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ORIGINAL PAPER

Local strategies to manage groundwater depletion under climate change scenarios—a case study: Hamedan-Bahar Plain (Iran)

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Abstract
Climate changes and the unremitting overexploitation of groundwater in the Hamedan-Bahar Plain have raised concerns about the sustainability of groundwater resources. The current research focused on the development of an integrated system dynamics model to examine the long-term effects of employing five adaptation strategies on groundwater. The model was calibrated and validated using a 21-year historical data set, and the strategies were combined into 21 management and climate change scenarios (seven management scenarios in tandem with three climate change scenarios) to project groundwater levels for the period 2020–2050. Future climatic conditions were projected by downscaling the data of the CanESM2 general circulation model under three representative concentration pathway scenarios (RCP2.6, RCP4.5, and RCP8.5). By applying the business-as-usual management scenario, the groundwater table change rates will be −0.37, −0.45, and −0.44 m/year under the RCP2.6, RCP4.5, and RCP8.5 scenarios, while the corresponding rates for the most efficient management scenario are +0.22, +0.11, and +0.13 m/year, respectively. The strategies have been ranked according to their effectiveness as follows: (i) reducing irrigated agriculture in favor of rainfed agriculture or fallow fields, (ii) applying an adaptive cropping pattern, (iii) developing early-maturing cultivars, (iv) practicing deficit irrigation, and (v) enhancing irrigation efficiency. The findings indicate that the local management strategies will play a greater role in future groundwater sustainability than global climate change.

Keywords Groundwater management; · Water resources; · Climate change; · Adaptation strategies; · Groundwater dynamics; · Hamedan-Bahar Plain

Introduction

Groundwater plays a vital role in supplying water for the irrigation, industrial, and municipal sectors in the Hamedan-Bahar Plain, with an estimated 99.6% contribution to the total water supply. Due to excessive groundwater withdrawal, the Hamedan water authorities have enforced a prohibition on drilling new deep-water wells since 1993. Similar management policies are also implemented by the governments of Pakistan, India, Egypt, and Yemen to preserve groundwater resources (Van Steenbergen 2006). Nevertheless, the decline in groundwater levels has continued at a rate of 0.84 m/year (1991–2018) and well yields have decreased (RWCH 2020), as a result, water production costs have increased (Yin et al. 2020). The same issue is addressed by Konikow and Kendy (2005), Foster et al. (2015), Konikow (2015), and Ruybal et al. (2019). Groundwater is connected in a sense to the climate of the region; therefore, a number of researchers have sought to determine the impacts of climate change on groundwater resources (Eckhardt and Ulbrich 2003; Ducci and Tranfaglia 2008; Mizyed 2009; Earman and Dettinger 2011; Meixner et al. 2016; Kahsay et al. 2018; Cotterman et al. 2018). However, it is still unclear as to what the impact of climate change on groundwater resources is and how it is likely to vary based on location, hence further research to extend our understanding of the joint behaviors of climate and groundwater is required (Green et al. 2011; Sutton 2019). Moreover, in some regions, reduced precipitation and increased air temperature, as a consequence of climate change, are likely to add more complications to the management of

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groundwater resources through the increased demand for irrigation water (Gondim et al. 2012; Kirby et al. 2016). The increase in irrigation water demand caused by climate change has been reported in several studies (Weatherhead and Knox 2000; Alcamo et al. 2007; Henriques et al. 2008; Thomas 2008; Mizyed 2009; Shahid 2011; Gohari et al. 2013; Hong et al. 2016; Ashofteh et al. 2017; Cho et al. 2019; Oumarou Abdoulaye et al. 2019; Kaushika et al. 2019). Conversely, there are studies demonstrating that the changes in climate will reduce crop water requirement (Munoz et al. 2007; Tukimat et al. 2017; Acharjee et al. 2017). Thus, it is important to assess the impacts of climate change at the local scale in the Hamedan-Bahar Plain. Concerns about continuous groundwater overexploitation and the effects of climate change have led researchers to propose, evaluate, and reassess water management mitigation strategies (Rosenzweig et al. 2004; Arnell and Delaney 2006; Alcamo et al. 2007; Upendram and Peterson 2007; Henriques et al. 2008; Ward and Pulido-Velazquez 2008; Portoghese et al. 2013; Philip et al. 2014; Pfeiffer and Lin 2014; Yang et al. 2015; Nazemi et al. 2020; Singh et al. 2020). In this regard, reliable groundwater models, capable of simulating the responses of subsurface water reservoirs to water resource policies (Serrat-Capdevila et al. 2007; Trichakis et al. 2009; Yoon et al. 2011; Hanson et al. 2012; Turner et al. 2015; Xu and Valocchi 2015; Meixner et al. 2016; Chang et al. 2016; Nazarieh et al. 2018; Xiang et al. 2020), can be effectively used in explaining the physical, and natural phenomena influencing groundwater. Traditional groundwater models, however, do not account for the impacts of human activity on the water cycle, thereby restricting their capability to model the response of hydrological systems to various anthropogenic forces (Wagener et al. 2010; Jeong and Adamowski 2016). This leads to an event-oriented model based on linear causal thinking, thus providing a limited representation of interactions between system components (Jeong and Adamowski 2016). The introduction of an object-oriented modeling approach based on system dynamics concepts instead of an event-oriented modeling approach in recent years, however, provided an edge to groundwater modeling and analysis. Object-oriented modeling of system dynamics uses system thinking to apprehend the interactions and feedback mechanisms between the hydrogeological and social subsystems; moreover, it is a holistic, integrated approach that considers the different subsystems of a water cycle as a complex whole.

There is a growing body of literature that uses system dynamics (SD) as a framework for the object-oriented worldview (Zomorodian et al. 2018). Using SD models, researchers have been able to simulate the complexity and dynamics of surface water and groundwater resources (Dai et al. 2013; Wu et al. 2013; Hassanzadeh et al. 2014; Mokhtar and Aram 2017; Ghasemi et al. 2017; Mahdavinia and Mokhtar 2019; Pluchinotta et al. 2018; Bates et al. 2019). Additionally, to assess the impacts of a changing climate on water resources, many recent studies (e.g., Tromboni et al. 2014; Xiao-jun et al. 2014; Gohari et al. 2017; Qin et al. 2019) have applied the output results of general circulation models (GCMs) to SD models. Balali and Viaggi (2015) presented an SD model to study the economic dynamics of Hamedan-Bahar plain groundwater and argued that an increase in water and energy prices would reduce groundwater extraction. Kotir et al. (2016) developed an SD model to simulate the interaction between the water resource, the agricultural production, and the population sub-sectors of the Volta River Basin in Ghana. According to the results, the development of water infrastructure provides the most benefit to the local community and is more important than cropland expansion. Barati et al. (2019) introduced an SD model to compensate for policy deficiencies in groundwater management in Iran. The aforementioned results indicated that groundwater balance is negative and proposes the strategy of increasing water efficiency through an increase in the infiltration rate and a decrease in the extraction rate in order to compensate for poor groundwater management. Together, these studies indicate that SD models can be successfully applied for water resources management and scenario assessment.

As explained, there is a growing concern over groundwater depletion and climate change impacts, which are threatening the sustainable development of the region. What remains unclear, however, is which adaptation strategy is more effective to address the concern and to what extent climate change affects groundwater resources. Thus, in this research, we attempted to answer these questions by (i) evaluating the probable future impacts of climate change on the crop water requirements and the groundwater resources of the study area, (ii) developing an SD model to improve the understanding of the dynamics of groundwater for sustainable water resources management, and (iii) considering adaptation strategies, including irrigation efficiency enhancement, deficit irrigation, the development of early-maturing cultivars, the development of rainfed agriculture and fallow fields, and cropping pattern changes, to control groundwater depletion and to mitigate the effects of climate change.

Materials and methods

Study area and groundwater data

The Hamedan-Bahar watershed is a subbasin of the Qara-Chay river basin, extending over an area of 2463 km^2. It is located in the northeast of the Alvand Mountains in the Hamedan province, Iran. The present study was conducted on the main unconfined alluvial aquifer, which is part of the Hamedan-Bahar watershed and is locally known as the Hamedan-Bahar Plain (HBP). The plain encompasses an area of 483 km^2 of which approximately 230 km^2 is under irrigation. The HBP ranges in elevation from approximately 1673 to 1871 m, with an average of 1739.25 m above mean sea level (Fig. 1).

