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ORIGINAL ARTICLE

# Integration of hydrologic and water allocation models in basin-scale water resources management considering crop pattern and climate change: Karkheh River Basin in Iran

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**Abstract** The paradigm of integrated water resources management requires coupled analysis of hydrology and water resources in a river basin. Population growth and uncertainties due to climate change make historic data not a reliable source of information for future planning of water resources, hence necessitating climate and landuse change impact studies. This work presents an integrated modeling approach by linking Soil and Water Assessment Tool (SWAT) and MODSIM. While SWAT produces hydrologic and water resources information, MODSIM provides a decision support system for water allocation. We used the coupled SWAT–MODSIM to analyze the effects of climate and cropping pattern changes on agricultural and hydroenergy production in the Karkheh River Basin, a semiarid region in south-west of Iran. Cropping patterns were considered by limiting the cereal production to 50 % (S1, near to historic), 17 % (S2), and 83 % (S3) of total agricultural areas. The future climate was provided by the Canadian Global Coupled Model (CGCM 3.1 version T63) for A1B, A2, and B1 scenarios. The results showed that based on future climate changes and landuse scenarios, wheat production had a large variation in five economically important agricultural regions ranging from 33,000 ton year$^{-1}$ (S2-A1B) to 74,000 ton year$^{-1}$ (S3-A2). Similarly, energy production, while increasing from 614 to 1,100 GWH in A2, decreased from 614 to 464 GWH in B1 climate scenario. Our analyses indicate that cropping pattern change can be used as an effective tool to adapt to the negative impacts of climate change.

**Keywords** Hydrologic modeling · Climate change adaptation · SWAT · MODSIM

## Introduction

Limited water supply is a major constraint in development of agricultural activities in many parts of the world. This is particularly relevant in arid and semiarid regions where water scarcity poses a severe constraint to food production (De Fraiture et al. 2003, Rijsberman 2006). The Karkheh River Basin (KRB), located in the arid south-west of Iran, is one of the most productive agricultural areas of the country. It is known as the food basket of Iran (Ahmad and Giordano 2010) and produces about 10 % of the country's wheat. The basin covers approximately 3.1 % of the total area of Iran (1,648,195 km$^2$). Average annual hydropower production of Karkheh dam is 600 GWH (Iran Water and Power Resources Development Co 2010).

Although drought has become a problem in recent years, low irrigation efficiency remains a leading cause of water loss in the region. It is projected that water problem will further exasperate due to climate change in the southern

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parts of the region (Ashraf Vaghefi et al. 2013). Several studies in KRB have concentrated on the issue of food production (Ahmad and Giordano 2010, Marjanzadeh et al. 2010) and hydropower generation (Jamali et al. 2013). Looking at the high variability of stream flows, changes in climate and landuse, and ongoing water resources development planning, it will be extremely difficult to meet the demands of all sectors in the future particularly during dry years (Masih et al. 2009).

A shortcoming of the above studies is that they do not consider integration of the processes that have feedbacks to each other. For example, water abstraction for irrigation has a significant impact on the hydrological process (Faramarzi et al. 2009). This paper aims to study the impact of climate change on net irrigation requirements, wheat yield, and hydropower generation on KRB using an integrated modeling approach through linking of Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) and MODSIM (Labadie 1995). SWAT is a continuous time, process-based, and spatially semi-distributed public domain model. It has been developed to quantify the impact of land management practices on water, sediments, and other components in a basin. MODSIM, on the other hand, is a decision support system (DSS) that can be used for optimizing water allocation among different users.

A number of studies have been conducted by SWAT to quantify the impact of climate change on water availability (Hanratty and Stefan 1998; Stone et al. 2001; Eckhardt and Ulbrich 2003; Jha et al. 2004; Gosain et al. 2006; Jha et al. 2006; Marshall and Randhir 2008; Abbaspour et al. 2009). Several studies have used MODSIM to address the problem of water allocation between nonconsumptive and consumptive water demands at the basin scale (Fredericks et al. 1998; De Azevedo et al. 2000; Dai and Labaie 2001; Shourian et al. 2008).

To adapt to future climate change, we consider three cropping patterns and three climate scenarios. The changes in cropping patterns include limiting cereal production to 50 % (S1, moderate production of cereal, similar to historic area), 17 % (S2, minimum production of cereal), and 83 % (S3, maximum production of cereal) of total area allocated to agriculture, which is constrained by minimum and maximum limits. The three climate scenarios (A1B, A2, and B1) are based on the Canadian Global Coupled Model (CGCM 3.1 version T63).

The objective of this study is to analyze the interaction between different cropping patterns and climate change using the coupled SWAT–MODSIM where net irrigation requirement, crop yield, and inflow to reservoir are provided by SWAT; and hydropower generation and irrigation scheduling are provided by MODSIM through minimization of a loss function.

The SWAT model used in this study was based on a previous published work (Ashraf Vaghefi et al. 2013) with some changes in the number of years of simulation and scheduling of irrigation. Details of calibration and validation of the hydrological model will not be repeated here.

