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Integrated surface and groundwater resources allocation simulation to evaluate effective factors on greenhouse gases production

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ABSTRACT

The water resources management in the developing countries calls for the adoption of the systems approach in accordance with the regulations of the Kyoto Protocol (1997) clean development mechanism. In this research, integrated modeling was carried out under multipurpose scenarios using six reservoir dams with a capacity of 10,500 MW (megawatt) to reduce the greenhouse gas productions. The simulation and development of the integrated water evaluation and planning (WEAP) model within a 50-year period, along with the development of the MODFLOW model in alluvial deposits that interacts with the river, allowed for the analysis of the integrated water resources management system of the Great Karun basin. Several scenarios were implemented following the calibration and validation of the linked integrated model. The components covered by these scenarios included the satisfaction of the in-basin and off-basin demands, the effect of the integrated consumption of water resources, and the effect of increased efficiency of irrigation networks with maximum clean hydroelectricity production and minimum aquifer level decline under drought-induced water shortage conditions. The second scenario, which generates 15,282 GWh (gigawatt-hour) of power, not only optimally meets the future and environmental demands as the best operating scenario but also minimizes the emission of the greenhouse gases in the basin.

Key words | clean development mechanism, greenhouse gas, hydroelectricity, MODFLOW, WEAP

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INTRODUCTION

The water crisis caused by population growth and economic development is the most important threat to human societies, limiting sustainable development. The demand for water is increasing with the population growth at a higher speed due to factors such as improved life and health quality, development of urbanism, industries, farming, and the effect of climate change. By 2030, almost half of the world's population will live in areas suffering from water stress, while only 508 million people lived in areas hit by the water crisis in 2000. It could be stated that in the next three decades, the population affected by water issues will increase from 8% to 47%. Moreover, the higher water and energy demand will definitely cause environmental damage. According to the Falcon mark index and the indices used by the Sustainable Development Commission and the International Water Management Institute (IWMI), Iran is going through an acute water crisis and it must increase its harvestable water resources by 112% by 2025, which sounds impossible. As regards the groundwater resources, the average supply volume in Iran is

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approximately 55 billion m^3 a year, while the annual harvest is more than 61 million m^3 a year. Thus, water resource policy-makers in such areas have resorted to water crisis management methods (Hutchinson *et al.* 2010). The existing evidence also suggests the growth of the water crises is due to unsustainable water resource decisions (Cai *et al.* 2003). The adoption of supply-centered policies in dry areas may be effective in the short term but it results in different secondary outcomes in the long term (Madani & Marino 2009). Failure to develop sustainable water resource management solutions for basins is indicative of our inadequate knowledge and the complexities of the integrated water resources system. Therefore, the application of systematic and integrated models, along with multi-objective optimization, facilitates understanding of the mutual effects of the subsystems in a master plan as well as sustainable water resources management and planning (Mirchi *et al.* 2010).

In addition, the increase in greenhouse gas emissions increases the Earth's temperature, and any activity that increases the emission of these gases and upsets their balance affects the entire planet Earth. The concentration of greenhouses gases in the atmosphere has increased to 35% in the past decades, while the Earth's temperature has increased by approximately one degree (Copenhagen Accord 2009). Evidently, the satisfaction of human's energy demands increases the production of greenhouse gases. For instance, the Intergovernmental Panel on Climate Change (IPCC) report revealed that almost 27 gigatons of carbon dioxide is produced by different sources in the world and the share of power generation is approximately 10 gigatons, accounting for 37% of the global emissions. Moreover, the need for electricity is expected to increase by 43% within the next 20 years (World Nuclear Association 2011).

According to the Clean Development Mechanism (CDM) regulations, which are part of the Kyoto Protocol mechanisms, the emission of greenhouse gases by countries must be limited. This commitment involves a 5% decrease in the emissions by 2008 and 2012 compared to 1990 and the violators will be fined.

In the 2015 COP21 Paris Climate Conference, notions such as the use of hydroelectricity as a renewable energy for reducing the global emissions of greenhouse gases were addressed (International Hydropower Association 2016). Many countries such as China, Brazil, and India are currently using hydropower (hydroelectricity) to fulfill their obligations and reduce greenhouse gas emissions (Jones *et al.* 2017). By creating novel energy projects in the past 5 years, these countries have earned a net income of over five billion dollars, securing a multibillion-dollar annual income.

The list of the projects approved by the National Development Fund of Iran and the resources allocated by this fund prove the key role of the generation of electricity in the national development plans. In the generation of electricity, hydroelectricity production accounts for 98.8% of the national production of renewable power in Iran (Islamic Parliament Research Center of the Islamic Republic of Iran, n.d.). In the case of a decrease in hydroelectricity, a fraction of this decline must be compensated by other methods that generate greenhouse gases. The importance of finding a scenario for the optimization of hydroelectricity production is also plain to see. Since more than 93% of the total hydropower plants in Iran are in the Great Karun basin, the integrated management of water resources in this basin is interwoven with the optimization of the allocation of surface and groundwater resources.

Recently, numerous studies have been carried out in Iran and other parts of the world on this issue. For instance, Dalir *et al.* (2017) introduced a conceptual method for the calculation of carbon footprint in the combined cycle power plants of Iran. Anugrah *et al.* (2015) studied the effect of climate change on the generation of hydroelectricity in the small-scale power plants in Bayang River basin in Indonesia using water evaluation and planning (WEAP) software under IPCC climate change scenarios, namely scenarios A2 and B2. Amponsah *et al.* (2014) compared the results from 79 studies carried out through the assessment of the life cycle of greenhouse gases and the effect of different hydropower plants on the emission of these gases and reported their findings. In addition, Haddad *et al.* (2013) developed a decision support system (DSS) using the WEAP model and MODFLOW model for the management of the Geous aquifer in the south of Tunisia. Poblete *et al.* (2012) modeled the water resources in Maule River basin under the climate change scenario using WEAP. Raadal *et al.* (2011) studied two types of power plants that produce minimum greenhouse gases, namely wind farms and hydropower plants. Mugatsia (2010) simulated and formulated a scenario for the water resources model of Perkerra Catchment in Kenya using the WEAP model. They proposed a DSS for this catchment that suits different results and uses. Droogers *et al.* (2009) explored the effect of climate change on hydropower generation and its profitability in Kenya using the WEAP model. Bharati *et al.* (2008) also developed an integrated simulation-optimization model to analyze the simultaneous use of surface and groundwater resources in the Volta irrigation network in Ghana. Haddad *et al.* (2007) implemented the Tulkarm basin decision model in Palestine using the WEAP model. Weisser (2007) compared the results from the recent studies on the emission of greenhouse gases by power generation resources through life-cycle assessments. Hondo (2005) estimated the emissions of greenhouse gases by nine power plant types, namely coal, petroleum, natural gas, combined cycle, nuclear, hydroelectricity, geothermal, wind, and photovoltaic power plants, through life-cycle assessments. Miller & Labadie (2003) analyzed the optimization of integrated operation on the regional scale, and used the MODFLOW model to calculate the response matrix coefficients. They also used MODSIM as the optimization model.

