# Adaptation of Water Resources System to Water Scarcity and Climate Change in the Suburb Area of Megacities

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## Abstract

The projection of climate change impacts can be very crucial for water resources planning and management. Hashtgerd plain is an immigrant destination due to socio-economic development and its proximity to the Tehran metropolis. The population growth has led to more water demand, resulting in excessive utilization of groundwater resources and water shortages in the agricultural sector. The water shortage and climate change in Hashtgerd plain could lead to more severe water crisis in the future. Therefore, this study aimed to provide adaptation strategies for minimizing the negative effects of climate change by taking into account the interaction between different sub-systems in Hashtgerd plain during 2020–2049 period. In order to assess the climate change impacts, the output of 19 AOGCMs models was used under RCP2.6, RCP4.5 and RCP8.5 emission scenarios. A comprehensive model was developed based on the system dynamics theory to investigate the interactions of water resources, agriculture, and socio-economic sub-systems and were used to investigate the impacts of climate change and evaluate various adaptation strategies on different sub-systems of the region. The simulation results showed the negative effects of climate change will intensify the water shortage in Hashtgerd Plain. The agricultural sector will be more vulnerable to climate change than the domestic and industrial sectors. The results of various policies showed that improving water use efficiency coupled with reducing the cultivation of high-consumption crops and changing the cropping pattern towards lower water requirement plants can effectively minimize the adverse impacts of climate change on water shortages in agriculture.

**Keywords** Adaptation · Climate change · System dynamics · Water shortage

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# 1 Introduction

Increasing greenhouse gases emissions and consequent global warming lead to a disturbance in hydrological cycle balance, causing enormous negative impacts on various socio-ecological systems, such as water resources, environment, agriculture, industry, and health (IPCC 2014). As a major environmental issue, climate change can negatively affect the future of economics, livelihoods and water and food security around the world (Herath and Hasanov 2017). Although the alteration of hydrologic and climate variables are expected under climate change, the severity and type of such changes vary around the earth (Silberstein et al.2012). To ensure the sustainability of hydro-ecological systems on the earth, studying the climate change effects on various natural and human systems and providing effective adaptation solutions are so crucial.

As the major water consumer, agriculture can be known as one of the most vulnerable water sectors to climate change in Iran. Therefore, studying the plausible climate change impacts on this sector is crucial to ensure food and water security in the future. Given that agriculture is completely interacted by other sectors, system thinking approaches should be applied in agricultural water management studies.

A systemic approach is known as a comprehensive way of addressing the complexity of water resources systems by taking into account the various interactions and complex feedbacks within the system (Simonovic and Rajasekaram 2004). System dynamics approach by capturing the interaction between hydrological processes, socio-economic and agricultural aspects is able to implement integrated water resources systems planning and management. System dynamics method has been widely used to investigate the various aspects of chronic problems in hydro-ecological systems (i.e., Simonovic and Rajasekaram, 2004; Langsdale et al. 2009; Gohari et al. 2013; Dawadi and Ahmad 2013; Chen and Wei 2014; Dace et al. 2015; Herath and Hasanov 2017). The system dynamics modeling has been also applied to investigate the climate change effect and minimize its adverse impacts on water resource systems (i.e., Gohari et al. 2017; Herath and Hasanov 2017).

Climate change impacts on agriculture, surface water, and groundwater resources have been widely studied in previous climate impacts assessment studies. But, the interaction between surface water and groundwater resources as well as their impacts on the agricultural system should be considered in a holistic view. On the other hand, providing effective adaptation strategies for the agricultural sector should be based on a holistic view of their impacts on the various aspects of economic and social sub-systems. Due to the importance of capturing the interactions of the agricultural sector with other sectors, the System dynamics approach has been used in this study.

Hashtgerd Plain is an immigrant destination due to socio-economic development and locating within the vicinity of Tehran and Karaj Metropolises. The population of this plain has experienced a rapid growth rate, leading to over withdrawal of groundwater and severe water shortages in the agricultural sector. The plain has suffered a sharp drop in groundwater tables in recent years, leading to drying the springs, aqueducts, and wells. Moreover, climate change is expected to exacerbate the current water shortage in the future. The ordinal priorities of water allocation in the Hashtgerd Plain are considered as domestic, industry, and finally, agriculture. Therefore, agriculture is known as more vulnerable sector to water scarcity.

