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Climate-Change Based Analysis of the Water-Food-Energy Nexus with System-Dynamics

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Abstract
Numerous countries face water crises due to population growth, shifting climatic patterns, limited water resources, rapid industrialization, societal changes, and poor resource governance, which pose challenges to the supply of water, food, and energy. This study develops a Water–Food–Energy Nexus (WFE) model using the System Dynamics (SD) approach to capture the complex interactions among domestic, industrial, and agricultural sectors while incorporating environmental protection policies. The proposed model is developed and applied to assess the water crisis in the Zayandeh-Roud River basin, which plays a strategic role in ensuring water, energy, and food security in central Iran. Climate change alters hydroclimatic patterns and directly and indirectly affects the subsystems of the water–food–energy nexus. Precipitation and temperature outputs from three Atmosphere–Ocean General Circulation Models (AOGCMs), obtained from the Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6), were used to evaluate the impacts of climate change on river flow under the SSP1 (optimistic) and SSP5 (pessimistic) emission scenarios. The simulation results indicate: (i) a reduction of 7.2% and 15.7% of the river flow under the optimistic and pessimistic emissions scenarios, respectively, (ii) a severe decline in groundwater levels, (iii) an increasing trend in agricultural water demand in most years, (iv) reduced crop yields, and (v) the drying of the Gavkhouni wetland in the future period (2025–2034). Several policy options for mitigating water deficits were evaluated. The most effective strategy involved fallowing 40% of rice cultivation areas, reducing groundwater extraction by 50%, and securing 70% of the environmental water rights of the Gavkhouni Wetland to restore water balance within the basin.

Highlights

- Developing a system dynamics-based Water–Food–Energy Nexus model
- Evaluating the climate change impacts on interconnected WFE subsystems
- Adopting water-demand policies for balancing water supply and demand
- Analyzing the climate change adaptation policies within the WFE nexus

Keywords Systems dynamics · Climate change · Water resources management · Zayandeh-Roud River

Extended author information available on the last page of the article

1 Introduction

Ensuring water, food, and energy security is one of the major global challenges associated with supporting the world's growing population. More than 1.06 billion people do not have access to electricity (Bank 2017), 2.1 billion lack access to safe drinking water, and 815 million face inadequate food and were undernourished in 2016 (UNICEF. & Organization 2017). This trend is expected to continue due to increasing resource demands, climate change, population growth, economic development, urbanization, changing lifestyles, and inadequate governance (Laspidou et al. 2020; Loaiciga 2025). The severe depletion of water resources in arid and semi-arid regions is driven by socio-economic development and increasing economic activities. The reliability of water supply is uncertain given the uneven spatiotemporal distribution of surface and groundwater resources, and the rapid socioeconomic growth that heightens the stress on water resources (Naghdi et al. 2021). Water, energy, and food resources are closely interconnected, and they form a multi-variable, reciprocal, dynamic system (Chen & Chen 2020). Numerous interdisciplinary approaches have been proposed to balance resource production and consumption, among which the water–food–energy (WFE) nexus is one of the most prominent. The WFE provides is an informed framework for implementing adaptive management strategies (Winz et al. 2009) and identifying critical trends and their main drivers within an integrated system (Mirchi et al. 2012). The WFE nexus identifies the interrelation between resources spatially and temporally and focuses on the enhancement of resources' security by facilitating inter-sector and holistic decision-making (El Gafy et al. 2017; Howarth & Monasterolo 2016; Ravar et al. 2020; Wu et al. 2021). The WFE nexus is an approach that balances the available resources, interests, and societal needs by integrating socioeconomic, environmental, and technical factors (Bakhshianlamouki et al. 2020; Hoff 2011; Kheirinejad et al. 2022; Purwanto et al. 2019; Saray et al. 2022). This integrated management framework is imperative to achieve the sustainable management of water resources (Bozorg-Haddad et al. 2022; Gohari 2013; Hjorth & Bagheri 2006; Madani 2010).

Climate change and related adaptation policies can adversely affect water, energy, and food security by intensifying water scarcity and impacting communities, natural resources, ecosystems, and economies worldwide (Mirchi et al. 2013; Momblanch et al. 2019). Global warming alters the regional hydrological cycle by changing the temporal and spatial distribution of precipitation, thereby affecting industrial, agricultural, environmental, and other sectors (Fig. 1) (Eslamian et al. 2011; Loaiciga et al. 1996; Zhang et al. 2010, 2008). Water management policies focused primarily on increasing supply in arid regions may appear effective in the short term; however, they often generate undesirable long-term impacts (Madani & Mariño 2009). Assessing the impacts of climate change is essential for reducing its negative consequences and supporting sustainable development and socioeconomic resilience (Baghban et al. 2022; Gohari et al. 2017; Hanak & Lund 2012). At the watershed scale, the failure to develop sustainable water resource solutions largely stems from an inadequate understanding of the interconnected dynamics among complex watershed sub-systems.

Various models, methods, and tools have been developed to analyze the interconnections among water, energy, food, and environmental systems, using qualitative, quantitative, or integrated approaches (Daher & Mohtar 2018). For example, (El Gafy et al. 2017) investigated the dynamic interactions among water, energy, and food systems associated with

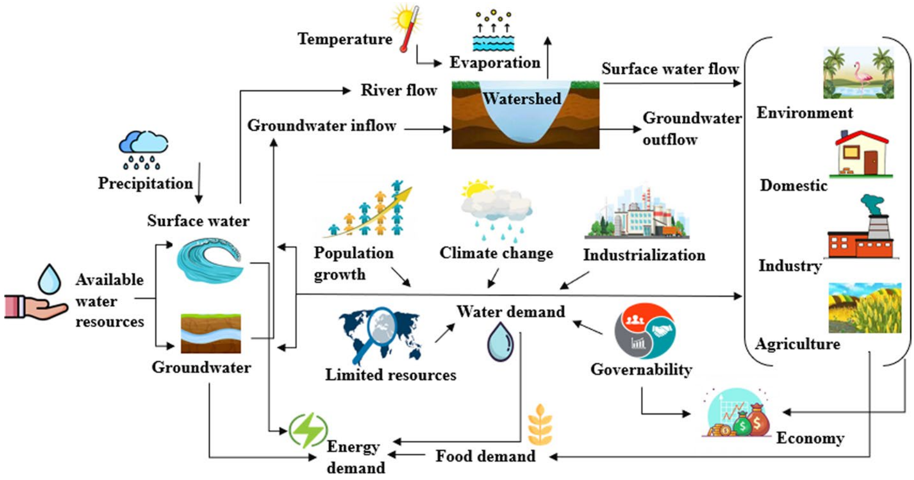

Fig. 1 The synthesis of climate change and water resources management by the Water-Food-Energy Nexus approach

crop production and consumption under different national-scale scenarios. Similarly, (Tan et al. 2017) analyzed water–energy interactions and their impacts on agriculture under multiple scenarios aimed at maximizing electricity production while reducing water shortages. Their results showed that the balanced-priority scenario for water and energy performed more effectively than the alternative scenarios. (Zarei et al. 2021) assessed agricultural sustainability using a System Dynamics framework combined with sustainability indicators related to water, energy, food, and environmental impacts. Similarly, (Kheirinejad et al. 2022) employed a system dynamics model to evaluate feedback mechanisms within the Water–Food–Energy Nexus at the national scale, considering the effects of reducing per capita water and energy consumption on system components. The System Dynamics approach has also been used to incorporate stakeholder perspectives and develop water management strategies for municipal, industrial, and agricultural sectors to improve Water–Food–Energy Nexus provisioning services (Chen & Chen 2020; Naderi et al. 2021; Ravar et al. 2020). Climate change modifies components of the hydrological cycle, increasing the occurrence of extreme events and altering the temporal and spatial distribution of water resources across many regions. Timely adaptation to climate change remains a major challenge for both societies and ecosystems. Consequently, numerous studies have investigated the Water–Food–Energy Nexus under changing climate conditions (Bozorg-Haddad et al. 2022; Conway et al. 2015; Laspidou et al. 2020; Sušnik et al. 2013; Trabucco et al. 2018; Wang XiaoJun et al. 2014; Wu et al. 2021). (Gohari et al. 2017) developed a SD model for the Zayandeh-Rud River Basin to evaluate climate change adaptation strategies by considering feedback among water resources, agricultural, and socioeconomic subsystems. Their findings highlighted water security as a major global challenge, particularly in arid regions. (Bakhshianlamouki et al. 2020) developed an SD-WFE model as a holistic, multi-sectoral framework to evaluate the impacts of restoration measures and climate change scenarios on the restoration of Urmia Lake. (Howarth & Monasterolo 2016) investigated nexus-related shocks and their implications for policy-making, concluding that the interactions among water, food, energy, and climate systems are non-linear, multi-sectoral, and time-dependent.

Most SD studies have highlighted the limitations of supply-oriented water management, which often creates unintended consequences by overlooking feedbacks between increased water supply and future demand (Gohari et al. 2013).

Many previous studies have focused on single-sector analyses or macro-scale assessments (Beygi et al. 2014; Bozorg-Haddad and Mariño 2011; Bozorg-Haddad et al. 2007, 2009; Fallah-Mehdipour et al. 2011, 2013; Karimi-Hosseini et al. 2011; Orouji et al. 2014; Sabbaghpour et al. 2012; Shokri et al. 2013; Soltanjalili et al. 2011). On the other hand, this study provides a holistic and dynamic evaluation of feedback mechanisms among multiple stakeholders and nexus components under changing climate conditions. This study aims to: (1) develop an integrated Water–Food–Energy Nexus model within a SD framework by simultaneously considering the interactions among water, food, energy, environmental, and socioeconomic sub-systems to evaluate water resources sustainability; (2) assess the impacts of climate change on the integrated system under future climate projections based on the Shared Socioeconomic Pathway (SSP) scenarios of CMIP6; and (3) propose adaptive water-resources management strategies, including climate adaptation measures and upstream water-demand rationing policies, to identify sustainable solutions to water scarcity. The proposed methodology is applied to the Zayandeh-Rud River Basin, where the effectiveness of sustainable WFE policies is evaluated to support the development of integrated and resilient water management strategies. Figure 2 illustrates the methodological framework adopted in this study.