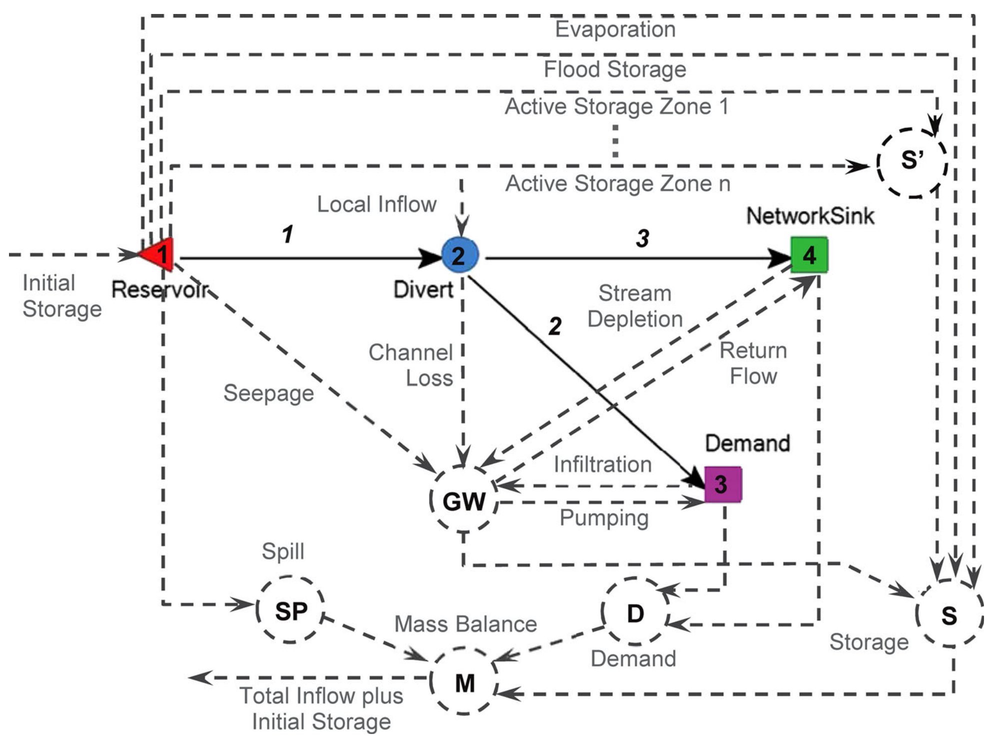


Fig. 1 Schematic of MODSIM network structure with artificial nodes and links

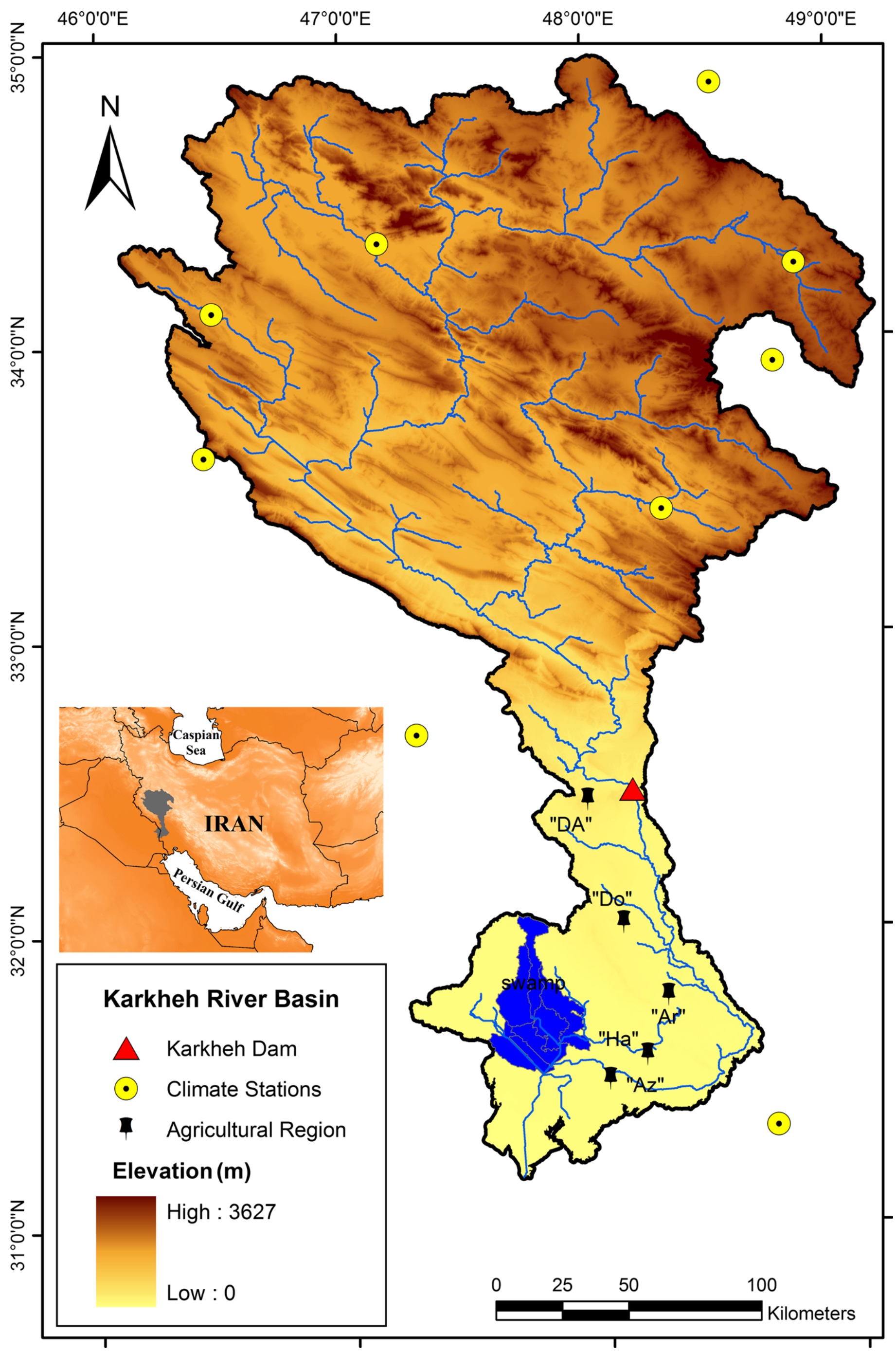


**Fig. 2** Study area in Iran showing the five important agricultural regions: Dasht-e Abbas (Dab), Dolsagh (Dol), Arayez (Ara), Hamidiyeh (Ham), Azadegan (Aza), Gauging stations: Aran (Ar), Polchehr (Po), Ghurbagh (Gh), Huliyan (Hu), Afarine (Af), Jelogir (Je), Pay-e-Pol (Pa), Hamidiyeh (Ha), and Karkheh Dam are also shown

