



# Simulation of the effects of climate change and reduce irrigation requirements on groundwater recharge using SWAT and MODFLOW models

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Received: 18 August 2022 / Accepted: 14 October 2022 / Published online: 31 October 2022  
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## Abstract

Improper extraction of groundwater resources has led to a sharp decline in the water level of aquifers. To achieve sustainable management of groundwater, it is very important to simulate the amount of recharging an aquifer by considering the physical properties of the relevant basin (such as soil properties, land use, irrigation, climate data and unsaturated layer). In the present study, a groundwater modeling was accomplished to predict the recharge rate under the conditions of climate change and irrigation reduction. Meteorological parameters in the next period (2021–2050) were simulated by ten climate change models (GCMs) under emission scenarios. The combination of SWAT and MODFLOW models was also used to predict the groundwater recharge rate. The results of forecasting climatic parameters in the next period (2021–2050) indicated that the temperature will increase (0.66–1.68 °C) while the precipitation will decrease (4–14%). The recharge rate modeling revealed that recharge values in heavy soils are less estimated compared to that of the light soils of the region. Also, the average recharge rate of the whole aquifer in the next period under the RCP4.5 and RCP8.5 scenarios will decrease by 23 and 34%, respectively. The simulation of reducing the irrigation requirements on the recharging rate indicated that with a 30% reduction of irrigation, the average recharging rate of the whole plain will decrease by 12%. Therefore, it is recommended to apply policies to decrease irrigation requirements, such as the development of pressurized irrigation systems and the cultivation of low-consumption plants, to help balance the aquifer.

**Keywords** SWAT · MODFLOW · Prediction · Recharge · Irrigation requirements

## Introduction

Recent climate change and droughts have led to severe depletion of surface water resources and uncontrolled extraction of groundwater resources. The imbalance between recharging and withdrawing from aquifers has resulted in the instability of groundwater. This event has posed basins with

various challenges such as the severe decline in aquifer water levels, drying up of streams and land subsidence (Sivakumar et al. 2005; Chunn et al. 2019; Chitsazan et al. 2020). Groundwater recharge is an important part of the hydrogeological cycle in arid and semi-arid regions, and understanding its processes is very vital for the sustainable development of water resources. Many basin parameters such as soil characteristics, topography, rainfall, saturated layer thickness, evapotranspiration, surface water, and climate changes are effective in the recharge amount. Therefore, these parameters should be considered for accurate simulation of recharging aquifers. For this purpose, integrated modeling of surface and groundwater in a basin is required (Fleckenstein et al. 2010; Gilfedder et al. 2012; Chunn et al. 2019; Gyamfi et al. 2017).

In recent decades, with the growth of computer systems, the accuracy of hydrological models for integrated modeling of surface and groundwater has increased. Models that are developed to simulate surface–groundwater interaction

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include MODFLOW, MODHMS, GSFLOW, WEAP and SWAT. Among different computer models, MODFLOW and SWAT are more used in the comprehensive management of surface and groundwater resources (McDonald and Harbaugh 1988; Arnold et al. 1998; Neitsch et al. 2011). AS the SWAT surface water model has significant conceptual limitations to groundwater flow simulation, its integration with the MODFLOW groundwater model has had a wide range of successful applications in various studies (Yidana and Chegbeleh 2013; Guzman et al. 2015; Abbaspour et al. 2015; Farhadi et al. 2016; Mishra et al. 2017).

Kim et al. (2008) simulated the groundwater recharge and groundwater level in South Korea's Musimcheon Basin using a combination of SWAT and MODFLOW models. They used the exchange of flow data between SWAT model HRUs and MODFLOW model cells, and calculated the spatial distribution of monthly recharging values according to climatic parameters, soil type, vegetation, and basin slopes between 15 and 200 mm per month. Their results illustrated that the combination of the SWAT-MODFLOW model will be very useful for the sustainable development of groundwater. Raposo et al. (2013) studied the effects of climate change on groundwater recharge using the SWAT model in the Galicia-Costa Basin of Spain. Their consequences showed that the effect of climate change on the average annual recharge is small, but its effects on the temporal distribution of recharge are high so that in the future the main recharge occurs in winter, and recharging in summer and autumn will be drastically reduced. In the dry season, the amount of reduction in recharge will reach 30%. Izady et al. (2015) used SWAT and MODFLOW models to concurrently simulate surface and groundwater in the Neishaboor Basin area of Iran. Their results showed that the spatial distribution of recharge is affected by natural features and varies between 0 and 960 mm along the aquifer surface. Also, the average annual recharge of the aquifer during the simulation period (2000–2010) is estimated to be about 176 mm. Gyamfi et al. (2017) used SWAT software for dynamic modeling of the groundwater recharge in the Olifants Basin of South Africa. Their results showed that the changes in land use created in urban, agricultural, and rangelands during 2000–2013 caused the amount of groundwater recharge to decrease continuously. Chunn et al. (2019) used the SWAT-MODFLOW integrated model in the Little Smoky Basin of Canada to simulate the impact of climate change and groundwater abstraction on surface water-groundwater interactions. Their consequences showed that more groundwater abstraction could have immediate and more severe effects on river surface water flow compared to future climate change (2010–2014). Their study also indicated the importance of simultaneously examining surface-groundwater interactions as an integrated system because the demand of one has a direct effect on the other. Azeref and Bushira

(2020) employed MODFLOW numerical model and water balance equations to simulate the groundwater level of the Kombolcha catchment in northern Ethiopia. To predict the behavior of the aquifer to future changes, they defined two scenarios of increasing well extraction and reducing groundwater recharge. Their results showed that with 25, 50, and 100% reduction in the recharging, the groundwater level will decline by 4.27, 6.34 and 11.25 m, respectively. Yifru et al. (2020) used the SWAT-MODFLOW hybrid model to study the spatial and temporal distribution of recharging in the Han River sub-basins of South Korea. Their results showed that the highest amount of recharging occurred in lowland areas between July and September, and the average annual recharging reached about 18% of the rainfalls. Therefore, the consequences of various studies display that the simultaneous use of SWAT and MODFLOW models has an important role in surface and groundwater interactions.

In recent decades, uncontrolled abstraction of groundwater resources has caused a sharp drop in groundwater levels and the creation of sinkholes in the Kavar plain of Fars province. In this study, to predict the behavior of an aquifer to future changes, the simulation of its groundwater recharge under the conditions of climate change and reduction of irrigation requirements has been evaluated using SWAT and MODFLOW models. To achieve this goal, the following questions will also be answered:

- (i) What will be the changes in climate parameters in the next period (2021–2050)?
- (ii) What is the spatial distribution of recharge values in the region?
- (iii) What will be the effects of the climate change on recharging in the next period?
- (iv) What effect will the reduction of the irrigation requirement have on recharge values?

The effects of different parameters on recharge values have been comprehensively evaluated for the first time in the region, which can help the sustainable water resources management.

## Materials and methods

### Study area

The study area of Kavar plain is one of the sub-basins of the Mand basin, which is located in Fars province of Iran. Kavar plain is one of the most fertile plains for agriculture. The average height of the plain is 1510 m, the area is 480 square kilometres, and the average annual rainfall is 320 mm. This plain is located in the range of 52°37' to 52°53' East longitude and 29°5' to 29°22' North latitude. According to the

statistics of the Agricultural Organization of Fars Province, the cultivation pattern of the region includes wheat, barley, canola, sugar beet, alfalfa, tomatoes, onions, legumes, maize (Grain), maize, grapes, pistachios, and orchards. The net agricultural area of the plain is about 13,700 hectares (Anonymous 2018; [www.fajo.ir](http://www.fajo.ir)). Plain water resources for agricultural purposes consist of surface water resources (Qara Aghaj River) and groundwater resources (wells). Thus, on average, 45 million cubic meters of surface water is supplied annually through traditional streams (Qara Aghaj River) and 140 million cubic meters through pumping from groundwater sources. In recent decades, groundwater extraction has been increased due to drought so that the aquifer of the region has been under pressure and the water level is decreased significantly. (Anonymous 2015; [www.frw.ir](http://www.frw.ir)). Therefore, it is necessary to plan for the sustainable use of groundwater. The location of Kavar plain is shown in Fig. 1.