2 Methodology

2.1 System Dynamics (SD)

System Dynamics (SD) is widely used for modeling complex, non-linear, and feedback-driven systems (Forrester 1961). Its flexibility enables simulation of interactions among interconnected sub-systems and supports long-term water resources planning and management (Forrester 1961, 1969; Simonovic & Fahmy 1999; Sterman 2000). Since water resources systems are highly complex and interconnected, linear or event-based approaches are often insufficient for their analysis (Hjorth & Bagheri 2006; Mirchi et al. 2012).

The first step in System Dynamics modeling is defining the system structure, including causal relationships and feedback loops among components. The qualitative stage involves developing a Causal Loop Diagram (CLD) to identify system boundaries, key variables, and their interactions through positive and negative feedback relationships (Sterman 2000). This is followed by the development of a Stock and Flow Diagram (SFD), which represents the system's dynamic behavior using stocks, flows, converters, and connectors. Changes in state variables are governed by inflow and outflow rates as expressed by mass conservation in Eq. (1):

$$S_t = \int_{t_0}^{t} [I_s - O_s] ds + S_{t_0} \tag{1}$$

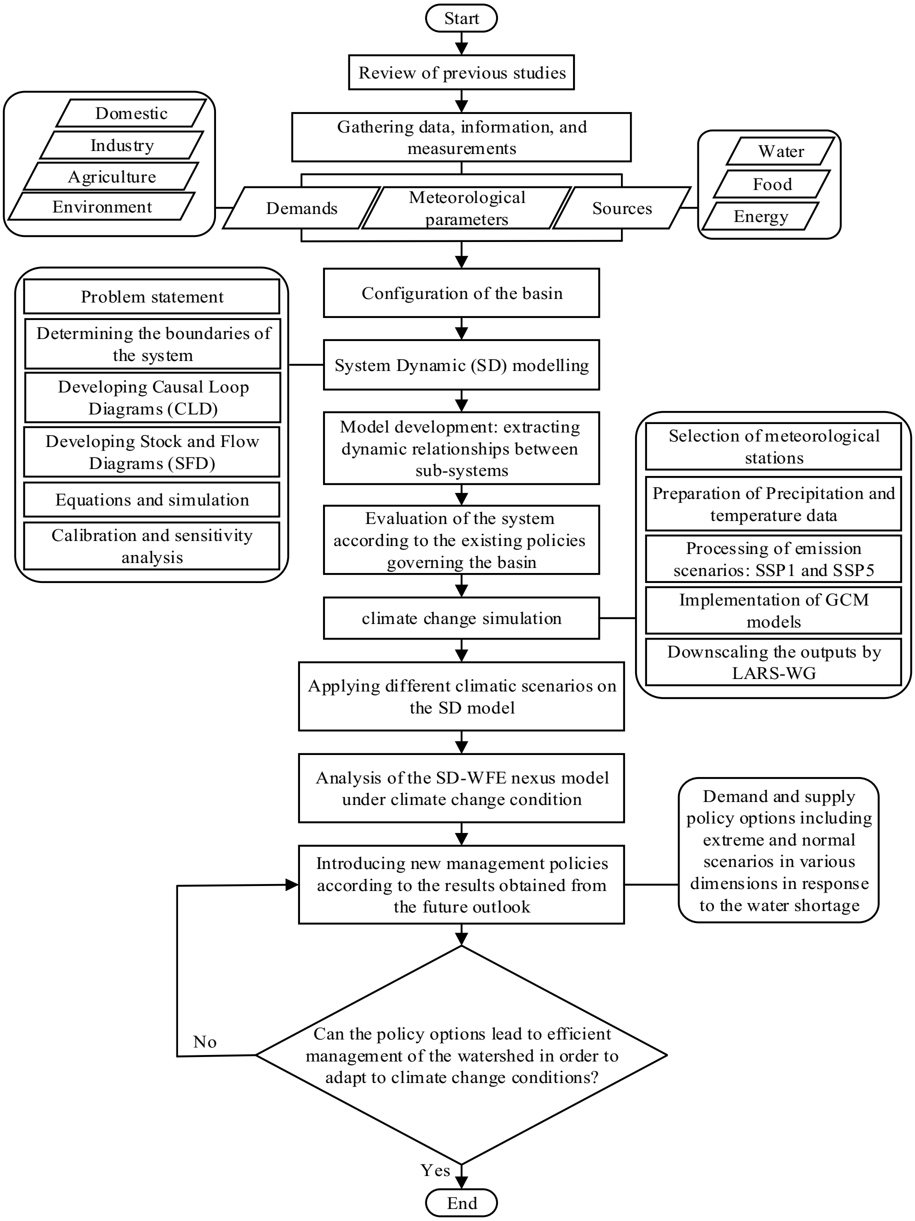

Fig. 2 Flowchart of the proposed framework

where S_t= basin's storage at time t, S_{t_0}= basin's storage at the initial time t_0, I_s= the inflow rate to the basin at time t (units of volume/time), and O_s= the outflow rate from the basin at time s (units of volume/time), s= integration variable.

The modeling framework incorporates meteorological, hydrological, agricultural, energy, demographic, and socio-economic data. Simulations were performed using the Vensim software developed by Ventana Systems. Model boundaries were defined based on the watershed extent, and simulations were conducted for the historical (2002–2011) and future (2025–2034) periods using annual time steps. The following sections describe the main subsystems of the SD-WFE model.

2.1.1 The Water Subsystem

Water balance analysis requires identifying the main hydrological processes and ecosystem factors affecting the basin. The CLD illustrates feedback interactions among system components (Fig. 3), while the SFD quantifies these relationships (Fig. 3). Surface water, groundwater, and population are considered state variables, whereas inflow and outflow components are treated as auxiliary variables. Surface water is assumed to be the primary supply source, with groundwater acting as a supplementary resource during shortages. The water sub-system represents water availability through interactions between surface water and groundwater under varying hydrological and meteorological conditions, as expressed in Eq. (2):

$$\begin{aligned} AWR_t = \Delta V\left(S_t\right) + \Delta V\left(G_t\right) = P_t + Q_{inf}(S)_t + QT_{inf}(S)_t + QP_{inf}(S,G)_t + \\ QRT_{inf}(S,G)_t + Q_{inf}(G)_t + QR_{inf}(G)_t - QE_{out}(S,G)_t - Q_{out}(S)_t - Q_{out}(G)_t - TWS(S,G)_t \end{aligned} \quad (2)$$

where in time step t: AWR_t= Available water resources (MCM = 10^6 m^3), P= Runoff from precipitation (MCM), $Q_{\inf}(S)_t$= surface water inflow (MCM), $QT_{\inf}(S)_t$= transferred water inflow (MCM), $QP_{\inf}(S,G)_t$= percolation (deep infiltration) (MCM), $QRT_{\inf}(S,G)_t$ = returned flow (MCM), $Q_{\inf}(G)_t$= groundwater inflow, $QR_{\inf}(G)_t$= groundwater recharge (MCM), $QE_{out}(S,G)_t$= evaporation of surface water and groundwater (MCM), $Q_{out}(S)_t$ = surface water outflow (MCM), $Q_{out}(G)_t$= groundwater outflow (MCM), $TWS(S,G)_t$ = total water supply, $\Delta V\left(S_t\right)$= change in surface water storage (MCM), and $\Delta V\left(G_t\right)$= change in groundwater storage (MCM).

The gap between water supply and demand represents the state variable representing the dynamic balance of available water resources within the water sub-system and is defined as follows:

$$GWSD = TWS - TWD \quad (3)$$

In which,

$$TWD = \sum_{i=1}^{i=n} D_i W_t \quad (4)$$

$$TWS = WS(S) + WS(G) = \sum_{i=1}^{i=n} U_i W_t \quad (5)$$

where $GWSD$= the gap between water supply and water demand (10^6 m^3 = MCM), TWD = total water demand (MCM), D_iW_t= water demand of sector i (MCM), TWS= total water supply which is the sum of surface water and groundwater supply (MCM), U_iW_t= water usage of sector i(MCM).

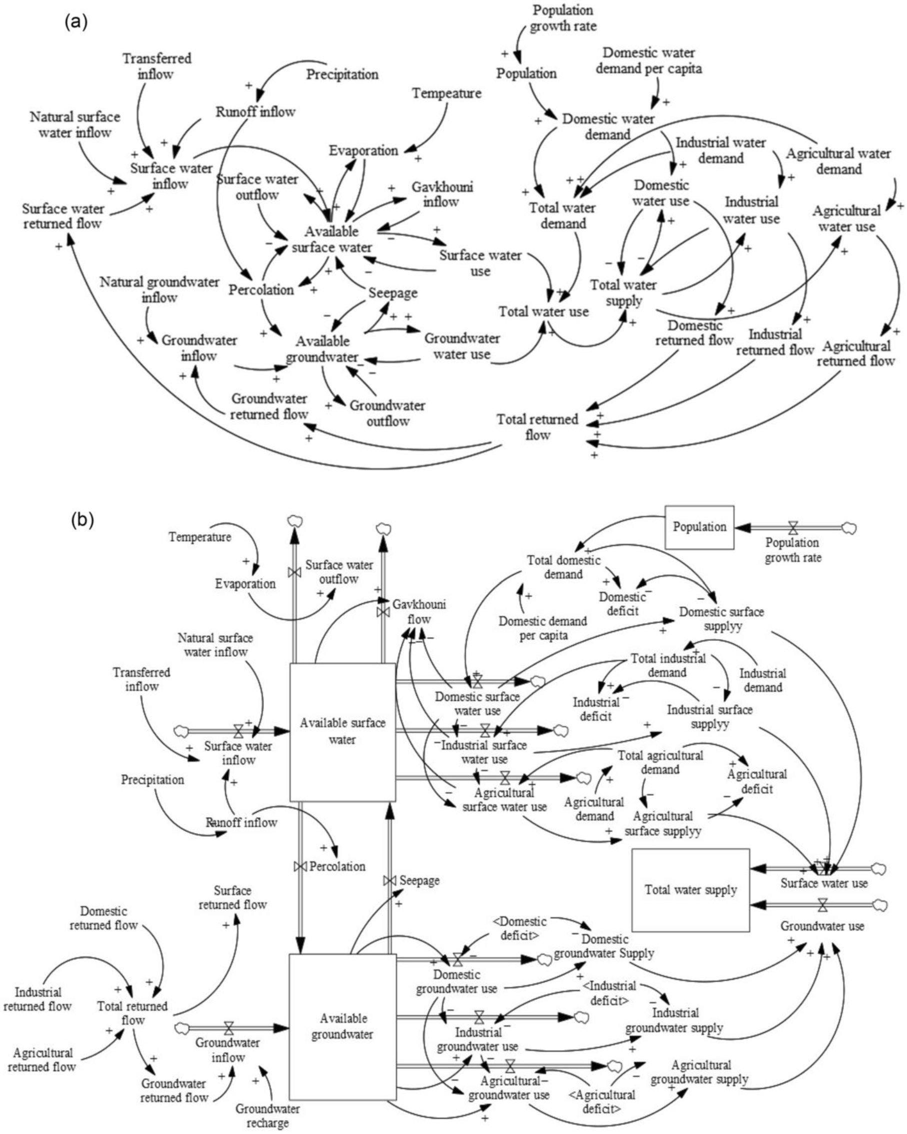

Fig. 3 (**a**) CLD of the water subsystem; (**b**) SFD of the water subsystem

The domestic water demand is calculated with Eq. (6):

