Multi-reservoir system management under alternative policies and environmental operating conditions

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ABSTRACT

In this paper, alternative reservoir operation models under different environmental operating conditions were developed to analyze the impacts of applying different policies in a multi-reservoir system in order to balance human and environmental requirements. Three scenarios/models were developed under four sub-scenarios/operating conditions. The scenarios were: (1) an optimization model to maximize the hydropower production, (2) an optimization model to minimize the squared of the difference between the release and need, (3) a simulation model under the Hydropower Standard Operating Policy. The sub-scenarios were developed as follows: (i) no environmental flow, (ii) minimum environmental flow, (iii) environmental flow bounded by the minimum and maximum flow, and (iv) maximum environmental flow. Hydropower production and system performance criteria were calculated and compared in all cases. Moreover, the Range of Variability Approach was used to assess the hydrological alterations of each of the 12 cases. The results in a two reservoir cascade of Seimare-Karkheh, located within the Karkheh River Basin in Iran, showed that sub-scenario 3 performed best in all three scenarios. Further comparison indicated that scenario 1, under sub-scenario 3, was a good compromise solution, as it provided adequate hydropower production and performance criteria and the least hydrological alterations.

Key words | environmental flow, hydrological alteration, hydropower, multi-reservoir system, optimization, performance criteria

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INTRODUCTION

Sustainable water resources systems are managed to meet the present and future human needs while preserving their environmental integrity (e.g. Loucks 1997). Management of river basins between diverse and increasing human objectives while maintaining the river flow requirements is a complex problem (e.g. Cardwell *et al.* 1996; Poff *et al.* 1997).

The construction and operation of reservoirs inevitably result in changes in the natural water flow, by reducing the downstream flow, and present a considerable threat to river ecosystems and the services they provide (e.g. Ward & Stanford 1995; Poff *et al.* 1997; Morán-Tejeda *et al.* 2012; Steinschneider *et al.* 2014). Hence, it is essential to mitigate environmental degradation while trying to supply water resources to the users efficiently (e.g. Suen *et al.* 2009; Saghafian & Hamzekhani 2015). To achieve this, water release from the reservoirs must be propitiously managed. The concept of environmental flow was proposed as a solution to thwart degradation of water ecosystems. In recent decades, researchers have used various approaches to evaluate environmental flow requirements, most of which are based on the minimum water flow that their dependent ecosystems require (e.g. Hamzekhani *et al.* 2015).

Consideration of environmental flow requirements, from different perspectives, in conjunction with human water demands has been one of the most important areas of water resources management research. Homa *et al.*

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(2005) introduced the concept of Eco deficit to enable a broad evaluation of instream flow requirements, while simultaneously exploiting the Flow Duration Curve (FDC) as a method of water allocation. Their study showed that the optimization approach, along with sensible regulatory strategies, may lead to improvements in instream flow and water supply reliability. Suen & Eheart (2006) developed a multi-objective approach for optimizing reservoir operation to balance ecosystem and human needs. The human needs objectives were agricultural, domestic, and power needs. Yin & Yang (2011) integrated a reservoir operation and a water diversion model to develop a coupled reservoir operation and water diversion (CROWD) model. The CROWD considered both human needs and environmental flow requirements and provided a balance between human and ecosystem needs. The results showed that the model is effective in optimization of the operation of reservoirs and water diversion schemes and provided solutions to reduce the risk of water shortages and minimize negative impacts on ecological integrity. Meijer *et al.* (2012) incorporated environmental flow requirements in water allocation modeling by presenting a new functionality in the RIBASIM water allocation package. The results showed that the approach can determine environmental flow release options that result in small losses for other water consumptive users. Docker & Robinson (2014) provided a perspective of the environmental management program in Australia's Murray-Darling basin. This program focused on seeking to balance the needs of the environment and other water users through an improved flow regime. This was in response to declining ecological conditions, exacerbated by drought and climate change impacts.

The present study aims to evaluate the impacts of applying different popular operation policies under different environmental conditions in a multi-reservoir system in order to balance human and environmental requirements and also indicate how these models are different from various aspects. In this regard, three scenarios/models, including two optimization models and a simulation model, subject to Hydropower Standard Operating Policy (HSOP) under four sub-scenarios in a multi-reservoir system, were developed. The objective functions of optimization models were the maximization of the hydropower production and minimization of the squared difference of the release and need. The required environmental flow was calculated using the Environmental Management Classes (EMCs) of the FDC shifting method. Sub-scenario 1 pays no regard to downstream environmental flow requirements and focuses only on the human needs. Sub-scenarios 2–4 contemplate both human and environmental requirements. These sub-scenarios were also considered (i) minimum environmental flow determined by EMC-C, (ii) environmental flow bounded by the minimum and maximum flow determined by EMC-B, and (iii) maximum environmental flow as determined by EMC-A. The Range of Variability Approach (RVA) was adopted to evaluate potential hydrological alterations of models in four sub-scenarios. Hydrological alterations, hydropower production and performance criteria of the system, including reliability, vulnerability, and resiliency, were computed and compared.

STUDY AREA

The Karkheh River, located in western Iran, originates from the Zagros mountain range. Its length is about 900 km and it joins the Tigris River close to the Iran–Iraq border. The Karkheh Basin, with an area of 48,000 km^2, lies between 46 °23′ to 49 °12′ E longitude and 33 °40′ to 35 °00′ N latitude. Elevation of the Karkheh Basin varies from a few meters at its outlet to more than 3,500 m above sea level. The basin enjoys a Mediterranean climate while more than 64% of annual runoff occurs in the January–May period (e.g. Jamali *et al.* 2013b). Spatial and temporal variation in precipitation within the basin are severe (e.g. Muthuwatta *et al.* 2010). For example, the Khuzestan plain and southern outlet area of the basin is semi-arid with mild winters and long hot summers. In the northern alpine regions, the basin has cold winters and mild summers. The temperature varies from as low as −25 °C to as high as 50 °C. The average annual precipitation varies from 150 mm in the south to 1,000 mm in the north and east. The average annual flow of the Karkheh River is 5,916 MCM (e.g. Jamali *et al.* 2013a).

Karkheh River Basin holds about 9% of the total irrigated area of the country and provides 10% of the total nationally produced wheat (e.g. Marjanizadeh 2008;

Muthuwatta *et al.* 2010). Agricultural production, urban water, and fish farming are the most important water consuming activities in the basin. In the upper basin areas, both rainfed and irrigated agriculture are practiced, while in the lower basin only irrigated agriculture is possible due to the drier conditions (e.g. IWPCO 2010). The primary purpose of Seimare dam in the basin is hydropower generation, while Karkheh dam was built to generate hydropower and supply irrigation water for the Khuzestan plains (e.g. IWPCO 2009, 2010).

