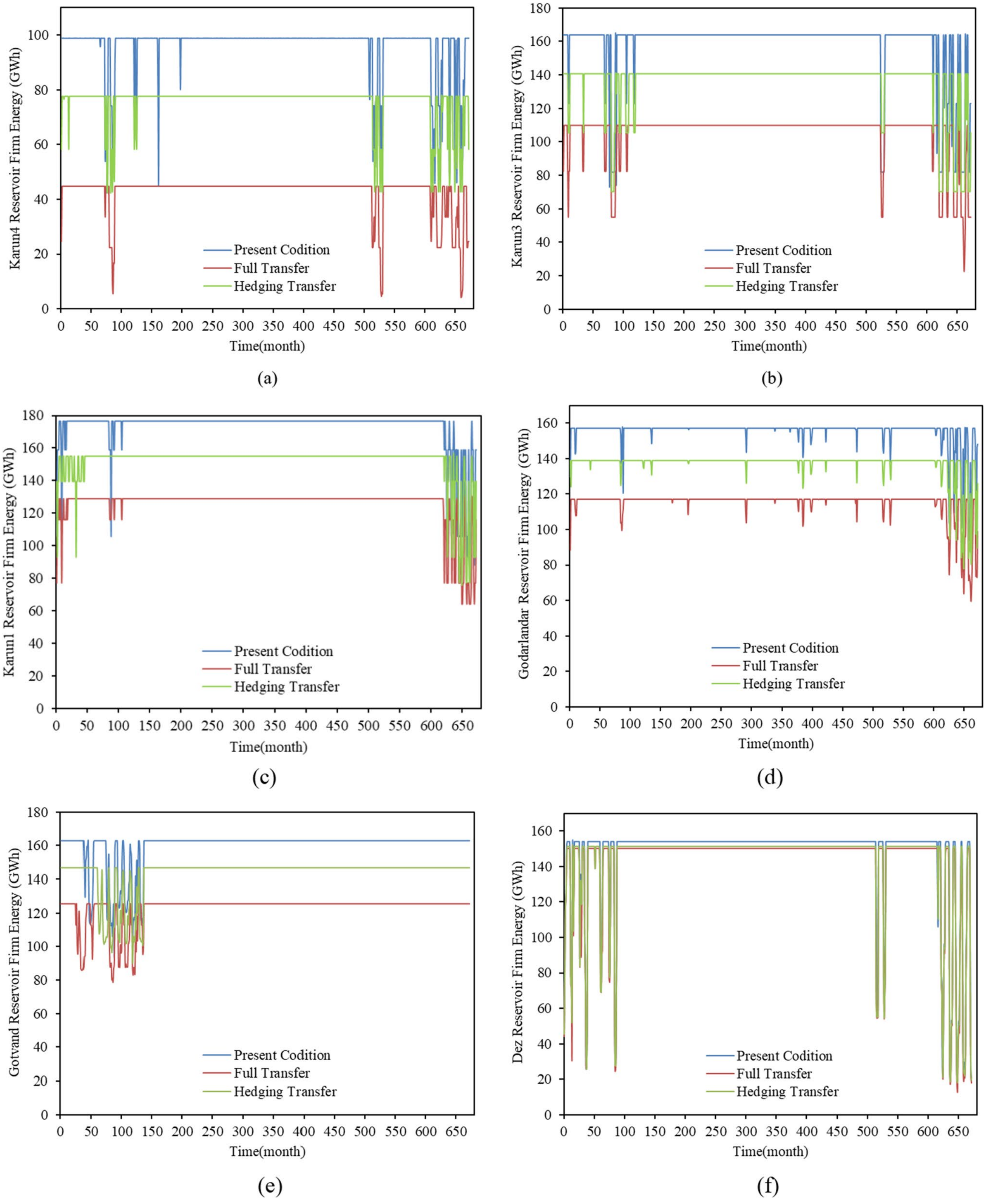


Fig. 10 Firm energy generated by the Hydropower Plant of (**a**) Karun-4, (**b**) Karun-3, (**c**) Karun-1, (**d**) Godarland, (**e**) Gotvand, and (**f**) Dez dams