In this research, the development of the best management scenario was studied to determine the role of the surface and groundwater consumptions along with all system factors such as the variation of efficiencies of irrigation networks through integrated modeling. The goal was to meet the demands, maximize hydroelectricity generation, and set the scene for the minimization of the emissions of greenhouse gases in the most important catchment in Iran.

In other words, the rationale behind this study was the simultaneous investigation of the impact of all natural and human factors on greenhouse gas production in a water resource system. An important natural factor was the effect of drought-induced discharge reduction and the simulation of tidal aquifers. One of the human factors was the role of inter-field water transfer and the effect of irrigation network efficiency on the basin water resources system. Only all the above mentioned factors can be combined together with CDM.

METHODOLOGY

Simulation and optimization

In this research, the WEAP model was used with the integrated approach to the simulation of water systems. This model functions on the basis of water balance and demand-related factors such as consumption patterns, efficiency, costs, and allocation considered in its equations, along with the resource-related factors such as surface and groundwater flows and reservoirs. The Stockholm Environment Institute has been the primary developer advocate of this model, and it has also been supported by the Hydrological Engineering Center of the American Society of Civil Engineers and the World Bank (Sieber *et al.* 2005). The MODFLOW model developed by the United States Geological Survey was also used to simulate groundwater resources. Visual MODFLOW Flex is a graphical user interface for MODFLOW groundwater simulations (Waterloo Hydrogeologic n.d.). For the correct simulation of river flows, the discharge statistics within the simulation period were incorporated into the model, and the model calibration and estimation of flow in rivers and branches were carried out in stations following the implementation of the two models. The normalization of river discharges was carried out to add the value to the branch nodes. The drinking, industrial, and present and future agricultural consumption values were entered into the software using relations such as the calculation of the population growth and industrial development. The environmental demand was also calculated using the Tennant (Montana) Method and was added to the related node.

The simulation process was completed separately and the models were calibrated and validated separately. Initial optimization of some parameters was performed in the form of special modules, such as the PEST module in the MODFLOW model for the required parameters such as aquifer hydrodynamic coefficients. In the final step after linking the two models, a target function was defined and implemented with the approach of maximizing energy production and minimizing aquifer loss. Finally, the operational scenarios were implemented with the optimal separation approach of water and hydropower allocation. The flowchart of the modeling process is presented in Figure 1.

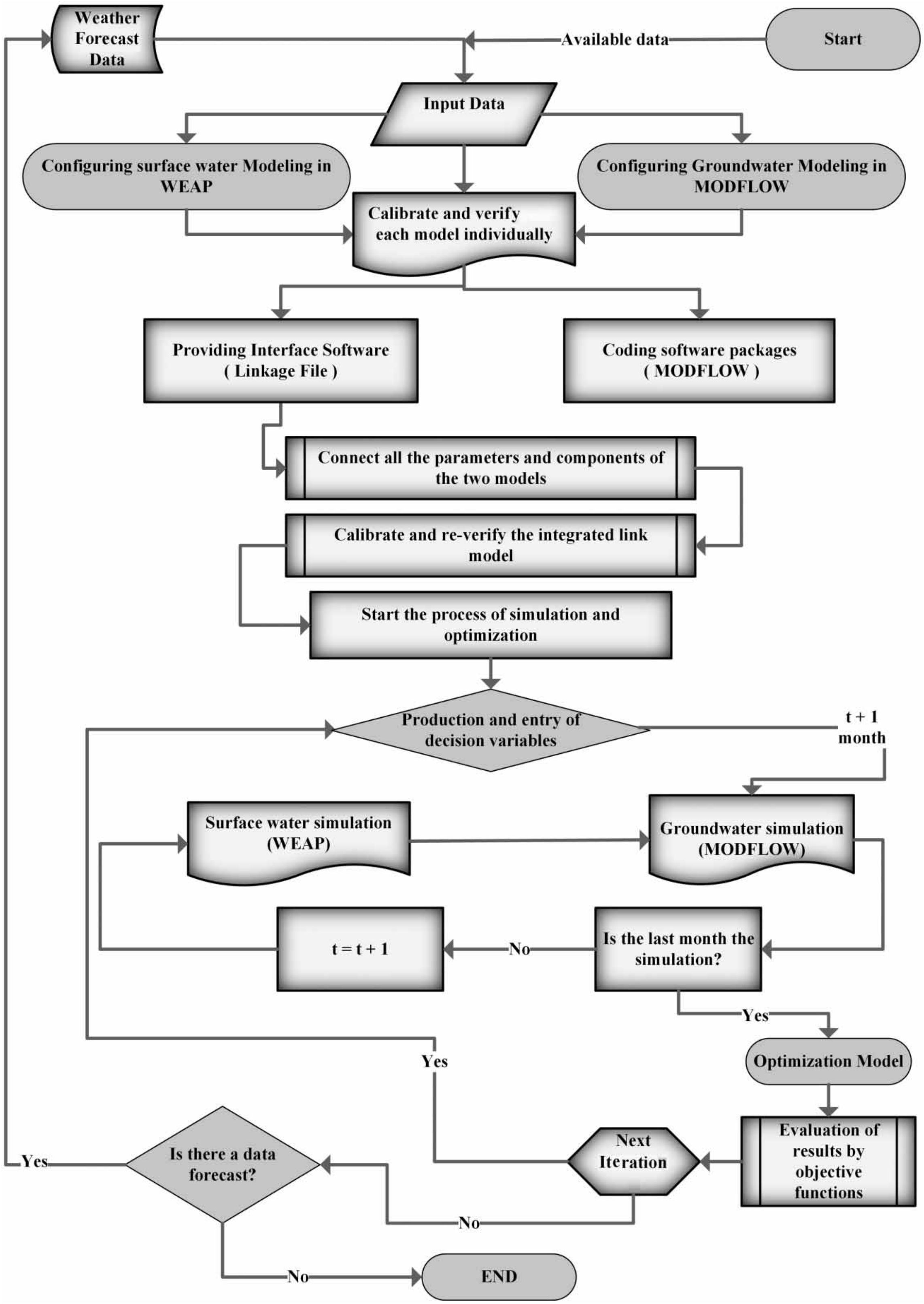

Figure 1 | Flowchart of modeling and implementation process.