Seimare dam is located in the Zagros Mountains in the north-western part of Khuzestan Province. Seimare dam is a double-arch concrete dam built on one of the branches of the Karkheh River named Seimare River which is mainly formed by the Gararsou and Gamasiab river branches (e.g. IWPCO 2009; Saghafian *et al.* 2014). Karkheh embankment dam is located well downstream on the Karkheh River, some 22 km northwest of Andimeshk City within Khuzestan Province (e.g. IWPCO 2010; Jamali *et al.* 2013a). The Seimare River joins the Kashkan River to form the Karkheh River. The Seimare and Karkheh dams are located in an area with serious water scarcity and environmental challenges. Hence, this study would help to find an appropriate compromise solution to balance human and environmental flow requirements. Figure 1 shows the location of Seimare and Karkheh reservoirs within the Karkheh River Basin. Figure 2 shows a schematic of the hydropower system and the hydrological stations used in this study. In Table 1, the characteristics of

Figure 1 | Location of Seimare and Karkheh dams within Karkheh River Basin.

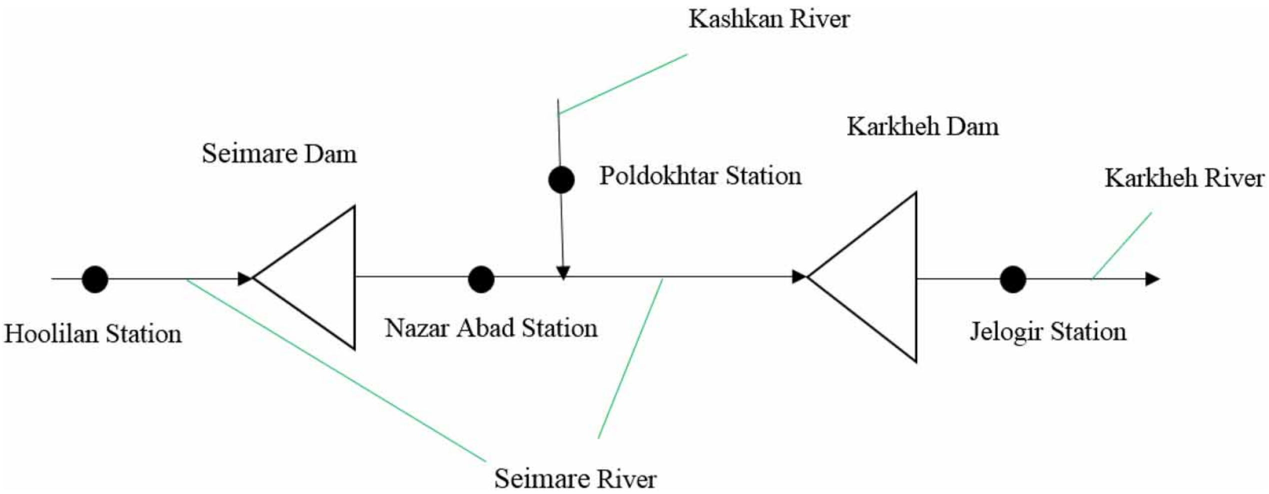

Figure 2 | Schematic of the hydropower/reservoir system and hydrometric stations used in this study.

Seimare and Karkheh dams and their power plants are presented (e.g. IWPCO 2009, 2010; Jamali *et al.* 2013a).

METHODOLOGY

Multi-reservoir operation considering environmental flow requirements

The study covers a data period of 55 years, from 1958 to 2012. To determine the downstream environmental flow requirements the 1958–1996 pre-construction data series of the Nazar Abad hydrometric station located downstream of Seimare dam and the 1958–1991 pre-construction data series of Jelogir hydrometric station located downstream of Karkheh dam were analyzed. Data series from Hoolilan hydrometric station were used as the inflow series to the Seimare reservoir. The release volume from Seimare reservoir along with Kashkan river flows (Poldokhtar hydrometric station data series) constituted the inflow series to Karkheh reservoir (Figure 2).

Table 1 | Characteristics of Seimare and Karkheh dams and power plants

Dam and power plant	Seimare	Karkheh
Normal water level (MASL)	720	220
Minimum operation level (MASL)	705	160
Maximum storage (MCM)	2,473.6	5,346.8
Minimum storage (MCM)	1,663.6	397.1
Plant efficiency (%)	93.5	92.5
Power plant capacity (MW)	480	400

In this study, three models/scenarios were developed under four different operating conditions/sub-scenarios (Table 2). Scenarios 1 and 2 contain optimization models in which the decision variables are minimum and maximum monthly operating storages. The total number of the decision variables equals 48 (24 variables for Seimare reservoir and 24 variables for Karkheh reservoir). By solving the optimization model in this study, the optimal set of monthly operating rule curves, including the upper and lower rule curves for two reservoirs, could be extracted.

The optimization model 1 used in this study is formulated as follows:

$$F_1 = Max \sum_{i=1}^{n} \sum_{t=1}^{T} E_i(t) \tag{1}$$

$$E_i(t) = 2.725 \times R_i(t) \times (0.5 \times (h_i(t) + h_i(t+1)) - h_{tail,i}(t) - h_{f,i}(t)) \times e_{p,i} \tag{2}$$

where F_1 is the objective function of the model 1, n is the total number of reservoirs, t is the time step/simulation period (month), T is the total number of simulation periods, $E_i(t)$ represents hydropower production of plant i during

Table 2 | Defined scenarios and sub-scenarios

Scenario	Description
1	Optimization model to maximize total hydropower production in Seimare–Karkheh system
2	Optimization model to minimize squared of the difference between release and need in Seimare-Karkheh system
3	Simulation model under Hydropower Standard Operating Policy (HSOP)
Sub-scenario	**Description**
1	Hydropower system operation with no consideration of the downstream environmental flow requirements
2	The release volume from the reservoirs is greater than or equal to the minimum environmental flow requirements (EMC-C of the FDC shifting method)
3	The release volume from the reservoirs is greater than or equal to the flow bounded by the minimum and maximum environmental flow requirements (EMC-B of the FDC shifting method)
4	The release volume from the reservoirs is greater than or equal to the maximum environmental flow requirements (EMC-A of the FDC shifting method)

time t (MWh), $R_i(t)$ is the release from reservoir i during time t (MCM), $h_i(t)$ and $h_i(t+1)$ are the initial and final forebay elevations of reservoir during time t, respectively (m), $h_{tail,i}(t)$ is the tail water elevation of reservoir i during time t(m), $h_{f,i}(t)$ is the head loss (m), and $e_{p,i}$ is the total efficiency of plant i.