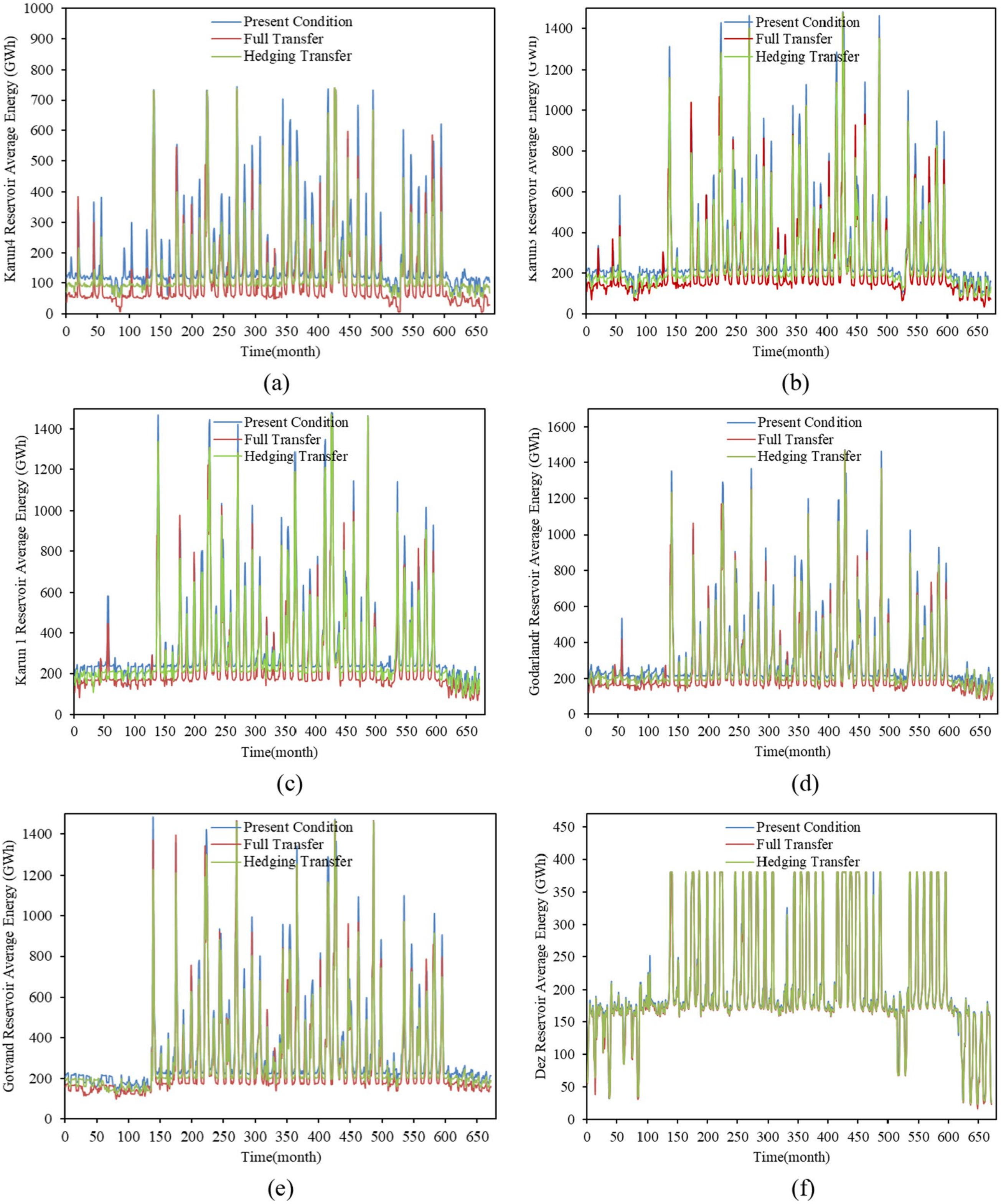


Fig. 11 Average energy generated by the HydroPower Plants of the (**a**) Karun-4, (**b**) Karun-3, (**c**) Karun-1, (**d**) Godarland, (**e**) Gotvand, and (**f**) Dez dams

Figure 9 shows the average annual hedging coefficients of the under-study inter-basin water transfer projects in the Big Karun basin. It is seen in Fig. 9 that only in a few years are all the water demand of the under-study inter-basin water transfer projects met in the Karun and Dez basins. During the years 2006–2013 the average hedging coefficients equals 0.4.

The results for hydropower powerhouse's coefficient, average annual firm energy, average annual average energy corresponding to each dam are listed in Table 6, which encompasses present conditions, full transfer conditions, and inter-basin water governance for under-study and operational (i.e., under operation) inter-basin water transfer projects.