Calculating the emissions of pollutants using the emission factor in power plants

In power plants, the emission factor regarding the mass of the produced pollutants or the combustion gases is expressed in terms of the generated electricity or the generated thermal energy. In general, the estimation of emission is expressed via Equation (1) (UN-Water 2008).

$$E = A \times EF \times \left(1 - \frac{ER}{100}\right) \tag{1}$$

E: Emission of pollutants (the pollutant mass)
A: Activity rate (the production of the industrial unit such as the produced cement (ton) or generated electricity (KWh))
EF: Emission factor (the emitted pollutant mass per unit product or activity rate)
ER: Overall decrease (%) in emission which is equal to 0 if pollutant reduction systems are not employed

Life-cycle assessment of the emission of greenhouse gases in power plants

The life-cycle emission (LCE) index can assess the emission of greenhouse gases by different power generation technologies. The amount of greenhouse gas emissions in the entire production life cycle per kilowatt hour of power is expressed in Equation (2) (Weisser 2007).

$$\mathrm{LCE} = \frac{\sum_i GWP_i \times (E_{f_i} + E_{c_i} + E_{o_i} + E_{d_i})}{Q} \tag{2}$$

E_f: Direct emission caused by the combustion of fossil fuels in power plants
E_c: Emissions during the construction of power plants
E_0: Emissions during operation and maintenance of power plants
E_d: Emissions at the end of the lifetime of power plants and demolition of power plants
i: Greenhouse gas type
GWP: Global Warming Potential of each greenhouse gas
Q: The net output during the power plant lifetime

In this relation, E_0, E_c, and E_d show the indirect emission of greenhouse gases. It should also be noted that the net power output equals the power supplied to the network minus the energy consumed for power plant operation.

STUDY AREA

The Great Karun basin is a large part of the Persian Gulf catchment and consists of the Dez and Karun rivers in the Middle Zagros heights. It is also mainly composed of the Khuzestan Plain. Karun basin is located at longitude 48°00′E to 52°30′E and latitude 30°00′ to 34°05′N. With an area of 67,112 km^2, this basin reaches the basins of Ghareh Chai, Saveh, Golpayegan, and Zayandeh Rud rivers in the north and reaches the basin of Karun River in the west. It also meets the basins of Zohreh, Marun, and Jarahi rivers in the east. Moreover, 68% of the surface area of this basin is formed of mountains, 32% is composed of plains, and the rest is made of foothills (Arshadi & Bagheri 2014). Given the share of the mountainous regions and the high water potential, this basin suits the development of hydropower plants. Figure 2 depicts the position of the Great Karun basin.

Surface water or river resources system

The Karun River is the largest and has the highest discharge volume of water in Iran in the Persian Gulf and Gulf of Oman basins. The basin covers Khuzestan, Lorestan, Chaharmahal and Bakhtiari, Kohgiluyeh and Boyer-Ahmad, and Isfahan Provinces. The Dez River is the most important branch of the Karun River and is composed of two major branches, namely the Caesar and Bakhtiari branches.

Hydrological studies were carried out based on the existing information over a 60-year statistical period from 1995–1996 to 2014–2015.

The normalized water yields of the rivers in the areas in this study were added to the model. Table 1 presents the monthly and annual average water yields of these rivers. Table 2 presents a summary of the information on the water reservoirs.

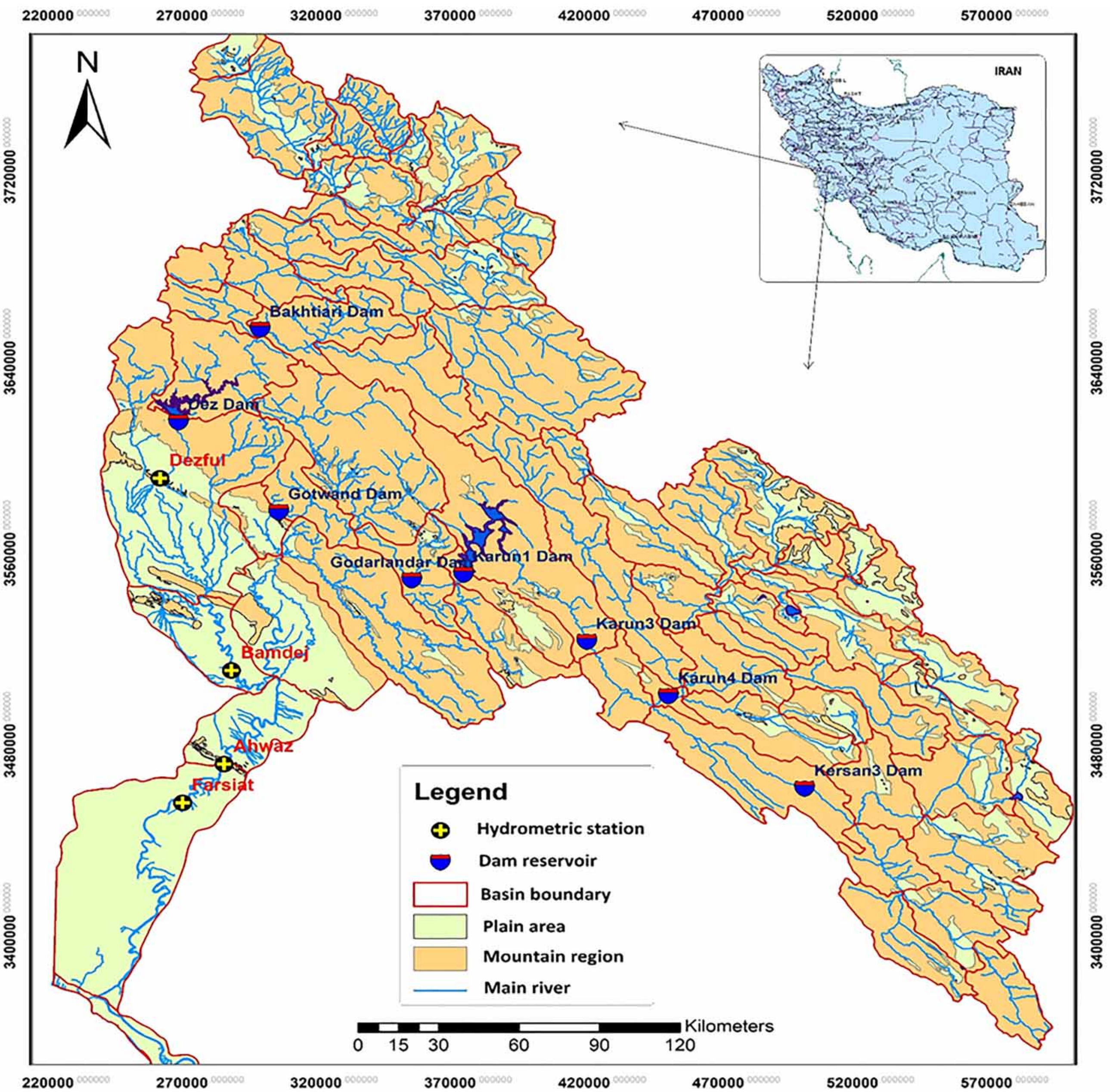

Figure 2 | The map of the Great Karun basin and the positions of the characteristic dams and hydrometric stations.