Similarly, optimization model 2 is expressed by:

$$F_2 = Min \sum_{i=1}^{n} \sum_{t=1}^{T} (f_i(t))^2 \tag{3}$$

$$f_i(t) = \begin{cases} 0 & ; R_i(t) \geq D_i(t) \\ R_i(t) - D_i(t) & ; R_i(t) < D_i(t) \end{cases} \tag{4}$$

where F_2 is the objective function of model 2, $D_i(t)$ is the need (required release) from reservoir i during time t (MCM).

A penalty function is defined to prevent the storage capacity values associated with the lower rule curve exceeding those of the upper rule curve in each month. The penalty function is as follows:

$$P = k \left| S_{ur,i}(t) - S_{lr,i}(t) \right| \quad if \quad S_{ur,i}(t) < S_{lr,i}(t) \tag{5}$$

where P is the penalty function, k is a constant which is set to 1×10^8 in this study; and $S_{ur,i}(t)$ and $S_{lr,i}(t)$ are the decision variables of the optimization problem and represent the maximum operating storage capacity (the upper rule curve) and the minimum operating storage capacity (the lower rule curve) of reservoir i during time t, respectively (MCM).

Constraints are listed as follows:

1. The water balance equation:

$$S_i(t+1) = S_i(t) + I_i(t) - R_i(t) - L_i(t) \tag{6}$$

where $S_i(t)$ and $S_i(t+1)$ represent the storage of reservoir i at the beginning of time periods t and $t+1$, respectively (MCM); $I_i(t)$ is the inflow of reservoir i during time t (MCM); and $L_i(t)$ is the loss from reservoir i due to evaporation and water leakage during time t (MCM).

2. The storage-elevation equation:

$$h_i(t) = f(S_i(t)) \tag{7}$$

3. The tail water elevation-release equation:

$$h_{tail,i}(t) = f(R_i(t)) \tag{8}$$

4. The required release constraint:

$$D_i(t) = Max(D_{HP,i}(t), D_{EF,i}(t)) \tag{9}$$

where $D_{EF,i}(t)$ is the environmental required release from reservoir i during time t (MCM); and $D_{HP,i}(t)$ is the hydropower required release from reservoir i during time t

(MWh) and is calculated as follows:

$$D_{HP,i}(t) = \frac{Pcap_i \times pf_i \times nhours}{2.725 \times (0.5(h_i(t+1) + h_i(t)) - h_{tail,i}(t) - h_{f,i}(t)) \times e_{p,i}} \tag{10}$$

where $Pcap_i$ is the installed capacity of plant i (MW); and pf_i is the plant factor associated with plant i.

5. The storage constraints:

$$S_{lr,i}(t) \le S_i(t) \le S_{ur,i}(t) \tag{11}$$

$$S_{\min,i} \le S_{ur,i}(t) \le S_{\max,i} \tag{12}$$

$$S_{\min,i} \le S_{lr,i}(t) \le S_{ur,i}(t) \tag{13}$$

where $S_{\max,i}$ and $S_{\min,i}$ are the designed maximum and minimum storage of reservoir i, respectively (MCM).

6. The release constraint:

$$R_{\min,i} \le R_i(t) \le R_{\max,i} \tag{14}$$

where $R_{\min,i}$ and $R_{\max,i}$ are the maximum and minimum release from reservoir i, respectively (MCM).

7. The power production constraint:

$$E_{\min,i} \le E_i(t) \le E_{\max,i} \tag{15}$$

where $E_{\max,i}$ and $E_{\min,i}$ are the maximum and minimum power production of plant i, respectively (MWh).

Particle Swarm Optimization (PSO) was used to solve the optimization scenarios. PSO is a population-based optimization technique inspired by the social behavior of birds flocking/fish schooling. The PSO algorithm was originally developed by Eberhart & Kennedy (1995). The algorithm has been widely used in many fields, including water resources/reservoir management. The successful application of the algorithm in this field and its details may be found in the literature (e.g. Mousavi & Shourian 2010; Ghimire & Reddy 2013; Spiliotis *et al.* 2016). In this paper, for the optimization models (scenarios 1 and 2), PSO parameters are shown in Table 3.

The operation policy in the optimization models is partially similar to the Hydropower Standard Operating Policy (HSOP), which is the adopted approach in the third model/scenario. However, the difference is that in scenarios 1 and 2, the upper and lower bounds, which are the maximum and minimum monthly operating storage capacities of the reservoirs, were optimized as decision variables in all 12 months of the year, while in model 3 (HSOP model), the reservoir storage varies between the designed maximum and minimum operating storages in each time step; that is: $S_{\min,i} \le S_i(t) \le S_{\max,i}$.

Performance criteria

Three performance criteria were used to evaluate different models under different operating conditions. They included reliability, vulnerability, and resiliency. According to Loucks (1997), Reliability (Re*l*) is the frequency with which water demand is satisfied during the simulation period:

$$\mathrm{Re}l = \frac{Nsv}{N} \times 100\% \tag{16}$$

where Nsv is the number of satisfactory values (Deficit = 0); and N is the total number of time steps.

Vulnerability (*Vul*) represents the average magnitude of deficits during the total number of years simulated. In this

Table 3 | PSO parameters and their values in scenarios 1 and 2

Scenario	Swarm size	Individual learning coefficient (C_1)	Group learning coefficient (C_2)	Max inertia weight (W_{max})	Min inertia weight (W_{min})	Max iteration
1	100	2.1	2	0.9	0.4	1,000
2	100	1.9	2.1	0.9	0.4	1,000

study, this value is divided by the annual water demand to make the index dimensionless:

$$Vul = \frac{\frac{\sum_{Deficit>0} Deficit}{Frequency\,(Deficit > 0)}}{Annual\,water\,demand} \times 100\% \tag{17}$$

Resiliency (Res) is the probability that a no-deficit period follows a water deficit period:

$$\mathrm{Res} = \frac{Frequency\ (Deficit = 0\ following\ Deficit > 0)}{Frequency\ (Deficit > 0)} \times 100\% \tag{18}$$

FDC shifting method

The FDC shifting method is considered a subset of hydrological methods of environmental flow assessment. This method provides six EMCs ranging from A to F (A: minor modification, B: small modification, C: medium modification, D: large modification, E: serious modification, F: critical modification). Each EMC is represented by its distinct FDC. The higher the EMC, the more water is needed for ecosystem conservation. In this method, 17 fixed percentage points are considered on the probability axis. For each month, estimation of the FDC under each EMC is performed by successively shifting the reference FDC to the left by one percentage point, i.e. EMC-A is formed by shifting the reference FDC one percentage point to the left, EMC-B by shifting it two points, etc. (Smakhtin & Anputhas 2006). These percentage points are used as steps within FDC Shifting.