This paper aims to adapt Hashtgerd Plain in responses to climate change. In particular, the paper estimates the climate change impacts on water resources and consumption within a probabilistic multi-model framework. In this framework the uncertainties of GCMs and emission scenarios are handled by a downscaling method that combines change factors and

a weather generator. An integrated system dynamics has been developed to take into account the interplay of biophysical processes, water resources management actions and associated socioeconomic dynamics within the Hashtgerd Plain. The developed system dynamics model was used to investigate the vulnerability of various water sector to climate change as well as the effectiveness of different adaptation strategies for minimizing the adverse effects of climate change on the Hashtgerd Plain water resources.

## 2 Materials and Methods

### 2.1 Study Area

The Hashtgerd Plain with an area of 1271 km$^2$ is one of the main sub-basins of Salt Lake watershed in Central Iran (Fig. 1). The Hashtgerd Plain surrounded by a number of important megacities including Tehran, Karaj, and Qazvin, between the 50$^o$ 22′ to 51$^o$ 5′ eastern longitudes and 35$^o$ 47′ to 36$^o$ 6′ northern latitudes. The annual precipitation and temperature of the study area are about 341 mm and 13 °C, respectively.

  To investigate the effects of climate change, there has been limitations in number of synoptic station and the length of available time series in the study area. Due to having the same climate as Hashtgerd plain, the Qazvin Synoptic Station was used for climate change
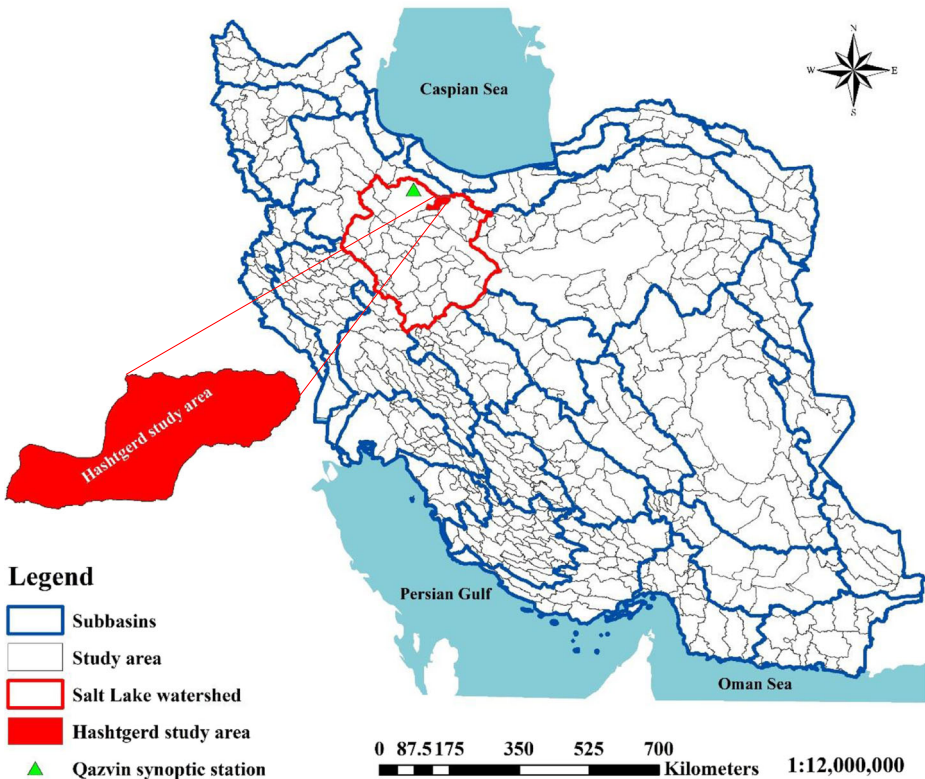


**Fig. 1** Location of the Hashtgerd Plain

impacts assessment. The Hashtgerd plain has a diverse cropping pattern including various types of aquatic products. The dominant agricultural products of the region are wheat, barley, maize, alfalfa and gardens products (apple, grapes, walnuts, and peaches). The average irrigation efficiency in Hashtgerd Plain is 45%.