## Materials and methods

### MODSIM water allocation module

MODSIM is a generic river basin management decision support system for developing basin-wide strategies for short-term water management, long-term operational planning, drought/climate change contingency planning, water rights analysis, and resolving conflicts between urban, agricultural, and environmental interests (Labadie 1995). In MODSIM, a river basin is represented as a network of links and nodes. MODSIM considers unregulated inflows, reservoir operating targets, consumptive and in-stream flow demands, evaporation and channel losses, reservoir storage rights and exchanges, and stream–aquifer modeling components (Fredericks et al. 1998). Within the confines of mass balance throughout the network, MODSIM sequentially solves the following linear optimization

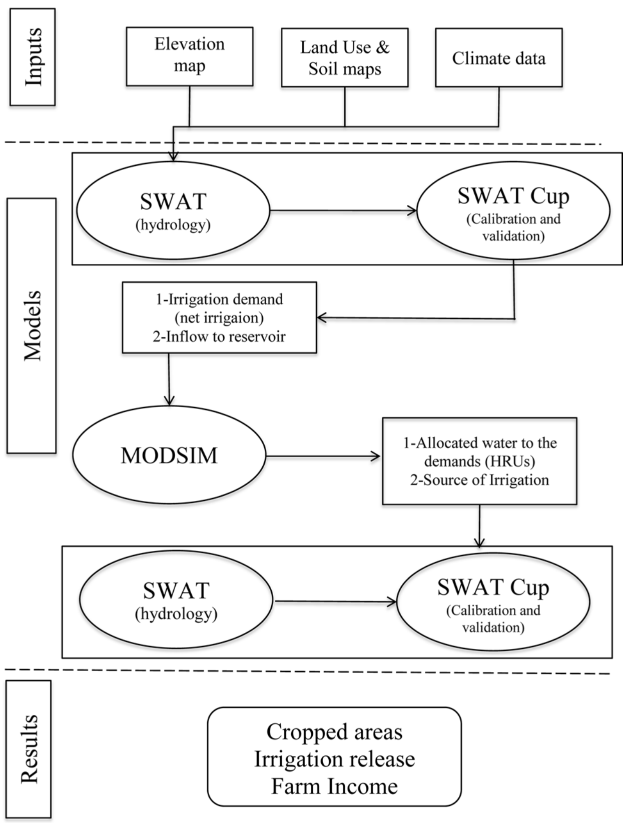


**Fig. 3** Overview of the input–output and integration of SWAT and MODSIM

expression over planning period of the record using an efficient minimum cost network flow program:

$$\text{Minimize} \sum_{l \in A} c_l q_l \quad (1)$$

Subject to:

$$\sum_{j \in O_i} q_j - \sum_{k \in I_i} q_k = 0; \text{for all } iN \quad (2)$$

$$l_l \le q_l \le u_l; \textit{for all } l \in A \quad (3)$$

where $A$ is the set of all arcs or links in the network; $N$ is the set of all nodes; $O_i$ is the set of all links originating at node $i$ (i.e., outflow links); $I_i$ is the set of all links terminating at node $i$ (i.e., inflow links); $q_l$ is the integer valued flow rate in link $l$; $c_l$ is the cost weighting factor, or priority number per unit flow rate in link $l$; $l_l$ is the lower bound on flow in link $l$; and $u_l$ is the upper bound on flow in link $l$. The database for the network optimization problem is completely defined by the link parameters for each link $l$: $[l_l, u_l, c_l]$ as well as the sets of $O_i$, $I_i$, $N$, and $A$. An example of fully circulating network is shown in Fig. 1. Nodes 1, 2, 3, and 4 are actual, physical system nodes. Node 1 is a reservoir, node 2 is an intermediate node, node 3 is a demand diversion, and node 4 is a network sink. Nodes and links that appear as dashed lines represent special accounting nodes and links; that is, they are not part of the physical system, but are included to properly account for mass balance throughout the entire system. Notice that there are always six accounting nodes, but the number of accounting links is directly related to the size of the physical system network. MODSIM employs a primal–dual network optimization algorithm incorporating a dual coordinate ascent procedure based on Lagrangian relaxation (Bertsekas 1991). MODSIM computes both power capacity and energy generation in high-head power plants using the basic power equation:

$$P_{it} = K \cdot Q_{it} \cdot \overline{H_{it}} \cdot e_i(Q_{it}, H_{it}) \quad (4)$$

$$P_{it} \le P_{i,\max} \quad (5)$$

where $P_{it}$ is power output during period $t$ (KW); $Q_{it}$ is turbine release (volume/time period); $\overline{H_{it}}$ is mean