The data required for the research were collected from the Agricultural Organization, the Regional Water Company, and the Meteorological Organization of Fars. Daily meteorological data including rainfall, air temperature (maximum and minimum), sunshine, and wind speed were collected from the stations located in the basin (Kavar rain gauge and Shiraz synoptic) for 57 years (1961–2018). To prepare the conceptual model of the region in GIS, first, geological, soil, topographic, hydrological boundaries, hydrogeological boundaries, abstraction sources, recharge sources, cross-sections of the inlet and outlet information were collected. Then, these data were processed as different information layers in ArcMap software. Maps of slope, landuse, soil, and pumping wells are shown in Figs. 2 and 3.

Climate change can affect groundwater recharge and irrigation requirements by changing meteorological parameters such as precipitation and temperature. In this study, GCMs provided by the Intergovernmental Panel on Climate Change (IPCC) have been employed to investigate climate changes in the region. These models are capable of predicting meteorological parameters for future conditions (Adopted 2014; Chunn et al. 2019). Estimating groundwater recharge is a complex task. Investigating surface and groundwater interactions by considering the physical properties of the basin can provide a better picture of the recharging rate of aquifers. Therefore, surface and groundwater models (SWAT and MODFLOW) were used to estimate the groundwater recharge. Accordingly, the characteristics of hydrological response units (HRUs) in the SWAT model were exchanged with the cells of the MODFLOW model. Then, with the help of this cell transformation, the spatial distribution of recharging rate in the whole aquifer was simulated. The behavior of the aquifer to future changes was also evaluated (Neitsch et al. 2011; Abbaspour et al. 2015; Gyamfi et al. 2017; Chunn et al. 2019).

### MODFLOW model

The MODFLOW model is the most common standard numerical model used to simulate groundwater flow in porous multilayer aquifers. This program has been developed and published by experts from the United States Geological Survey (McDonald and Harbaugh 1988; Harbaugh 2005). The MODFLOW model can simulate recharging, discharge, evapotranspiration, and groundwater flow. The