The groundwater data used in this study were obtained from the Regional Water Company of Hamedan (RWCH) who has maintained 28 observation wells since 1991 to monitor monthly changes in groundwater levels and storage (Fig. 1). RWCH (2020) reported that the groundwater level in the HBP has declined on average by 0.84 m annually from 1991 to 2018, which shows a significant downward trend at a 99% confidence level. It was based on the aforementioned data that the HBP was chosen as the case study of the current research due to its key role in the production of agricultural products and the creating of food security, which have in themselves been affected by groundwater level decline and depletion (Moench et al. 2003).

Climate projections

To project how future climate change may affect groundwater resources, three Representative Concentration Pathway (RCP) scenarios (RCP 2.6, 4.5, and 8.5) of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) were evaluated. The RCP 2.6, 4.5, and 8.5 scenarios are the projections of future radiative forcing at levels of 2.6, 4.5, and 8.5 W/m^2 by the end of the twenty-first century respectively used in climate models (Moss et al. 2010). RCP2.6 is the most optimistic scenario, whereas RCP8.5 is the most pessimistic scenario. In order to simulate global climate projection based on the RCP scenarios, the Canadian Centre for Climate Modelling and Analysis (CCCma) has developed a general circulation model (GCM), called the second generation Canadian Earth System Model (CanESM2) (Arora et al. 2011). The daily series of the CanESM2 outputs under the RCP 2.6, 4.5, and 8.5 scenarios were acquired from the CCCma website (CCCma 2019) and were downscaled to the study area using the Statistical Downscaling Model [SDSM, Wilby et al. 2002] that projects future maximum air temperature (TX), minimum air temperature (TN), and precipitation (PRCP).

Groundwater demand

Groundwater is the main source of water for irrigation, household, and industrial use, with irrigation being the primary use, representing about 88.7% of abstractions within the study area. Wheat, alfalfa, potatoes, barley, garlic, cucumbers, watermelon, pumpkin, sugar beet, rapeseed, grain maize, and beans are among the major irrigated crops cultivated in the HBP. The net irrigation requirements (I_n) of the crops were calculated by subtracting the monthly effective precipitation (P_e) from the total monthly crop evapotranspiration (ET_c). P_e and ET_c were computed following the USDA-SCS and FAO-56

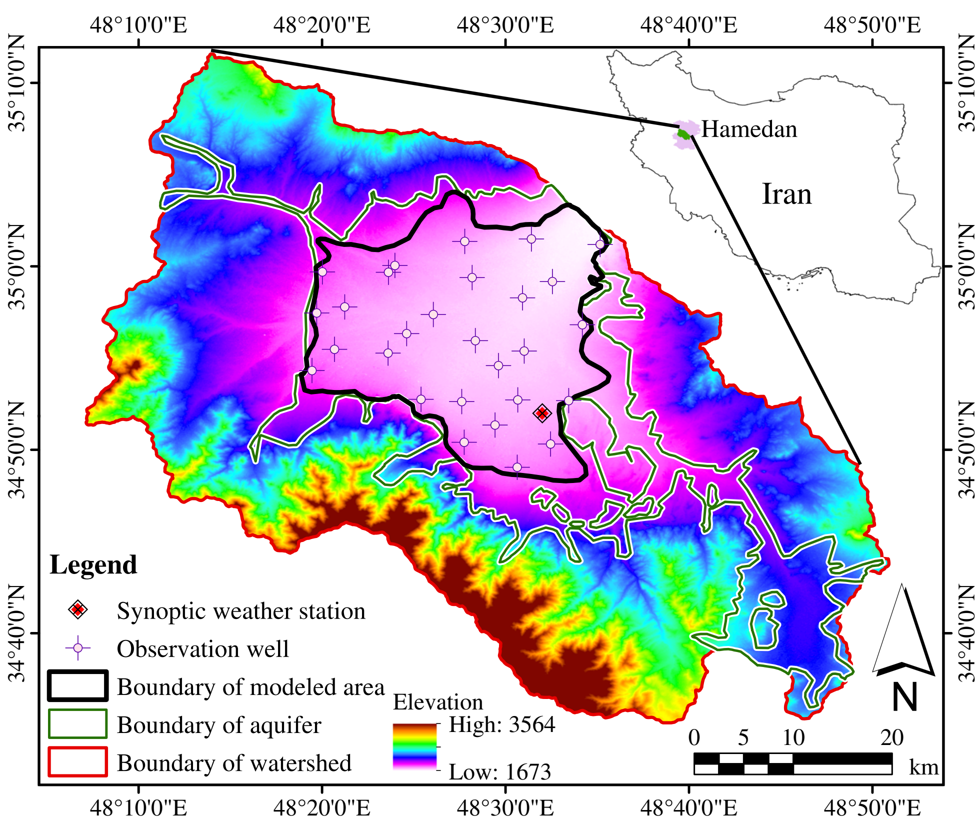


Fig. 1 The Hamedan-Bahar watershed, the study area, and the HBP's groundwater monitoring network

procedures, respectively (Martin and Gilley 1993; Allen et al. 1998). Taking into account the yearly average irrigation efficiency (E_i) depicted in Fig. 2, in the next stage, the gross irrigation requirement (I_g) was estimated for each crop ($I_g = I_n / E_i$). Then, the irrigation water demand for each crop was calculated through the multiplying of I_g by the annual crop area, and the total irrigation water demand was obtained by adding the results together. The household and industrial water demand data were obtained from the Hamedan water authorities (RWCH and Hamedan Province Water and Wastewater Company, i.e., HWW).

System dynamics modeling

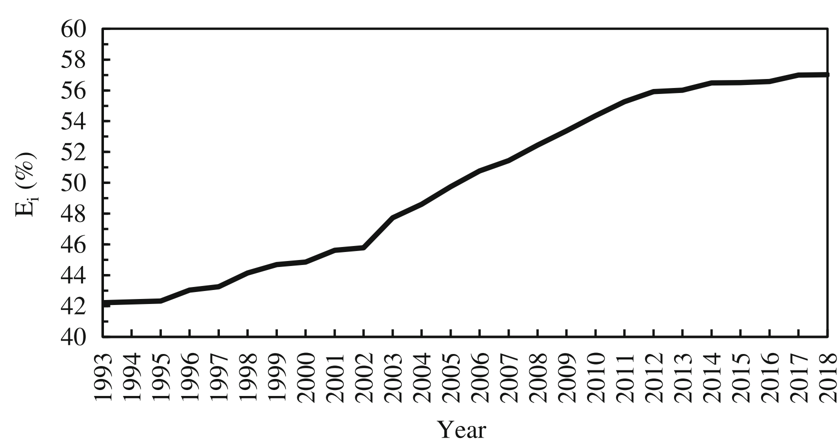
The SD can be used to develop models for which the interactions and dependencies between the components of a system are supported (Sterman 2000). The key advantage of utilizing the SD for the complex and interconnected groundwater system of the HBP is that it elucidates the endogenous structure of the system and examines how adaptation strategies can be applied to reduce the vulnerability of groundwater to overexploitation and climate change. Developing an SD model begins with defining a dynamic hypothesis (a structure that explains the dynamic behavior of interest). Then, the causal loop diagram is constructed and the model is quantified by using stock-and-flow diagrams (Sterman 2000; Ford 2019). We presented the causal loop diagram of the groundwater system of the HBP (Fig. 3). The system includes the main inflows and outflows of groundwater storage and their key variables. A positive (+) or negative (−) sign next to the arrowhead indicates the direction of change in cause and effect variables. A positive polarity relationship denotes that both variables change in the same direction. Conversely, negative polarity indicates that two variables change in the opposite direction. Combinations of positive and negative causal link polarities may form feedback loops, which are either reinforcing or balancing (Sterman 2000). A reinforcing feedback loop is a closed cycle in which the effect of a change in a variable propagates through the loop and returns to the variable reinforcing the initial change. On the other hand, in a balancing feedback loop, the effect of a change in a variable propagates through the loop and returns to the variable a change opposite to the initial one. Balancing loops display equilibrium-seeking behavior and try to bring stocks to a desired state (Ford 2019).

As shown in Fig. 3, the causal loop diagram includes 18 variables, which are connected by 28 causal links (arrows). The interactions generate four reinforcing and five balancing feedback loops. For instance, B2 is a balancing loop. In this loop, a decrease in groundwater storage (groundwater depletion) raises concerns about groundwater sustainability among decision-makers, and consequently, the decision-makers decide to increase groundwater protection measures by developing adaptive cropping patterns that lead to a decrease in agricultural water use. A decrease in agricultural water use decreases groundwater outflow (withdrawal). Finally, a decrease in groundwater outflow leads to an increase in groundwater storage.