**Table 1** Description of three cropping pattern scenarios modeled in this study (Iran Water and Power Resources Development Co. 2010)

| Scenarios | Conditions | Description |
|---|---|---|
| S1 | Priority 1: $A_{\text{wheat}} + A_{\text{maize}} + A_{\text{barley}} = A_{\min} + 0.5(A_{\max} - A_{\min})$<br>Priority 2: $A_{\text{othercrops}} = A_{\min}$<br>Priority 3: all remaining area of crops to reach to the $A_{\max}$ | To limit the cereal production to 50 % of allowable area between minimum and maximum ranges (Moderate production of cereal) |
| S2 | Priority 1: $A_{\text{wheat}} + A_{\text{maize}} + A_{\text{barley}} = A_{\min} + 0.17(A_{\max} - A_{\min})$<br>Priority 2: $A_{\text{othercrops}} = A_{\min}$<br>**Priority 3**: all remaining area of crops to reach to the $A_{\max}$ | To limit the cereal production to 17 % of allowable area between minimum and maximum ranges (Minimum production of cereal) |
| S3 | Priority 1: $A_{\text{wheat}} + A_{\text{maize}} + A_{\text{barley}} = A_{\min} + 0.83(A_{\max} - A_{\min})$<br>Priority 2: $A_{\text{othercrops}} = A_{\min}$<br>Priority 3: all remaining area of crops to reach to the $A_{max}$ | To limit the cereal production to 83 % of allowable area between minimum and maximum ranges (Maximum production of cereal) |

**Table 2** Maximum, minimum area of agricultural lands downstream of Karkheh dam in the drafted future plans reported by Iran Water and Power Resources Development Co. (2010)

| Agricultural land name, crop | | Future pattern based on developed plans (Area ha) | |
|---|---|---|---|
| | | Min | Max |
| Dasht-e Abbas | Winter Wheat | 2,210 | 4,710 |
| | Barley | 1,480 | 2,730 |
| | Maize | 735 | 1,985 |
| | Other Crops | 10,470 | 12,970 |
| Dolsagh | Winter Wheat | 2,050 | 3,300 |
| | Barley | 1,350 | 2,600 |
| | Maize | 650 | 1,900 |
| | Other Crops | 9,550 | 12,050 |
| Arayez | Winter Wheat | 3,780 | 6,280 |
| | Barley | 2,340 | 3,590 |
| | Maize | 1,650 | 2,900 |
| | Other Crops | 11,730 | 14,230 |
| Hamidiyeh | Winter Wheat | 2,165 | 4,665 |
| | Barley | 1,450 | 2,700 |
| | Maize | 715 | 1,965 |
| | Other Crops | 9,800 | 12,300 |
| Azadegan | Winter Wheat | 11,250 | 15,000 |
| | Barley | 6,600 | 9,100 |
| | Maize | 3,900 | 6,400 |
| | Other Crops | 31,050 | 34,800 |

effective head for time period $t$; $.e_i(Q_{it}, H_{it})$ is plant efficiency, interpolated from an efficiency table as a function of discrete release $Q$ and heads $H$; $K$ is a conversion constant; and $P_{i,\max}$ is the maximum capacity of the power plant.

## Future climate data and model scenarios

For climate change analysis, the third generation of the models developed by the Canadian Centre for Climate Modeling and Analysis (CCCma) Coupled Global Climate Model (CGCM3.1) version T63 is used. This version has a surface grid with latitude/longitude resolution of 2.8° and 31 vertical levels. With this specification, four grid points fell in the study area. Future climate data for the period of 2020–2049 were generated from this model for scenarios A1B, A2, and B1, which represent, respectively, rapid economic growth, regionally oriented economic development, and global environmental sustainability.

Nine observational climate stations were used in the calibration of the SWAT model. The GCM temperature and rainfall data were spatially corrected for the nearest station data using 30 years (1976–2005 baseline period) of measurements through bias correction. Therefore, each GCM grid point was used for more than one observational station.

For temperature, daily observed data were regressed against the historic GCM for each month using:

$$\text{Observed Data} = a. + b \times \text{GCM} + c \times \text{GCM}^2 + d \times \text{GCM}^3 + e \times \text{GCM}^4 \quad (6)$$

We then used this transformation to correct the future GCM. For precipitation, we used a linear correction method. GCM daily precipitation amounts, $P$, are transformed into $P^*$

**Table 3** Distribution (%) of crops in agricultural lands (Iran Water and Power Resources Development Co. 2010)

| Crops | | Dasht-e Abbas | Dolsagh | Arayez | Hamidiyeh | Azadegan |
|---|---|---|---|---|---|---|
| Cereal | Wheat | 21.0 | 16.6 | 23.3 | 21.6 | |
| | Barley | 12.2 | 13.1 | 13.3 | 12.5 | |
| | Maize | 8.9 | 9.6 | 10.7 | 9.1 | |
| Other Crops | Broad Beans, | 1.9 | 2.2 | 2.1 | 4.3 | 3.3 |
| | Beans, Green | 0.0 | 4.4 | 3.6 | 0.0 | 0.0 |
| | Sesame Seed | 3.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Cucumbers | 4.7 | 13.1 | 11.7 | 7.4 | 5.5 |
| | Tomato | 2.7 | 4.0 | 6.0 | 5.0 | 3.7 |
| | Watermelon | 4.1 | 7.3 | 6.9 | 5.5 | 4.0 |
| | Alfalfa | 18.8 | 19.3 | 16.2 | 10.7 | 8.4 |
| | Sorghum | 4.1 | 0.0 | 0.0 | 6.1 | 4.6 |
| | Sugarcane | 3.5 | 5.3 | 0.0 | 0.0 | 0.0 |
| | Rapeseed | 1.6 | 2.2 | 3.4 | 4.5 | 3.5 |
| | Eggplant | 4.2 | 0.0 | 0.0 | 8.8 | 6.4 |
| | Citrus Fruit | 9.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Carrots | 0.0 | 3.0 | 2.7 | 4.5 | 3.5 |
| | Dates | 0.0 | 0.0 | 0.0 | 0.0 | 10.5 |
| Sum | | 100 | 100 | 100 | 100 | 100 |