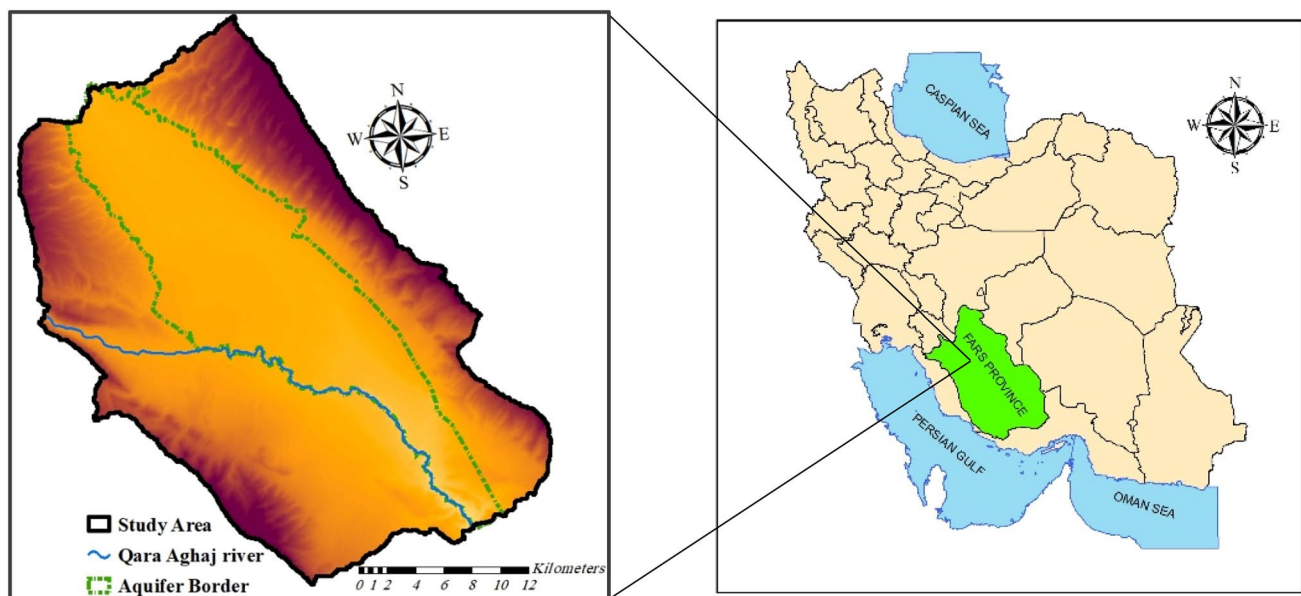


Fig. 1 Location map of Kavar plain in Fars province of Iran

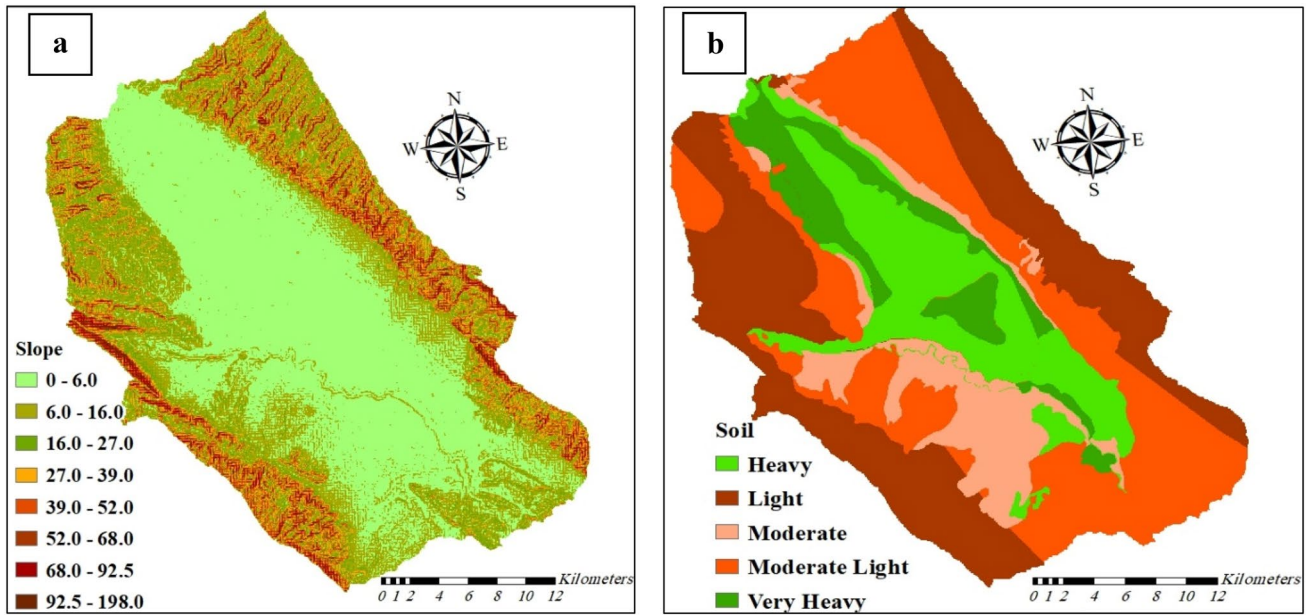


Fig. 2 a Slope and b soil maps of the study area

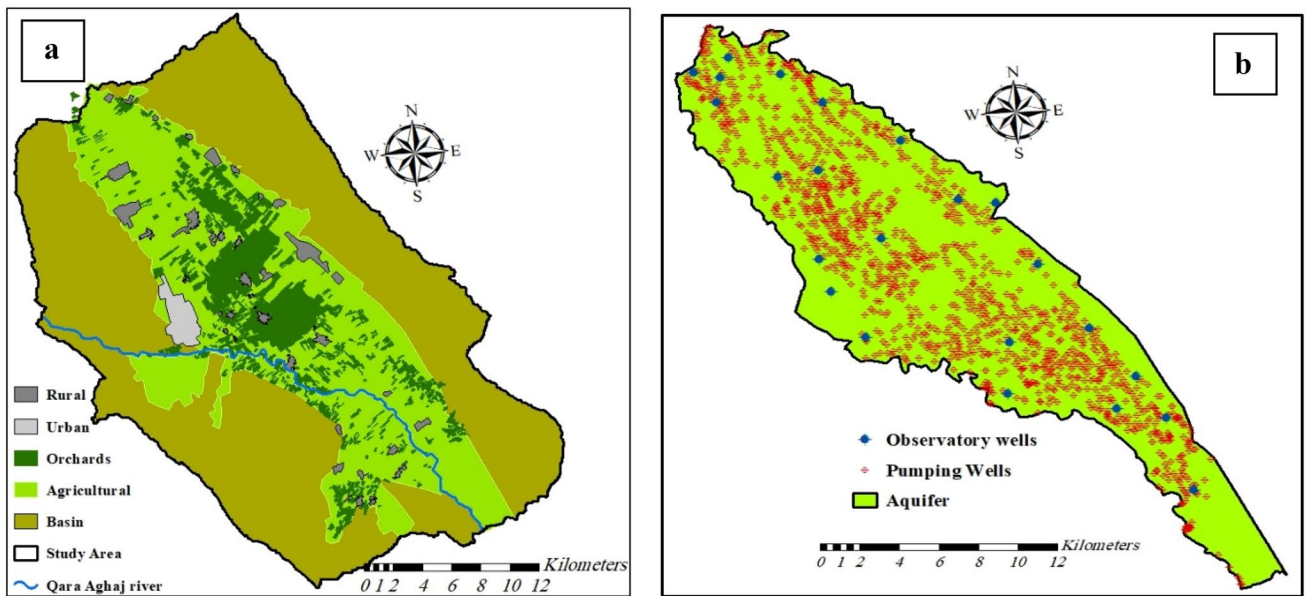


Fig. 3 a Land use and b Pumping Wells maps of the study area

equations governing groundwater flow are the combination of the Darcy equation and continuity. The resulting equation can be developed by accepting hypotheses for hydraulic conductivity and the geometric position of the aquifer in certain modes. The equation governing open aquifers with the unstable flow is Eq. 1, which is known as the Boussinesq differential equation (Kashef 1986; Harbaugh 2005).

$$\frac{\partial}{\partial x} \left( h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( h \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( h \frac{\partial h}{\partial z} \right) = \frac{S_y}{K} \frac{\partial h}{\partial t}, \quad (1)$$

where  $S_y$  is the specific discharge,  $K$  is the hydraulic conductivity, and  $h$  is the hydraulic head at any point on the groundwater surface. There are 1253 deep and semi-deep wells in the study area, which discharge an average of 140 million cubic meters of water annually for agricultural uses.

Fluctuations in the aquifer water level are measured monthly by 23 observation wells. The consequences of these measurements show that the water table drop in the aquifer during the census period (1996–2018) is 32 m. In case of uncontrolled abstraction of groundwater, in addition to drying of the water surface of wells in the areas where the thickness of the saturation layer is low, the annual subsidence rate will also increase (Anonymous 2015).

As the MODFLOW model has limitations in the field to calculate the groundwater recharge accurately, surface water models are used to simulate the interaction of surface water with groundwater (Izady et al. 2015; Chunn et al. 2019; Yifru et al. 2020).

### SWAT model

The SWAT model has been developed by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) to simulate hydrological processes such as runoff, evapotranspiration, deep percolation, and subsurface flows (Arnold et al. 1998). The SWAT model divides the basin into several sub-basins and also each sub-basin into several hydrological reaction units (HRUs). HRUs are homogeneous in terms of land use, topography, waterways, and soil characteristics. SWAT calculations are performed for each HRU; then based on the percentage of HRU area in the sub-basin, the outputs are expanded for the whole basin. (Abbaspour et al. 2015). The water balance equation in the SWAT model is calculated by Eq. 2 (Arnold et al. 1998; Neitsch et al. 2011) as follows:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}), \quad (2)$$

where  $SW_t$  is the final soil moisture content (mm),  $SW_0$  is the initial soil moisture content (mm),  $t$  is the time (days),  $R_{day}$  is the amount of precipitation (mm),  $Q_{surf}$  is the amount of runoff (mm),  $E_a$  is the evapotranspiration (mm),  $W_{seep}$  is the amount of water leakage from the soil profile that enters the unsaturated area (mm), and  $Q_{gw}$  is the amount of the returned water (mm). To model the surface water of the study area, at first, basic information such as meteorology, hydrometric, DEM map, and land use were entered into the SWAT model, then the SWAT-CUP model was employed for calibration and validation (Abbaspour 2011). In the SWAT model, the study area is divided into 56 sub-basins and 491 HRUs as shown in Fig. 4. To calibrate and validate the models, the measured data were used during a period from 2008 to 2018. The data of the period from 2008 to 2014 were employed for calibration and the period from 2015 to 2018 were used for validation.

In this research, the simulation results have been evaluated by statistical criteria of the determination coefficient

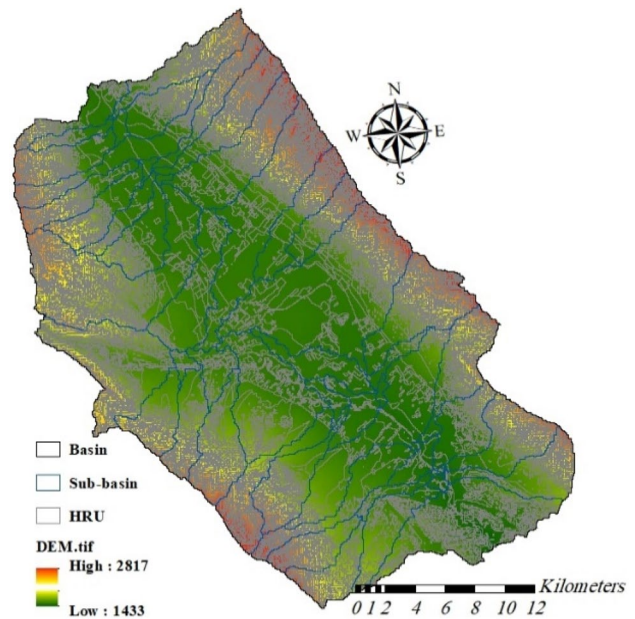


Fig. 4 Dividing Kavar basin in SWAT model

( $R^2$ ), mean square root error (RMSE), and Nash–Sutcliffe coefficient (NSE).

### Climate change models

In this study, the outputs of 10 GCM climate change models under the emission scenarios of RCP 2.6, RCP 4.5, and RCP 8.5 were used to predict the meteorological parameters of temperature, rainfall and also to calculate the water requirement in the future (2021–2050) (Adopted 2014). Various downscaling methods have been developed to generate regional climatic scenarios from General Atmospheric Cycle Models (GCM). The LARS-WG model is a downscaling model generating climate time series that can simulate atmospheric data for future conditions. This model has been employed in different climates and has provided satisfactory consequences in the production of various climatic parameters (King et al. 2012; Etemadi et al. 2014; Khajeh et al. 2017; Al-Safi and Sarukkalige 2020).

To evaluate the simulation of climatic parameters obtained from GCM models in the future, the weighted average method was used. Thus, each of the GCM models was given a weight based on the amount of deviation of the mean temperature or rainfall deviation simulated in the base period from the average of the observed observational data according to Eq. 3 (Gohari et al. 2013; Kouhestani et al. 2016; Goodarzi et al. 2016; Al-Safi and Sarukkalige 2020) as follows:

$$W_{i,j} = \frac{\left(\frac{1}{\Delta d_{ij}}\right)}{\sum_{j=1}^{10} \left(\frac{1}{\Delta d_{ij}}\right)}, \tag{3}$$

where  $W_{i,j}$  is model weight  $j$  per month  $i$ ,  $\Delta d$  is the difference between the mean temperature or simulated rainfall and its observational value in the base period. The study development and modeling process is presented diagrammatically in Fig. 5.

## Results and discussion

### Evaluation of SWAT and MODFLOW model results

In the MODFLOW model, the input parameters to the model, including the relevant recharge can be simulated by changing the initial values through the PEST software package. However, since such calculation of recharging values has uncertainties, we used the SWAT surface water model to do the same. Calibration and validation of the SWAT model is performed through the SWAT-CUP software package and the MODFLOW model is fulfilled through the PEST software package (Doherty et al. 1994; Abbaspour 2011).

The observed and simulated monthly discharge of the basin output (hydrometric station) presented by the SWAT model in both calibration and validation modes from 2008 to 2018 are shown in Fig. 6. The results of the values of statistical parameters for calibration ( $R^2=0.86$ , RMSE=2.56, NSE=0.88) and validation ( $R^2=0.82$ , RMSE=3.05, NSE=0.85) illustrated that there is a good agreement between the observed and simulated values. The model also predicts the runoff well. Only the maximum runoff is less than the actual values simulated, which is probably due to the inaccuracy of the snowmelt process in the modeling. This challenge has also been observed in other studies (Izady et al. 2015; Kouhestani et al. 2016; Abbaspour et al. 2015). To calibrate the MODFLOW model, at first, the recharge values obtained from the SWAT model were replaced by the MODFLOW recharge package, then the water table was simulated. Observational and simulated water table levels during the whole period (2008–2018) in an unstable state are presented in Fig. 6. The consequences of statistical analysis of  $R^2=0.82$ , RMSE=3.45, and NSE=0.83 showed that the simulated water table was associated with an acceptable error.