Based on the causal loop diagram (Fig. 3), the *H*amed*an*-*Bahar* *S*ystem *D*ynamics model (HanBarSD) was developed by Vensim DSS (Ventana Systems 2015) to simulate changes in groundwater storage caused by natural and artificial groundwater recharge and discharge. The model consists of three subsystems that represent the main characteristics of the agricultural groundwater demand and soil water balance, municipal (urban and rural) and industrial water demands, and groundwater storage sectors (see Figs. 9, 10, and 11 in Appendix). The HanBarSD model has a time step of 0.0625 months. A complete description of the variables included in the HanBarSD model is represented in Table 5 in the Appendix.

The equation used to assess groundwater storage is the widely accepted groundwater-balance equation (Zhang and Kennedy 2006; Martínez-Santos and Martínez-Alfaro 2010; Xu et al. 2010; Mohammadi et al. 2014; Yue et al. 2016) which is calculated as:

Fig. 2 Changes in the total irrigation efficiency of the HBP



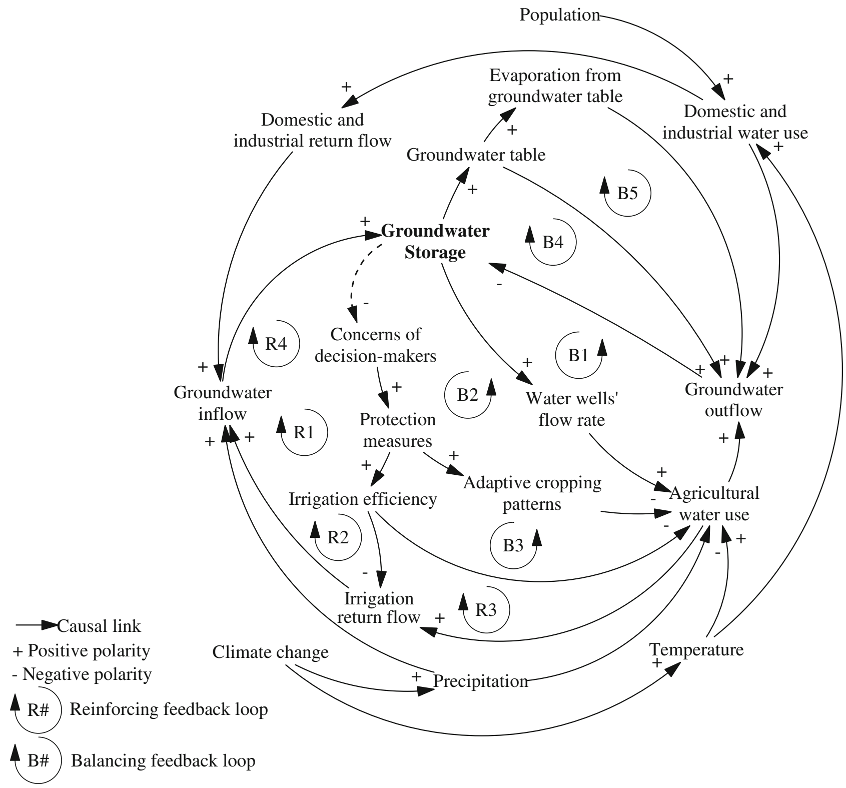


Fig. 3 Causal loop diagram of the HBP groundwater storage

$$I_p + I_i + I_a + I_s + I_w + G_{in} - G_{out} - Q_g - W_{irrig} - W_{muni} - W_{rural} - W_{ind} - E_g = \Delta S_g \quad (1)$$

where I_p is the recharge from precipitation, I_i is the irrigation return flow, I_a is the artificial groundwater recharge, I_s is the infiltration from surface flow, I_w is the seepage from domestic and industrial wastewater, G_{in} is the groundwater flow into the aquifer, G_{out} is the groundwater flow out of the aquifer, Q_g is the groundwater flow into the stream, W_{irrig}, W_{muni}, W_{rural}, and W_{ind} are the groundwater withdrawal for irrigation, municipal, rural, and industrial purposes, respectively, E_g is the groundwater evaporation, and ΔS_g is the change in groundwater storage. All the variables in the groundwater balance equation use values of MCM/month (million cubic meters per month). Using the RWCH guideline (RWCH 2020), I_p, I_a, I_w, and E_g were estimated as follows

$$I_p = 10^{-3} C_p \cdot A \cdot P_m \quad (2)$$

$$I_a = C_{ar} \cdot AR_{CPTY} \quad (3)$$

$$I_w = C_w \cdot (W_{ind} + W_{muni} + W_{rural}) \quad (4)$$

$$E_g = C_E \cdot E_{pan} \cdot A_E \quad (5)$$

where C_p is the dimensionless recharge coefficient of precipitation (C_p = 0.16), A is the area of the region under study (km^2), P_m is the amount of monthly precipitation (mm), C_{ar} is the dimensionless artificial recharge coefficient (ranging from 1 to 0.6 for wet and drought years), AR_{CPTY} is the maximum capacity of artificial groundwater recharge in the study region (MCM/month), C_w is the dimensionless domestic and industrial return-flow coefficient ($C_w = 0.65$), C_E is the dimensionless evaporation coefficient of groundwater (C_E = 0.02), E_{pan} is the amount of pan evaporation (m), and A_E is the sum of the areas wherein the depth of the groundwater table is less than 5 m. Since all the streams in the plain are ephemeral, I_s and Q_g are small and negligible (I_s and $Q_g \approx 0$). Irrigation return flow which plays an important role in groundwater recharge is defined as the amount of irrigation water that drains down beneath the root zone and was calculated using the balance equation within the root zone as follows:

$$I_i = 10^{-3} \sum_{j=1}^{n} \left(P_m + I_g^j - E_l - S_r - ET_c^j - \Delta S_{rz}^j \right) \cdot A_c^j \quad (6)$$

where j is the crop index, n is the number of crops (here n = 12), I_g^j is the gross irrigation requirement of the jth crop (mm), E_l is the evaporation loss (mm), S_r is the surface runoff (mm), ET_c^j is the evapotranspiration of the jth crop (mm), ΔS_{rz}^j is the water content change in the root zone of the jth crop (mm), and A_c^j is the area of the jth crop (km^2). The aquifer of the HBP is bounded by 19 inflow boundaries and one outflow boundary that are used to assess the groundwater flow into (G_{in}) and out of (G_{out}) the aquifer based on Darcy's law:

$$G_{in/out} = 10^{-6} \sum_i T_i \cdot L_i \cdot \left(\frac{dh}{dx} \right)_i \tag{7}$$

where i is the boundary index, T_i is the transmissivity of the aquifer at the ith boundary (m^2/month), L_i is the length of the ith boundary (m), and $(dh/dx)_i$ is the hydraulic gradient at the ith boundary (m/m). By identifying the average groundwater table drawdown (Δh), the specific yield of the aquifer (S_y), and the area of the study region (A), groundwater storage change (ΔS_g) can be determined as per the equation below.

$$\Delta S_g = \Delta h \cdot A \cdot S_y \tag{8}$$

Observed groundwater data for model calibration and validation were collected from Oct. 1998 to Sep. 2019. The calibration and validation of the model were carried out using the data from Oct. 1998 to Sep. 2015 and the data from Oct. 2015 to Sep. 2019, respectively. To evaluate the performance and accuracy of the HanBarSD model, simulated results for both the calibration and validation periods were compared with the observed data using the three indicators of the overall goodness-of-fit, including the root mean-square-error (RMSE), the Nash–Sutcliffe model efficiency coefficient (NSEC), and the Pearson correlation coefficient (r). A perfect match of the observed and simulated values of groundwater elevations is obtained if NSEC is equal to one (Nash and Sutcliffe 1970). Figure 4 shows the results of the calibration and validation. It can be seen that the simulation results follow the same trend as the observed groundwater elevations, indicating that the model is well-calibrated: 65% indicates that the difference is less than 1 m between the simulated and observed groundwater elevations; simulated groundwater elevations at 27% differed between 1 m and 2 m from the observed data. In addition, the model did not over-predict or under-predict the patterns and behaviors inherent in the HBP groundwater system. The values of RMSE, NSEC, and r were 1.12 m, 0.95, and 0.97 for the calibration period and 1.13 m, 0.98, and 0.84 for the validation period, respectively, which also demonstrate that the model adequately reproduces the observed values. Hence, the HanBarSD model can be utilized to simulate monthly groundwater level variations and project future scenarios in the HBP.