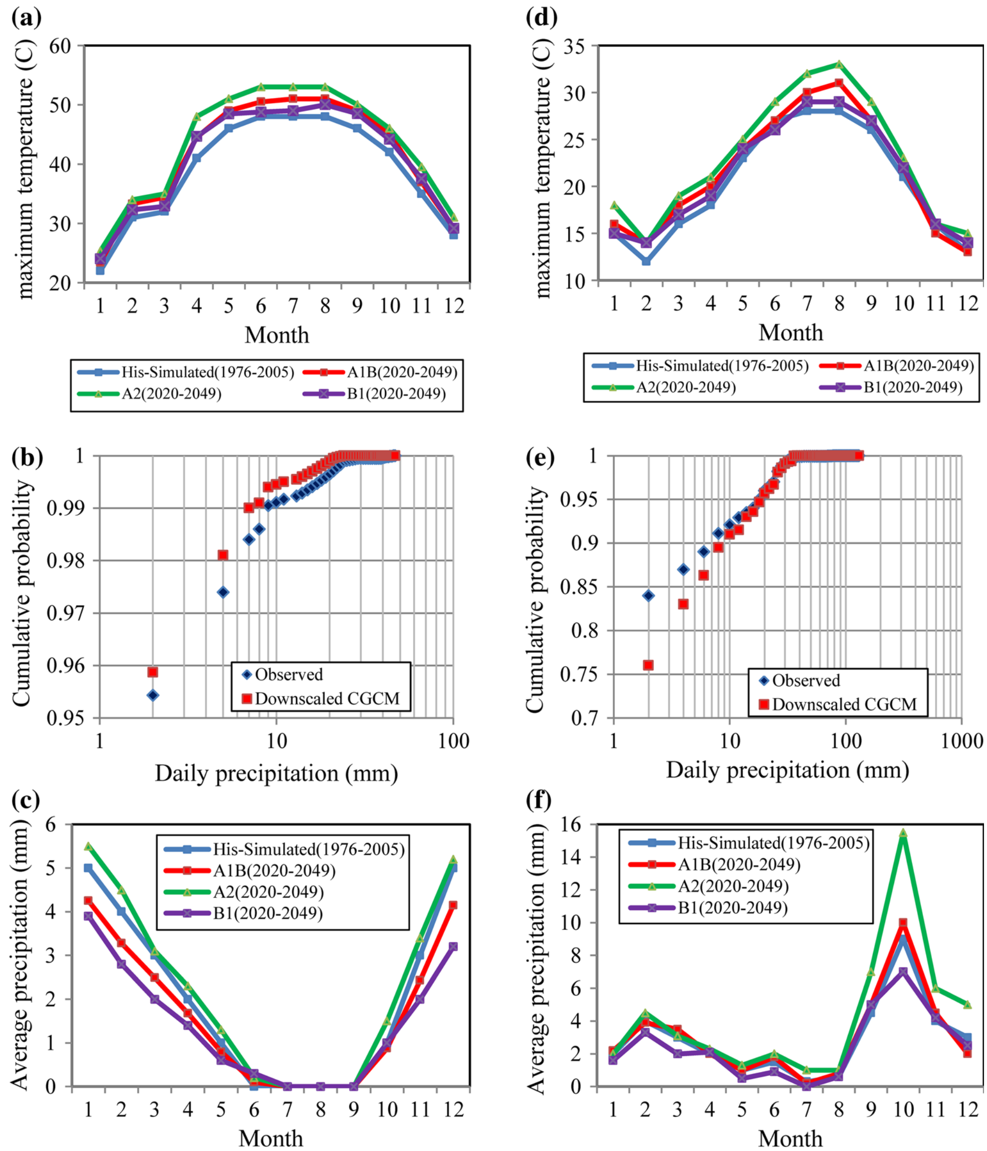


**Fig. 4** Comparison of the maximum temperatures for the reference (using the bias-corrected GCM climate) (1976–2005) and future climate scenarios (2020–2049) in dry (**a**) and wet (**d**) regions. Comparison of the downscaled precipitation (scenario A1B) in Azadegan (dry) (**b**) and Dasht-e Abbas (wet) (**e**) stations. Comparison of the monthly average precipitation for the reference (using the bias-corrected GCM climate) (1976–2005) and future climate scenarios (2020–2049) h in Azadegan (dry) (**c**) and Dasht-e Abbas (wet) (**f**) stations

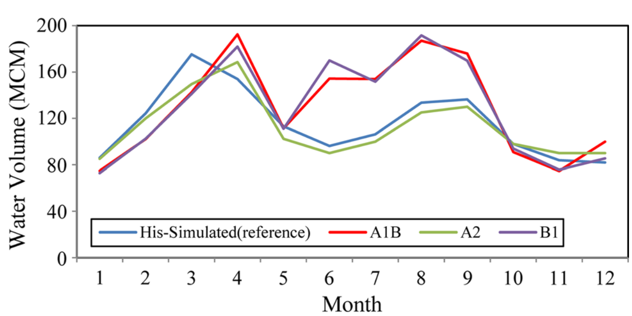


**Fig. 5** Monthly average of net irrigation requirements for the reference (using the bias-corrected GCM climate) (1976–2005) and future climate scenarios (2020–2049) (Sum of all regions)

such that $P^* = a \times P$, using a scaling factor, $a = O/P$, where O and $P$ are the monthly mean observed and GCM precipitation, respectively. Here, the monthly scaling factor is applied to each uncorrected daily observation of that month, generating the corrected future daily time series.