This study used the Global Environmental Flow Calculator (GEFC) software version 2.0 (Smakhtin *et al.* 2007) to implement the FDC shifting method. GEFC was developed cooperatively by the International Water Management Institute and the Water Systems Analysis Group of the University of New Hampshire.

To determine the downstream environmental flow requirements based on the GEFC, monthly 1958–1996 flow data series of Nazar Abad station and the 1958–1991 flow data series of Jelogir station were used.

Evaluation of hydrological alterations

The RVA was applied in this study to evaluate hydrological alterations caused by the operation of hydropower multi-reservoir system. The RVA adopts 32 Indicators of Hydrological Alteration (IHA) for detailed analysis and quantification of hydrological alterations. These parameters are grouped into five categories: magnitude, timing, duration, frequency and the rate of change (Richter *et al.* 1997). The pre-dam impact variation of the IHA parameter values were used as a reference for determining the extent of natural flow regimes alterations.

This study took advantage of IHA software version 7.1 (The Nature Conservancy 2007) to implement the RVA, based on the daily flow data series from 1958–1996 and 1997–2012 for the pre- and post-operation of Seimare dam, respectively; and from 1958–1991 and 1992–2012 for the pre- and post-operation of Karkheh dam, respectively. The median values of each 32 parameters were determined for both time series.

The degree of hydrological alteration, DHA, quantifies the deviation of the post-dam flow regime from the pre-dam flow regime:

$$DHA_i = \left|\frac{N_o - N_e}{N_e}\right| \times 100 \quad i = 1, 2, 3, \ldots 32 \tag{19}$$

where DHA_i is the degree of hydrological alteration for the indicator i, N_o is the observed number of post-dam years for which the value of the hydrological parameter falls within the RVA target range, and N_e is the expected number of post-dam years for which the parameter value falls within the RVA target range. The ranges of hydrological alteration are divided into three equal categories: 0–33, 33–67, and 67–100% representing little or no alteration, moderate alteration, and high degree of hydrological alteration, respectively.

Furthermore, the average value of the 32 degrees of hydrological alteration for the 32 IHA parameters represents the overall hydrological alteration, DHA_o (Richter *et al.* 1998):

$$DHA_o = \left(\frac{1}{32}\sum_{i=1}^{32} DHA_i^2\right)^{\frac{1}{2}} \tag{20}$$

In this study, hydrological alterations were calculated based on the pre-dam flow data and post-dam simulated flow data at the Nazar Abad and Jelogir hydrometric stations. The monthly simulated flow data were obtained from each model output and downscaled to the daily flow data for the RVA analysis.

RESULTS AND DISCUSSION

Figure 3 shows the reference and environmental flow duration curves of Seimare and Karkheh rivers at the Nazar Abad and Jelogir hydrometric stations derived by the GEFC version 2.0. Table 4 represents the monthly environmental flow determined by the FDC shifting method under different operating conditions.

It is apparent that the maximum hydropower generation and the best performance criteria in the Seimare-Karkheh system were achieved in sub-scenario 1 for each scenario. However, the results of the RVA method in this sub-scenario represented high degrees of hydrological alterations for the system and thus this case cannot be environmentally justifiable. The degrees of hydrological alterations and their classes (low, moderate, and high levels of hydrological alteration associated with each of the 32 IHA parameters) are listed only for scenario 1 in Table 5 for both the Seimare and Karkheh rivers. In sub-scenario 1, most IHA parameters under this sub-scenario were out of RVA target range. By applying higher EMCs leading to an increase in total demand of the system, the power production and performance criteria declined to some extent, whereas the hydrological alterations were significantly improved

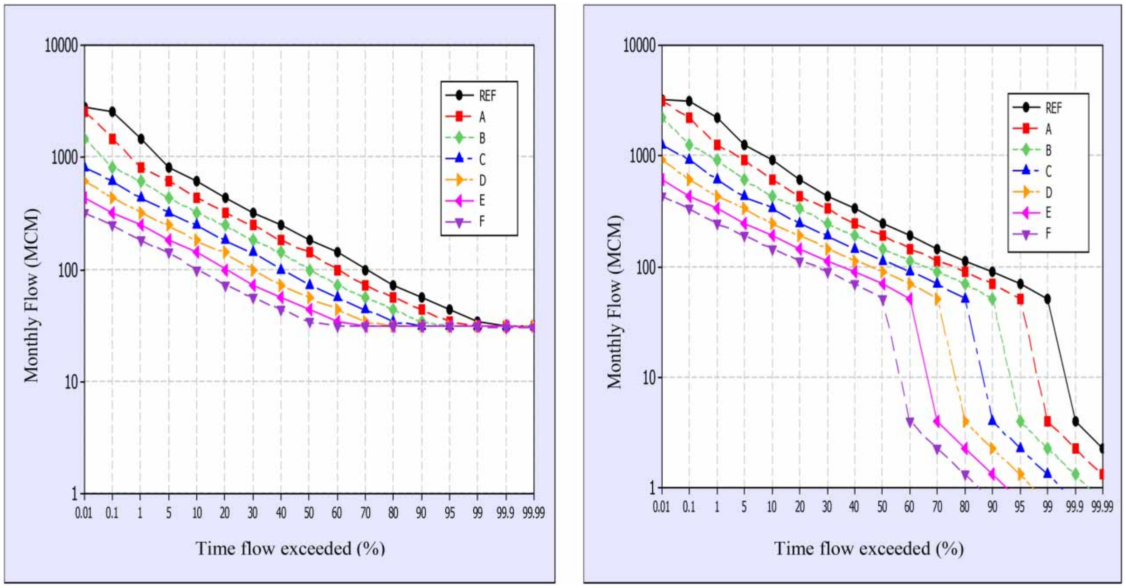

Figure 3 | Reference and environmental flow duration curves of Seimare River (left) and Karkheh River (right).