$$D_1W_t = Population_t \times PerCapW \tag{6}$$

where D_1W_t= volume of domestic water demand during period t (MCM), $Population_t$ = population during period t, and $PerCapW$= annual per capita water use (MCM/Year/Person). The industrial water demand is given by Eq. (7):

$$D_2W_t = \sum_{i=1}^{i=n} (IndPro_{i,t} \times IndWD_i) \tag{7}$$

where D_2W_t= industrial water demand during period t (MCM), $Ind\text{Pro}_{i,t}$= production capacity of industry i during period t (MWh), $IndWD_i$= Per capita water use of industry$i$,)MCM/MWh), and n= number of industries. The agricultural water demand is calculated with Eq. (8):

$$D_3W_t = \sum_{i=1}^{i=n} (D_3NW_{i,t}) \tag{8}$$

where D_3W_t= total agricultural water demand during period t (MCM), and $D_3NW_{i,t}$= net irrigation water requirement to irrigate crop i during period t (MCM), and n= number of crops.

Historically, the environmental sector has received the lowest priority among WFE sectors; however, recent regulations have allocated a specific annual water share to the Gavkhouni Wetland, represented in the model by D_4W_t as the basin's environmental water demand (Nikouei et al. 2012; Soltani 2009) (Fig. 4).

Based on basin water management strategies and Iran's water-rights priority system, water allocation from programmable available water resources $(PAWR_t)$ is prioritized sequentially for domestic, industrial, agricultural, and environmental sectors according to Eq. (9) to Eq. (12). Accordingly, U_1W, U_2W_t, U_3W_t, and U_4W_t are defined as follows:

$$U_1W_t = MIN\,(PAWR_t, D_1W_t) \tag{9}$$

$$U_2W_t = MIN\,((PAWR_t - U_1W_t)\,, D_2W_t) \tag{10}$$

$$U_3W_t = MIN\,((PAWR_t - U_1W_t - U_2W_t)\,, D_3W_t) \tag{11}$$

$$U_4W_t = \left\{ \begin{matrix} 0 & (AWR_t - U_1W_t - U_2W_t - U_3W_t) \le 0 \\ (PAWR_t - U_1W_t - U_2W_t - U_3W_t) & (AWR_t - U_1W_t - U_2W_t - U_3W_t) > 0 \end{matrix} \right\} t = 1, 2, 3, \ldots, T \tag{12}$$

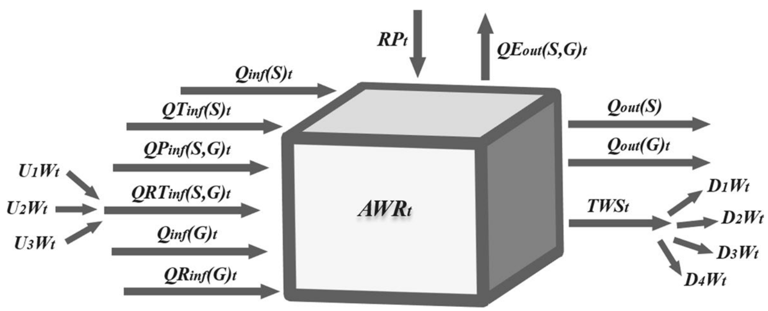

Fig. 4 Schematic of the Water Sub-system

where $PAWR_t$ = a proportion of AWR_t= in time t based on the basin's characteristics (MCM), U_1W_t, U_2W_t, U_3W_t, and U_4W_t denote the water usage of domestic, industrial, agricultural, and environmental sectors in time t, respectively (MCM).

2.1.2 The Food Subsystem

The agricultural sector consumes more than 70% of the basin's total water allocation. This study considers seven major irrigated crops, including wheat, barley, rice, corn, potato, onion, and alfalfa. In the food sub-system (Fig. 5), crop yield is modeled as a function of cultivated area and yield functions. At the same time, water requirement per hectare is estimated based on cropland area and crop evapotranspiration. Total agricultural water demand is calculated as the sum of water requirements for all crops based on Eq. (13) and Eq. (14):

$$\sum_{i=1}^{i=n} ExP_{i,t} = \sum_{i=1}^{i=n} (Area_{i,t} \times ExY_{i,t}) \tag{13}$$

$$\sum_{i=1}^{i=n} D_3NW_{i,t} = \sum_{i=1}^{i=n} (Area_{i,t} \times ETC_{i,t}) \tag{14}$$

where $ExP_{i,t}$= the expected production of crop i during period t (tons), $Area_{i,t}$= the cultivated land area of the crop i during period t (hectares), $ExY_{i,t}$= the expected yield of crop i during period t (tons per hectare), $D_3NW_{i,t}$= the net irrigation water requirement to grow crop i during period t (MCM), and $ETC_{i,t}$= evapotranspiration of crop i during period t (mm/day).

Estimating crop evapotranspiration and yield is essential for relating cultivated area, the crop's net water requirement, and agricultural production. Potential evapotranspiration represents water loss through evaporation and transpiration under non-limiting soil moisture

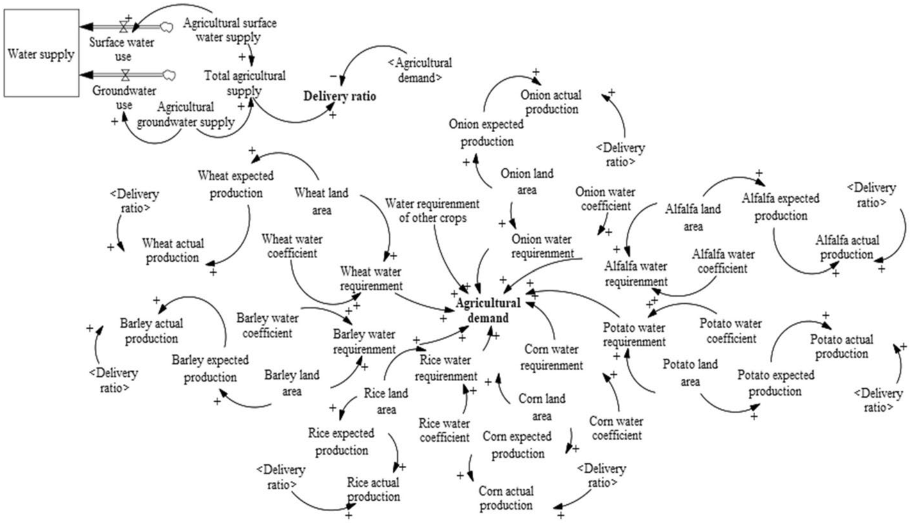

Fig. 5 SFD of the food sub-system

conditions (Doorenbos et al. 1986; Steduto et al. 2012, 2009), while reference evapotranspiration refers to evapotranspiration from a standard short crop surface (Jensen & Allen 2016). Due to its simplicity and accuracy the Hargreaves equation was adopted in this study (Hargreaves & Samani 1982, 1985):

$$\begin{aligned} &ET_0 = 0.0023 R_a (T + 17.8)\sqrt{TR} \\ &T = \tfrac{T_{\max} + T_{\min}}{2} \\ &TR = T_{\max} - T_{\min} \end{aligned} \tag{15}$$

where ET_0= reference crop evapotranspiration (mm/day), R_a= average extra-terrestrial radiation for the desired latitudes expressed as the equivalent of mm/day of evaporated water, T= average daily temperature in the desired period (°C), $T_{\max}$= maximum daily temperature in the desired period (°C), and $T_{\min}$= the minimum daily temperature in the desired period (°C).

$ETC_{i,g}$ (mm/day) denotes the actual evapotranspiration of crop i during stage g of growth, which varies during a crop growth stage (Smith et al. 1998). It is calculated using Eq. (16):

$$ETC_{i,g} = Kc_{i,g} \times ET_0 \tag{16}$$

in which $Kc_{i,g}$ denotes the crop coefficient for the $i - th$ crop during stage g of growth.

The actual evapotranspiration of crop i in growth stage g is reduced when the soil is not well watered by modifying the $ETC_{i,g}$ by a coefficient K_s (Jensen & Allen 2016):

$$ETa_{i,g} = Ks\, ETc_{i,g} = Ks\, Kc_{i,g} \times ET_0 \tag{17}$$

in which $ETa_{i,g}$ denotes the actual evapotranspiration of crop i in growth stage g (mm/day) Ks denotes a soil-moisture coefficient that varies between 0 and 1, with Ks= 1 when the soil is well watered, and Ks= 0 when the soil moisture reaches the wilting point.

The crop yield function can be defined seasonally or for different crop growth stages. It is based on the relationship between yield reduction and evapotranspiration deficit (Smith et al. 1998) and is expressed using Eq. (18):

$$\frac{Ya_i}{Ymax_i} = 1 - \sum_{g=1}^{n} Ky_{i,g}\left(1 - \frac{ETa_{i,g}}{ETC_{i,g}}\right) \tag{18}$$

where $Ky_{i,g}$ = yield sensitivity coefficient for the water stress of each crop i in each growth stage g, n= the number of growth stages, Ya_i= the actual yield of crop i (kg per hectare) and $Y\max_i$= the potential yield of crop i (kg per hectare), and other terms defined above. The actual production of each crop is determined by multiplying the yield ratio by $Y\max_i$ of crop i in period t.