The average parameters of surface water balance calculated by the SWAT model for the whole basin in the simulation period (2008–2018) are summarized in Table 1.

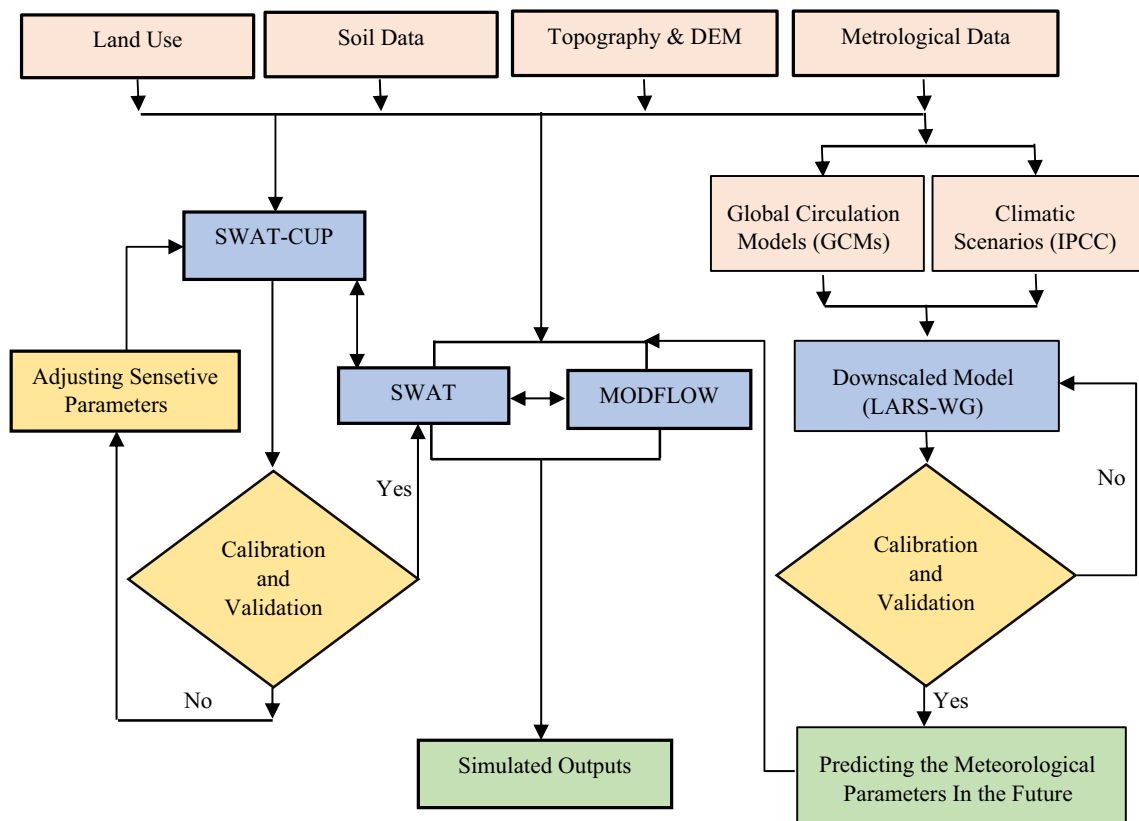
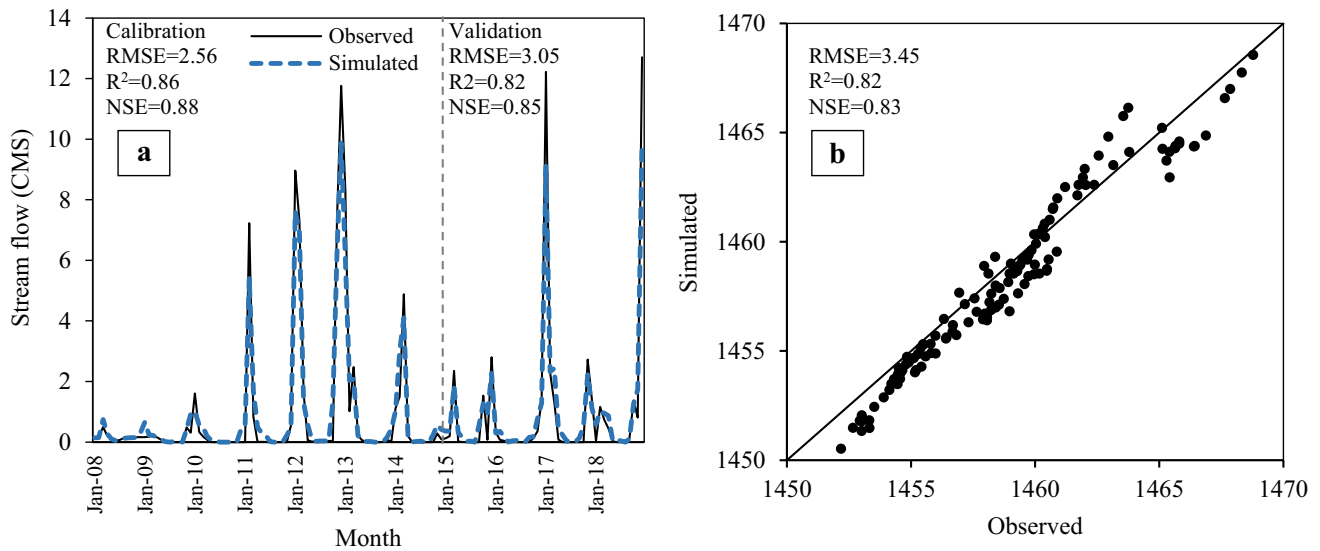


Fig. 5 The flowchart of the study procedure

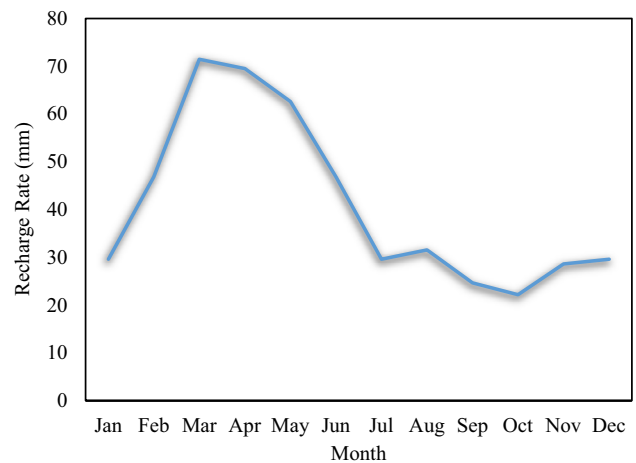


**Fig. 6** a Observational and simulated monthly discharges for calibration and validation periods at the hydrometry station. b Observational and simulated water table values in the Modflow model

**Table 1** Mean values of surface water balance parameters calculated by SWAT during the simulation period (2008–2018) for the basin

Parameters	Value
Precipitation (mm)	357.30
The net amount of water that leaves the subbasin and contributes to the streamflow in the reach (Water Yield; mm)	102.54
Actual Evapotranspiration (mm)	235.0
Percolation (mm)	33.02

These parameters include precipitation, total surface runoff, lateral flow, and groundwater flowing in the main river flow (Water Yield), actual Evapotranspiration, and percolation. The results indicated that the average annual percolation is estimated at 33 mm. According to the combined model of SWAT and MODFLOW, the Kavar plain aquifer is generally charged through three main sources. These three sources include rainfall, underground inflow, and irrigation. The average monthly recharging rate over the simulation period (2008–2018) is shown in Fig. 7. It can be seen that the highest charging rates in February, March, April, and May are estimated at 47, 71, 69, and 63 mm, respectively. These months have the largest share of recharge. Therefore, during these months, it is possible to charge the aquifer by collecting rain and runoff through the implementation of artificial charging schemes. Similar results have also been reported in other studies (Goodarzi et al. 2016; Zarei et al. 2016).