The Hashtgerd plain water demand including domestic, industry, and agriculture provided by surface water coupled with groundwater resources. This area experiences increase in water consumption especially domestic and industrial sectors due to socioeconomic development as well as population growth. As the ordinal priorities of water allocation in the Hashtgerd Plain are considered as domestic, industry, and agriculture, the study area has experienced a reduction in surface water allocation to the agriculture sector in the recent years. The decrease in surface water supply for agricultural activities led to over withdrawal of groundwater resources leading to a significant drop in groundwater level.

## 2.2 Climate Change Scenario Projections

### 2.2.1 General Circulation Models

In this research, the outputs of 19 AOGCMs models under three RCP2.6, RCP4.5 and RCP8.5 scenarios for the Fifth Assessment Report of the IPCC (AR5) were used. The detailed description of the selected models is provided in Table 1. The monthly temperature and precipitation data for the baseline period (1976–2005) and future period (2020–2049) were extracted from the data distribution center of IPCC. The historical meteorological data of Qazvin's synoptic Station used in this study (Fig. 1).

**Table 1** Description of the selected AOGCM models under AR5

| AOGCM Models | Centre | RCP 2.6 | RCP 4.5 | RCP 8.5 |
|---|---|---|---|---|
| BCC-CSM1–1 | Beijing Climate Center China | * | * | * |
| BCC-CSM1–1-m | | * | * | * |
| BUN-ESM | Beijing Normal University- China | * | * | * |
| CanESM2 | Canadian Center for Climate Modelling and Analysis- Canada | * | * | * |
| CMCC-CMS | Centro Euro-Mediterraneo sui Cambiamenti Climatici- Italy | | * | * |
| CNRM-CM5 | Centre National de Recherches Météorologiques,Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique- France | * | * | * |
| MIROC-ESM | Atmosphere and Ocean Research Institute (The University of | * | * | * |
| MIROC-ESM-CHEM | Tokyo), National Institute for Environmental Studies, and | * | * | * |
| MIROC5 | Japan Agency for Marine-Earth Science and Technology Japan | * | * | * |
| MPI-ESM-LR | Max Planck Institute for Meteorology Germany | * | * | * |
| MPI-ESM-MR | | * | * | * |
| GISS-E2-H | NASA/GISS(Goddard Institute for Space Studies)- USA | * | * | * |
| GISS-E2-R | | * | * | * |
| CCSM4 | National Center for Atmospheric Research- USA | * | * | * |
| CESM1-CAM5 | | * | * | * |
| CESM1-WACCM | | * | * | * |
| NorESM1-M | Bjerknes Centre for Climate Research, Norwegian Meteorological Institute- Norway | * | * | * |
| GFDL-CM3 | Geophysical Fluid Dynamics Laboratory USA | * | * | * |
| GFDL-ESM2G | | * | * | * |

## 2.2.2 Climate Change Scenario Generation

To generate climate change scenarios, the differences of the GCM's outputs for temperature (Eq. 1) and relative precipitation (Eq. 2) between future (2020–2049) period and baseline (1976–2005) period were calculated for each month.

$$\Delta T_{ij} = \left( \overline{T}_{GCM,fut,ij} - \overline{T}_{GCM,base,i} \right) \tag{1}$$

$$\Delta P_{ij} = \left( \overline{P}_{GCM,fut,ij} / \overline{P}_{GCM,base,i} \right) \tag{2}$$

where, $\Delta T_{ij}$ and $\Delta P_{ij}$ represent the climate change scenario for temperature and precipitation for month i and model j, respectively. $T_{GCM,fut,i}$ and $T_{GCM,base,i}$ are the 30-year average of the GCM's outputs for temperature in the month i for future and baseline periods, respectively. $P_{GCM,fut,i}$ and $P_{GCM,base,i}$ are the 30-year average of the GCM's outputs for precipitation in the month i for future and baseline periods, respectively. In this study, the climate change scenarios for the future period were created separately for each GCM models under three RCP2.6, RCP4.5 and RCP8.5 scenarios.