The water-delivery ratio indicates the extent to which actual crop production may fall below the expected yield. After estimating agricultural water demand, this ratio is separately applied to the yield function of each crop using Eq. (19):

$$Deliveryratio_{i,t} = \frac{ETa_{i,t}}{ET\max_{i,t}} \tag{19}$$

The delivery ratio is the linkage between the water and agriculture sub-systems based on Eq. (20):

$$Deliveryratio_t = \left\{ \begin{matrix} 1 & U_3W_t \geq D_3W_t \\ \frac{U_3W_t}{D_3W_t} & U_3W_t < D_3W_t \end{matrix} \right\} t = 1,2,3,...,T \tag{20}$$

Therefore, actual production is calculated with Eq. (21):

$$\sum_{i=1}^{i=n} ActPro_{i,t} = \sum_{i=1}^{i=n} (Area_{i,t} \times ActY_{i,t}) \tag{21}$$

where $ActPro_{i,t}$= actual production of crop i during period t (tons), $Area_{i,t}$= cultivated land area of crop i during the period t (hectares), and $ActY_{i,t}$= actual yield of agricultural product i during period t (tons per hectare).

2.1.3 The Energy Subsystem

The energy sub-system considers energy supply and population as state variables, while input and output parameters are treated as auxiliary variables (Fig. 6). The model includes conventional and renewable energy sources, including thermal, gas, electric, solar, and wind power, based on Eq. (22). These energy sources support water extraction, treatment, storage, distribution, transport, and reuse.

$$EGen_t = \sum_{i=1}^{i=n} (PP_{1,t} + ... + PP_{n,t}) \tag{22}$$

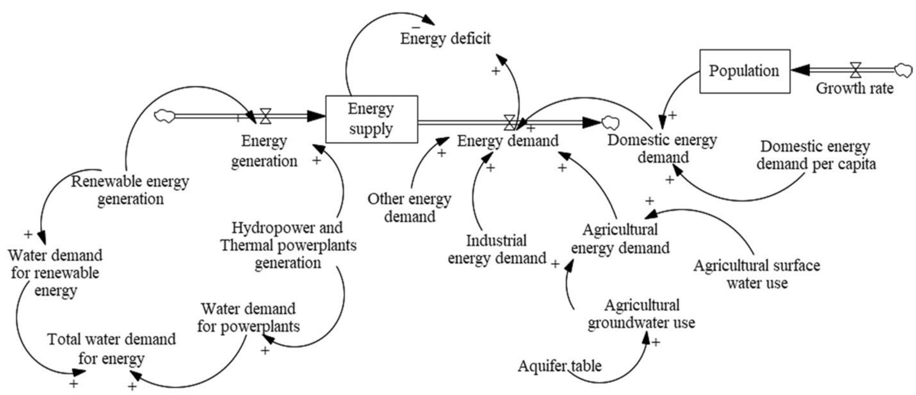

Fig. 6 SFD of the energy subsystem

where $EGen_t$= total power generation of the power plants and other energy sources during the period t (MWh), and $PP_{1,t}$= power generation of power plant i during the period t (MWh).

The total water consumption in the power plants is calculated with Eq. (23):

$$PPW_{i,t} = PPEnerg_{i,t} \times PerCapWP_{i,t} \tag{23}$$

where $PPW_{i,t}$= volume of water consumed by power plant i during period t (MCM), $PPEnerg_{i,t}$= generation capacity of power plant i during period t (MWh), and $PerCapWP_{i,t}$= unit of water consumed by power plant i during period t for the generation of 1 MWh of electricity (MCM per MW).

Energy demand includes electricity consumption for urban and rural water supply, agricultural irrigation pumping, industrial water pumping, and other basin-related uses. The domestic sector's energy consumption is estimated using Eq. (24):

$$EDUR_t = \sum (WDN_t + GWP_t + WWT_t) \tag{24}$$

where $EDUR_t$= energy usage in domestic sector for urban and rural water supply during period t (MWh), WDN_t= electricity usage in water distribution networks during period t (MWh), GWP_t= electricity usage for pumping groundwater (with an efficiency of 60%) during period t (MWh), WWT_t= electricity usage for wastewater treatment, purifying, pumping, and pipe repairs during period t (MWh).

In the agricultural sector, most energy consumption is associated with groundwater extraction. Increased pumping lowers groundwater levels and raises the energy required for water withdrawal from deeper aquifers. The energy required for groundwater extraction is calculated using Eq. (25) (Karimi et al. 2012; Rothausen & Conway 2011):

$$EPW_t = \frac{9.81 \times Lift \times Mass}{3.6 \times 10^6 \times Efficiency} \tag{25}$$

where EPW_t= electricity required for pumping groundwater (MWh), $Lift$= vertical distance from the groundwater water level to the elevation where water is delivered (meters), $Mass$= mass of water (which is calculated according to $\rho = \frac{m}{V}$) and, $Efficiency$= pump efficiency (percentage).

2.2 Projecting Precipitation and Temperature under Climate Change

Climate projection development involves three main steps: selecting future climate scenarios based on population growth, technological development, and greenhouse gas emissions; simulating future climate conditions using climate models; and downscaling coarse-resolution AOGCM outputs to the basin scale.

2.2.1 General Circulation Models

Atmosphere–Ocean General Circulation Models (AOGCMs) are among the most reliable tools for climate scenario generation, simulating physical climate processes through math-

Table 1 Characteristics of AGCMs implemented in the IPCC's sixth assessment report

Model	Atmospheric Resolution (Lat. × Long.)	Developer
BCC-CSM2-MR	1.1° × 1.1°	Beijing Climate Center, China Meteorological Administration
CESM2	1.25° × 0.9°	Community Earth System Model Contributors
CanESM5	2.8° × 2. 8°	Canadian Centre for Climate Modelling and Analysis-Canada

ematical equations. In this study, precipitation and air temperature projections from three AOGCMs presented in the Intergovernmental Panel on Climate Change Sixth Assessment Report were selected (Table 1).

2.2.2 Emissions Scenario Selection

The Shared Socioeconomic Pathways (SSPs), the latest greenhouse gas emission scenarios, introduced by the Intergovernmental Panel on Climate Change, describe future greenhouse gas emission trajectories and associated adaptation and mitigation pathways (Riahi et al. 2017). In this study, AOGCM projections under SSP1 and SSP5 were used to represent optimistic and pessimistic climate conditions, respectively. SSP1 reflects sustainable development pathways, whereas SSP5 assumes continued reliance on fossil fuels.

2.2.3 Stochastic Downscaling

LARS-WG model was used to generate daily precipitation (mm), minimum and maximum temperature (°C), and solar radiation data under baseline and future climate conditions due to its simplicity, efficiency, and low data requirements (Racsko et al. 1991; Semenov 2007; Semenov et al. 2002). The LARS-WG model applies observed climatic data from 1980–2014 together with climate scenarios to simulate future meteorological series based on Eq. (26) and Eq. (27). Daily data were generated for two weather stations presented in Table 2.

$$\Delta P_t = \frac{\overline{P}_{fut,t}}{\overline{P}_{his,t}} \tag{26}$$

$$\Delta T_t = \overline{T}_{fut,t} - \overline{T}_{his,t} \tag{27}$$

Table 2 Description of the selected observation weather stations

			Geographical position	
Station Name	Parameter	Elevation (m)	Longitude	Latitude
Chelgerd	Precipitation	2300	50°05′	32°27′
Isfahan	Temperature	1500	51°39′	32°36′

where ΔP_t= the ratio of relative changes in long-term average precipitations simulated by GCM for the future ($\overline{P}_{fut,t}$) and historical period ($\overline{P}_{his,t}$) in month t (mm), ΔT_t= the difference in long-term average temperatures simulated by GCM for the future ($\overline{T}_{fut,t}$) and historical period ($\overline{T}_{his,t}$) in month t (°C).

2.3 Calibration

A common calibration approach for SD models is the reproduction test, in which simulated outputs are compared with observed data. Model performance was evaluated using goodness-of-fit tests, including extreme-condition, structure-assessment, dimensional-consistency, and surprise-behavior tests. The accuracy of model simulations was assessed using the R, NSE, RMSE, and MAE indices presented in Eq. (28) to Eq. (31):

$$R = \frac{\sum_{i=1}^{i=n} \left(Q_{pre,i} - Q_{avepre}\right)\left(Q_{obs,i} - Q_{aveobs}\right)}{\sqrt{\sum_{i=1}^{i=n} \left(Q_{pre,i} - Q_{avepre}\right)^2} \sqrt{\sum_{i=1}^{i=n} \left(Q_{obs,i} - Q_{aveobs}\right)^2}} \tag{28}$$

$$NSE = 1 - \frac{\sum_{i=1}^{i=n} \left(Q_{pre,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{i=n} \left(Q_{obs,i} - Q_{aveobs}\right)^2} \tag{29}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{i=n} \left(Q_{pre,i} - Q_{obs,i}\right)^2}{n}} \tag{30}$$

$$MAE = \frac{1}{n} \sum_{i=1}^{i=n} \left|Q_{pre,i} - Q_{obs,i}\right| \tag{31}$$

where R= correlation coefficient, *NSE*=Nash–Sutcliffe Efficiency, *RMSE*=Root Mean Square Error, *MAE*=Mean Absolute Error, $Q_{pre,i}$= predicted value of variable i, $Q_{obs,i}$ = observed value of variable i, Q_{avepre}= average of predicted values, Q_{aveobs}= average of observed values, i = time step and n= number of time steps.