**Fig. 7** Average monthly recharge rate calculated during the simulation period (2008–2018)

**Effects of climate change**

In this study, 10 general circulation models (GCMs) under different emission scenarios (RCP2.6, RCP4.5 and RCP8.5) were used to predict climatic parameters (Adopted 2014). Meteorological parameters of rainfall as well as maximum and minimum temperatures for the next period (2021–2050) were simulated by the LARS-WG exponential downscaling model. To evaluate the results of GCMs models, the weighted averaging method was applied. Thus, the models whose consequences were more consistent (less mean deviation) with the base period time series were given more weight. The weights of the different GCM models for the

predicted climatic parameters are presented in Table 2. The results of this table showed that the MRI-CGCM3 model has a good accuracy for forecasting the rainfall. Also for maximum and minimum temperatures, MIROC5 and CSIRO-Mk3.6.0 models have the best performance of prediction. These results are consistent with the results of other researchers who employed the same method (Gohari et al. 2013; Goodarzi et al. 2016; Kouhestani et al. 2016; Al-Safi and Sarukkalige 2020).

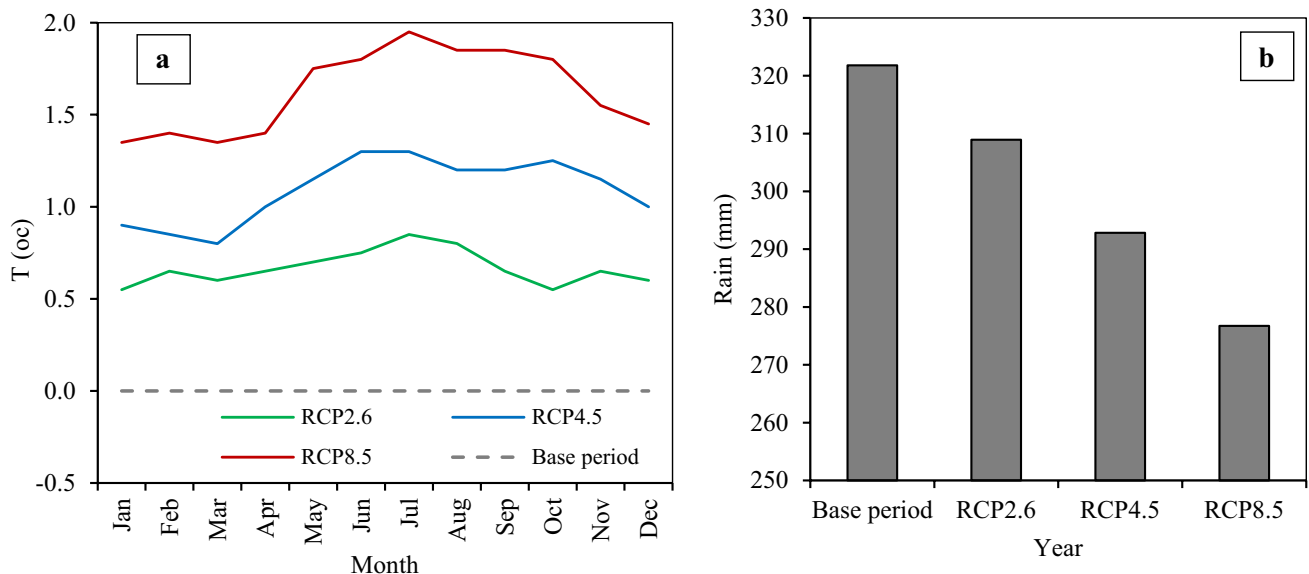
The simulation of temperature and rainfall parameters in the next period (2021–2050) is presented in Fig. 8. The consequences indicated that the increase in temperature varies in different months of the year. The maximum temperature increase was simulated under the emission scenarios of RCP2.6, RCP4.5, and RCP8.5 at 0.69, 1.14 and 1.68 °C,

respectively. Also, the minimum increase of temperatures including 0.66, 1.05, and 1.61 °C is predicted. The outcomes of rainfall simulation show its average annual decrease in the next period. This decrease varies under different scenarios. The highest rainfall reduction under the RCP8.5 scenario is estimated at 42 mm (14% reduction). Also, the decrease amounts in rainfall under the scenarios of RCP2.6 and RCP4.5 are predicted to be 14 and 31 mm (decreases of 4 and 9%) for the next period, respectively. The temperature and precipitation changes estimated for the next period are very close to the research conducted in regions with similar climates (Gohari et al. 2013; Goodarzi et al. 2016; Khajeh et al. 2017).

The SWAT model utilizes the following three methods: Penman–Monteith, Priestley–Taylor, and Hargreaves, to calculate the evapotranspiration of the reference plant. Considering that the outcomes of using the Penman–Monteith method were satisfactory in comparison with the data of measuring soil and water balance in areas with similar climates, this method was employed (Sepaskhah and Fooladmand 2004; Rafiee et al. 2016). Therefore, the effect of climate change on the annual evapotranspiration of different plants (ET<sub>c</sub>) in the region under different emission scenarios in the next period (2021–2050) was estimated. The consequences revealed the increase in water requirement of different plants (ET<sub>c</sub>) for the RCP2.6 scenario between 3 and 4.5, while for the RCP4.5 scenario between 5 and 7 and for RCP8.5 scenario between 8 and 10% are foreseen. The review of previous studies also shows that the water requirement of plants will increase due to climate change (Gohari et al. 2013; Goodarzi et al. 2016; Chaemiso et al. 2016).

**Table 2** The Weights of different GCMs models for estimating climatic parameters

Number	Model	Tmax	Tmin	Rain
1	BCC-CSM1.1	0.04	0.04	0.08
2	CanESM2	0.21	0.17	0.12
3	CSIRO-Mk3.6.0	0.17	0.22	0.10
4	GFDL-CM3	0.09	0.10	0.09
5	GISS-E2-R	0.04	0.09	0.09
6	HadGEM2-ES	0.10	0.08	0.07
7	MRI-CGCM3	0.05	0.05	0.15
8	MIROC5	0.24	0.19	0.13
9	MIROC-ESM	0.04	0.05	0.08
10	NorESM1-M	0.03	0.03	0.08



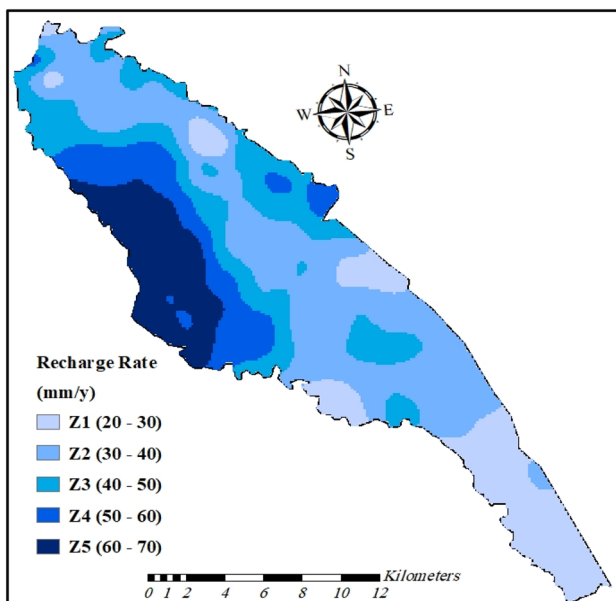
**Fig. 8** **a** Monthly temperature changes in the next period (2021–2050) compared to the base period. **b** Reduction of annual rainfall in the next period (2021–2050) compared to the base period



## The effects of the climate change on the groundwater recharge

In order to investigate the impacts of the climate change on the groundwater recharge, a spatial distribution map of aquifer recharge must first be prepared. Therefore, the spatial recharge values calculated by the SWAT model were entered into the MODFLOW model, and other corrections were made in this model. Then, utilizing ArcGIS software, a spatial distribution map of the recharge values or homogeneous recharge zones was prepared according to Fig. 9. It can be seen that the underground aquifer of Kavar plain is divided into 5 homogeneous recharge zones in which the average annual recharge values vary from 20 to 70 mm. Areas with high recharge are the main zones that charge the aquifer, which is significant. Therefore, excessive water abstraction in these zones must be avoided because it causes vulnerability to the entire plain. Areas with lower values are also at greater risk for changes in recharge parameters. Also, the average annual net recharge of the whole aquifer is estimated at 43 mm, which reaches about 12% of the rainfall. In general, the spatial distribution of the groundwater recharging rate is estimated to be variable according to the physical characteristics of the aquifer (Izady et al. 2015; Goodarzi et al. 2016; Zarei et al. 2016; Yifru et al. 2020).