Policy scenarios design

Six policy scenarios were developed based on i) the key variables of the model that have the most impact on the groundwater storage; ii) the interviews conducted with water managers, field experts, and stakeholders; and iii) literature reviews to support the decision making for sustainable groundwater resources management and agricultural development over a period of 31 years (2020–2050). A business-as-usual (BAU) scenario was also included as a benchmark to consider and evaluate the effects of different mitigation and adaptation strategies. The strategies examined in this paper are named E0, E1, C0, C1, C2, C3, C4, FI, and DI and are defined in Table 1. E0, C0, and FI represent the status quo of irrigation efficiency, cropping pattern, and irrigation management that are assumed to be constant in the future.

Furthermore, the mitigation and adaptation strategies, including (i) irrigation efficiency improvement as shown in Fig. 5 (applied in strategy E1), (ii) changing the cropping pattern through a shift from more water-intensive crops to less water-intensive crops as illustrated in Fig. 6 (applied in strategies C1, C2, C3, and C4), (iii) the development of early-maturing cultivars as observed in Fig. 6 (applied in strategies C2, C3, and C4), (iv) practicing deficit irrigation (applied in strategy DI), and (v) reducing irrigated agriculture in favor of rainfed agriculture or fallow fields as outlined in Fig. 6 (applied in strategies C3 and C4), have been considered. A combination of these management strategies has been used to define the scenarios that are named C0E0FI, C0E1FI, C1E1FI, C2E1FI, C2E1DI, C3E1DI, and C4E1DI respectively. A summary of these scenarios is given in Table 1.

Fig. 4 A comparison between the observed and simulated results of groundwater elevation for the calibration and validation periods

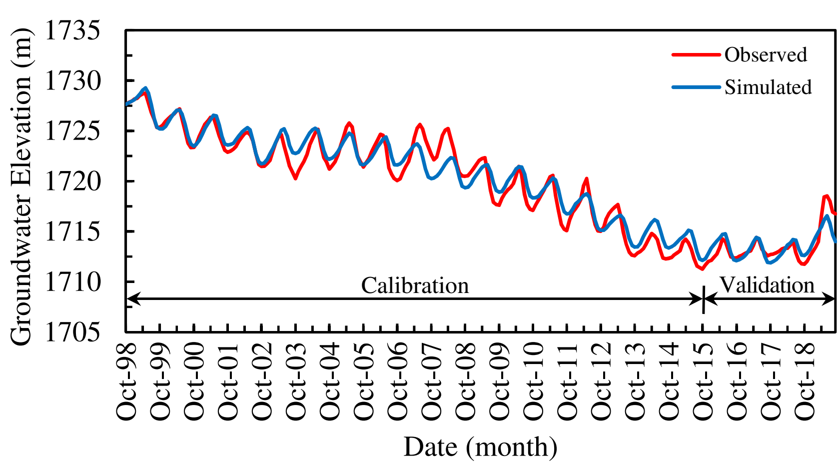


Table 1 Summary of management strategies and scenarios

Scenario	Description of strategies		
	Irrigation efficiency (E)	Cropping pattern (C)	Irrigation management (FI or DI)
C0E0FI[1]	It is considered that E_i is constant and equal to 57.02%, therefore there is no improvement in irrigation efficiency hence this strategy is named E0.	The cropping pattern remains constant at the average of the last five crop years (2015–2019). This strategy is named C0 and is shown in Fig. 6-C0.	Full irrigation (FI)
C0E1FI	Enhancement in irrigation efficiency is achieved by improving irrigation practice through annual growth rates of 1.00%, 0.75%, and 0.50% in E_i during the 2020s, 2030s, and 2040s, respectively. Changes in E_i are depicted in Fig. 5 and are equivalent to a cumulative total change of 22.56% in E_i. This leads to the maximum attainable irrigation efficiency (Solomon 1988; Ali 2011).	C0	FI
C1E1FI	E1	Changes in cropping pattern are classified as C1 and these include (i) refraining from growing highly water-intensive crops, including alfalfa, pumpkin, and sugar beet, within the next ten years (2020–2029), (ii) to develop alternative crops such as corn to replace alfalfa, (iii) to reduce water-intensive crops, including wheat and garlic, (iv) to encourage raising new, less water-intensive crops, including rapeseed and beans, and (v) to encourage raising less water-intensive crops, including barley and potatoes. More details are given in Fig. 6-C1.	FI
C2E1FI	E1	In the C2 strategy, two new, early-maturing cultivars of potato and corn (EM. Potato and EM. Corn) have been developed as replacements for common potatoes and corn cultivars within the next ten years (2020–2029). The cropping pattern changes in C2 are the same as in C1 (Fig. 6-C2).	FI
C2E1DI	E1	C2	Deficit irrigation (DI)
C3E1DI	E1	In the C3 strategy, in addition to the mitigation and adaptation strategies that have been considered in C1 and C2, irrigated agriculture is linearly reduced by 30% during the 2030s and 2040s and the irrigated agriculture area will be 161 km^2 in 2050 (Fig. 6-C3).	DI
C4E1DI	E1	The cropping pattern changes are similar to C3, but reducing irrigated agriculture by 40% is implemented during the 2030s and 2040s and the irrigated agriculture area will be 138 km^2 in 2050. These changes are named C4 and are shown in Fig. 6-C4.	DI

[1] C0E0FI is the business-as-usual scenario including population growth

Results and discussion

The observed and projected minimum and maximum air temperature, precipitation, and reference crop evapotranspiration (ET_o) under the RCP2.6, RCP4.5, and RCP8.5 climate change scenarios in the HBP up to the end of the twenty-first century are depicted in Fig. 7. In this figure, trend analysis using a regression coefficient was carried out to determine whether a statistically significant trend exists at the 95% (*) and 99% (**) confidence levels over the study period (2020–2050). Figure 7 shows a significant increase in TN, TX, and ET_o under the RCP4.5 and RCP8.5 scenarios, with the greatest rates of change in the highest-emission scenario (i.e., RCP8.5), which is expected, due to the higher rate of increase

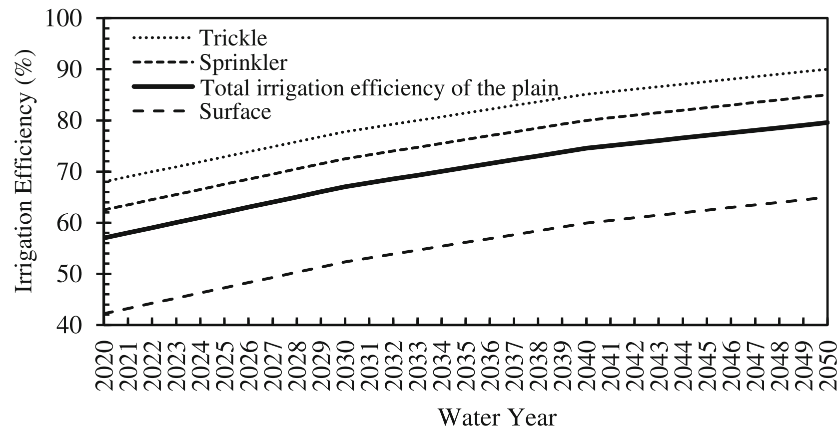


Fig. 5 Changes used in strategy E1 in the total irrigation efficiency of the HBP

in the concentration of atmospheric greenhouse gases in the RCP8.5 scenario (Oliveira et al. 2017; Andrade et al. 2021). Whereas, under the RCP2.6 scenario, the changes in these variables are not significant. Furthermore, the results indicate that there is no significant trend in the total annual precipitation. Regarding the increase in temperature and evapotranspiration, agricultural, household, and industrial water demands will increase throughout the region, which in itself will put more pressure on the groundwater resources. In addition to Fig. 7, the mean values of TN, TX, PRCP, and ET_o, during the observed and projected periods, as well as the changes in the mean values of the projected weather