3 Case Study

The Zayandeh-Roud River Basin, covering about 26,917 km^2 in central Iran, is a strategically important watershed extending from the Zagros Mountains to the Gavkhouni Wetland (Fig. 7). The basin has experienced severe water stress in recent decades due to population growth, urbanization, industrial and agricultural expansion, and prolonged droughts. Annual precipitation ranges from 1500 mm in the west to 50 mm in the east, while average

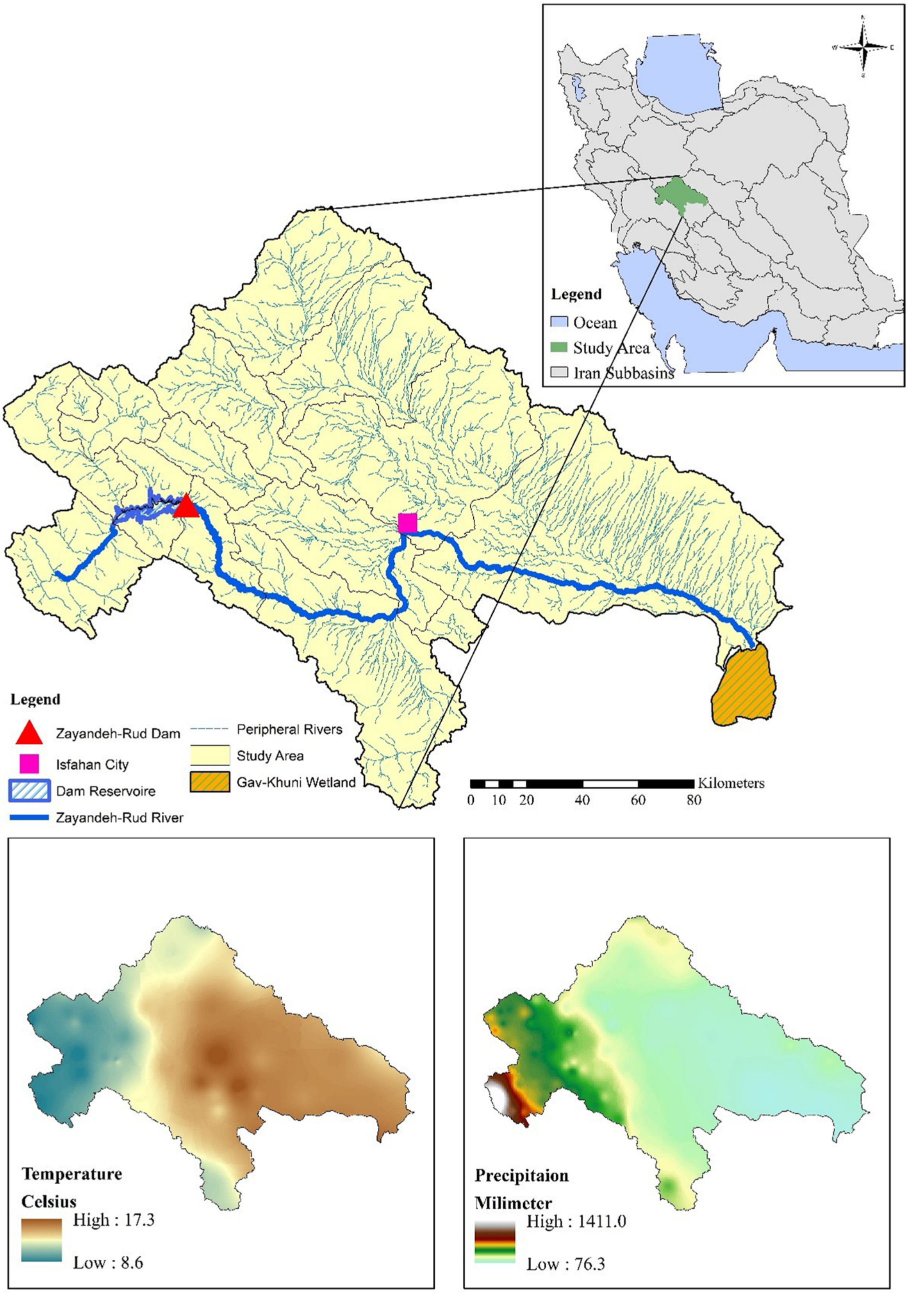

Fig. 7 Study area map prepared using ArcGIS 10.8 (ESRI, Redlands, CA, USA)

monthly temperatures vary between 3 °C and 29°C. The Zayandeh-Rud River, with an average annual flow of approximately 1400 MCM, supplies water to nearly 5 million people, major industries, and over 200,000 ha of agricultural land, which consumes more than 70% of the basin's water resources (Zayandab 2008). Due to surface water scarcity, groundwater supplies more than 70% of the total demand, resulting in an average annual groundwater decline of about 56 cm.

The construction of the Zayandeh-Rud Dam, inter-basin water transfer projects, and modern irrigation networks has considerably expanded agricultural areas within the basin (Zayandab 2008). Moreover, the development of steel, iron, and power industries has accelerated regional population growth and water demand. Despite inter-basin water transfers, water managers have been unable to balance water supply and demand because of the complex interactions among water, food, and energy sub-systems (Gohari 2013). Like many arid and semi-arid regions, the basin faces increasing pressure from agricultural, industrial, and population growth under limited water availability.

4 Results and Discussion

4.1 Model Application

Model validation was conducted to evaluate the reliability of the SD-WFE framework. Calibration results, including reproduction and extreme-condition tests, are presented in Fig. 8 and Table 3. The results show good agreement between simulated and observed data. Figure 8 presents the extreme-condition test under zero population growth, confirming the robustness and reliability of the model predictions.

The basin's mean annual inflow is approximately 1455 MCM, including runoff, transferred flow, seepage, and other inflows of 628, 600, 77, and 190 MCM, respectively (Fig. 9). The average annual outflow from the upstream basin is 281 MCM, mainly associated with evaporation, deep percolation, and other losses. Interactions between surface water and groundwater, including seepage and percolation, were simulated linearly within the water sub-system. Although more than twenty aquifers with varying characteristics exist in the basin, a lumped modeling approach was adopted. The model assumes that resource production occurs in the upstream basin, whereas resource consumption mainly takes place downstream.

Under current management policies, the mean annual water consumption of the domestic, industrial, agricultural, and environmental sectors is 358, 134, 2419, and 0 MCM, respectively, in the downstream basin (Fig. 9). More than 80% of the allocated water is consumed by the agricultural sector; nevertheless, persistent water shortages have reduced agricultural water deliveries in recent years (Fig. 9). The average water-delivery ratio under baseline conditions, without considering climate change impacts, is estimated at 0.57 (Fig. 9). Electricity consumption shows an increasing trend across all sectors, with the agricultural sector exhibiting the highest growth due to rising groundwater extraction and declining groundwater levels. During the baseline period, annual energy shortages averaged approximately 4500 kWh (Fig. 9), requiring electricity imports from the national grid. The Gav-Khouni Wetland is regarded as the downstream physical boundary of the system, which has not received its minimum water right from the Zayandeh-Rud River due to persistent severe

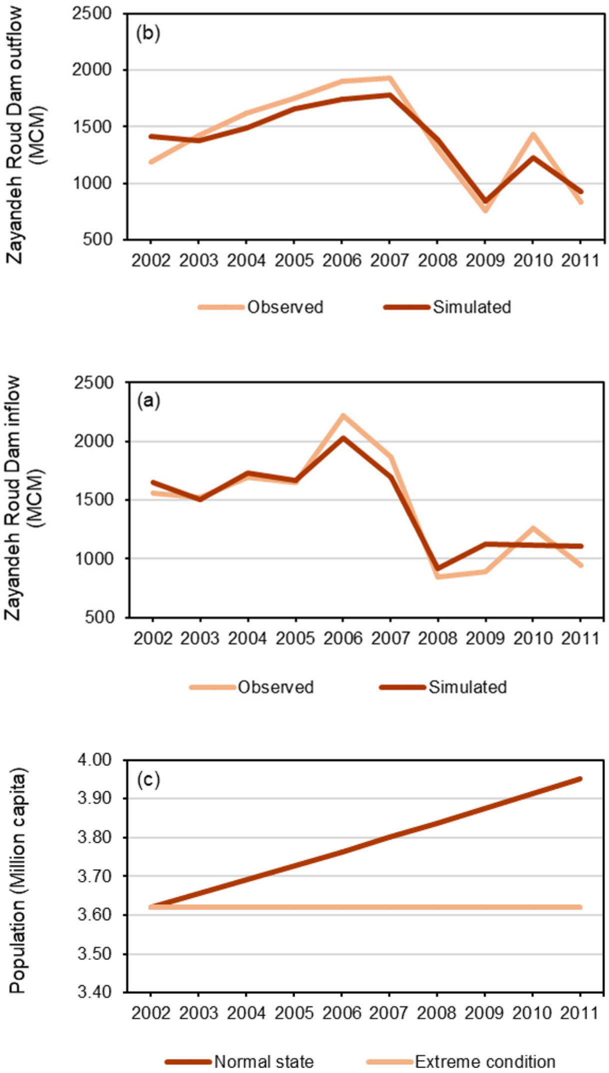

Fig. 8 The results of model calibration; (**a**) and (**b**) correspond to the Reproduction test; (c) population under Normal (with population growth) and Extreme conditions (zero population growth)

Table 3 The evaluation indices obtained in the reproduction test

	R^2	NSE	RMSE	MAE
Reservoir inflow	0.98	0.99	165	133
Reservoir outflow	0.98	0.98	183	151