By applying the parameters of different emission scenarios of RCP4.5 and RCP8.5 in the SWAT-MODFLOW model, the impacts of climate change on groundwater recharge values in the future period (2021–2050) was evaluated. The spatial distribution map of the possible percentage

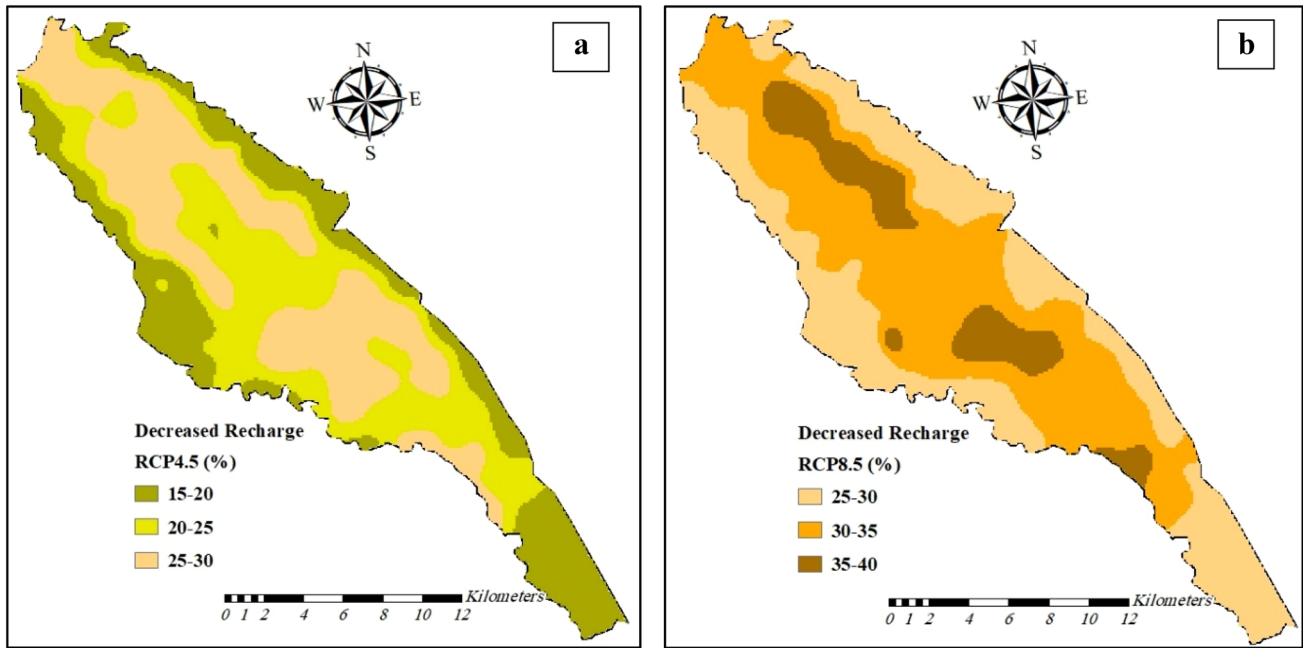


**Fig. 9** Spatial distribution map of the average annual recharge rate to the underground aquifer

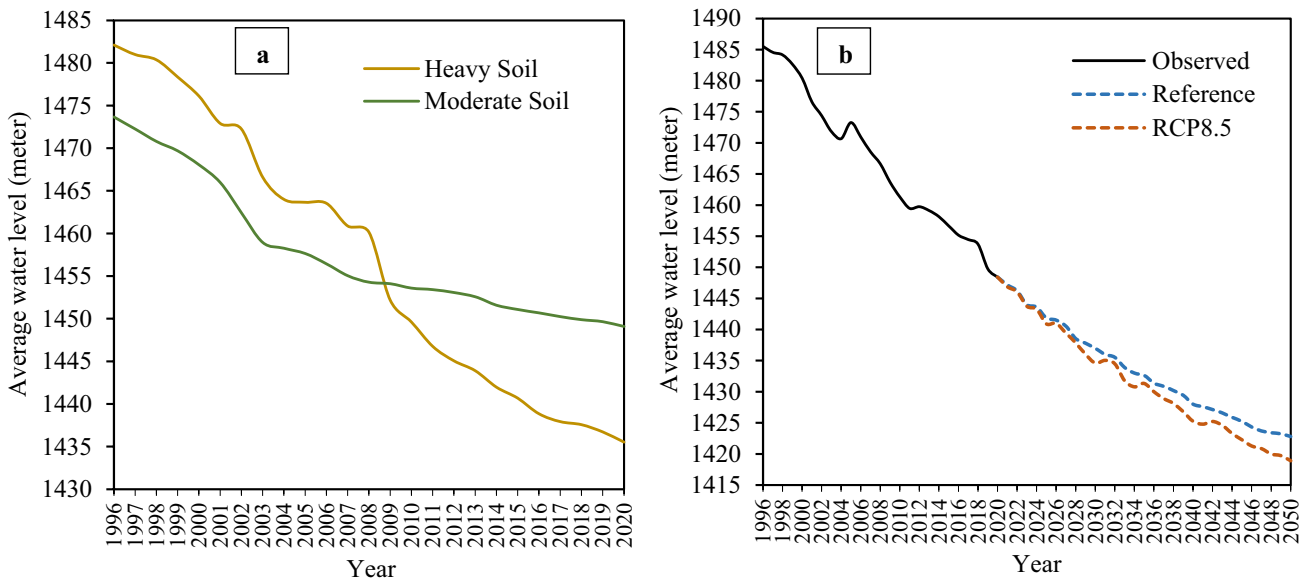
reduction of recharge under two scenarios of RCP4.5 and RCP8.5 is presented in Fig. 10. The simulation results under the RCP4.5 scenario in the next period showed that with increasing the average temperature by 1.1 °C and decreasing the annual rainfall by 9%, the amounts of the reduced recharge in different parts of the region will reach about 15–25%. Also, the average rate of reduction of the total aquifer recharge under this scenario is predicted to be about 23%. The percentage of the reduced recharge in the next period under the RCP8.5 scenario is further estimated. Thus, with a 14% decrease in the rainfall and an average temperature increase of 1.65 °C, the rate of the possible reduction of the recharge in different places is predicted to be between 25 and 40%. Also, the average reduction of the total aquifer recharge under this scenario is estimated to be 34%. The results of previous studies also show that the rate of groundwater recharge is reduced due to climate change, and this reduction is significant, especially in vulnerable areas (Raposo et al. 2013; Goodarzi et al. 2016; Haidu and Nistor 2020).

A comparison of soil maps with spatial distribution maps of recharge under emission scenarios showed that recharge changes are different according to the characteristics of the aquifer soils. In general, the heavier the soil texture (Clay and Clay Loam), the lower the recharging values will be estimated. The reason is a higher water storage capability in this type of soil. Also, the lighter the soil texture (Loam and Sandy Loam), the more recharging values are obtained due to the greater deep percolation. In the study area, water level fluctuations have been measured monthly by 23 observation wells. The results of measurements indicated that the rate of drop in the aquifer water levels in different wells varied during the census period. The average annual values of the measured water level of two observation wells in two different soils during the period from 1996 to 2018 are presented in Fig. 11. It is observed that the rate of the water level drop in heavy soil (Clay) was about 45 m (average 2 m per year) and in the medium soil (Loam) it is about 24 m (average 1 m per year). It can be concluded that the amount of recharge in the heavy soils of the region is much less compared to that of the light soils. Therefore, to prevent further decline in groundwater levels, the abstraction in these areas should be reduced. Accordingly, the development of pressurized irrigation systems (especially drip irrigation) and the cultivation of low-consumption plants can be prioritized for these zones. In previous studies, the investigation of recharging rate in terms of soil type has received less attention (Goodarzi et al. 2016; Chunn et al. 2019; Haidu and Nistor 2020), while the results of this study showed that considering this issue can help to balance the aquifer.