Groundwater resources or aquifers system

In the study basin, there are several aquifers with a surface area of 9,205 km^2. Some of these aquifers have water exchanges with the river system. The average total volume of the aquifers in the basin is approximately 31,931 million m^3. The discharge of the aquifer water into the river is approximately 1,363 million m^3 per year. The aquifer parameters were entered into the linked software and were simulated.

Needs and demands

Since the existing parameters were entered into the model to calibrate it and then the future management policies were

Table 1 | The monthly and annual average water yields of the Dez and Karun rivers in the study areas (m^3/sec)

Location	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual (cms)	Annual (MCM)[a]
Bakhtiari River	43.5	57.2	90.8	96.8	143.1	203.3	298.8	287.3	171.2	107.1	71.6	52.7	135.3	4,266.2
Sezar River	20.5	47.3	85.5	81.6	121.4	181.2	243	183.5	83.5	43.6	30	23.1	95.4	3,007.1
Dez Dam	6.8	9.8	17.3	19.7	27.8	39.5	54.4	47.9	26.1	15.7	10.6	7.9	23.6	744.9
Dez River	1.2	8.8	21.5	23.3	22.2	28.6	22.3	11.1	3.3	2.2	1.6	1.1	12.3	387
Khersan River	41.1	39.6	68.6	88.1	115.5	164.1	200.6	148.9	120.7	88.9	66.7	50.7	99.5	3,137.2
Karun 4 Dam	86.4	94.3	139.2	140.5	187.9	289.1	412.1	374.3	272.3	190.4	137.5	101.6	202.1	6,374.3
Karun 3 Dam	60.1	65.5	96.7	97.7	130.6	200.9	286.3	260.1	189.2	132.3	95.5	70.6	140.5	4,429.6
Karun 2 Dam	133.1	149.1	215.2	244.6	311.2	467	671.7	601.4	431.1	298.8	211.8	158.2	324.4	10,231.8
Karun 1 Dam	1.5	10.2	51.1	40.9	34.2	28.2	27.3	8.7	3.5	2.5	2	2	17.7	557.2
Godar Dam	1.2	9.3	39.7	32.4	27.7	23.6	21.7	7.5	2.7	1.9	1.5	1.5	14.2	448.5
Gotvand Dam	2.5	19.8	35.3	38.7	37.1	60.3	72.1	32.8	4.4	3.1	2.3	3.1	26	818.6
Karun River	1	14.6	26.1	26.1	23	24.3	14.5	6.1	1.3	0.8	0.8	0.7	11.6	366.7

[a]MCM = million cubic meters.

analyzed, the present and future consumptions are presented in the following separately.

Present demands and consumptions

The current agricultural needs of the study area are approximately 11 billion m^3 considering the withdrawal points during different periods (sum of withdrawals during different periods). In sum, the total drinking and industrial water demands of the study area are about 496 million m^3. The total aquaculture demand in the study area is also approximately 2 billion m^3. In addition to the mentioned needs, the environmental demand at the Persian Gulf inlet is 90 m^3. In sum, the total agricultural need in the study area will be allocated approximately 15.5 billion m^3 in the future.

Future consumptions and demands

In the future, the Ghadir Water Transmission Plan for the transfer of water from the Dez Dam will supply 498 million m^3 of drinking water in the area between Ahwaz and Abadan, while the rest of the demand will be met by the Karun River. The total drinking and industrial water demand of the study area will be about 2 million m^3 in the future. As regards the aquiculture demand, the present need equals the future need as mentioned. The plan for the transfer of Dez River water to the Karkheh basin is designed for the future. The monthly supply of water will be 100 million m^3, and a total of 1 billion and 200 million m^3 of water will be conveyed from the Dez River to the Karkheh basin on an annual basis. This point of consumption is located after the Dez Dam and is included in the model.

Table 2 | A summary of the information on the reservoirs in the study area

Power plant capacity (MW)	Latitude	Longitude	Main river	Province	Power plant
1,000	50°24′05″N	31°35′53″E	Karun	Chaharmahal	Karun 4
2,000	31°48′08″N	50°05′41″E	Karun	Khuzestan	Karun 3
2,000	32°03′06″N	49°36′25″E	Karun	Khuzestan	Karun 1
2,000	32°01′40″N	49°24′01″E	Karun	Khuzestan	Godar
1,500	32°16′08″N	48°56′10″E	Karun	Khuzestan	Gotvand
520	32°36′20″N	48°27′49″E	Dez	Khuzestan	Dez
1,500	32°58′00″N	48°47′00″E	Bakhtiari	Lorestan	Bakhtiari

Moreover, considering the measures taken to meet the environmental demands of the Persian Gulf from another source and replacing the current source with the Karun River, a discharge rate of 40 m^3/sec is assumed for meeting the environmental demand of the Persia Gulf in the future. The total upstream need is 3.5 billion m^3, which is included in the simulation model.

Surface water and groundwater simulations and scenarios

Surface water simulation using WEAP

In the surface water simulations in this research we used the data required for modeling the Great Karun basin, including the natural water yield of the Dez and Karun rivers, the future and predicted consumptions in different basin areas, specifications of the reservoirs and power plants in the drainage basin, evaporation in the reservoirs, data from the hydrometric stations in the basin, the raw geographic information system (GIS) data on the basin, and other minor information. After collecting, controlling, and preparing in the desired formation, this data was used to model the basin. Figure 3 illustrates the schematic configuration of the integrated water resources model developed in this research.

Groundwater simulation

The mathematical model indirectly simulates groundwater flow using a governing equation and series of equations describing hydraulic load and flow along the model boundaries. Thus, the three-dimensional model of the aquifer area is the mathematical expression of groundwater flow using the Groundwater Modeling System (GMS; initially developed for the U.S. Department of Defense) interphase, which is based on MODFLOW 2000. Different steps of developing a mathematical model include setting the goal, designing the conceptual model, selecting a suitable validated computer code or program, calibrating, sensitivity analysis, and finally prediction (Anderson et al. 2015).