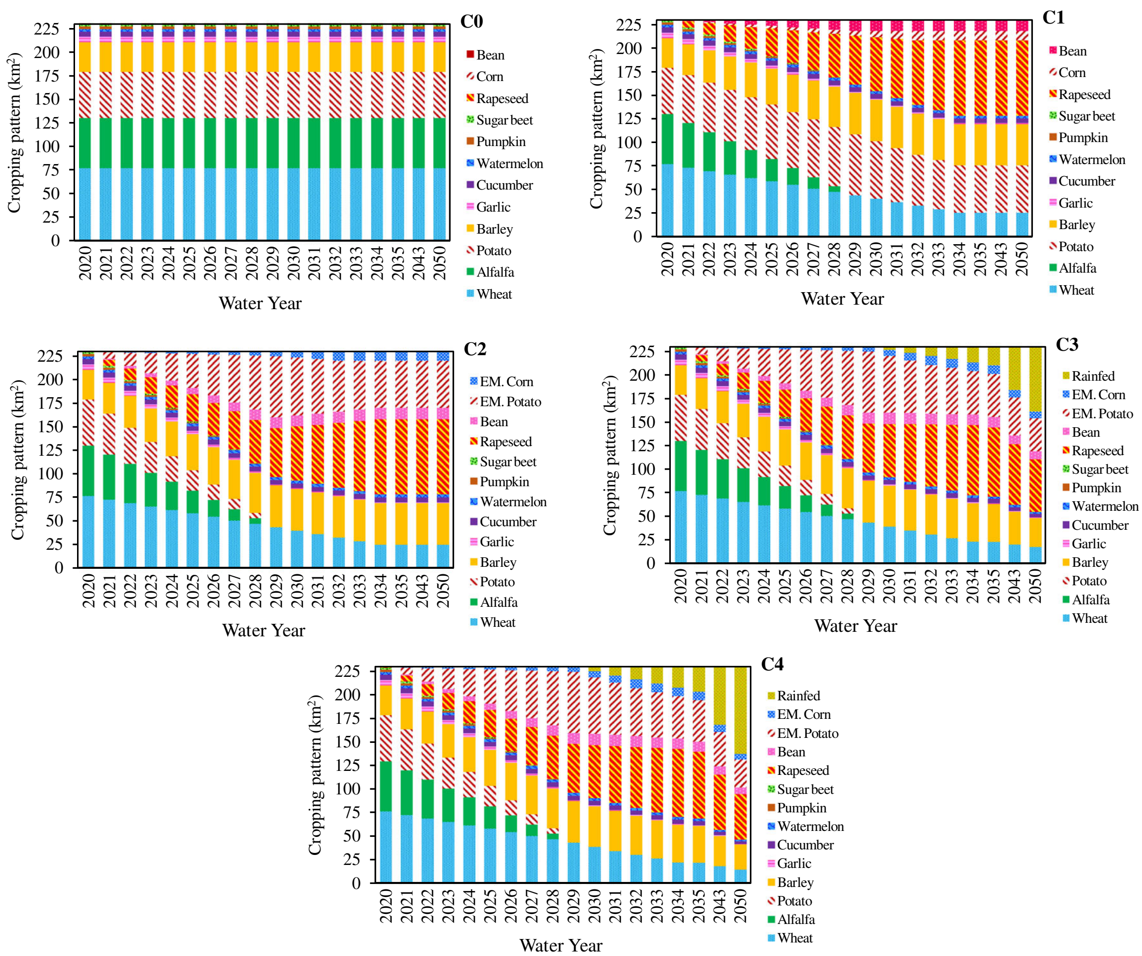


Fig. 6 The cropping pattern changes (C0–C4) implemented in the scenarios between 2020 and 2050 (EM. stands for early-maturing)

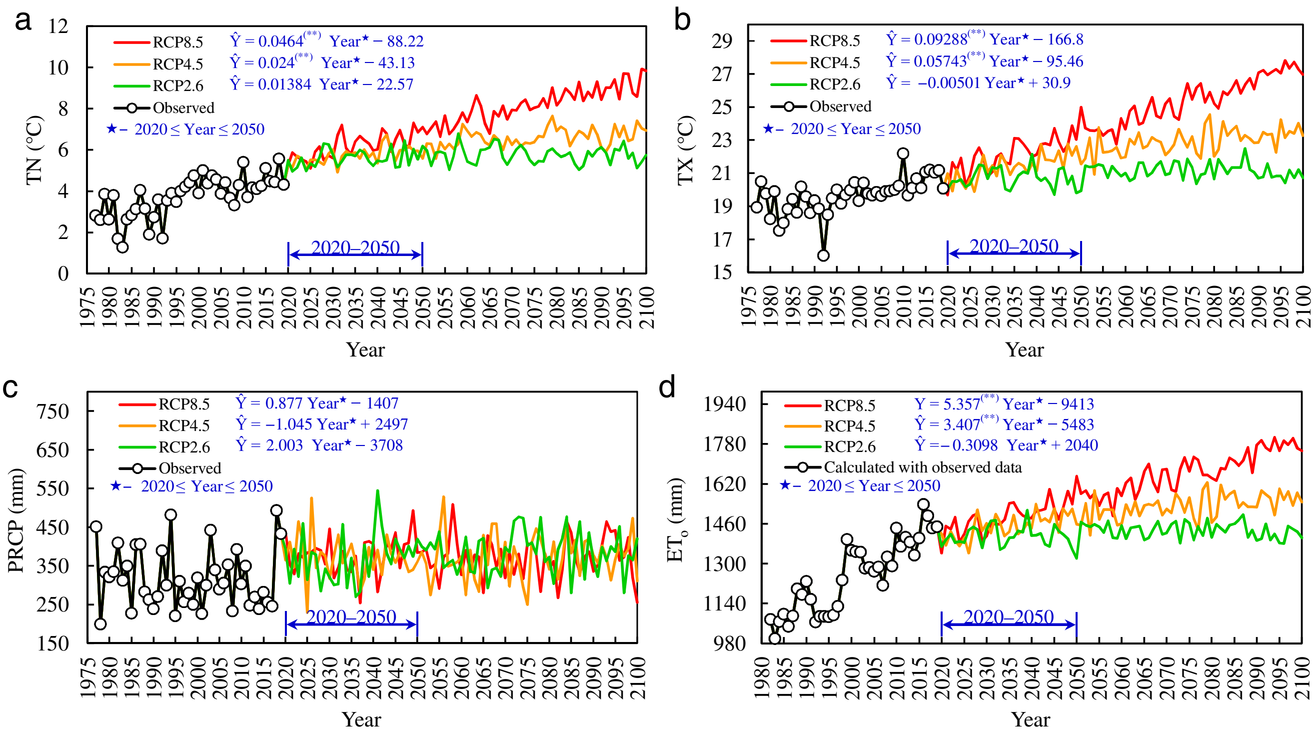


Fig. 7 Observed and projected TX, TN, PRCP, and ET_o in the HBP (the linear equations were fitted to the projected data using the least-squares method between 2020 and 2050); * and ** indicate significance at the 95% and 99% confidence levels, respectively

variables in relation to the historical observed values are presented in Table 2. The results show that the average annual minimum and maximum temperatures, along with the average total annual precipitation and evapotranspiration in the period 2020–2050 will increase by 1.87 °C, 1.05 °C, 52.5 mm, and 168.2 mm under RCP2.6; 1.99 °C, 1.75 °C, 54.7 mm, and 214.4 mm under RCP4.5; and 2.46 °C, 2.56 °C, 62.0 mm, and 261.1 mm under RCP8.5, respectively. The minimum and maximum variations in the projected weather variables are attributable to the low-emission mitigation scenario (RCP2.6) and the high-emission scenario (RCP8.5).