The hydrograph of the aquifer unit is plotted in Fig. 11 to better understand the water table drop between 1996 and 2018. It is observed that the average drop of the aquifer was about 32 m (average of 1.5 m per year). Also in this



**Fig. 10** Spatial distribution map of the recharge reduction under **a** RCP 4.5 and **b** RCP8.5 scenarios in the next period (2021–2050)



**Fig. 11** **a** Average annual water level measured in two observation wells from 1996 to 2018. **b** Aquifer unit hydrograph from 1996 to 2050

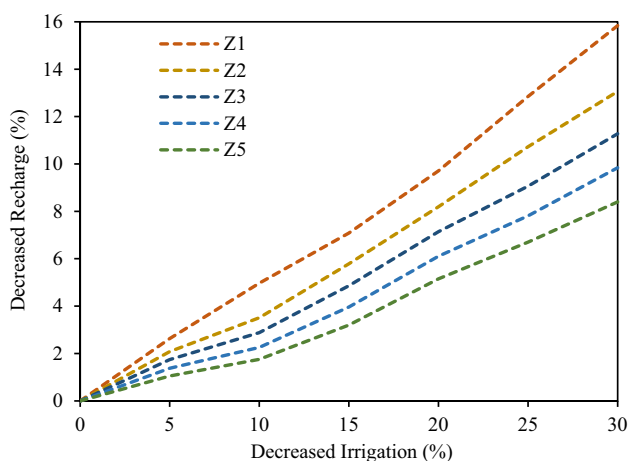
figure, the aquifer water level is simulated by the MODFLOW model under the current operation trend (reference) and the RCP8.5 emission scenario for the next period (2021–2050). It is observed that the drop in the aquifer water level will increase by about 15% on average annually, considering the future climate change. Izady et al. (2015) reported the average annual drop in groundwater level for a semi-arid region in Iran to be about 1 m without considering climate changes.

**Assessing the reduction of irrigation requirements on the groundwater recharge**

In order to balance the supply and demand of water in the study area, the development of pressurized systems and changing the cultivation pattern towards low-consumption crops is inevitable. At present, according to the measurements, the gravity irrigation efficiency of the region is about 47% and the efficiency of pressurized irrigation

(mainly tape irrigation) is about 67% (Abbasi et al. 2017). Since up to 60% of the region is irrigated by gravity, increasing irrigation efficiency, especially in zones with low recharge capacity, will help to balance the groundwater aquifer. This factor, along with replacing high-consumption plants in the region such as alfalfa, sugar beet, corn, wheat, grapes, and orchards with plants such as canola, legumes, and pistachios will have a significant impact on reducing water consumption.

In this study, it is assumed that by applying different policies, the irrigation requirements of the plain will be reduced by about 30%. For this purpose, sensitivity analysis was used to investigate the effect of reducing the irrigation requirements on the amount of the recharge. Accordingly, the amount of irrigation was reduced between 0 and 30% in the SWAT model and while other input parameters were kept constant, the amount of recharge to the aquifer was estimated. The sensitivity analysis of the irrigation reduction in the homogeneous recharge zones is presented in Fig. 12. It is observed that with a 30% reduction in irrigation, the amount of recharge in different zones declines between 8 and 16% (average 12%). Decreasing irrigation, in addition to reducing abstraction from aquifers, will also reduce the loss of water transport and distribution of water. Consequently, the implementation of these policies, which have received less attention in previous research, despite the fact that it will lead to a reduction in the groundwater recharge, can greatly contribute to balance the groundwater in the long run and also be considered by executives (Liu et al. 2013; Bushira et al. 2017; Chunn et al. 2019; Yifru et al. 2020; Wable et al. 2021; Izady et al. 2022).



**Fig. 12** Sensitivity analysis of the recharge rate to the decrease of irrigation in different zones

## Conclusion

In this study, the simulation of the effects of climate change and reducing the irrigation requirements on the groundwater recharge were studied using a combination of SWAT and MODFLOW models, and also the spatial distribution of plain recharge rates for different conditions was analyzed.

Evaluation of different climate change models showed that MRI-CGCM3, MIROC5, and CSIRO-Mk3.6.0 models have the highest accuracy for predicting rainfall, and maximum and minimum temperatures, respectively. The average temperatures of the region under RCP2.6, RCP4.5, and RCP8.5 emission scenarios will be increased by 0.68, 1.05, and 1.65 °C for the next period (2021–2050), respectively. Also, the average annual rainfall of the region under RCP2.6, RCP4.5 and RCP8.5 scenarios will be decreased by 4, 9 and 14%, respectively, for the next period.

Recharge rate modeling revealed that the highest amount of the aquifer recharge occurs in February, March, April and May. Therefore, by controlling the runoff, the aquifer can be artificially charged during these months. Also, the average annual recharge of the aquifer is estimated at 43 mm, which reaches about 12% of the rainfall.

Assessing the effects of climate change on the aquifer recharge in the next period revealed that the spatial distribution of reduced recharging rates in different parts of the aquifer is varied. The average recharge rate of the whole aquifer under RCP4.5 and RCP8.5 scenarios will be reduced by 23 and 34%, respectively. Also, the simulation of the groundwater level by the MODFLOW model in the next period showed that the annual drop of the groundwater level will increase under the conditions of climate change.

The outcomes of comparing the spatial distribution maps of groundwater recharge with physical properties of the aquifer indicated that the recharge values vary according to the type of soil. Heavier-textured soils (Clay and Clay Loam) had lower recharge values than lighter-textured soils (Loam and Sandy Loam). Investigating the water levels measured in the observation wells also confirmed that the drop in the water level was more in the heavy soils of the region. It can be said that the main reason for this is less recharge of these types of soils. Therefore, it is suggested to prioritize the development of pressurized irrigation systems and cultivation of low-consumption plants in soils with heavy texture. This strategy can prevent the further drop of the groundwater level in the region.

The outcomes of reducing the irrigation requirements on the recharge rate showed that with a 30% reduction in irrigation, the average recharge rate of the whole plain

decreases by 12%. Consequently, the implementation of policies to reduce the irrigation requirements, especially in areas that are more vulnerable to changes in recharging rate, can help to balance the groundwater in the region in the long term.

**Acknowledgements** The authors sincerely appreciate the experts of the Regional Water Company, and the Agricultural Organization of Fars for providing all the required information.

**Author contributions** MKS performed conceptualization; writing original draft; data analysis; methodology; software; and validation. JA-K performed supervision; conceptualization; methodology; validation; visualization; investigation; writing, reviewing and editing of the manuscript. SSE performed supervision; reviewing of the manuscript. SARG performed investigation; reviewing of the manuscript.