AOGCMs models are recognized as one of the most important sources of uncertainty in climate change studies. To handle the uncertainty in climate change projection, various methods like Mean with the same weights, Weighted Mean have been used to implement the multi-model projection in such studies. In the study, the Mean Observed Temperature–Precipitation (MOTP) method (Massah Bavani and Morid 2005) was used to weight each of the GCM models (Eq. 3). Climate change scenarios of temperature and rainfall of each of the 19 AOGCM models were individually weighted based on the ability of that model in simulating the observed climate variables, i.e., the difference between the simulated average temperature and average precipitation in each month in the baseline period and the corresponding observed values:

$$R_i = \frac{\left( {1}/{\Delta T_i} \right)}{\sum_{i=1}^{N} \left( {1}/{\Delta T_i} \right)} \tag{3}$$

where, $R_i$ is the weight of each model in the month i and $\Delta T_i$ is the long-term average deviation of the temperature or precipitation simulated by each GCM of the base period and the corresponding observed value.

The AOGCM models outputs are at large scale and cannot properly capture the local climatic conditions at synoptic stations. Therefore, downscaling methods are commonly used to address this concern in climate change studies. In this study, the LARS-WG model as a stochastic weather generator was used for statistical downscaling. The LARS-WG model is one of the most widely used random data generation models that can be used to simulate climatic data at station (Semenov et al. 1998). LARS-WG has been tested in various climate conditions (Li et al. 2019a; Li et al. 2019b; Bayatvarkeshi et al. 2019; Ahmadzadeh et al. 2018; Kwok et al. 2013) and shown good results in various climate statistics generation including severe weather events (Semenov 2007; Msowoya et al. 2016). Also, LARS-WG were identified a tool to generate scenarios with high temporal and spatial resolutions based on the AOGCMs model output (Wilks 1992, Barrow and Semenov 1995, Wilks and Wilby 1999, Hansen 2002).

## 2.3 System Dynamics Approach

System Dynamics is a simulation technique to capture the structure of complex systems and monitor their dynamical behavior (Forrester 1961). System dynamics, which is based on systems thinking theory, help us to understand how dynamics can be created. Therefore, system dynamics modeling provides insight into the best policies to improve system performance. (Vlachos et al., 2007). Unlike mathematical models, the system dynamics methodology can be used to express good links between socio-economic, environmental, water resources, flood control and natural disaster risk reduction (Chen and Wei 2014).

Water resource systems include the interaction between different sub-systems, and the uncertainty in the linear and nonlinear relationships between these sub-systems complicates the assessment and evaluation of water resource issues (Chen and Wei, 2014). It is hence necessary to apply the notion of a systemic approach that evaluate the current state of system and evaluate the influence effective management strategies on different sub-systems in future period.

The stages of system dynamics modeling are as (Stave, 2003): (1) Definition the problem, which involves the determination of the problem; (2) Determination of the system boundary as well as the dynamic hypotheses; (3) Developing the Casual Loop Diagram (CLD) and the stock and flow diagram (SFD) of the problem; and (4) Validation of the Model.

### 2.3.1 Integrated Modeling of Hashtgerd Plain Water Resources System

The developed conceptual model in this study was comprised of hydrologic, socio-economic and agricultural sub-systems. Each sub-system includes various parts of the Hashtgerd Plain water resources system. The population growth rate of Hashtgerd Plain located in Alborz Province is more than the average population growth rate in Iran due to the industrial development in this region and its proximity to megacities of Tehran and Karaj. A Casual Loop Diagram (CLD) as a comprehensive conceptual model of the basin's water resources system was developed based on the understanding of the interactions between the hydrologic, socio-economic, and agricultural sub-system in the Hashtgerd plain. Afterwards, the stock and flow diagrams (SFD) of sub-systems were developed based on the developed CLD for each sub-system.