## Study area

The Karkheh River Basin (KRB) with an area of approximately 51,000 km$^2$ is located between 30°N to 35°N and 46°E to 49°E (Fig. 2). The southern part of the basin receives an average annual precipitation of about 250 mm year$^{-1}$ while the northern part receives up to 700 mm year$^{-1}$ (Oweis et al. 2008). Precipitation in many areas is generally insufficient to meet crop water requirements, and therefore irrigated agriculture is important in the basin (Keshavarz et al. 2005, Farahani and Oweis 2008, Ahmad et al. 2009). Five important regions (Dasht-e Abbas, Dolsagh, Arayez, Hamidiyeh, and Azadegan) in the

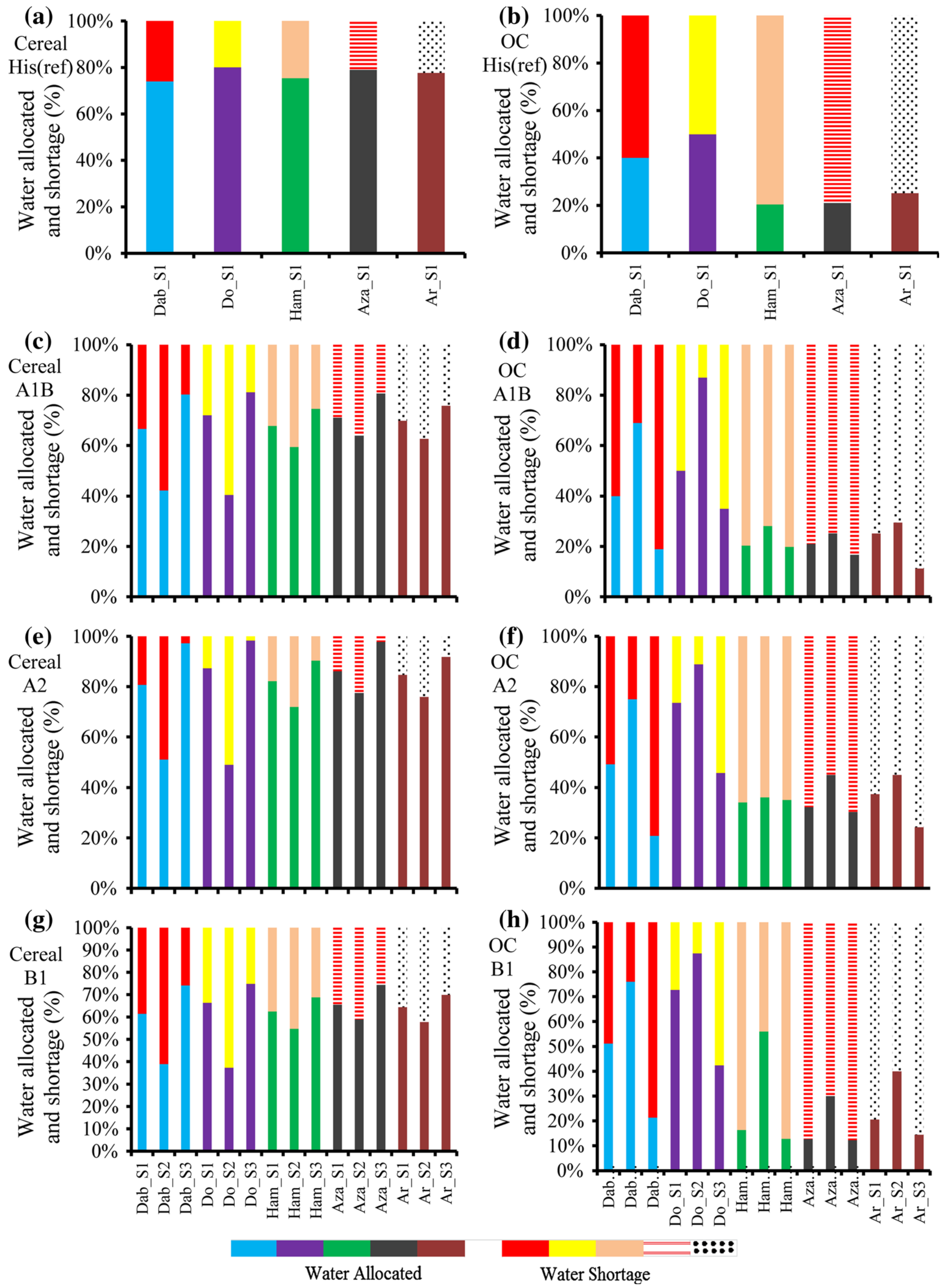


**Fig. 6** Percentage of the allocated water and shortages in Dasht-e Abbas (Dab), Dolsagh (Do), Hamidiyeh (Ham), Azadegan (Aza) and Arayez (Ar) for different cropping pattern scenarios (S1, S2, S3) considering bias-corrected GCM climate for reference period (1976–2005) for: **a** Cereal, **b** OC (Other Crops), A1B scenario (2020–2049) for: **c** Cereal, and **d** OC, A2 scenario (2020–2049) for: **e** Cereal, and **f** OC and B1 scenario (2020–2049) for: **g** Cereal, and **h** OC

southern part of the basin (Lower Karkheh) were selected for cropping pattern analysis, while no landuse change was considered in other parts of the basin. The Karkheh reservoir, the most downstream and the largest reservoir in the basin, is operated considering irrigation and hydropower as the major objectives.

## Models setup

To determine the potential crop yield, we initially considered auto-irrigation in SWAT with an unlimited source of water from outside the region (Fig. 3). Next, we extracted the necessary outputs from SWAT at required HRUs and rivers and converted them into MODSIM input formats. The amount of water allocated to each demand node (HRU) is determined in MODSIM using a priority-based scheme. Subsequently, SWAT was run again considering an updated irrigation scheduling based on releases from surface reservoir as a limited source where the amount of water transferred to each HRU in each time step is determined by MODSIM.