The greatest and most important aquifer in this study area is located to the west of Dez and Ahudasht, where the annual discharge is 1,500 million m^3 through 2,000 wells. To determine the geometry, type, quantity, and constituents of the two top layers of the aquifer, geological surveys, drilling logs of 12 exploration wells, 49 piezometric wells, 90 operational wells, and geophysical surveys were employed. More than 13 of these wells have reached the bedrock.

This area is surrounded by the Dez and Karkheh rivers on the sides. According to the hydrological studies, Dez River feeds the plain from the inlet of Dezful-Andimeshk Plain to the intersection of the upstream and Dez rivers, and functions as groundwater drainage thereafter. In addition to the hydrodynamic, surface recharge, and groundwater recharge coefficients, all of the drainages in the great irrigation network of Dez were entered into the DRAIN module of the software, along with the conductance values. The underground conceptual model of the greatest two-layer aquifer simulated in the study area is depicted in Figure 4.

The general form of the equation governing the groundwater flow from the flow system viewpoint is as follows:

$$\partial/\partial_x(K_x\,\partial h/\partial_x) + \partial/\partial_y(K_y\,\partial h/\partial_y) + \partial/\partial_z(K_z\,\partial h/\partial_z) = S_s\,\partial h/\partial t \pm R \tag{3}$$

where k_x, k_y, and k_z are the hydraulic conductivity tensor components, h is watertable depth and t is time. Besides, S_s denotes the specific capacity and R is the recharge or discharge (positive and negative signs) of the aquifer.

Considering the conceptual model, this aquifer is an unconfined aquifer in the northern part of the model and is composed of two layers in the southern part. In the unconfined aquifer, $T_x = K_x \times h$ and $T_y = K_y \times h$, where T_x and T_y denote the transfer potentials and h shows the diameter of the saturated section of the aquifer. Therefore, the equation governing the groundwater flow from the aquifer point of view is expressed as follows, which is known as the non-linear Boussinesq equation:

$$\frac{\partial}{\partial x}\left(k_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y h \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z h \frac{\partial h}{\partial z}\right) = S_s \times \frac{\partial h}{\partial t} \pm R \tag{4}$$

Since

$$\partial x/\partial h \times 2h = \partial x/\partial h^2$$

$$\partial y/\partial h \times 2h = \partial y/\partial h^2$$

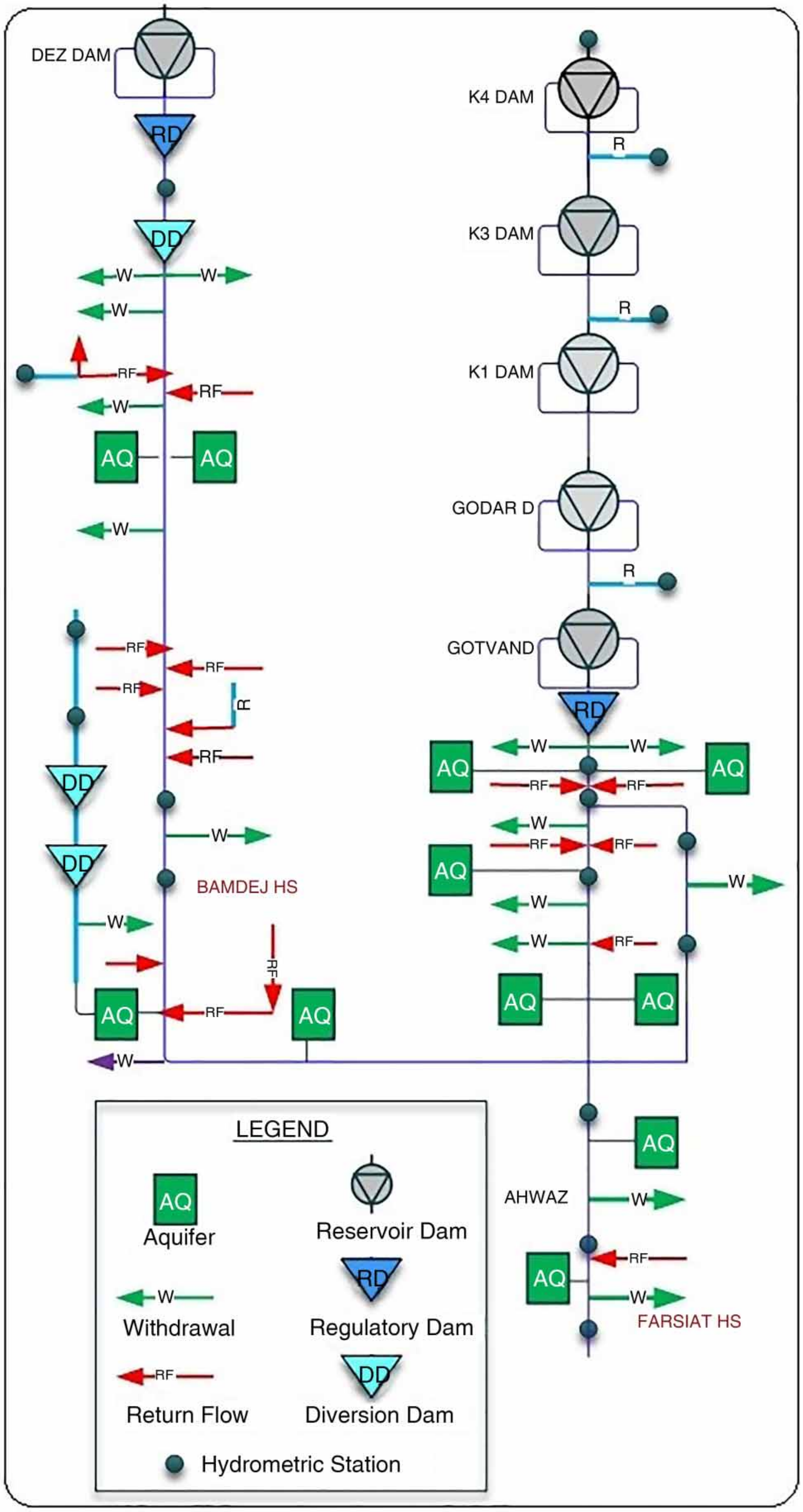

Figure 3 | Schematic configuration of the integrated water resources model of the study basin.