Policy scenario analysis

Having validated the HanBarSD model with the observed groundwater elevation data, the model was used for projecting groundwater level variations for six groundwater management scenarios (i.e., C0E1FI, C1E1FI, C2E1FI, C2E1DI, C3E1DI, and C4E1DI) and the BAU scenario (i.e., C0E0FI) under three climate change scenarios (i.e., RCP2.6, RCP4.5, and RCP8.5). The results are presented in Fig. 8 and Table 3. The figure shows that the greatest decline in the groundwater level will be 11.6, 13.9, and 13.5 m under the RCP2.6-C0E0FI, RCP4.5-C0E0FI, and RCP8.5-C0E0FI scenarios, respectively. Accordingly, at the end of the 31-year projection period, under the RCP4.5-C0E0FI and RCP8.5-C0E0FI scenarios, the groundwater levels will approximately be parallel to each other and lower than that of the RCP2.6-C0E0FI scenario. The elevation of the groundwater table under the RCP8.5-C0E0FI scenario is a little higher than that of the RCP4.5-C0E0FI scenario, which can be attributed to the higher groundwater recharge from precipitation under the RCP8.5 scenario. In the most optimistic scenario, i.e., RCP2.6-C4E1DI, the elevation of the groundwater table will

Table 2 Mean values of weather variables during the observed and projected periods in the HBP

Variable	Observed (1977–2019)	Projected (2020–2050)		
		RCP2.6 (**Change**)	RCP4.5 (**Change**)	RCP8.5 (**Change**)
TN (°C)	3.72	5.59 (**+1.87**)	5.71 (**+1.99**)	6.18 (**+2.46**)
TX (°C)	19.65	20.70 (**+1.05**)	21.40 (**+1.75**)	22.21 (**+2.56**)
PRCP (mm)	316.1	368.6 (**+52.5**)	370.8 (**+54.7**)	378.1 (**+62.0**)
ET_o (mm)	1251.6	1419.8 (**+168.2**)	1466.0 (**+214.4**)	1512.7 (**+261.1**)

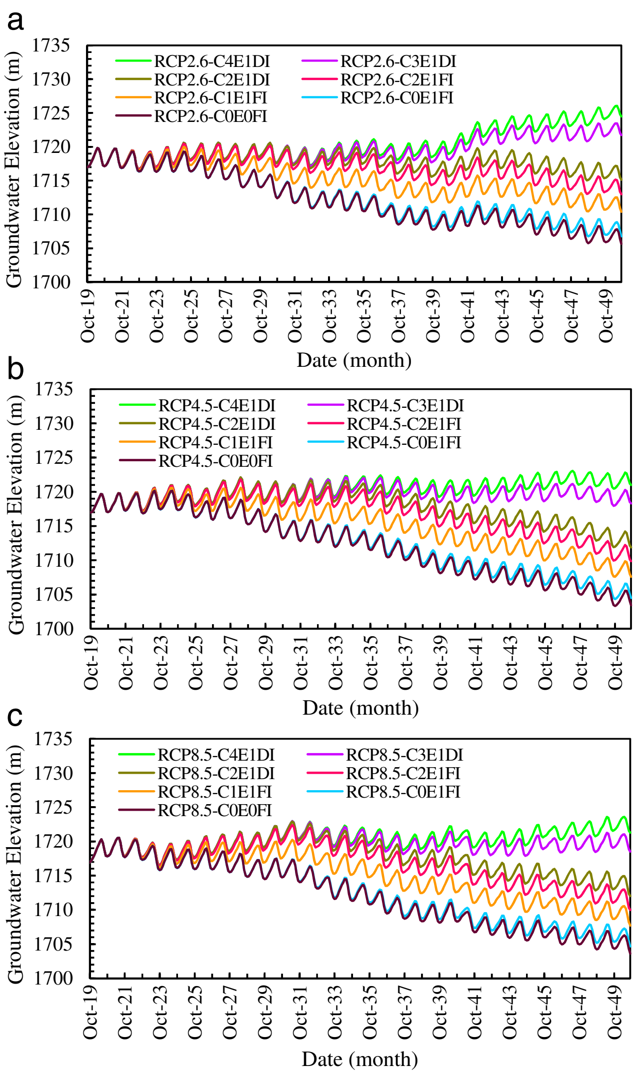


Fig. 8 Projected groundwater elevations between water-years 2020 and 2050 under the different management and climate scenarios in the HBP

rise by 6.81 m by the end of the projection period (Table 3). By comparing the groundwater levels in the first and last year of the projection period, it can be deduced that the changes under the RCP2.6-C3E1DI, RCP2.6-C4E1DI, RCP4.5-C3E1DI, RCP4.5-C4E1DI, RCP8.5-C3E1DI, and RCP8.5-C4E1DI scenarios will be positive and equal to 4.21, 6.81, 0.83, 3.38, 1.31, and 3.88 m, respectively. However, in the other scenarios, the groundwater levels are expected to decline between −2.12 and −13.89 m by 2050 (Table 3). Considering the projected groundwater elevations in 2050, the effect of each strategy on groundwater level rise has been summarized in Table 4. From the table, it can be inferred that implementing an irrigation efficiency enhancement plan, practicing deficit irrigation, choosing an adaptive cropping pattern, developing early-maturing cultivars, and developing rainfed agriculture by 30% and 40% strategies will cause the groundwater table to rise by 1.03, 2.01, 3.42, 2.44, 6.21, and 8.79 m, respectively. Based on the results (Table 4), the most useful strategies to protect groundwater resources, in order of effectiveness, are (i) reducing irrigated agriculture in favor of rainfed agriculture or fallow fields, (ii) applying an adaptive cropping pattern, (iii) developing early-maturing cultivars, (iv) practicing deficit irrigation, and (v) enhancing irrigation efficiency. Reducing irrigated area is, therefore, the most effective way of stabilizing groundwater levels, which has been identified by Deines et al. (2019) as the first conservation strategy that can lead to reduced water use. The results show that increases in irrigation efficiency have the least effect on groundwater protection. Despite the small positive effect of enhancing irrigation efficiency on groundwater resources, this strategy is recommended to reduce evaporation losses, save energy by decreasing groundwater pumping, and minimize groundwater contamination caused by nitrate leaching. As a result of Fig. 8, all the strategies must be applied to protect groundwater resources and to raise the groundwater table in the HBP. A comparison of the effects of the management and climate change scenarios on the HBP groundwater resources showed that the control of climate change will cause a 1.9–2.3 m increase in the groundwater table while the improvement in the management strategies will raise the groundwater table up by 18.4 m. Therefore, applying the current BAU management strategy will result in more groundwater depletion than climate change effects do. This finding is in agreement with the results obtained by Fujihara et al. (2008) and Tzabiras et al. (2016).

Conclusion

In this research, we developed a system dynamics model for the HBP (HanBarSD) to examine the long-term effects of applying five adaptive strategies on improving groundwater resources, and to investigate the impacts of climate change on water demand. The HanBarSD was used to project the outcomes of six different policy scenarios and the BAU scenario from 2020 to 2050. The results showed that all the strategies must be combined to prevent groundwater depletion. Under the most optimistic scenario (RCP2.6-C4E1DI), the groundwater table will rise up to 6.81 m by 2050. On the other hand, under the BAU management scenario (C0E0FI) and the RCP4.5 climate scenario, the decline in the groundwater table will be about −13.89 m by 2050. The climate change model showed that higher temperatures and evapotranspiration for both the RCP4.5 and RCP8.5 scenarios will increase the water demand, leading to more pressure on the groundwater resources. Under the most optimistic climate change scenario (i.e., RCP2.6), the groundwater table will be approximately 2.3 and 1.9 m higher than that of the RCP4.5 and RCP8.5 climate scenarios by 2050. The results also showed that the current BAU management

Table 3 Projected groundwater in 2020 and 2050 and the effect of the management scenarios on the groundwater elevation change

Scenarios	Mean groundwater elevation in water year (m)		Change (m)	Change with respect to the BAU scenario (m)
	2020	2050		
RCP2.6-C0E0FI (BAU scenario)	1718.30	1706.70	−11.59	-
RCP2.6-C0E1FI	1718.30	1707.77	−10.52	1.07
RCP2.6-C1E1FI	1718.30	1711.50	−6.80	4.80
RCP2.6-C2E1FI	1718.30	1714.10	−4.20	7.40
RCP2.6-C2E1DI	1718.30	1716.17	−2.12	9.47
RCP2.6-C3E1DI	1718.30	1722.50	+4.21	15.80
RCP2.6-C4E1DI	1718.30	1725.10	+6.81	18.40
RCP4.5-C0E0FI (BAU scenario)	1718.24	1704.35	−13.89	-
RCP4.5-C0E1FI	1718.24	1705.35	−12.89	1.00
RCP4.5-C1E1FI	1718.24	1708.61	−9.63	4.26
RCP4.5-C2E1FI	1718.24	1710.95	−7.29	6.60
RCP4.5-C2E1DI	1718.24	1712.93	−5.31	8.58
RCP4.5-C3E1DI	1718.24	1719.07	+0.83	14.72
RCP4.5-C4E1DI	1718.24	1721.62	+3.38	17.27
RCP8.5-C0E0FI (BAU scenario)	1718.62	1705.12	−13.51	-
RCP8.5-C0E1FI	1718.62	1706.13	−12.49	1.01
RCP8.5-C1E1FI	1718.62	1709.39	−9.23	4.28
RCP8.5-C2E1FI	1718.62	1711.77	−6.86	6.65
RCP8.5-C2E1DI	1718.62	1713.75	−4.87	8.64
RCP8.5-C3E1DI	1718.62	1719.93	+1.31	14.81
RCP8.5-C4E1DI	1718.62	1722.50	+3.88	17.38

poses much more serious threats to groundwater resources sustainability than climate change impacts.