Vensim PLE software was here used to develop the system dynamics model for the study area. Vensim PLE is fully functional system dynamics software for developing system dynamics model for educational and research uses. Vensim has been created by Ventana Systems in 1985 at Harvard University. As a simulation language, Vensim simulates the behavior of the system by solving the differential equations in the system during the simulation period.

### 2.3.2 Hydrological Sub-System

The hydrological sub-system includes the relationships between hydrologic cycle, water supply, and ecosystem. As shown in Fig. 2, climatic and hydrologic variables such as temperature, precipitation, evaporation, runoff, natural flows, and groundwater feed through the return water are water balance controllers in the basin. The allocation priority was given respectively to domestic, industrial and agricultural sectors. The water demand for the entire area is first taken from surface water resources and, if there is a shortage of surface water resources, it is taken from groundwater resources. The return water flow is known as the part of the untapped water from various sectors of agriculture, industry, and services, which feed into surface water and groundwater resources. The leakage from groundwater to surface water was not considered in the study
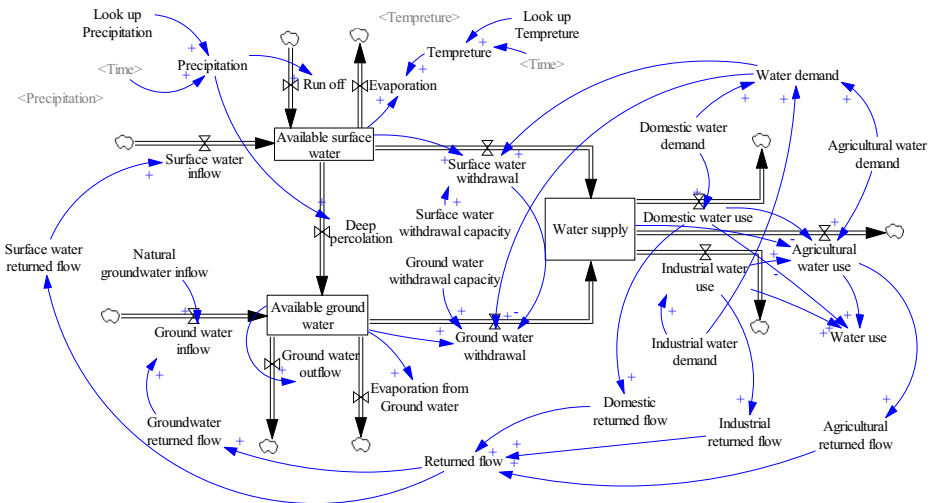
**Fig. 2** Stock and flow diagram of hydrological sub-system

area due to the low level of groundwater in the study area and the lack of groundwater suspended aquifers. The annual averages of temperature and rainfall variables for the baseline period and future periods are the most important inputs of this sub-system.

### 2.3.3 Socio-Economic Sub-System

Population, regional utility and added value of agriculture, industry and domestic sectors are the main variables of the socio-economic sub-system. Water demand in the industrial and domestic sectors is affected by the socio-economic status of the basin, which depends on the well-being of residents and the migration of people from neighboring areas to the region. In this study, the regional utility is influenced by factors such as the national economic growth rate, the added value of water consumption and the per capita water use. The higher regional utility has increased the immigration and population absorption in the region, leading to increasing per capita water use in industrial and domestic sectors. Increase in per capita water use will also lead to the higher growth rate of per capita water use in different sectors, and consequently the more total water requirement in the basin. Since the economic productivity of water use in various water sectors is different, value-added is hence defined as the sum of economic productivity of water consumption in agriculture, industry, and domestic sectors in the model. The national economic growth rate is defined as an exogenous factor affected the regional utility. The basin's economic growth is also defined by assessing the added value of water consumption in the same year. Per capita, water use in the basin is also directly related to total water use. Figure 3 shows the socio-economic sub-system developed in this study.