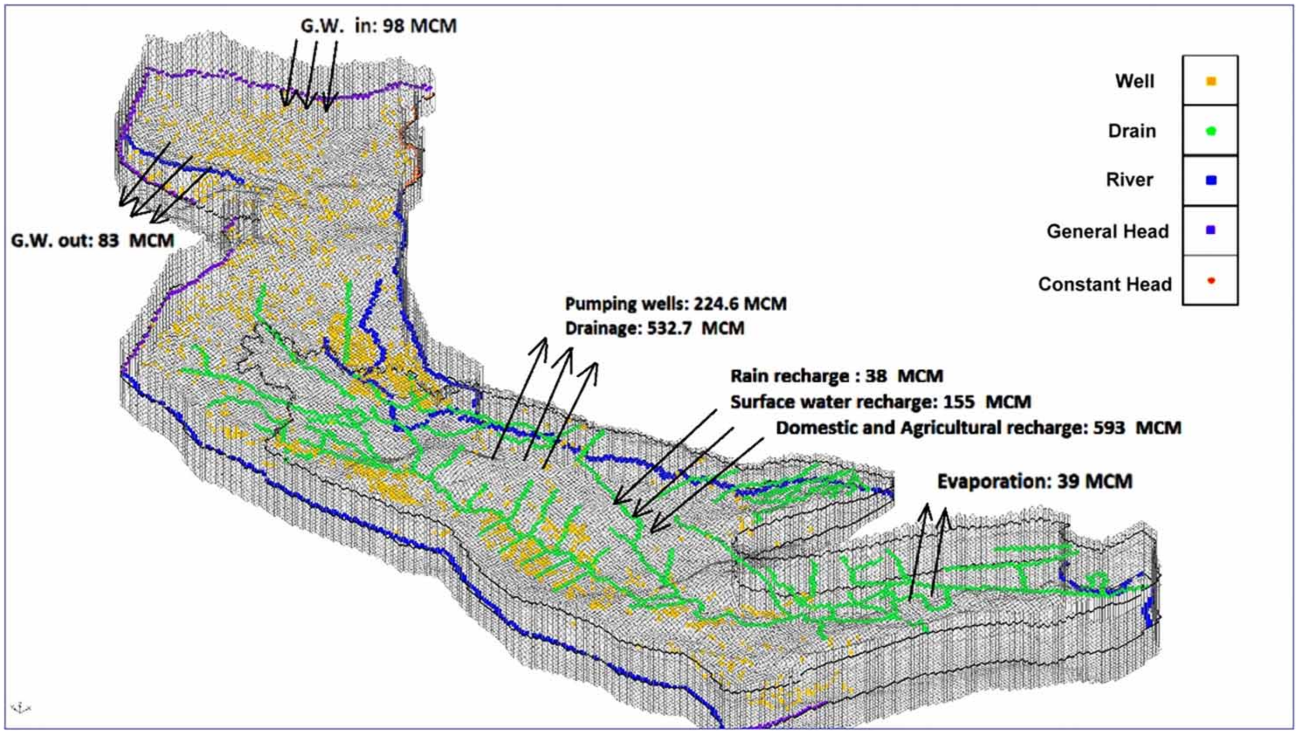

Figure 4 | The underground conceptual model of the greatest two-layer alluvial zone simulated in the research.

Equation (4) can be written as follows:

$$\frac{\partial}{\partial x}\left(k_x \times \frac{\partial h^2}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \times \frac{\partial h^2}{\partial y}\right) = 2S_y \times \frac{\partial h}{\partial t} \pm \mathrm{R} \tag{5}$$

The above equation is also nonlinear.

Numerous researchers such as Hornberger *et al.* (1970) and Sartoretto *et al.* (1989) have solved this equation using the numerical methods designed for nonlinear equations. This equation is linearized using a known saturation diameter value in the numerical model, which is the same as the method used in MODFLOW (Anderson *et al.* 2015).

The MODFLOW code uses the finite difference and block-centered network elements to solve the problems. Considering the geological and topographic conditions, equipotential maps, water resources maps, and the surface area of the region, a network with 250×250 m^2 cells consisting of 187 rows and 346 columns was developed for the study area. The parameters such as the bedrock, elevation, hydraulic conductivity, storage coefficient, surface recharge, and initial water table were allocated to each model network cells. Thus, the model network consisted of 64,702 cells.

The mathematical model of the aquifer groundwater flow was prepared and implemented in the steady and unsteady states. The annual hydraulic cycle was also divided into four seasonal periods. The length of each period equaled the number of days in each season (3 months). These four periods are known as the stress periods in MODFLOW because the hydraulic stresses vary by period but they remain invariant during each period. A time step is defined for each stress period, while a stress period in the steady state lasts 365 days. The unsteady model was also developed for a 7-year period consisting of 11 stress periods. Moreover, the unsteady model was validated during three seasonal stress periods in the 2013–2014 water year.

Figure 5 shows the model sensitivity to the hydraulic conductivity variations. The three conventional methods of identifying the calibration criterion are as follows.

Mean error (ME): This is the mean difference between the measured hydraulic load (h_m) and the simulated hydraulic

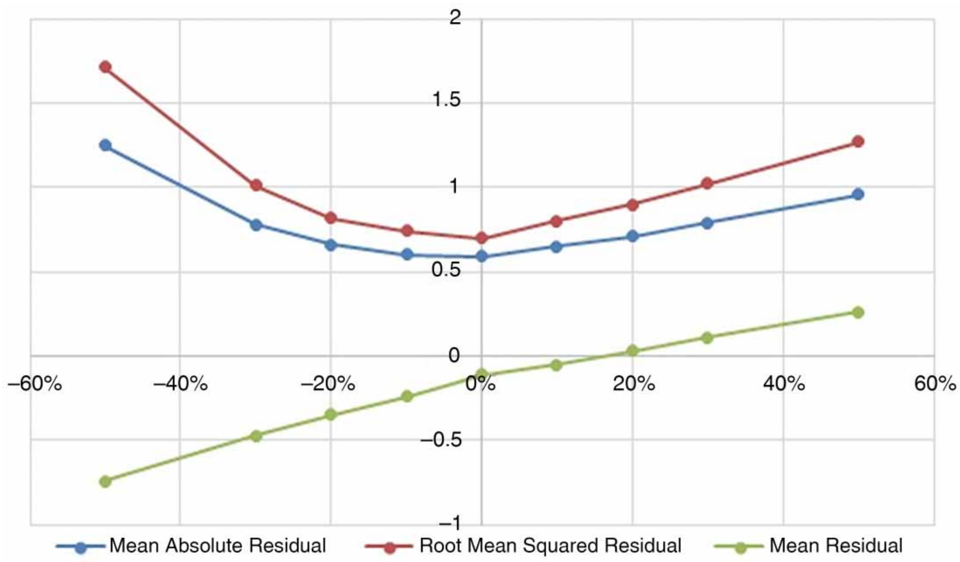

Figure 5 | Sensitivity of the model to the variations of hydraulic conductivity.

load (h_s).

$$\mathrm{ME} = 1/n\,\Sigma_{i=1}^{n}(h_m - h_s)_i \quad (6)$$

where n is the number of piezometers and i is the index of piezometers. ME is easy to measure, but it is not a good measure because the algebraic sum of the positive and negative means neutralize each other's effects. Therefore, a low ME is not indicative of an effective calibration.