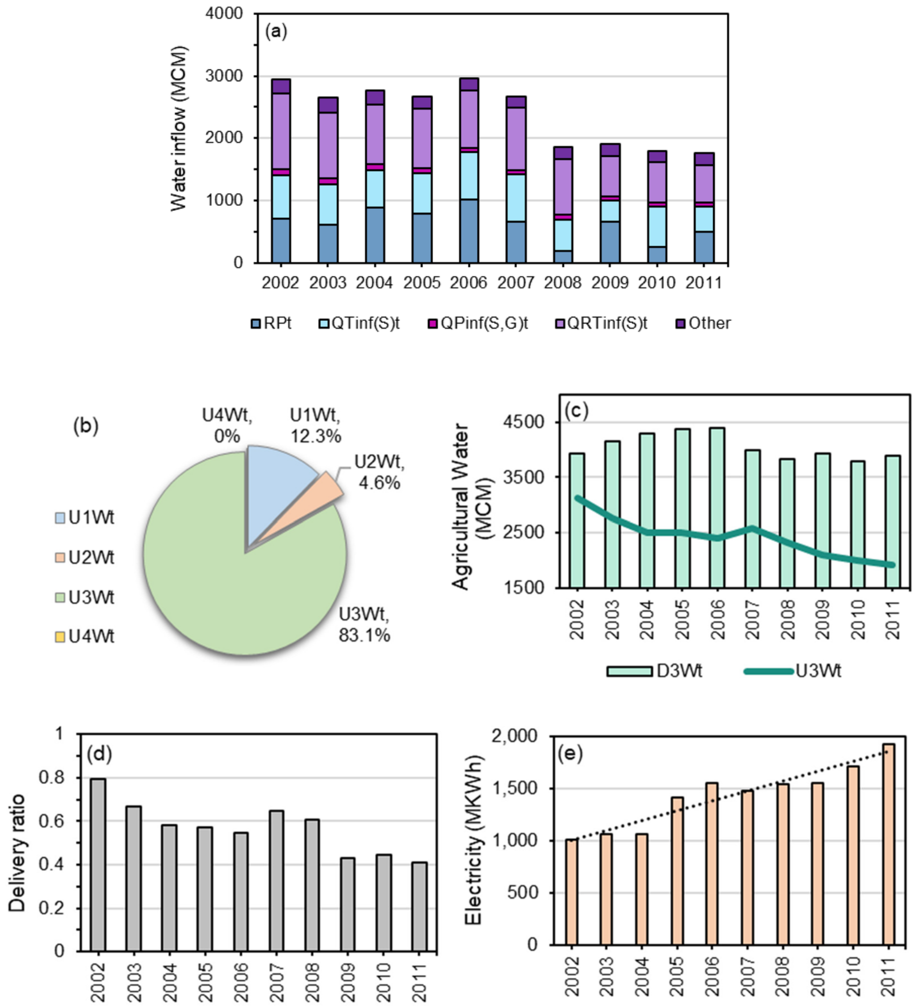

Fig. 9 (**a**) Total water inflow to the basin; (**b**) Average water usage among various stakeholders; (**c**) Comparison between agricultural water demand and usage, (**d**) Water-delivery ratio index; (**e**) Total agricultural energy demand

water shortages and the existing priority order for meeting demands. Under unconstrained water supply conditions, increasing demand leads to higher sectoral water consumption.

4.2 System Archetypes

System archetype analysis was used to identify the main drivers of water imbalance in the basin. Figure 10 presents two dominant archetypes: "Limits to Growth" and "Fixes that Fail." The "Limits to Growth" pattern results from increasing agricultural and industrial water demands exceeding the basin's carrying capacity, while the "Fixes that Fail" pattern reflects temporary measures, such as inter-basin water transfers, that initially reduce short-

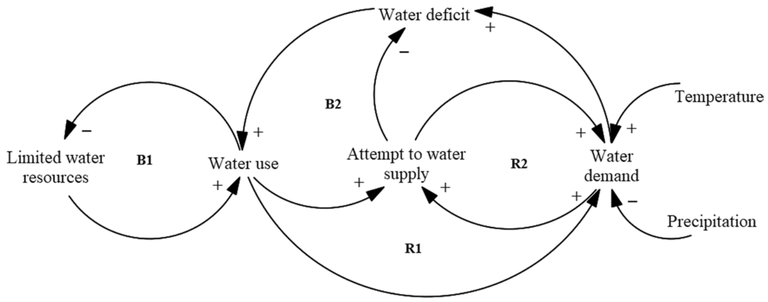

Fig. 10 The archetype of water resources system in the Zayandeh-Roud River basin

ages but eventually create unsustainable long-term impacts. These findings indicate that management strategies effective in one region may generate adverse consequences when applied elsewhere.

4.3 Impacts of Climate Change

Figure 11 shows that future precipitation patterns (2025–2034) vary among climate models and emission scenarios. Under SSP1, mean annual precipitation is projected to increase by 6.1% and 4.2% according to BCC-CSM2-MR and CESM2, respectively, while CanESM5 projects a 10.3% decrease. Under SSP5, precipitation decreases in all models, with reductions of 8.8%, 17.8%, and 1.8% projected by BCC-CSM2-MR, CanESM5, and CESM2, respectively. Overall, basin precipitation shows a declining trend, particularly under SSP5. Across all models, average precipitation is projected to decrease by 6.5% under SSP1 and 17.8% under SSP5. In contrast, mean temperature is projected to rise under both scenarios. Under SSP1, temperatures increase by 1.15°C, 1.04°C, and 1.38°C in BCC-CSM2-MR,

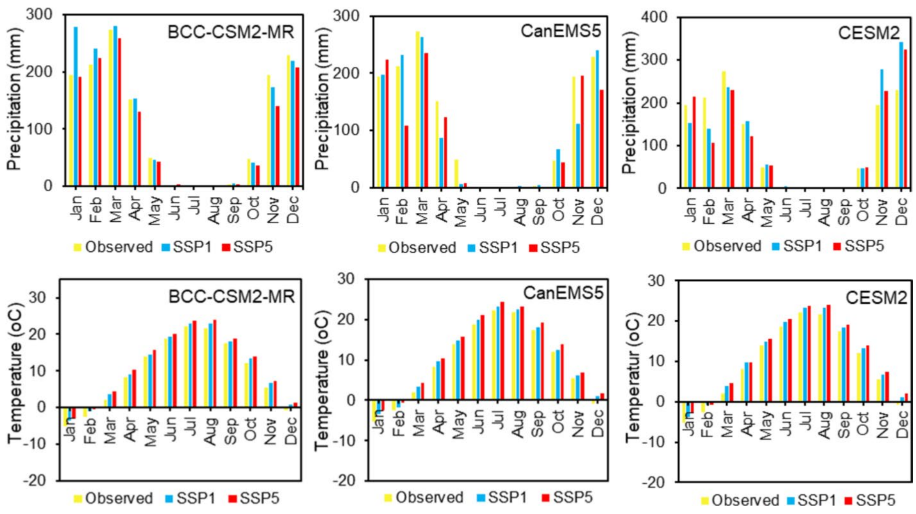

Fig. 11 Average monthly precipitation and temperature under the SSP1 and SSP5 emissions scenarios by three AOGCMs

CanESM5, and CESM2, respectively, while SSP5 projections indicate increases of 1.96°C, 2.04°C, and 1.99°C. Overall, temperature increases are more pronounced under SSP5, with average rises of 0.74°C and 1.17°C under SSP1 and SSP5, respectively.

Model results indicate that runoff is projected to decline by 2.4% under SSP1 and 24% under SSP5. Rising temperatures increase evaporation by 8.4% under SSP1 and 12.6% under SSP5, resulting in reductions in deep percolation of 16.5% and 35.7%, respectively. In addition, SSP5 is associated with greater rainfall variability and a higher likelihood of intense precipitation events in dry regions. Consequently, total basin inflow is projected to decrease by 7.2% under SSP1 and 15.7% under SSP5 (Fig. 12). Reduced surface flows under future climate scenarios are expected to negatively affect groundwater storage by decreasing groundwater recharge and deep infiltration. In addition, high-intensity rainfall events projected under SSP5 are likely to increase surface runoff while further limiting

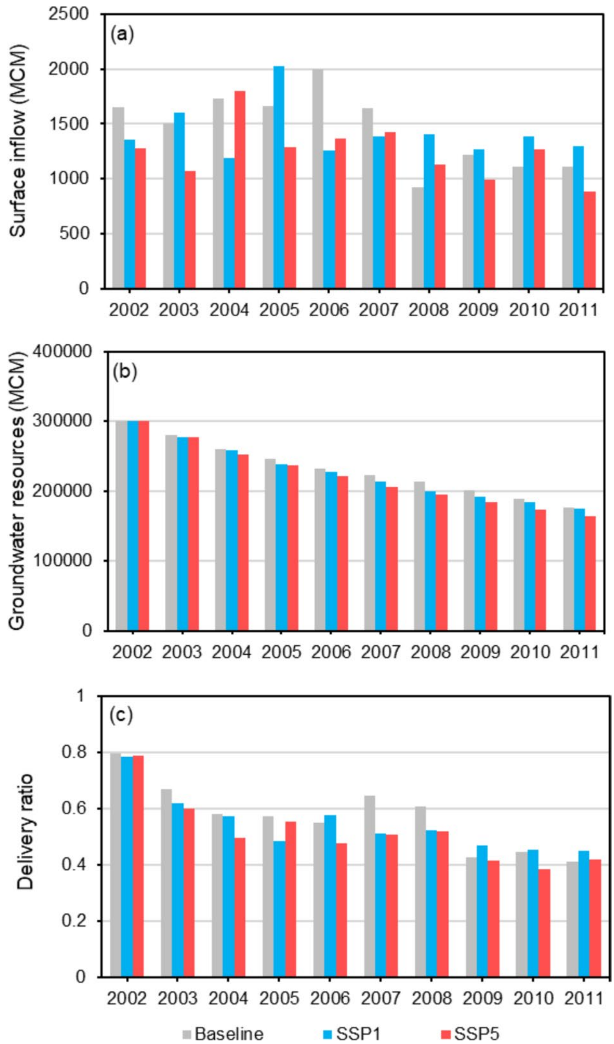

Fig. 12 Some key variables under the baseline climate and the SSP1 and SSP5 emissions scenarios: (**a**) Total inflow to the basin; (**b**) Groundwater resources; (**c**) Water-delivery ratio

groundwater recharge. As shown in Fig. 12, groundwater resources are projected to decline under both scenarios, with more severe depletion under SSP5.

Increasing temperature and evapotranspiration are expected to raise crop water requirements under both climate scenarios, while total basin inflow is projected to decline significantly. Since water availability is the main limiting factor for agriculture in arid and semi-arid regions, the water-delivery ratio is projected to decrease by 0.03 under SSP1 and 0.06 under SSP5 despite some fluctuations (Fig. 12). Figure 13 compares actual and expected crop production based on Eq. (18). Overall, crop yields are projected to decline under SSP1 and SSP5, respectively, by 7% and 16% for wheat, 5% and 11% for barley, 1% and 5% for rice, 13% and 24% for corn, 4% and 12% for potato, 7% and 15% for alfalfa, and 6% and 14% for onion.