Table 4 | Monthly average environmental flow under different sub-scenarios (m^3/s)

Month		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Sub-scenario 2	$Q_{Seimare}$	13.10	21.01	29.94	31.97	40.40	61.39	77.20	58.76	24.24	13.78	12.81	12.18
	$Q_{Karkheh}$	9.06	23.96	42.19	45.11	59.03	84.42	104.49	80.83	35.58	15.57	8.85	5.86
Sub-scenario 3	$Q_{Seimare}$	15.15	27.02	40.50	42.83	54.26	82.13	103.51	78.52	31.56	16.30	14.11	13.25
	$Q_{Karkheh}$	18.50	35.31	55.04	58.22	77.37	112.33	141.20	106.81	47.53	22.49	15.16	11.05
Sub-scenario 4	$Q_{Seimare}$	18.70	35.44	54.35	58.16	72.74	109.96	139.54	105.91	42.08	20.35	16.67	15.48
	$Q_{Karkheh}$	27.15	46.70	70.93	75.96	102.04	153.29	196.68	146.13	62.78	32.42	22.93	19.12

Table 5 | Degrees of hydrological alteration and IHA classes for scenario 1 under alternative sub-scenarios (bold text = high alteration, italic text = moderate alteration, bold/italic text = low alteration)

Sub-scenario	**1**		**2**		**3**		**4**	
River	**Seimare D (%)**	**Karkheh D (%)**	**Seimare D (%)**	**Karkheh D (%)**	**Seimare D (%)**	**Karkheh D (%)**	**Seimare D (%)**	**Karkheh D (%)**
Parameter Group 1:								
October	**100**	**100**	**100**	**74**	**100**	*65*	**100**	*65*
November	**88**	*65*	**88**	*65*	**88**	*37*	**77**	***30***
December	**88**	*48*	**88**	*56*	**77**	***23***	**77**	***30***
January	77	*48*	**88**	*48*	*65*	***23***	*65*	*48*
February	*65*	*48*	*65*	*48*	*65*	***23***	*65*	*37*
March	*65*	*48*	**77**	*48*	*53*	***23***	*53*	*48*
April	*53*	***23***	***30***	*23*	***18***	***4***	***11***	*56*
May	*53*	***23***	***48***	*23*	***30***	***13***	***30***	***23***
June	*65*	*56*	**77**	*48*	*65*	***13***	*65*	***30***
July	**77**	**83**	**77**	*56*	*65*	*37*	*65*	***23***
August	**77**	**91**	**88**	*56*	**77**	*48*	**77**	*48*
September	**77**	**100**	*65*	*56*	*65*	*48*	*65*	*48*
Parameter Group 2:								
1-day minimum	**88**	**83**	**100**	*63*	**88**	*48*	**88**	**74**
3-day minimum	**88**	**83**	**100**	*56*	**88**	*48*	**88**	**74**
7-day minimum	**88**	**83**	**88**	*56*	**76**	*48*	*65*	*65*
30-day minimum	*65*	**83**	**88**	*56*	*65*	***33***	*65*	*65*
90-day minimum	*53*	**74**	*65*	*56*	*53*	***33***	*53*	*65*
1-day maximum	**88**	**74**	**77**	*48*	**77**	***22***	77	*56*
3-day maximum	**88**	**83**	*65*	*39*	*65*	***22***	**65**	*65*
7-day maximum	**88**	**74**	**77**	*48*	*53*	***33***	*53*	*56*
30-day maximum	**77**	*39*	**77**	***33***	*53*	***22***	*53*	*39*
90-day maximum	**88**	*48*	**88**	*48*	**77**	***33***	**77**	*48*
Base flow index	**100**	**91**	**100**	**91**	**100**	**91**	**100**	**91**
Parameter Group 3:								
Date of minimum	*36*	*67*	***15***	***33***	***15***	***31***	***15***	***33***
Date of maximum	**88**	*53*	*65*	*43*	**77**	*37*	**77**	*43*
Parameter Group 4:								
Low pulse count	***20***	*63*	***33***	*63*	***25***	*48*	***25***	*41*
Low pulse duration	*57*	*37*	***30***	*41*	***15***	***26***	***15***	*54*
High pulse count	**71**	**100**	*49*	*67*	*57*	*49*	*57*	*52*
High pulse duration	*57*	**100**	*38*	*67*	*48*	*49*	*48*	*52*
Parameter Group 5:								
Rise rate	**88**	**100**	*50*	**78**	*50*	*62*	*50*	*62*
Fall rate	**88**	**93**	*38*	**86**	***25***	**69**	***25***	**69**
Number of reversals	*41*	**100**	*50*	**100**	*50*	**100**	*50*	**100**

D, Degree of hydrological alteration.

compared to sub-scenario 1. Table 6 and Figure 4 separately summarize and compare the results of the models under different sub-scenarios.

All in all, the models under sub-scenario 3 resulted in the least hydrological alterations. In sub-scenario 3 most parameters fell within the target range of the RVA. In scenario 1, under this sub-scenario, the average hydrological alteration in Karkheh River were 16 and 14% less than those of sub-scenarios 2 and 4, respectively. The hydrological alteration in Seimare River under sub-scenario 2 lay in the high alteration class, although it was only slightly more than the range of moderate hydrological alteration. Furthermore, under sub-scenario 3, the average hydrological alteration associated with Seimare River was 8% less than sub-scenario 2 and only 1% higher than sub-scenario 4. In scenario 2, the overall degree of hydrological alteration in Karkheh River was 12 and 10% less than those of sub-scenarios 2 and 4, respectively. The average hydrological alteration in Seimare River under sub-scenario 2 was placed in the high alteration class. Therefore, this sub-scenario cannot be environmentally adaptable. The average hydrological alteration under sub-scenario 3 was 6% less than that of sub-scenario 2, and only about 1% higher than sub-scenario 4. In sub-scenario 3 of the third model, the average hydrological alteration for Karkheh River was 16 and 14% less than sub-scenarios 2 and 4, respectively. The hydrological alteration in Seimare River under sub-scenario 2 was more than 67% and was placed within the high hydrological alteration class. The hydrological alteration under sub-scenario 3 was 7% less than that of sub-scenario 2 and only 1% higher than that of sub-scenario 4.

Furthermore, the reduction in hydropower production and performance criteria of the system under sub-scenario 3 were appropriate and acceptable compared to sub-scenario 1. Therefore, in all scenarios, the system under sub-scenario 3 policy is identified as the best sub-scenario to balance human and environment requirements.