### 2.3.4 Agricultural Sub-System

The Hashtgerd study area has a diverse cropping pattern including various types of aquatic products. The dominant agricultural products of the region are wheat, barley, maize, alfalfa and gardens products (apple, grapes, walnuts, and peaches), which are considered here in the agricultural sub-system. The irrigation water requirement of the selected crops under climate
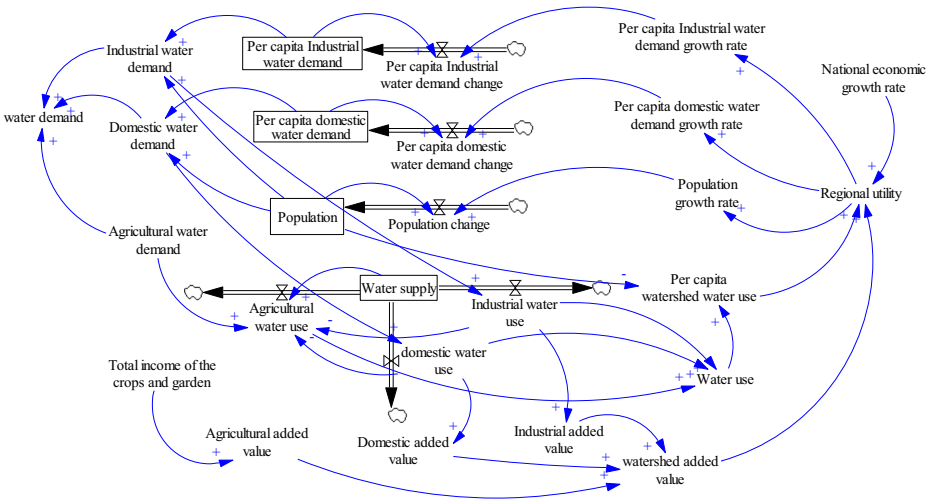
**Fig. 3** Stock and flow diagram of socio-economic sub-system

change was considered as input to the developed model. The gross water requirement of each plant was calculated by the irrigation efficiency and the total net water requirement calculated for all crops. Moreover, the maximum expected value for each crop production is also given as input to the model. The actual yield of each crop production is calculated using the maximum yield of the crop, the amount of water allocated and the amount of gross irrigation requirement for that crop. The price function for each crop was defined individually to calculate the income for each crop and the total income from all products in the Hashtgerd Plain. Total income agricultural affects total add value and region's desirability. The stock and flow diagram of the agricultural sub-system for wheat and maize are shown in Fig. 4.

## 2.4 Water Resources Assessment Indicators

Four metrics have been here used to evaluate the effectiveness of different policies in the future. These indices include reliability index, vulnerability index, maximum deficit index, and system sustainability index. The reliability index is defined by Eq. 4 as the probability of supplying water demand during the simulating period using available water resources (Hashimato et al. 1982):

$$Rel = \frac{Number\ of\ years\ with\ D = 0}{N} \tag{4}$$

where, D indicates the water deficit and N is the length of the simulation period. Water deficit (D) is calculated from difference between the water demand and the water used.

The vulnerability index in the year i is defined as the expected value of deficit or average deficit compared to the average annual demand during the deficit period (Eq. 5). This index indicates the probability that water resources are not capable of supplying water (Sandoval-Solis et al. 2011):

$$Vul = \frac{\sum_{i=1}^{n} D_i / Number\ of\ years\ with\ D > 0}{Water\ demand} \tag{5}$$
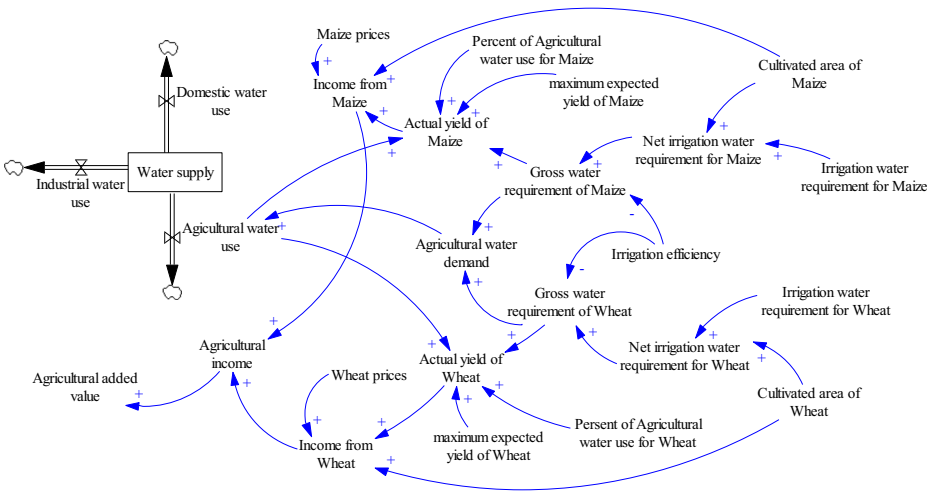
**Fig. 4** Stock and flow diagram of agricultural sub-system