In this study, domestic and industrial water demands, as well as their associated energy consumption, are assumed to remain constant under climate change scenarios, while agricultural energy demand varies with water availability. The projected decline in the water-delivery ratio reduces the volume of surface water and groundwater pumping, resulting in a slight decrease in basin energy consumption, estimated at 1% under SSP1 and 2% under SSP5.

4.4 Policy Options Analysis

The previous results illustrated basin resource and consumption dynamics under optimistic (SSP1) and pessimistic (SSP5) climate scenarios. The next step involves evaluating management options for improving water supply and demand management in the Zayandeh-Roud River Basin. Ten management options were classified into two categories: extreme and normal options. Extreme options were used to assess the basin's long-term strengths and weaknesses under severe management conditions, whereas normal options were designed considering legal, social, and water-right constraints. As shown in Table 4, the proposed policies include limiting groundwater withdrawal, reducing water-intensive industrial activities, modifying crop patterns, and prioritizing environmental water allocations.

Figure 14 shows that groundwater storage recovers under option H1 (complete cessation of groundwater withdrawal) during the baseline period. However, this option is impractical due to legal, political, and social constraints. Therefore, options H2 and H3, which reduce groundwater withdrawal to 25% and 50% of current levels by restricting unauthorized wells, are considered more feasible. Figure 14 indicates that the water-delivery ratio generally declines over time under all policy options. However, options I1, I2, and I3 increase the water-delivery ratio by reducing industrial water allocation and increasing water availability for agriculture. Similarly, options A1, A2, and A3 improve the water-delivery ratio by eliminating cultivation of water-intensive crops and reducing evapotranspiration losses. In contrast, option E1 allocates part of the available surface water to the environmental requirements of the Gavkhouni Wetland, thereby reducing the agricultural water-delivery ratio. Since agriculture is the primary consumer of groundwater resources, options H1, H2, and H3 also reduce agricultural water use and consequently increase energy savings, as shown in Fig. 14.

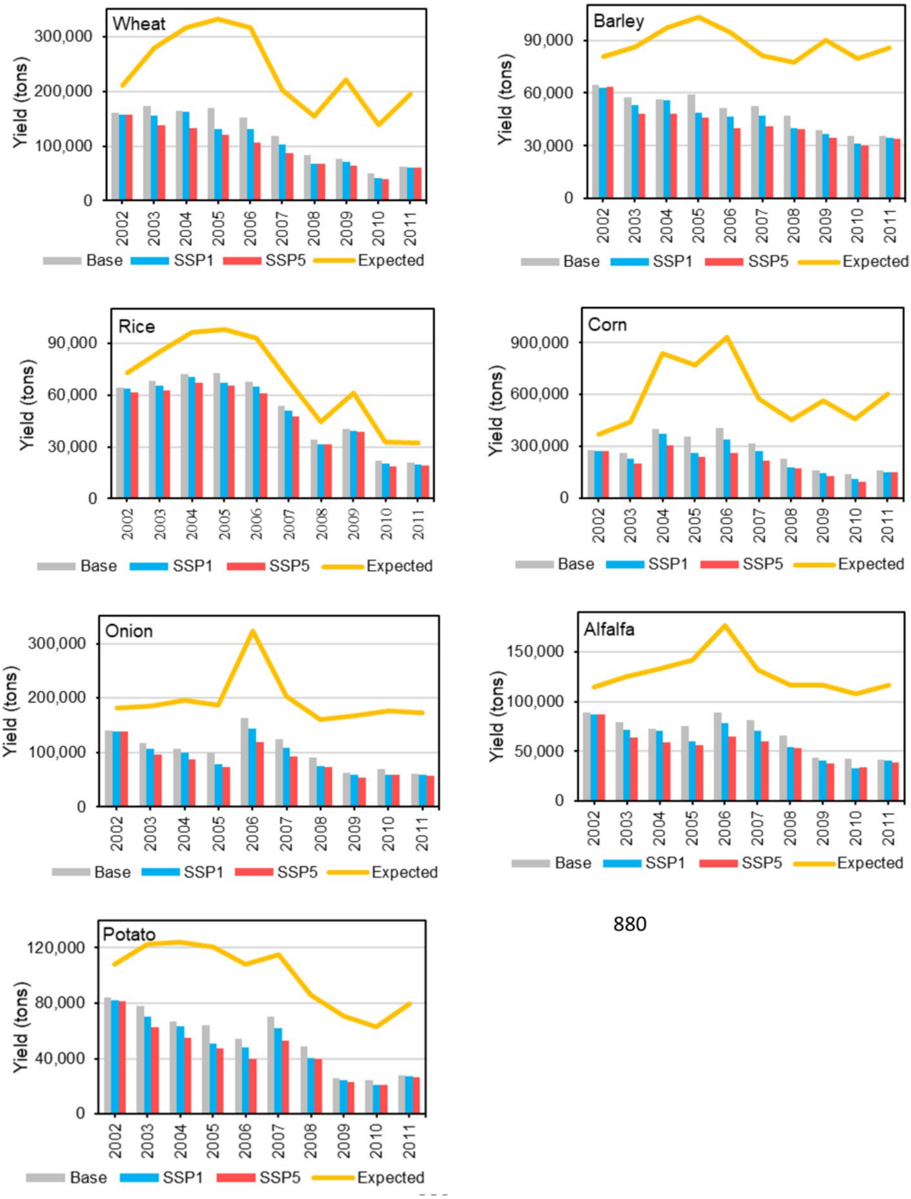

Fig. 13 Comparison between the expected production and actual production of each crop in the Base climatic condition, SSP1, and SSP5

4.4.1 Proposed Policy Options

Applying individual management options may generate both benefits and negative impacts, particularly in the agricultural sector; therefore, single-policy implementation is not considered effective. A combined management strategy is more suitable, especially when it

Table 4 Description of new sectoral management policies regarding water resource security

Related Sector	Policy Option	Symbol	Normal	Extreme
Hydrological (Groundwater)	Declaring the ban on groundwater withdrawal (use 0%)	H1		•
	Limiting groundwater withdrawal to 25% of the current use	H2	•	
	Limiting groundwater withdrawal to 50% of the current use	H3	•	
Industrial	Shutting down Isfahan Steel Company (No.1*)	I1		•
	Shutting down Isfahan Steel Company (No.2*)	I2		•
	Shutting down both No.1 and No.2 Isfahan Steel Companies	I3		•
Agricultural	Not planting of rice	A1	•	
	Not planting of wheat	A2	•	
	Not planting of wheat, barley, rice, and alfalfa	A3		•
Environmental	Securing 50% environmental rights of the Gavakhouni wetland as the first priority	E1	•	

*No.1: Zob-Ahan Isfahan and *No.2: Foolad-Mobarakeh Isfahan

maximizes resource recovery while minimizing impacts on stakeholders. Based on trial-and-error analysis, the optimal scenario includes 50% implementation of option A1 (rice cultivation reduction), 70% implementation of option E1 (allocation of environmental water rights to the Gavkhouni Wetland), and option H3 (limiting groundwater withdrawal to 50% of the current use). The impacts of this combined policy on key WFE nexus variables during the baseline period are presented in Fig. 15.

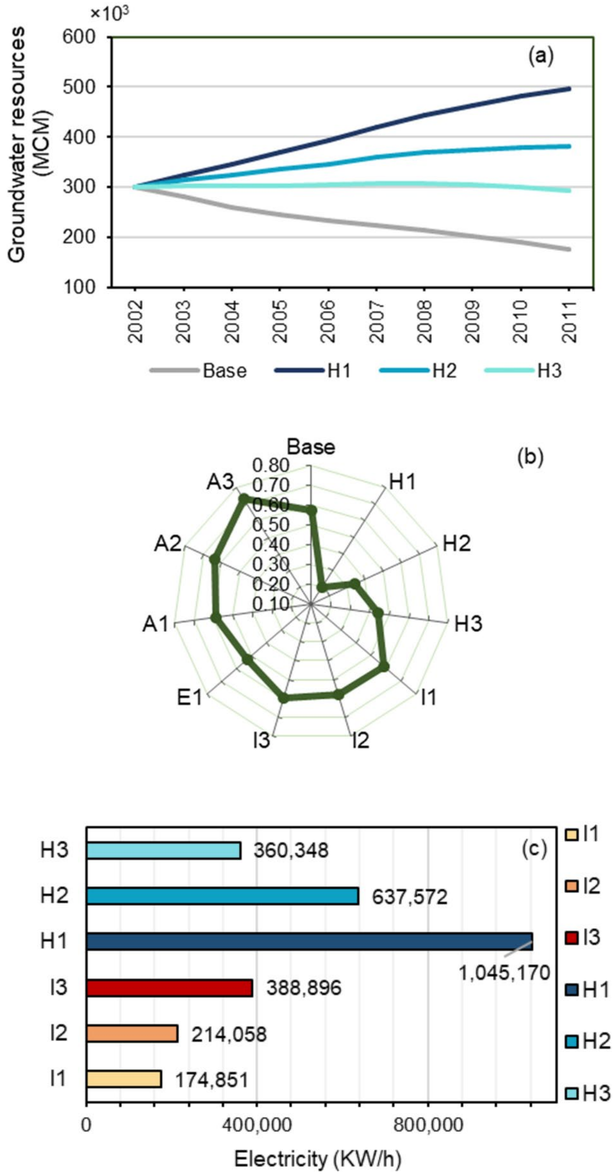

Fig. 14 (**a**) Groundwater resources; (**b**) Water-delivery ratio; and (**c**) Average energy saving, under different policy options

Figure 16 present the estimated changes in farmers' income and the economic benefits of energy savings under ten management policy options. Figure 16 shows the economic benefits associated with protecting the Gavkhouni Wetland through implementation of 70% of option 7 related to environmental water rights. Compared with the baseline income of $105.561 million, average farmers' income is projected to decrease by approximately $41.837 million, mainly due to the high economic value of rice cultivation. In contrast, average energy savings are estimated at $5.293 million, while wetland protection generates an average economic benefit of about $17.719 million (Nikouei et al. 2012).