Comparison of scenarios

As observed, all scenarios provided better results under sub-scenario 3. The first scenario resulted in more hydropower generation than other scenarios under all sub-scenarios. Scenario 1 under sub-scenario 3 resulted in 6.5 and 3%

Table 6 | Summary results of the multi-reservoir operations

			Performance criteria relative to sub-scenario 1 (%) change in						Number of IHA parameters in each level of hydrological alteration						Change in hydrological alteration relative to sub-scenario 1 (%)		IHA class	
			Reliability		Vulnerability		Resiliency		Seimare			Karkheh						
Scenario	Sub-scenario	Change in power production relative to sub-scenario 1 (%)	Seimare	Karkheh	Seimare	Karkheh	Seimare	Karkheh	H	M	L	H	M	L	Seimare	Karkheh	Seimare	Karkheh
1	1	–	–	–	–	–	–	–	1	11	20	2	12	18	–	–	H	H
	2	−2.5	−2.4	−8.6	+3.1	+4.4	−4.5	−8.2	4	11	17	4	23	5	−5	−16	H	M
	3	−4.5	−4.2	−12.9	+6.7	+9.6	−6.6	−10.1	6	15	11	16	13	3	−13	−32	M	M
	4	−6.1	−8.3	−17	+15.9	+18.2	−11.6	−14.7	6	16	10	6	20	6	−14	−18	M	M
2	1	–	–	–	–	–	–	–	1	6	25	3	4	25	–	–	H	M
	2	−1.9	−1.7	−2.4	+4.2	+4.6	−5.3	−7.7	4	8	20	2	21	9	−8	−14	H	M
	3	−2.4	−2.9	−5.2	+7.4	+9.2	−9	−9.3	4	13	15	8	19	5	−14	−26	M	M
	4	−3.1	−5.6	−9.1	+14.3	+17.8	−12.5	−13.4	4	15	13	1	25	6	−15	−16	M	M
3	1	–	–	–	–	–	–	–	1	11	20	3	11	18	–	–	H	H
	2	−2.7	−2.6	−5.5	+9.3	+7.9	−4.8	−6.8	4	10	18	1	23	8	−5	12	H	M
	3	−3.5	−3.2	−7.9	+14.2	+13.1	−7.4	−9.2	4	15	13	6	22	4	−12	−28	M	M
	4	−4.8	−5.1	−10.6	+19	+17.9	−10.9	−13	5	15	12	1	24	7	−13	−14	M	M

L, Low hydrological alteration; M, Moderate hydrological alteration, = High hydrological alteration.

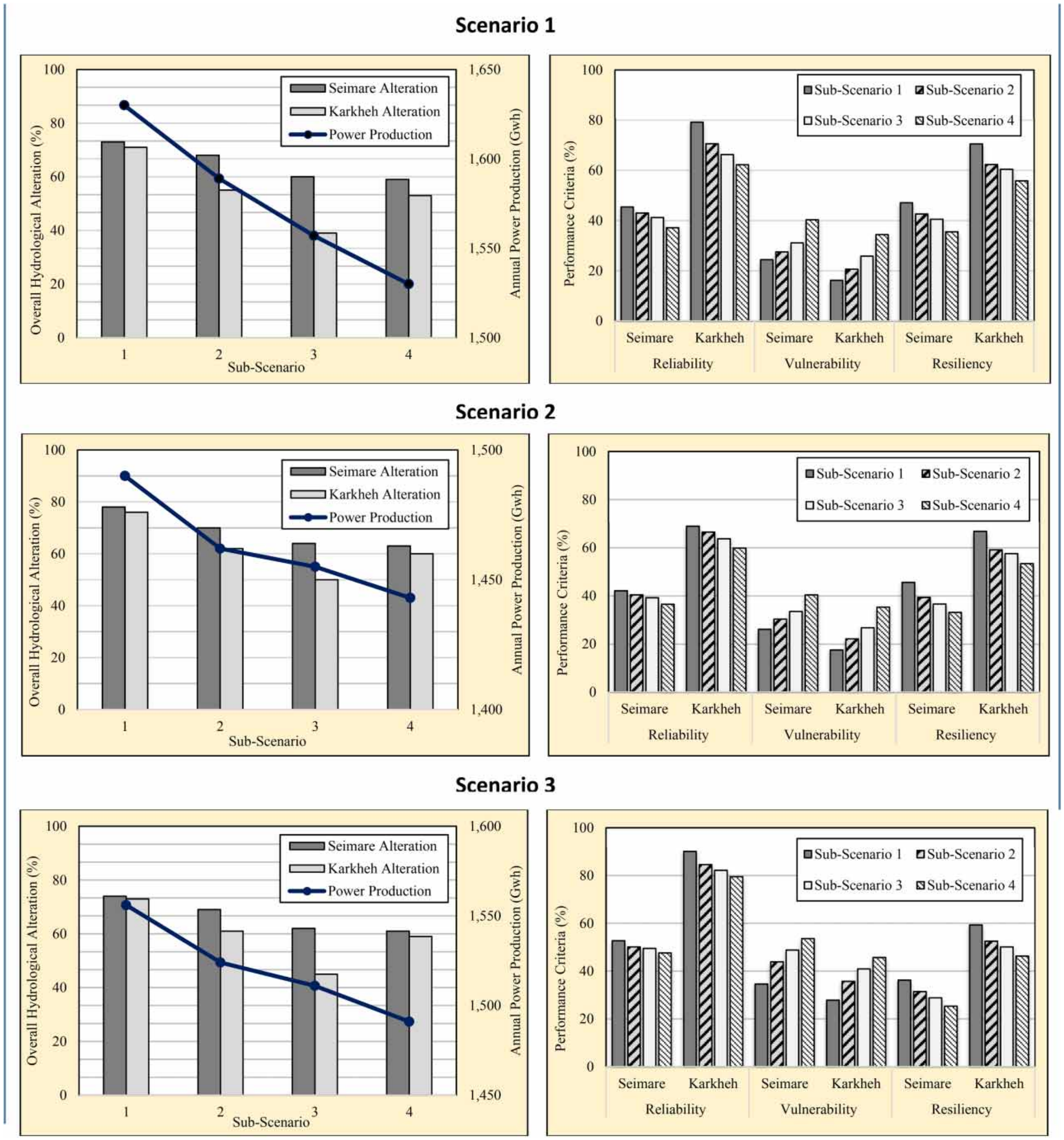

Figure 4 | Annual power production and overall degree of hydrological alteration (left), and performance criteria of the system (right) for alternative scenarios and sub-scenarios.

increase in power production compared to scenarios 2 and 3, respectively. In addition, the comparison of the RVA indicated that the first scenario under sub-scenario 3 presented the least hydrological alteration compared to other sub-scenarios in all three scenarios. In this case, the average hydrological alteration for Seimare River was 4 and 2% and for Karkheh River was 11 and 6% less than those of sub-scenario 3 in model 2 and 3, respectively. The results of the system performance criteria showed that the resiliency associated with scenario 1 under sub-scenario 3 was greater by 3.9 and 11.7% for Seimare reservoir, and 2.9 and 10.3% for Karkheh reservoir, compared to those of sub-scenario 3 of scenarios 2 and 3, respectively. Furthermore, the vulnerability in scenario 1 under sub-scenario 3 was smaller by 2.4 and 17.7% for Seimare reservoir and 0.9 and 15.1% for Karkheh reservoir compared to those of sub-scenario 3 in models 2 and 3, respectively. However, the third scenario under sub-scenario 3 provided greater reliability being 8.3 and 10.3% for Seimare reservoir and 15.9 and 18.5% for Karkheh reservoir compared to those of scenarios 1 and 2, respectively. Therefore, the third scenario provided better reliability than other scenarios, but presented poor vulnerability and resiliency. That is because the HSOP model always tries to reduce the number of system failures and does not pay sufficient attention to the severity of failures and resiliency of the system. As a result, the first model under the third sub-scenario is identified as the best policy to balance human needs and environmental requirements.