Mean absolute error (MAE): This refers to the mean difference between the simulated hydraulic load and the measured hydraulic load.

$$\mathrm{MAE} = 1/n\,\Sigma_{i=1}^{n}|(h_m - h_s)_i| \quad (7)$$

Root mean squared error (RMS): The root mean squared error or the standard deviation is the mean squared difference between the simulated hydraulic load and the measured hydraulic load.

$$\mathrm{RMS} = [1/n\,\Sigma_{i=1}^{n}\ (h_m - h_s)_i]^{1/2} \quad (8)$$

To carefully assess the calibration results, the measured and simulated loads, their differences, and different mean errors (Table 3) were included in the calibration.

Among the 70 piezometers, the observed and calculated water levels were in the calibration target range except for a few piezometers.

Designing multipurpose scenarios

After entering the data into the model, six scenarios were defined to evaluate the objectives of the integrated model system.

1. Increasing the volume of water exchanged between the basins in the river upstream areas; keeping the downstream consumptions invariant; keeping the river water yields unchanged; and keeping the efficiency of the irrigation networks and withdrawals from aquifers constant.
2. Maintaining the exchange of water between the river upstream basins; increasing the downstream consumptions; keeping the river water yields invariant; increasing the efficiency of the irrigation networks by 5%; and using groundwater and surface water resources simultaneously.

Table 3 | Different mean errors for the assessment of the calibration error

Item	Value
Mean residual (Head)	−0.11
Mean absolute residual	0.59
Root mean squared residual	0.7

3. Increasing the volume of water exchanged between river upstream basins; increasing the downstream consumptions; keeping the river water yields unchanged; keeping the efficiency of the irrigation networks unchanged; and integrated use of ground and surface water resources.
4. Increasing the volume of water exchange between the upstream basins; keeping the downstream consumptions unchanged; reducing the river water yield by 5%; increasing the irrigation network efficiency by 5%; and keeping the withdrawal from aquifers unchanged.
5. Keeping the exchange of water between the upstream basins invariant; increasing the downstream consumptions; reducing the river water yield by 5%; keeping the irrigation network efficiency unchanged; and using the ground and surface water resources simultaneously.
6. Increasing the volume of water exchanged between the river upstream areas; increasing the downstream consumptions; keeping the river water yields unchanged; increasing the efficiency of the irrigation networks by 5%; and using ground and surface water resources simultaneously.

RESULTS AND DISCUSSION

After linking the surface and groundwater resource model, the drainage basin was simulated for the present time. Afterwards, the results from the implementation of the model using the downstream hydrometric stations of the Dez and Karun rivers real data were compared. The last three years of the statistical period were selected to compare and validate the model. A comparison was also drawn between the cumulative inflows of the rivers in Bamdezh hydrometric stations in the downstream area of the Dez and in Farsiat hydrometric station in the downstream part of Great Karun. Figure 6 presents the acceptable model performance results in the validation phase through a comparison between the discharges observed in Farsiat hydrometric station and the calculated discharge. The positions of these stations in the Great Karun basin are also shown in Figures 1 and 2.

As mentioned, the validated integrated model was implemented and studied under six management scenarios. These scenarios were designed and compared for the optimum satisfaction of needs and supply of energy, for the minimization of greenhouse gas emissions, and for the supply of the minimum environmental nodes in the river downstream. In these scenarios, the integrated use of the surface and groundwater resources, the irrigation network efficiencies, and basin drainage are considered the important components with effective weights. The rational effect of drought is also taken into account in relation to a decrease in river inflows under the designed scenarios. Figure 7 presents the comparison between the hydropower generation in the present and in the defined scenarios. The average drainage basin production is currently 15,454 MW.

In Figure 8, the effects of the management policies of the Great Karun basin on the emissions of greenhouse gases in

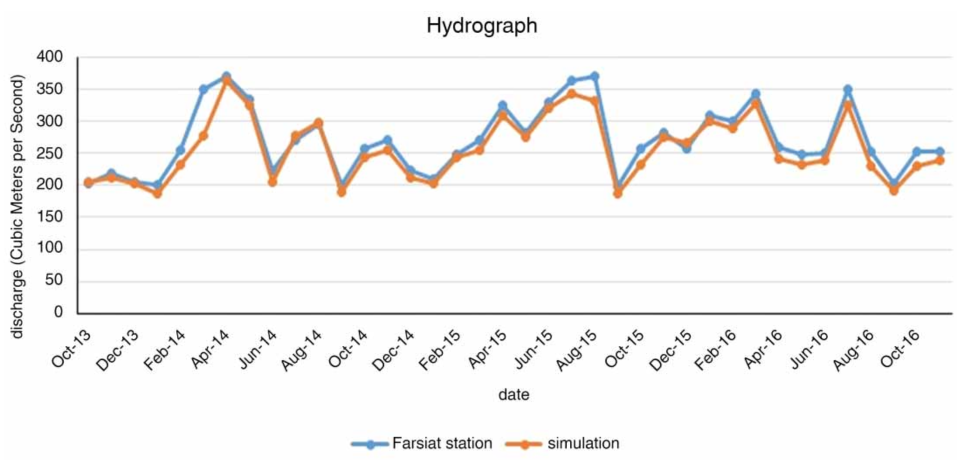

Figure 6 | The comparison of the discharges in Farsiat hydrometric station and the location of this station in the model (m^3/sec).