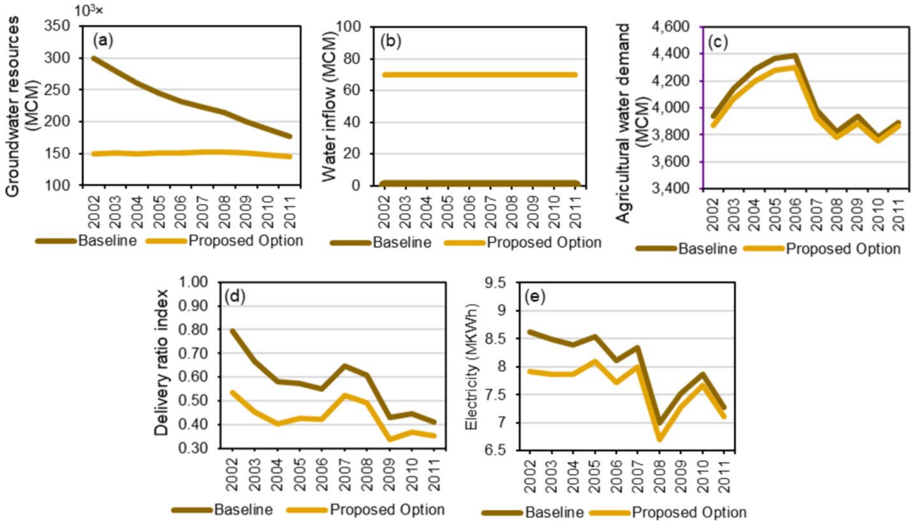

Fig. 15 Comparison of the results of implementing proposed option with the baseline management option: (**a**) Groundwater resources; (**b**) Inflow to the Gavkhouni Wetland, (**c**) Agricultural water demand; (**d**) Water-delivery ratio; (**e**) Energy deficit

Reducing water allocations without providing financial incentives for conservation can threaten the economic welfare of water users and reduce public support for water management policies. These challenges become more severe under climate change and drought conditions. In this context, financial support and conservation subsidies can help maintain or improve users' economic conditions. Results indicate that the proposed management strategy could offset nearly 50% of farmers' economic losses through energy savings and environmental protection benefits. Moreover, reduced cultivation costs resulting from lower rice production would further decrease farmers' financial losses, while the remaining impacts could be compensated through appropriate subsidy policies.

4.4.2 The Proposed Option under Climate Change Conditions

Figure 17 shows that continuing current basin policies without restrictions on groundwater extraction would lead to severe groundwater depletion, particularly under SSP5. Under these scenarios, the average water-delivery ratio is projected to decline by 0.03 under SSP1 and 0.06 under SSP5, reducing the energy required for surface water and groundwater pumping. In contrast, Fig. 17 demonstrates that the proposed management strategy would stabilize groundwater resources under both climate scenarios. By reducing agricultural water demand, the average water-delivery ratio would improve by 0.17 under SSP1 and 0.19 under SSP5, while basin energy savings would increase by approximately 6% and 7%, respectively. Although implementation of the proposed strategy would reduce agricultural income by 40% during the baseline period and by 44% and 48% under SSP1 and SSP5, lower agricultural water consumption would generate additional economic benefits through increased energy savings and surplus energy sales, estimated at 12% and 20% above baseline conditions under SSP1 and SSP5, respectively.

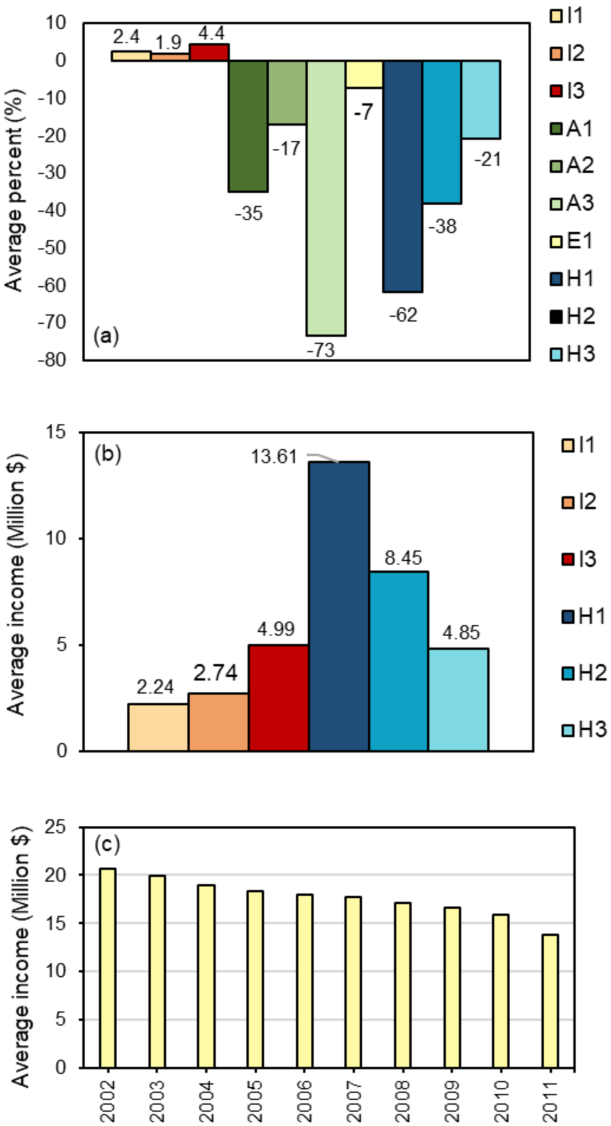

Fig. 16 Results of the change in stakeholder's economic benefits or loss caused by the management options: (**a**) Average change in farmers' income; (**b**) Economic benefits from energy-saving; (**c**) Economic benefits of wetland restoration (option E1)

5 Concluding Remarks

Developing integrated models improves the holistic understanding of complex watershed systems and supports the formulation of sustainable water management policies. In this study, a Water–Food–Energy Nexus model was developed to capture the interactions, synergies, and feedbacks among water, food, and energy systems. Evaluation of different policy scenarios demonstrated the critical role of water within the WFE nexus. The proposed management strategy generated substantial environmental and energy-related benefits while imposing relatively limited impacts on the agricultural sector. Economic gains from wetland restoration and surplus energy sales compensated for approximately 42% and 13% of

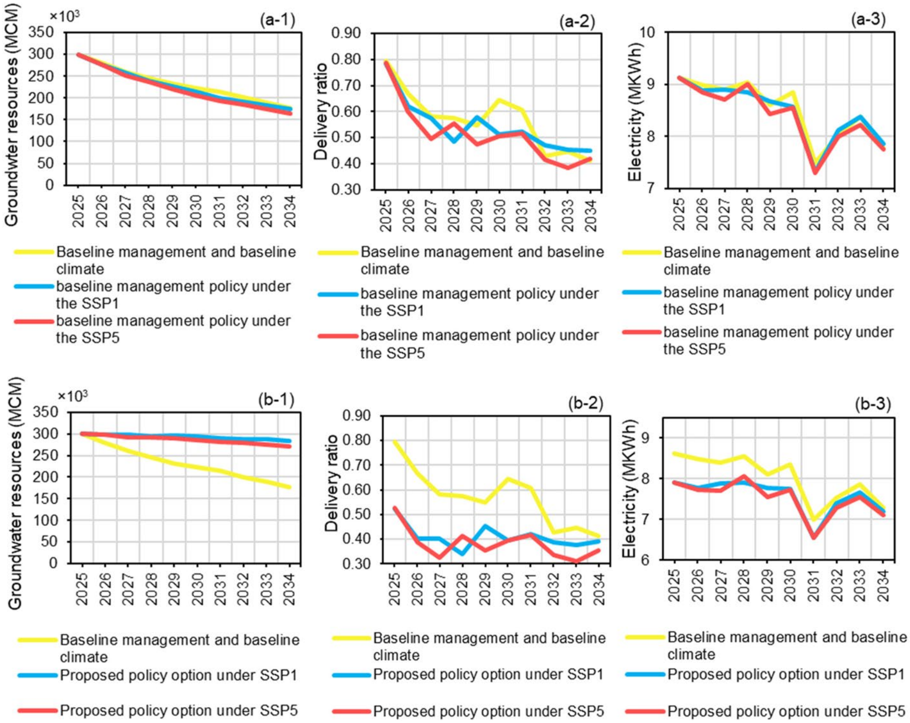

Fig. 17 Comparison of the baseline management option under baseline climate with the baseline management policy under the SSP1 and SSP5 climate scenarios with respect to (a-1) groundwater resources, (a-2) Water-delivery ratio, and (a-3) Electricity demand from the national electricity grid. Comparison of the baseline management policy under baseline climate with the proposed management policy under the SSP1 and SSP5 climate scenarios with respect to (b-1) groundwater resources, (b-2) Water-delivery ratio, and (b-3) electricity

agricultural losses, respectively. Under climate change conditions, the proposed strategy improved basin management by increasing groundwater storage by 20%, securing 70% of environmental flow requirements for the Gavkhouni Wetland, and reducing the agricultural water-delivery ratio by 18%. These findings suggest that reducing agricultural water demand through crop pattern modification and promoting water-saving irrigation technologies through conservation subsidies can provide effective solutions to basin water scarcity.

System Dynamics provides an effective framework for understanding complex water resource systems and identifying the key feedback mechanisms governing their behavior. Rapid development and increasing sectoral demands have intensified water scarcity in the Zayandeh-Roud River Basin, making sustainable balance between water supply and demand a critical challenge. The results indicate that increasing water supply without considering the dynamic interactions within the WFE nexus would further increase water demand and aggravate resource stress. The proposed management strategy demonstrates the potential benefits and trade-offs of integrated WFE management under climate change conditions. In contrast, continuation of business-as-usual (or baseline) policies is expected to intensify environmental degradation and economic losses in the basin. The findings also highlight the importance of agricultural water-conservation subsidies and demand-management policies, particularly reducing cultivation of water-intensive crops such as rice and promoting efficient irrigation technologies to improve long-term water and energy sustainability.

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Omid Bozorg-Haddad; Conceptualization, Supervision, Project administration.
Mohammad-Hosein Omid; Validation; Visualization; Writing—review and editing.
Alireza Gohari; Validation, Writing—Review and Editing.
Hugo A. Loáiciga; Validation, Writing—Review and Editing.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code Availability The codes that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval All authors abide by all ethical standards.

Consent to Participate All authors consent to participate.

Consent for Publish All authors consent to publish.

Competing interests There is no conflict of interest.

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