The optimal operating rule curves of the Seimare and Karkheh reservoirs based on scenario 1 under sub-scenario 3 is shown in Figure 5. Table 7 presents the monthly hydropower production and hydrological alterations in scenarios 1–3 under sub-scenario 3. According to Table 7, it is obvious that scenario 1 under sub-scenario 3 demonstrated the best hydrological alterations and hydropower production. In general, benefitting from higher inflows into the reservoirs, the hydropower generation during the spring and winter seasons increased, especially from February to May. Concurrently, the hydrological alterations reduced in these

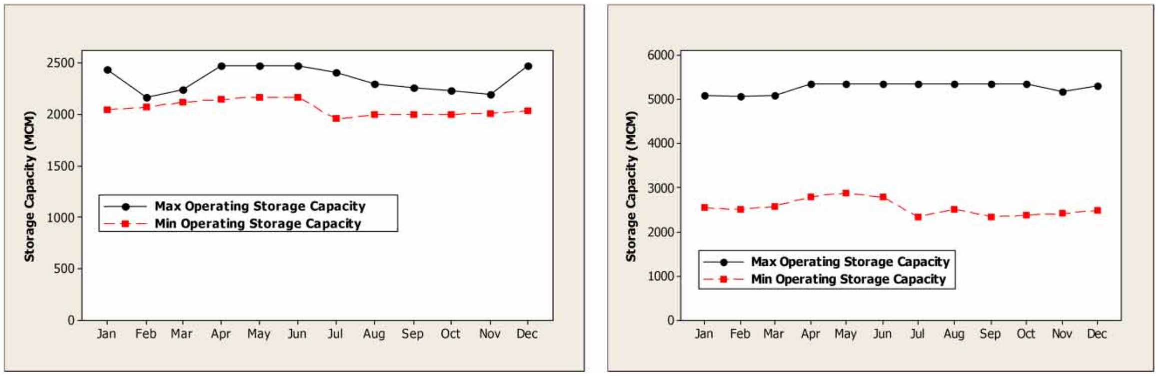

Figure 5 | Optimal reservoir operating rule curves of Seimare (left) and Karkheh (right) reservoirs for scenario 1 under sub-scenario 3.

Table 7 | Monthly power production and hydrological alterations for all scenarios under sub-scenario 3

	Scenario 1				**Scenario 2**				**Scenario 3**			
	Seimare		**Karkheh**		**Seimare**		**Karkheh**		**Seimare**		**Karkheh**	
Month	**HP (MWh)**	**D%**	**HP (MWh)**	**D%**	**HP (MWh)**	**D%**	**HP (MWh)**	**D%**	**HP (MWh)**	**D%**	**HP (MWh)**	**D%**
Oct	31,943.7	100	48,608.1	65	29,687.5	100	48,330.7	74	32,283.0	100	48,429.7	74
Nov	34,711.3	88	53,038.3	37	33,743.7	88	52,489.9	56	34,127.2	77	53,228.8	51
Dec	42,983.7	77	60,721.9	23	39,866.5	77	56,399.3	48	40,384.4	77	61,555.2	48
Jan	43,735.4	65	69,690.1	23	41,832.6	77	58,959.0	56	42,696.1	77	61,977.5	39
Feb	56,755.7	65	91,541.2	23	48,779.5	65	83,443.6	37	50,631.6	65	75,636.0	30
Mar	81,554.2	53	110,284.7	23	75,127.7	65	100,463.8	23	73,509.5	65	108,615.8	39
Apr	98,073.5	18	135,543.3	4	92,610.1	19	130,567.9	13	108,521.7	41	142,068	13
May	94,834.2	30	124,431.6	13	89,417.1	53	121,823.4	23	89,964.4	41	117,102.3	30
Jun	55,188.5	65	70,476.5	13	52,998.3	65	65,078.6	37	50,190.7	53	63,323.4	56
Jul	42,247.4	65	52,014.1	37	39,799.7	65	49,689.7	56	41,498.8	65	51,437.7	56
Aug	34,987.2	77	47,272.8	48	31,873.9	77	45,397.8	56	35,462.5	65	47,645.3	48
Sep	32,013.8	65	44,182.0	48	29,946.4	77	43,290.1	56	33,534.7	77	46,748.7	56

HP, Hydropower production; D, Degree of hydrological alteration.

months. The least hydrological alterations and the most hydropower production belong to April and May. During the summer and autumn seasons (from July–December), the hydropower production reduced and the hydrological alterations increased due to the seasonal shifts and reduced inflow into the reservoirs.

CONCLUSIONS

In this paper, the tradeoff between hydropower generation and environmental flow requirements in a multi-reservoir system was analyzed via simulation-optimization approaches under alternative popular reservoir operation policies in different environmental operating conditions. In this regard three reservoir operation models/scenarios were developed, including two optimization models with objective functions related to maximizing hydropower generation and/or minimizing the difference of release and need, and a simulation model under HSOP approach. The required downstream environmental flows were determined using the EMCs C, B, and A of the FDC shifting method. The hydrological alterations were evaluated using the RVA method. The results of the first sub-scenario with no environmental flow consideration showed severe hydrological alterations in the river reaches downstream of the reservoirs.

The hydrological alteration could be reduced by appropriate changes in operating conditions with no significant impact on the hydropower generation. Of all sub-scenarios, the system under sub-scenario 3, which relied on the EMC-B bounded by EMC-A and EMC-C, presented better results in all scenarios. Therefore, considering the sub-scenario 2 cannot be a suitable approach since the human water demand has higher priority over the environmental requirements in this approach. On the contrary, considering the sub-scenario 4 pays less attention to human water demands. Therefore, both approaches are in conflict with the objectives of sustainable development and cannot simultaneously balance between human needs and environmental requirements. Finally, comparison of the scenarios indicated that scenario 1 under sub-scenario 3 was a good compromise solution to balance human needs and environmental requirements among all the 12 scenario/sub-scenarios defined in this study. It provided adequate hydropower production and performance criteria and also resulted in the least hydrological alterations.

In most developing countries, such as Iran, water managers pay less attention to environmental impacts when operating the reservoirs thus causing ecological predicaments, particularly downstream of dams. We believe that this study draws managers' attention to environmental considerations alongside other demands and is a step forward by offering an optimum compromising solution for balancing various requirements. The solution proposed in this paper is a practical way that is applicable in any reservoir system which is managed to provide an efficient balance between human and environmental needs.