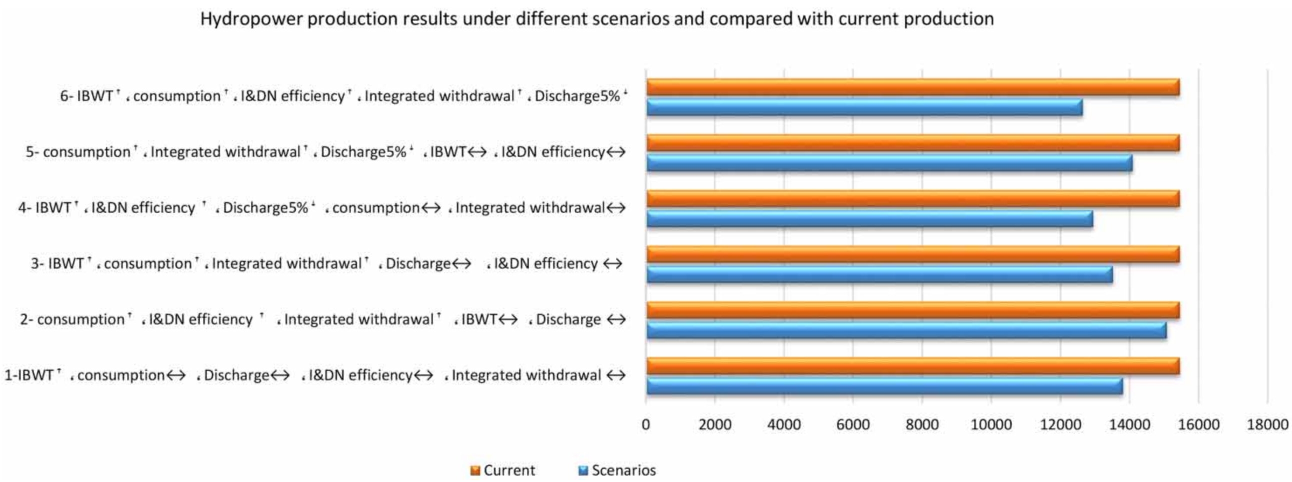

Figure 7 | A summary of the comparison of the hydropower productions in the present and different scenarios (GWh).

different scenarios are summarized based on the two study methods.

As seen in Figures 7 and 8, the comparison between the scenarios indicates that the second scenario is the best scenario considering the components of concern. In this scenario, the inter-basin water transfer remains unchanged while the downstream consumptions increase in accordance with the long-term plan. Moreover, the river water yield is assumed to be invariant. In this scenario, production of hydroelectricity can be effectively managed along with the optimum satisfaction of the demands through the integrated use of the surface and groundwater resources and a 5% increase in the irrigation network efficiency. In other words, in this scenario it is possible to meet the demands and adopt an environmental approach to the supply of the environmental node to the river downstream. It is also possible to increase the consumptions and manage water-oriented development and minimize the production of greenhouse gases with the maximum hydroelectricity production.

Therefore, the amount of hydroelectricity generated in the aforesaid condition is presented in Table 4 for an average 60-year production period.

According to the results, through the integrated use of resources and only a 5% increase in the efficiency of the networks, an almost 172-GWh decrease will be witnessed in the hydroelectricity production despite the 7 billion m^3 increase in the future consumptions in the Great Karun basin. This decrease is much smaller than the effect of inter-basin water exchange. It is also equal to a 1.1% decrease in the production of hydroelectricity in the basin.

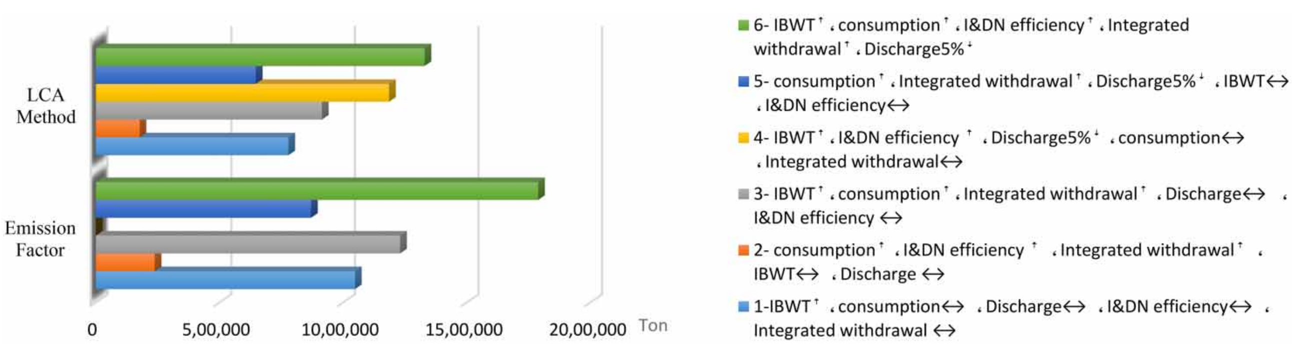

Figure 8 | The resulting emissions of greenhouse gases (ton) in different scenarios using the two study methods.

Table 4 | The comparison of the mean hydroelectricity productions in the present and future conditions under the best scenario (GWh)

Dam and power plant	Present production Mean 60-year production	Future production Mean 60-year production	Present – Future Future production variations	Production variations (%)
DEZ	2,350	2,233	117	−4.97
GODAR	2,740	2,737	3	−0.1
GOTVAND	2,986	2,910	76	−2.54
KARUN 1	2,690	2,710	−20	+0.74
KARUN 3	2,806	2,805	1	−0.03
KARUN 4	1,882	1,887	−5	+0.26
TOTAL	15,454	15,282	172	−1.1

CONCLUSION

In this research, we aimed to explore the roles and weights of the hidden and evident determinants of hydroelectricity production and its optimum management. The results suggested that the inter-basin water exchange is the most important cause of the decrease in hydropower production in this basin and accounts for 93% of the hydroelectricity production of the country. This factor causes the maximum decrease in the generation of hydroelectricity in the basin and an increase in the emission of greenhouse gases resulting from the alternative energy production methods by reducing the river branch flows. The results from weighting priorities of the components determining hydroelectricity production and emission of greenhouse gases are as follows in order of importance.

1. According to the model results, inter-basin water exchange with the 1.5 billion m^3 increase results in a 10% decrease in the annual average hydroelectricity production in the basin. Thus, this component has the most significant effect and weight compared to the other parameters in the decrease in energy production (~1,500 GWh) and the increase in greenhouse gas emissions (1.3 million tons).
2. The second component involves the effect of climate change and the decreased water yield of the rivers, which cause a 5% decrease in the annual hydroelectricity production of the drainage basin.
3. The third component shows the role of an increase in the basin consumptions, which results in a 3% decrease in the annual production of hydroelectricity in this basin by causing a 7 billion m^3 increase in the basin consumptions.
4. The fourth component mirrors the effect of a 5% increase in the irrigation network efficiency. The results revealed that following the increase in the efficiency, the hydroelectricity production increases by 2%, preventing the production of 250,000 tons of greenhouse gases by the alternative power plants.
5. The fifth component is the integrated consumption of surface and groundwater resources. The results from the implementation of the model revealed that the hydroelectricity production in the drainage basin increases through the integrated management of the operation of water resources, preventing the production of 125,000 tons of greenhouse gases by the alternative power plants.

Since the increase in the basin needs is often inevitable, it is concluded that it is possible to optimally manage the production of hydroelectricity and meet the future demands through the integrated use of the water resources and a 5% change in the irrigation network efficiency (the best scenario).

Finally, the results from the integrated modeling of this basin reflected the high potential of this great basin for preventing an increase in greenhouse gas emissions. These results also mirrored the possibility of obtaining a Certified Emission Reductions license using the clean development mechanism through proper management.

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