We considered three different scenarios of cropping patterns based on future development plans from Iran Water and Power Resources Development Co., (IWPC 2010) (Table 1). These include limiting cereal production to, respectively, 50 % (S1, moderate production of cereal), 17 % (S2, minimum production of cereal), and 83 % (S3, maximum production of cereal) of an allowable area expressed within a minimum and maximum range (Table 2).

The HRUs in SWAT were split further into different crops based on the distribution of crops in each agricultural land (Table 3).

## Results and discussion

### Downscaling climate variables

The downscaled temperature data from CGCM agreed quite well with the recorded historical data. All nine stations had $R^2$ values in the range of 0.9–1.0. Average monthly changes in maximum temperature show the largest increases in the summer season for all scenarios in dry (Fig. 4a) and wet areas of the region (Fig. 4d). The GCM prediction of rainfall slightly underestimates the historic (1976–2005) data in a dry station in the Azadegan region (Fig. 4b) and overestimates rainfall in a wet station in Dasht-e Abbas region (Fig. 4e). The projected long-term average precipitations (mm $d^{-1}$) show that all seasons except summer experience some changes (Fig. 4c, f). Climate scenario A2 projects an increase in the rainfall for the whole region.

### Impact of climate change on net irrigation requirement and water supply

Net irrigation requirement (NIR) for potential crop growth is a function of crop water requirement and effective rainfall. Hence, climatic variation has a significant impact on NIR, which in turn affects the reservoir operation. As rainfall increases in A2, the critical summer months show a decrease in NIR in the whole region (Fig. 5). Scenarios B1 and A1B, however, show a substantial increase in water demand during summer.

The percentages of water supplies and shortages for cereal and other crops during 1976–2005 (reference period; driven by the bias-corrected GCM climate), as provided by MODSIM outputs, indicate that there existed a deficit of around 18–22 % for cereal and a 50–65 % for other crops (Fig. 6a, b) in all five agricultural zones.

For future scenarios, A1B and B1 projected a reduction of 10–17 %, while A2 projects an increase in water supply by 14 %. Water allocation varied substantially among different regions and scenarios. The highest deficit for cereals occurred for scenario S2-B1 in Dolsagh at 60 % (Fig. 6g), while the smallest water deficit for cereals was experienced at around 5 % for scenario A2 in Dasht-e Abbas and Azadegan regions (Fig. 6e). For other crops, the largest deficit at 90 % was seen for scenario S3-A1B in Arayez region (Fugure 6d), with the smallest deficit experienced in the Dolsagh region for S2-A2 scenario. Overall, S2 suffers the largest and S3 the smallest deficit for cereal production, while for other crops, S3 has the largest and S2 the smallest water deficit.

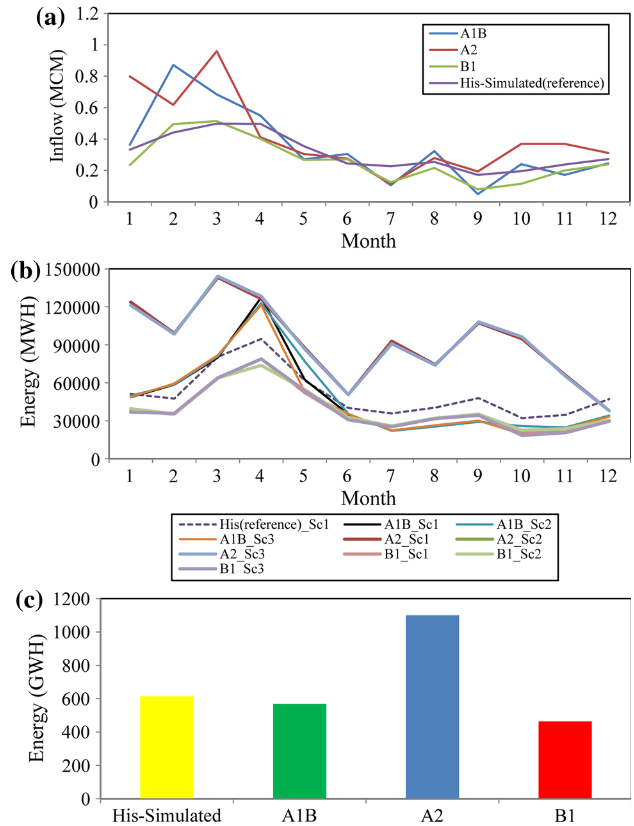


**Fig. 7** **a** Monthly average inflow to Karkheh reservoir in reference period (2000–2005) and future scenarios (2020–2049), **b** Energy generation of Karkheh dam, and **c** Annual average of energy generation (GWH)

### Impact of climate change on hydropower energy

To analyze the impact of future climate change on energy generation, we first analyzed the long-term average inflow to Karkheh Dam in historical (average of six years from 2000 to 2005 when Karkheh Dam became operational) and future climate scenarios (average of 30 years). In general, inflow decreased in B1, stayed almost the same in A1B and increased in A2. But monthly variations show increased