In conclusion, the results demonstrate that by applying mitigation and adaptation strategies, the HBP groundwater resources can be protected from overexploitation and depletion. In this regard, the top three strategies are i) reducing irrigated area, ii) applying an adaptive cropping pattern, and iii) developing early-maturing cultivars. Furthermore, using the model as a learning tool, the researchers were able to improve the understanding of the long-term dynamics of the HBP groundwater system. The researchers believe that assessing the effects of other adaptation strategies, such as the development of new and alternative sources of water supply, the expansion of recycled water production, and the development of new drought-resistant crops, on groundwater resources could provide interesting results in the future studies.

Table 4 The effect of the strategies on groundwater level rise under the climate change scenarios, between water years 2020 and 2050 in the HBP

Strategy	Groundwater level rise (m)			
	RCP2.6	RCP4.5	RCP8.5	Mean
Irrigation efficiency enhancement	1.07	1.00	1.01	1.03
Deficit irrigation	2.07	1.98	1.99	2.01
Early-maturing cultivars development	2.60	2.34	2.37	2.44
Adaptive cropping pattern	3.73	3.26	3.26	3.42
Reducing irrigated area by 30%	6.33	6.14	6.18	6.21
Reducing irrigated area by 40%	8.93	8.69	8.75	8.79

Appendix

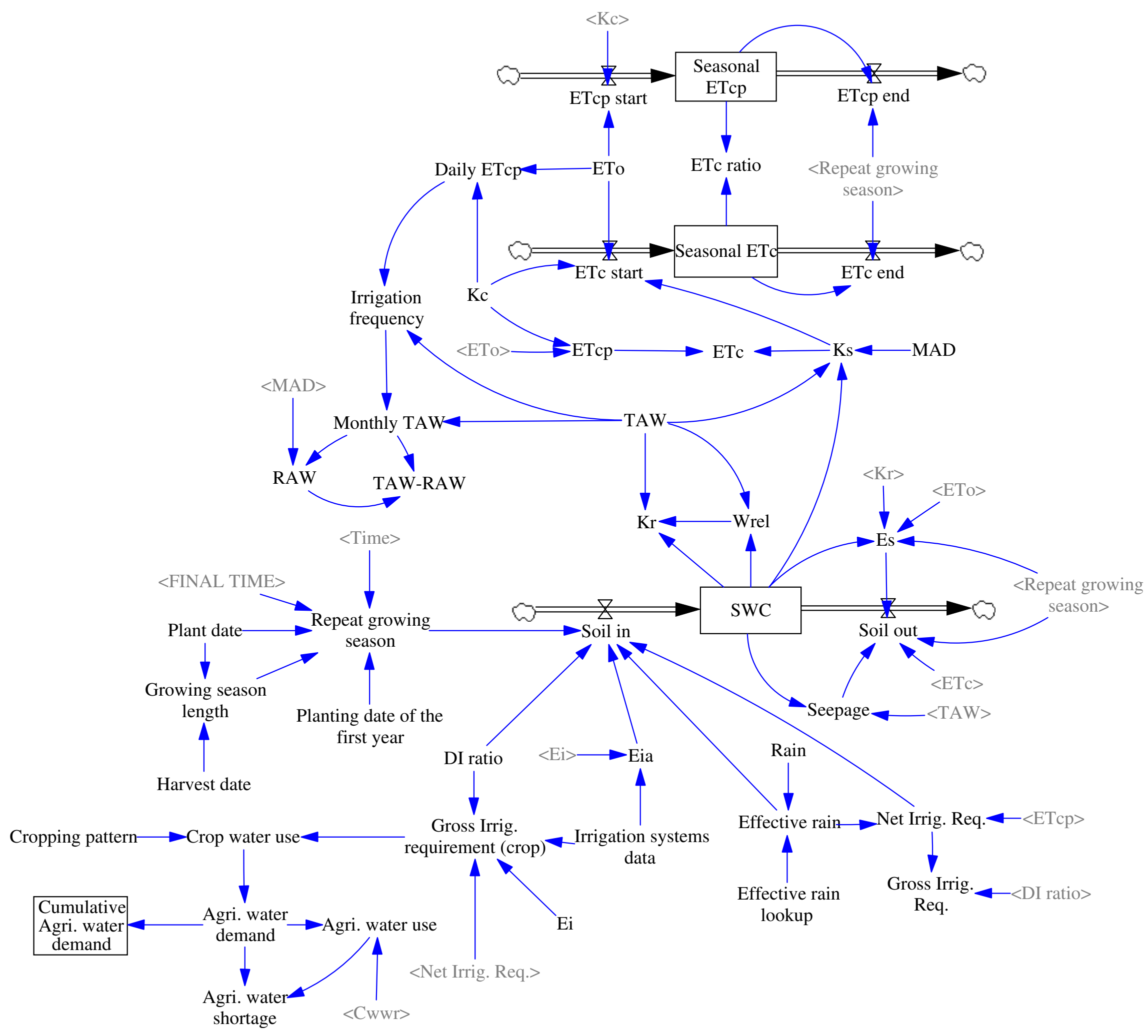


Fig. 9 Stock-and-flow diagram of the agricultural groundwater demand and soil water balance subsystem

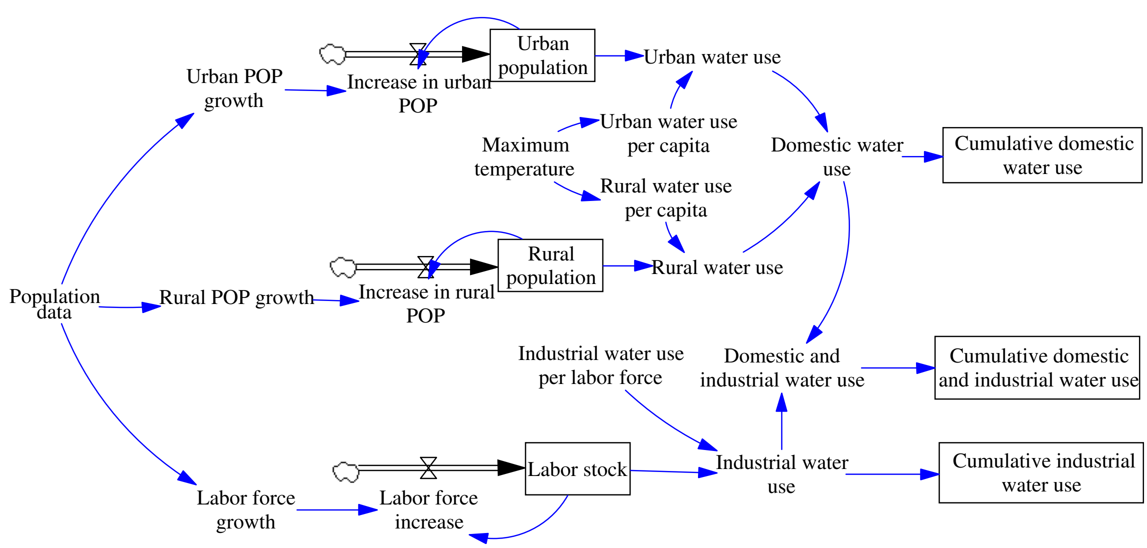


Fig. 10 Stock-and-flow diagram of the municipal (urban and rural) and industrial water demands subsystem