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REFERENCES

Cardwell, H., Jager, H. I. & Sale, M. J. 1996 Designing instream flows to satisfy fish and human water needs. *Water Resour. Plan. Manage.* **122** (5), 356–363.

Docker, B. & Robinson, I. 2014 Environmental water management in Australia: experience from the Murray-Darling basin. *Int. J. Water Resour. Dev.* **30** (1), 164–177.

Eberhart, R. C. & Kennedy, J. 1995 A new optimizer using particle swarm theory. In: *Proceedings of the Sixth International Symposium on Micro Machine and Human Science*. IEEE Service Center, Piscataway, NJ and Nagoya Japan, pp. 39–43.

Ghimire, N. S. B. & Reddy, M. J. 2013 Optimal reservoir operation for hydropower production using particle swarm optimization and sustainability analysis of hydropower. *ISH J. Hydr. Eng.* **19** (3), 196–210.

Hamzekhani, F. G., Saghafian, B. & Araghinejad, S. 2015 Environmental management in Urmia Lake: thresholds approach. *Int. J. Water Resour. Dev.* **32** (1), 77–88.

Homa, E. S., Vogel, R. M., Smith, M. P., Apse, C. D., Lee, A. H. & Sieber, J. 2005 An optimization approach for balancing human and ecological flow needs. In: *World Water and Environmental Resources Congress*. ASCE, Anchorage, Alaska, USA.

Iran Water and Power Resources Development Company (IWPCO) 2009 *Seimare Dam and Power Plant Study*. Technical Report. IWPCO, Tehran, Iran (in Persian).

Iran Water and Power Resources Development Company (IWPCO) 2010 *Karkheh River Basin Water Resources Planning Study*. Technical Report. IWPCO, Tehran, Iran (in Persian).

Jamali, S., Abrishamchi, A. & Madani, K. 2013a Climate change and hydropower planning in the Middle East: Implications for Iran's Karkheh hydropower systems. *J. Energy Eng.* **139** (3), 153–160.

Jamali, S., Abrishamchi, A., Marino, M. A. & Abbasnia, A. 2013b Climate change impact assessment on hydrology of Karkheh Basin, Iran. *Proc. Inst. Civil Eng. Water Manage.* **166** (2), 93–104.

Loucks, D. P. 1997 Quantifying trends in system sustainability. *Hydrol. Sci. J.* **42** (4), 513–553.

Marjanizadeh, S. 2008 *Developing a 'Best Case Scenario' for Karkheh River Basin Management (2025 Horizon); a Case Study From Karkheh River Basin, Iran*. PhD dissertation, University of Natural Resources and Applied Life Sciences of Vienna (BOKU), 185 p.

Meijer, K. S., van der Krogt, W. N. M. & van Beek, E. 2012 A new approach to incorporating environmental flow requirements in water allocation modeling. *Water Resour. Manage.* **26** (5), 1271–1286.

Morán-Tejeda, E., Lorenzo-Lacruz, J., López-Moreno, J. I., Ceballos-Barbancho, A., Zabalza, J. & Vicente-Serrano, S. M. 2012 Reservoir management in the Duero Basin (Spain): impact on river regimes and response to environmental change. *Water Resour. Manage.* **26** (8), 2125–2146.

Mousavi, S. J. & Shourian, M. 2010 Capacity optimization of hydropower storage projects using particle swarm optimization algorithm. *J. Hydroinform.* **12** (3), 275–291.

Muthuwatta, L. P., Ahmad, M. D., Bos, M. G. & Rientjes, T. H. M. 2010 Assessment of water availability and consumption in the Karkheh river basin Iran – using remote sensing and geo-statistics. *Water Resour. Manage.* **24** (3), 459–484.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. & Stromberg, J. C. 1997 The natural flow regime: a paradigm for river conservation and restoration. *Bioscience* **47** (11), 769–784.

Richter, B. D., Baumgartner, J. V., Wigington, R. & Braun, D. P. 1997 How much water does a river need? *Freshw. Biol.* **37** (1), 231–249.

Richter, B. D., Baumgartner, J. V., Braun, D. P. & Powell, J. 1998 A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers Res. Manage.* **14** (4), 329–340.

Saghafian, B. & Hamzekhani, F. G. 2015 Hydrological drought early warning based on rainfall threshold. *Nat. Hazards* **79** (2), 815–832.

Saghafian, B., Golian, S. & Khodadadi, H. 2014 Quasi-online flood forecasting in downstream of dams based on rainfall thresholds. *Hydrol. Res.* **45** (4–5), 519–528.

Smakhtin, V. & Anputhas, M. 2006 *An Assessment of Environmental Flow Requirements of Indian River Basins, IWMI Research Report 107*. International Water Management Institute, Colombo, Sri Lanka.

Smakhtin, V., Arunachalam, M., Behera, S., Chatterjee, A., Das, S., Gautam, P., Joshi, G. D., Sivaramakrishnan, K. G. & Unni, K. S. 2007 *Developing Procedures for Assessment of Ecological Status of Indian River Basins in the Context of Environmental Water Requirements*. IWMI Research Report 114. International Water Management Institute, Colombo, Sri Lanka.

Spiliotis, M., Mediero, L. & Garrote, L. 2016 Optimization of hedging rules for reservoir operation during droughts based on particle swarm optimization. *Water Resour. Manage.* **30** (15), 5759–5778.

Steinschneider, S., Bernstein, A., Palmer, R. & Polebitski, A. 2014 Reservoir management optimization for basin-wide ecological restoration in the Connecticut River. *Water Resour. Plan. Manage.* **140** (9), 04014023.

Suen, J. P. & Eheart, J. W. 2006 Reservoir management to balance ecosystem and human needs: incorporating the paradigm of the ecological flow regime. *Water Resour. Res.* **42** (3), 1–9.

Suen, J. P., Eheart, J. W., Herricks, E. E. & Chang, F. J. 2009 Evaluating the potential impact of reservoir operation on fish communities. *Water Resour. Plan. Manage.* **135** (6), 475–483.

The Nature Conservancy 2007 *Indicators of Hydrologic Alteration*, Version 7, User's Manual. The Nature Conservancy, Charlottesville, Virginia, USA.

Ward, J. V. & Stanford, J. A. 1995 Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers Res. Manage.* **11** (1), 105–119.

Yin, X. A. & Yang, Z. F. 2011 Development of coupled reservoir operation and water diversion model: balancing human and environmental flow requirements. *Ecol. Model.* **222** (2), 224–231.

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