It is seen in Table 6 that full transfer to meet all inter-basin water transfer demands in the Karun River Basin has a dramatic impact on hydropower generation at the Karun-4, Karun-3, Karun-1, Godarland and Gotvand dams. The coefficient of each dam's hydropower powerhouse decreases to achieve 90% reliability in hydropower generation under the full-transfer condition and hedging transfer. Firm energy and average energy decrease at Dez dam under full transfer and inter-basin water governance of water demand with transfer projects. Yet, this reduction is negligible compared to the Karun River basin. The powerhouse coefficient at the Dez dam is also low under present, full transfer, and hedging transfer conditions. This is due to the Dez reservoir high volume of spills. It follows from Fig. 8 that the volume of inter-basin water transfers from the Dez river is smaller than the transfers from the Karun River Basin.

Figures 10 and 11 display the changes in firm energy and average energy generated from each reservoir in the Karun and Dez River Basins. The largest and smallest values of generated energy correspond to the Karun-1 dam and Karun-4 dam, respectively. This is justified by the powerhouse coefficient and installed capacity of the powerhouses. During the years 2013–2016 the firm energy generation for all dams except Gotvand dams was reduced because of the its installed capacity. Furthermore, overflow (spills) at Gotvand Dam during average and wet periods is larger than in other dams.

Table 7 lists the results for system efficiency in meeting water demands for drinking, industrial, fish farming, and hydropower generation sectors under present condition, full transfer conditions, and inter-basin water governance of inter-basin water transfer projects. Hydropower dams under present, full transfer, and inter-basin water governance conditions correspond to 90% reliability. The results indicate that under the three conditions the reliability of meeting water demand exceeds 90%, specially in the drinking and industrial sectors. No shortage for supplying drinking and industrial occurred under the three conditions (present condition, full transfer conditions, and inter-basin water governance of inter-basin water transfer projects). The results also

Table 7 Reliability and vulnerability performance measures to meet water demands under system conditions

	Present Condition				Full Transfer				Hedging Transfer			
	Water Quantity	Water Quality	Water Quantity	Water Quality	Water Quantity	Water Quality	Water Quantity	Water Quality	Water Quantity	Water Quality	Water Quantity	Water Quality
	Vulnerability	Reliability	Vulnerability	Reliability	Vulnerability	Reliability	Vulnerability	Reliability	Vulnerability	Reliability	Vulnerability	Reliability
Hydropower	90.0	5.9	-	-	90.0	6.3	-	-	90.0	6.1	-	-
Domestic and Industrial	100.0	0.0	91.5	33.0	100.0	0.0	86.5	44.9	100.0	0.0	89.2	38.4
Fish	99.0	1.1	81.3	41.6	99.0	1.2	75.0	52.2	99.0	1.0	78.4	46.5
Agriculture	98.7	12.0	57.4	74.8	97.8	16.4	54.9	79.4	98.3	14.2	56.2	77.0

indicate the vulnerability of the water system with respect to the supply of quality water for various users. The complexity of water-quality characteristics rises under the full transfer condition.

5 Conclusion and discussion

This study applied system dynamics modeling (SDM) to assess the impact of inter-basin water transfer on hydropower and water supply in the Big Karun Basin's water system, Iran. This work's results indicate that under full-transfer conditions the water demands can be met reliably, yet the vulnerability of the water system increases with respect to water quality. The results demonstrate that under full-transfer condtions the water system capacity declines dramatically with respect to firm hydropower generation. This issue requires consideration because of the central contribution of the Big Karun Basin to Iran's hydropower generation. Water demands associated with inter-basin water transfer projects were revised based on the concept of water governance. Also, this work's results indicate the minimum water demands of destination basins for drinking and industrial consumers would be met. The firm energy from hydropower produced by the Big Karun Basin system would decrease by 12% relative to existing water transfer conditions, and the vulnerability of the water system would increase in terms of required quality for downstream demands and water users. Therefore, providing effective solutions for improving water quality due to the full transfer condition is a topic deserving future research.

Implementing inter-basin water governance, aided by the determination of suitable water tnrasfers may reduce the firm energy; yet this reduction can be compensated by the Big Karun currently under construction. Moreover, implementing water demand management in destination basin would meet most water demands thus avoiding social crises. This paper's results indicate that considering equity among multiple water users requires even distribution of water benefits from inter-basin water trsansfers among the source and target basins.

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Omid Bozorg-Haddad, First Author, Corresponding author, Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Validation; Visualization; Roles/Writing—original draft.

Abdolrahim Salavitabar, Third author, Software; Formal analysis; Visualization.

Hugo A. Loáiciga, author, Fifth Validation; Visualization; Writing—review & editing.

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Declarations

Ethics approval All authors accept all ethical approvals.

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