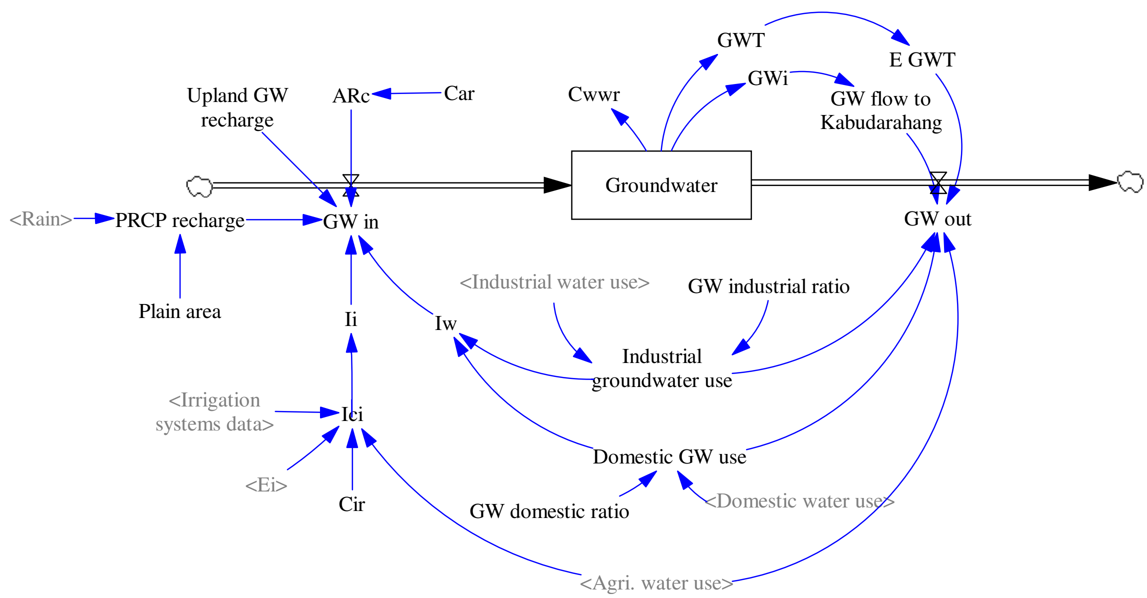


Fig. 11 Stock-and-flow diagram of the groundwater storage subsystem

Table 5 The variables of the HanBarSD model

Variable type Subsystem	Variable name	Description	Unit
Stock			
Agricultural groundwater demands and soil water balance	Cumulative Agri. water demand	Cumulative water demand of agriculture sector	MCM
	SWC	Soil water content	mm/m
	Seasonal ET_{cp}	The total amount of potential evapotranspiration for a crop over an entire growing season	mm
	Seasonal ET_c	The total amount of actual evapotranspiration for a crop over an entire growing season	mm
Municipal and industrial water demands	Urban population	Total urban population	Persons
	Rural population	Total rural population	Persons
	Labor stock	Total Labor force population	Persons
	Cumulative domestic water use	The cumulative volume of water consumed by urban and rural households	MCM
	Cumulative industrial water use	The cumulative volume of water consumed by industrial plants	MCM
	Cumulative domestic and industrial water use	Cumulative domestic water use + Cumulative industrial water use	MCM
Groundwater storage	Groundwater	The volume of water in the groundwater reservoir of the HBP	MCM
Flow			
Agricultural groundwater demands and soil water balance	ET_{cp} start	Determines the start of the growing season for the potential evapotranspiration of the crops	mm/month
	ET_{cp} end	Determines the end of the growing season for the potential evapotranspiration of the crops	mm/month
	ET_c start	Determines the start of the growing season for the actual evapotranspiration of the crops	mm/month
	ET_c end	Determines the end of the growing season for the actual evapotranspiration of the crops	mm/month
	Soil in	Water inflow rate to the root zone	mm/m/month
	Soil out	Water depletion rate from the root zone	mm/m/month
Municipal and industrial water demands	Increase in urban POP	Net increase in urban population	% per year
	Increase in rural POP	Net increase in rural population	% per year
	Labor force increase	Net labor force increase	% per year

Table 5 (continued)

Variable type Subsystem	Variable name	Description	Unit
Groundwater storage	GW in	Groundwater inflow	MCM/month
	GW out	Groundwater outflow	MCM/month
Auxiliary variable			
Agricultural groundwater demand and soil water balance	ET_{cp}	Potential crop evapotranspiration	mm/month
	ET_c	Actual crop evapotranspiration	mm/month
	ET_c ratio	Seasonal ET_c / Seasonal ET_{cp}	-
	Daily ET_{cp}	Daily potential evapotranspiration of the crops	mm/day
	Irrigation frequency	The number of days between two consecutive irrigation events	days
	K_s	Water stress coefficients	-
	Monthly TAW	Total available water in a month	mm/m
	RAW	Readily available water	mm/m
	TAW − RAW	Subtract RAW from TAW	mm/m
	K_r	Evaporation reduction coefficient	-
	W_{rel}	Relative soil water content	mm/m
	E_s	Soil water evaporation	mm/m/month
	Growing season length	Length of the growing season for the crops	days
	Repeat growing season	Repeats the growing season pattern of the crops	days
	FINAL TIME	The time at which the simulation ends	month
	Time	Internally defined simulation time	month
	Crop water use	The volume of water needed to be applied for the crops	MCM/month
	Agri. water demand	Total agricultural water demand	MCM/month
	Agri. water use	Total agricultural water use	MCM/month
	Agri. water shortage	Subtract Agri. water demand from Agri. water use	MCM/month
	Gross Irrig. requirement (crop)	Gross irrigation requirement of the crops	MCM/month
	E_{ia}	Applied irrigation efficiency	%
	Effective rain	Effective rainfall	mm/month
	Net Irrig. Req.	Net irrigation requirement	mm/month
	Gross Irrig. Req.	The total gross irrigation requirement	MCM/month
	Seepage	Deep percolation	mm/month
Municipal and industrial water demands	Urban POP growth	Rate of urban population growth	%
	Rural POP growth	The monthly growth rate of the rural population	%
	Labor force growth	The monthly growth rate of labor force growth	%
	Urban water use per capita	Mean urban water use per capita	m^3/month
	Urban water use	Total urban water use	MCM/month
	Rural water use per capita	Mean rural water use per capita	m^3/month
	Rural water use	Total rural water use	MCM/month
	Domestic water use	Total urban and rural water use	MCM/month
	Industrial water use	Total industrial water use	MCM/month
	Domestic and industrial water use	Domestic water use + Industrial water use	MCM/month
Groundwater storage	GWT	Groundwater table depth	m
	GWi	Groundwater hydraulic gradient	m/m
	GW flow to Kabudarahang	Groundwater outflow to Kabudarahang Plain	MCM/month
	E_GWT	Evaporation from the groundwater table	MCM/month
	PRCP recharge	Direct recharge from precipitation to the HBP	MCM/month
	I_{ci}	Irrigation return flows for crops	MCM/month
	I_i	The sum of the irrigation return flows for crops	MCM/month

Table 5 (continued)

Variable type Subsystem	Variable name	Description	Unit
	Domestic GW use	Domestic groundwater use	MCM/month
	GW Domestic ratio	Industrial groundwater use	MCM/month
	I_w	Recharge from domestic and industrial water use	MCM/month
	C_{wwr}	Water wells' flow rate coefficient	-
Constant			
Agricultural groundwater demand and soil water balance	TAW	Total available water	mm/m
	MAD	Management allowed depletion	-
	Harvest date	Crops harvest date	date
	Plant date	Crops planting date	date
	Planting date of the first year	Planting date of the crops for the first year	date
	DI ratio	Deficit irrigation ratio	-
Municipal and industrial water demands	Industrial water use per labor force	Mean industrial water use per labor force	m^3/month
Groundwater storage	C_{ar}	Artificial recharge coefficient	-
	Plain area	the HBP area	Km^2
	GW domestic ratio	The proportion of the groundwater resources to fulfill domestic water demand	%
	GW industrial ratio	The proportion of the groundwater resources to fulfill industrial water demand	%
Data			
Agricultural groundwater demand and soil water balance	ET_o	Reference evapotranspiration	mm/month
	K_c	Crop coefficient	-
	Rain	Precipitation	mm/month
	Cropping pattern	The proportion of land under cultivation of different crops	km^2
	E_i	Irrigation efficiency	%
	Irrigation systems data	Types and areas of Irrigation systems	km^2
	Effective rain lookup	Lookup function for effective rainfall	mm/month
Municipal and industrial water demands	Population data	The monthly growth rate of the urban and rural population and labor force	%
	Maximum temperature	Monthly maximum temperature	°C
Groundwater storage	AR_c	The capacity of artificial groundwater recharge projects	MCM/month
	Upland GW recharge	Groundwater recharge from upland	MCM/month
	C_{ir}	Irrigation return flow coefficient	-

Code availability The corresponding author confirms that the model used in this study is available upon request.

Data availability The authors do not have the permission to share the database that supports the findings of this study, due to RWCH and HWW data access permissions. However, one can apply for the databases using the following contact information: info@hmrw.ir and info@hww.ir.

Declarations

Conflict of Interest The authors declare that they have no competing interests.

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