**Funding** The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

## References

- Abbasi F, Sohrab F, Abbasi N (2017) Evaluation of irrigation efficiencies in Iran. *Irrig Drain Struct Eng Res* 17(67):113–120. <https://doi.org/10.22092/ARIDSE.2017.109617>
- Abbaspour KC (2011) SWAT-CUP2: SWAT calibration and uncertainty programs manual version 2. Eawag, swiss federal institute of aquatic science and technology, department of systems analysis. Integrated Assessment and Modeling (SIAM), Duebendorf, Switzerland, p 106
- Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Kløve B (2015) A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. *J Hydrol* 524:733–752. <https://doi.org/10.1016/j.jhydrol.2015.03.027>
- Adopted I (2014) Climate change 2014. Synthesis report. IPCC: Geneva, Switzerland
- Al-Safi HIJ, Sarukkalgige PR (2020) The application of conceptual modelling to assess the impacts of future climate change on the hydrological response of the Harvey River catchment. *J Hydro-Environ Res* 28:22–33. <https://doi.org/10.1016/j.jher.2018.01.006>
- Anonymous (2015) Studies of the second phase of the irrigation and drainage network Mirza Shirazi dam (Kavar plain). Regional water company of Fars, Technical Report, Iran
- Anonymous (2018) Statistics and performance Agriculture section Fars province. Agricultural organization of Fars, Technical Report, Iran
- Arnold JG, Srinivasan R, Mutiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development 1. *J Am Water Resour Assoc* 34(1):73–89. <https://doi.org/10.1111/j.1752-1688.1998.tb05961.x>
- Azeref BG, Bushira KM (2020) Numerical groundwater flow modeling of the Kombolcha catchment northern Ethiopia. *Model Earth Syst Environ* 6(2):1233–1244. <https://doi.org/10.1007/s40808-020-00753-6>
- Bushira KM, Hernandez JR, Sheng Z (2017) Surface and groundwater flow modeling for calibrating steady state using MODFLOW in Colorado River Delta, Baja California Mexico. *Model Earth Syst Environ* 3(2):815–824. <https://doi.org/10.1007/s40808-017-0337-5>
- Chaemiso SE, Abebe A, Pingale SM (2016) Assessment of the impact of climate change on surface hydrological processes using SWAT: a case study of Omo-Gibe river basin Ethiopia. *Model Earth Syst Environ* 2(4):1–15. <https://doi.org/10.1007/s40808-016-0257-9>
- Chitsazan M, Rahmani G, Ghafoury H (2020) Investigation of subsidence phenomenon and impact of groundwater level drop on alluvial aquifer, case study: Damaneh-Daran plain in west of Isfahan province Iran. *Model Earth Syst Environ* 6(2):1145–1161. <https://doi.org/10.1007/s40808-020-00747-4>
- Chunn D, Faramarzi M, Smerdon B, Alessi DS (2019) Application of an integrated SWAT–MODFLOW model to evaluate potential impacts of climate change and water withdrawals on groundwater–surface water interactions in West-Central Alberta. *Water* 11(1):110. <https://doi.org/10.3390/w11010110>
- Doherty J, Brebber L, Whyte P (1994) PEST: model-independent parameter estimation. *Watermark Comput Corinda Aust* 122:336
- Etemadi H, Samadi S, Sharifikia M (2014) Uncertainty analysis of statistical downscaling models using general circulation model over an international wetland. *Clim Dyn* 42(11–12):2899–2920. <https://doi.org/10.1007/s00382-013-1855-0>
- Farhadi S, Nikoo MR, Rakhshandehroo GR, Akhbari M, Alizadeh MR (2016) An agent-based-nash modeling framework for sustainable groundwater management: a case study. *Agri Water Manag* 177:348–358. <https://doi.org/10.1016/j.agwat.2016.08.018>
- Fleckenstein JH, Krause S, Hannah DM, Boano F (2010) Groundwater-surface water interactions: new methods and models to improve understanding of processes and dynamics. *Adv Water Resour* 33(11):1291–1295. <https://doi.org/10.1016/j.advwatres.2010.09.011>
- Gilfedder M, Rassam DW, Stenson MP, Jolly ID, Walker GR, Littleboy M (2012) Incorporating land-use changes and surface–groundwater interactions in a simple catchment water yield model. *Environ Model Softw* 38:62–73. <https://doi.org/10.1016/j.envsoft.2012.05.005>
- Gohari A, Eslamian S, Abedi-Koupaei J, Bavani AM, Wang D, Madani K (2013) Climate change impacts on crop production in Iran's Zayandeh-Rud River Basin. *Sci Total Environ* 442:405–419. <https://doi.org/10.1016/j.scitotenv.2012.10.029>
- Goodarzi M, Abedi-Koupaei J, Heidarpoor M, Safavi HR (2016) Evaluation of the effects of climate change on groundwater recharge using a hybrid method. *Water Resour Manag* 30(1):133–148. <https://doi.org/10.1007/s11269-015-1150-4>
- Guzman JA, Moriasi D, Gowda PH, Steiner JL, Starks P, Arnold JG, Srinivasan R (2015) A model integration framework for linking SWAT and MODFLOW. *Environ Model Softw* 73:103–116. <https://doi.org/10.1016/j.envsoft.2015.08.011>
- Gyamfi C, Ndambuki JM, Anornu GK, Kifanyi GE (2017) Groundwater recharge modelling in a large scale basin: an example using the SWAT hydrologic model. *Model Earth Syst Environ* 3(4):1361–1369. <https://doi.org/10.1007/s40808-017-0383-z>
- Haidu I, Nistor MM (2020) Long-term effect of climate change on groundwater recharge in the Grand Est region of France. *Meteorol Appl* 27(1):e1796. <https://doi.org/10.1002/met.1796>
- Harbaugh AW (2005) MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process. US Department of the Interior, vol. 6. US Geological Survey Reston, VA, USA
- Izady A, Davary K, Alizadeh A, Ziaei A, Akhavan S, Alipoor A, Joodavi A, Brusseau M (2015) Groundwater conceptualization and modeling using distributed SWAT-based recharge for the semi-arid agricultural Neishaboer plain Iran. *Hydrogeol J* 23(1):47–68. <https://doi.org/10.1007/s10040-014-1219-9>
- Izady A, Joodavi A, Ansarian M, Shafiei M, Majidi M, Davary K, Ziaei AN, Ansari H, Nikoo M, Al-Maktoumi A (2022) A

- scenario-based coupled SWAT-MODFLOW decision support system for advanced water resource management. *J Hydroinform* 24(1):56–77. <https://doi.org/10.2166/hydro.2021.081>
- Kashef AI (1986) *Groundwater engineering*. McGraw-Hill, New York
- Khajeh S, Paimozd S, Moghaddasi M (2017) Assessing the impact of climate changes on hydrological drought based on reservoir performance indices (case study: ZayandehRud River basin, Iran). *Water Resour Manag* 31(9):2595–2610. <https://doi.org/10.1007/s11269-017-1642-5>
- Kim NW, Chung IM, Won YS, Arnold JG (2008) Development and application of the integrated SWAT–MODFLOW model. *J Hydrol* 356(1–2):1–16. <https://doi.org/10.1016/j.jhydrol.2008.02.024>
- King LM, Irwin S, Sarwar R, McLeod AIA, Simonovic SP (2012) The effects of climate change on extreme precipitation events in the Upper Thames River Basin: a comparison of downscaling approaches. *Can Water Resour J* 37(3):253–274. <https://doi.org/10.4296/cwrj2011-938>
- Kouhestani S, Eslamian SS, Abedi-Koupai J, Besalatpour AA (2016) Projection of climate change impacts on precipitation using soft-computing techniques: a case study in Zayandeh-rud Basin Iran. *Glob Planet Change* 144:158–170. <https://doi.org/10.1016/j.gloplacha.2016.07.013>
- Liu L, Cui Y, Luo Y (2013) Integrated modeling of conjunctive water use in a canal-well irrigation district in the lower Yellow River basin China. *J Irrig Drain Eng* 139(9):775–784. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000620](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000620)
- McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. *Techniques of Water Resources Investigations, U.S. Geological Survey, Book 6*, Reston, Virginia
- Mishra BK, Regmi RK, Masago Y, Fukushi K, Kumar P, Saraswat C (2017) Assessment of Bagmati river pollution in Kathmandu Valley: scenario-based modeling and analysis for sustainable urban development. *Sustain Water Qual Ecol* 9:67–77. <https://doi.org/10.1016/j.swaqe.2017.06.001>
- Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2011) *Soil and water assessment tool theoretical documentation version 2009*, Texas Water Resources Institute, Technical Report, 406:647
- Rafiee MR, Moazed H, Boroomandnasab AA, Gaemi S (2016) FAO-56 method for estimating evapotranspiration and crop coefficients of eggplant in greenhouse and outdoor conditions. *Irrig Sci Eng* 39(2):59–77. <https://doi.org/10.1016/j.jare.2016.02.005>
- Raposo JR, Dafonte J, Molinero J (2013) Assessing the impact of future climate change on groundwater recharge in Galicia-Costa Spain. *Hydrogeol J* 21(2):459–479. <https://doi.org/10.1007/s10040-012-0922-7>
- Sepaskhah AR, Fooladmand HR (2004) A computer model for design of microcatchment water harvesting systems for rain-fed vineyard. *Agric Water Manag* 64(3):213–232. [https://doi.org/10.1016/S0378-3774\(03\)00197-5](https://doi.org/10.1016/S0378-3774(03)00197-5)
- Sivakumar M, Das H, Brunini O (2005) Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics. *Clim Change* 70:31–72. [https://doi.org/10.1007/s1-4020-4166-7\\_4](https://doi.org/10.1007/s1-4020-4166-7_4)
- Wable PS, Chowdary V, Panda S, Adamala S, Jha C (2021) Potential and net recharge assessment in paddy dominated Hirakud irrigation command of eastern India using water balance and geospatial approaches. *Environ Dev Sustain* 23(7):10869–10891. <https://doi.org/10.1007/s10668-020-01092-3>
- Yidana SM, Chegbeleh LP (2013) The hydraulic conductivity field and groundwater flow in the unconfined aquifer system of the Keta Strip, Ghana. *J Afr Earth Sci* 86:45–52. <https://doi.org/10.1016/j.jafrearsci.2013.06.009>
- Yifru BA, Chung IM, Kim MG, Chang SW (2020) Assessment of groundwater recharge in agro-urban watersheds using integrated SWAT-MODFLOW model. *Sustainability* 12(16):6593. <https://doi.org/10.3390/su12166593>
- Zarei M, Ghazavi R, Vali A, Abdollahi K (2016) Estimating groundwater recharge, evapotranspiration and surface runoff using land-use data: a case study in northeast Iran. *Biol Forum Int J* 8(2):196–202

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