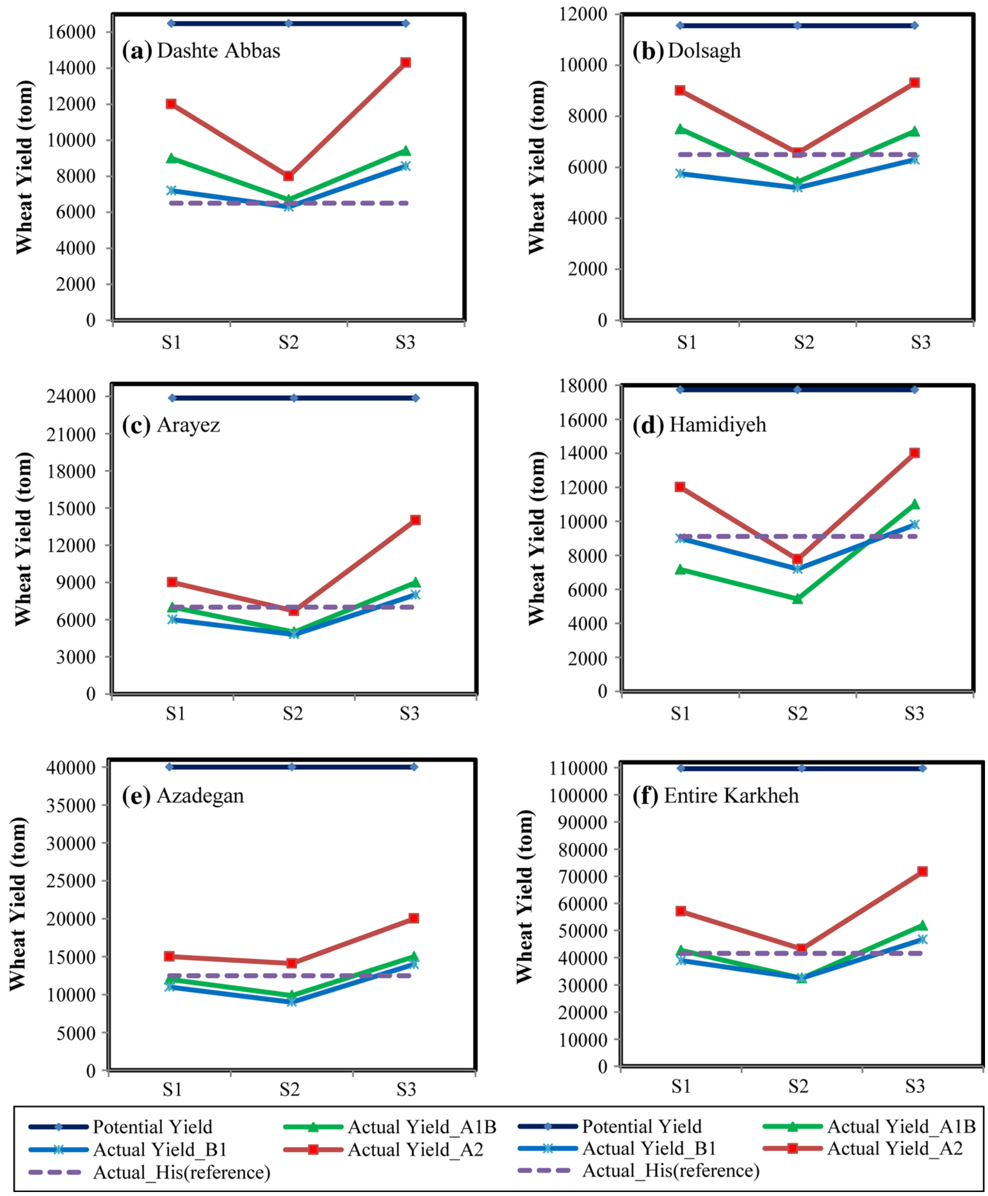


**Fig. 8** Mean annual potential wheat yield and actual wheat yield in **a** Dasht-e Abbas **b** Dolsagh, **c** Arayes, **d** Hamidiyeh, **e** Azadegan, **f** Entire Karkheh regions considering three cropping patterns

inflow in winter and spring months for A1B and A2 (Fig. 7a).

The results of the long-term average monthly energy generation at Karkheh power plant for A1B indicate an increase in hydropower production in the first half of the year, except for scenario S2, and a decrease in the second half of the year for all scenarios (Fig. 7b). As rainfall increases in A2, it subsequently results in the largest increase in energy production. The long-term annual energy production shows an increase from 614 to 1,100 GWH in A2, and decreases to 464 GWH in B1, and 590 in A1B (Fig. 7d).

## Impact of climate change on wheat production and adaptation measures

There are significant differences between the wheat production estimates of different climate scenarios, with A2 projecting the largest production in all regions. Crop pattern S2 shows the smallest production with all climate scenarios, with S3 having the largest wheat production. It is therefore feasible that crop pattern S3 would be recommended as a possible adaptation to climate change (Fig. 8).

## Summary and conclusion

We analyzed the impact of different cropping patterns and climate scenarios on the production of five important agricultural regions in the KRB. An integrated SWAT–MODSIM model was used for the analysis of reference (using the bias-corrected GCM climate) (1976–2005) and future climate scenarios (2020–2049). We extracted the net irrigation requirements and inflow to the Karkheh reservoir from SWAT and provided them to MODSIM as inputs. The results indicated that the models are compatible and can be used to assess and manage water resources in complex watersheds. The model determines total crop yield from agricultural activities and the percentage of water shortages in different scenarios of cropping pattern and climate change.

Analysis of the three cropping patterns in five economically important regions of the basin showed that total wheat production varies significantly with a minimum of 3,3,000 ton year$^{-1}$ (S2, A1B) up to a maximum of 74,000 ton year$^{-1}$ (S3, A2).

The outputs of the modeling approach presented here provide a basis for identifying adaptation options that might be required by farmers and decision makers in the region in order to respond to changing water availability. The integrated SWAT–MODSIM could be used as a decision support tool to provide farmers with guides for the adjustment of their irrigation calendars considering actual weather and future predicted climate conditions. The model is relatively easy to apply and has a great potential as a decision tool for cropping pattern analysis of a system under water scarcity constraints. This approach could be valuable to water users in semiarid areas to more efficiently utilize and manage the scarce water resources.

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