The maximum deficit index indicates the maximum water deficit in each water use sector in the year i. This index is calculated as the division of the maximum annual deficit of each sector into the annual water demand of the same sector (Eq. 6).

$$\text{Max Deficit} = \frac{\text{Max}(D_{annual})}{\text{Water demand}} \tag{6}$$

The sustainability index of water resources is calculated as a function of reliability, vulnerability, and maximum deficit indicators according to Eq. 7 (Loucks 1997).

$$\text{SI} = \left[\text{Rel} \times (1-\text{Vul}) \times (1-\text{Max.Def})\right]^{1/3} \tag{7}$$

# 3 Results and Discussion

## 3.1 Precipitation and Temperature Changes

Table 2 shows the monthly climate change scenarios for temperature and precipitation under RCP2.6, RCP4.5 and RCP8.5 emission scenarios in the future 2020–2049 period relative to the baseline 1976–2005 period. The positive values of temperature change show that the temperature is expected to increase in all months of year in the study period. The maximum increase in temperature will be in July to September under all three scenarios. The lowest increase in temperature was projected for April under all three scenarios. The results indicate that the maximum increase in precipitation was projected in September under RCP8.5 (Table 2). A significant increase in the precipitation change will be expected in September and August relative to the baseline period. Significant increase in precipitation changes in the summer will be due to the small values of observed precipitation for these months.

The 30-year seasonal average of temperature change are presented in Fig. 5. At the seasonal scale, the temperature will increase under all climate change scenarios in all seasons of the

**Table 2** Climate change scenarios for temperature and precipitation change

| Emission scenarios | RCP2.6 | | RCP4.5 | | RCP8.5 | |
|---|---|---|---|---|---|---|
| Month | temperature | precipitation | temperature | precipitation | temperature | precipitation |
| | **(C)** | **(%)** | **(C)** | **(%)** | **(C)** | **(%)** |
| January | +1.25 | 0.00 | +1.45 | −0.01 | +1.56 | −0.01 |
| February | +1.23 | 0.02 | +1.66 | −0.02 | +1.61 | −0.08 |
| March | +1.22 | 0.00 | +1.39 | 0.04 | +1.69 | −0.04 |
| April | +1.09 | 0.06 | +1.46 | 0.01 | +1.45 | 0.02 |
| May | +1.38 | −0.06 | +1.69 | 0.03 | +1.73 | −0.04 |
| June | +1.54 | 0.16 | +1.94 | 0.05 | +1.90 | −0.02 |
| July | +1.71 | 0.17 | +1.93 | 0.35 | +2.22 | 0.36 |
| August | +1.74 | 2.12 | +2.01 | 0.43 | +2.29 | 1.27 |
| September | +1.92 | −0.08 | +2.06 | 1.52 | +2.31 | 3.44 |
| October | +1.53 | 0.21 | +1.75 | 0.16 | +1.87 | 0.17 |
| November | +1.23 | 0.11 | +1.45 | 0.11 | +1.63 | 0.16 |
| December | +1.29 | 0.06 | +1.49 | 0.03 | +1.50 | 0.07 |

year. In general, temperature is expected to increase 1.81, 1.69 and 1.43º C under the three RCPs scenarios.

The 30-year seasonal changes in the future precipitation relative to the baseline period are presented in Fig. 6. The precipitation will not be changed significantly in the future. Therefore, the Hashtgerd Plain will face warmer and more difficult conditions due to climate change in the future.

## 3.2 System Dynamics Model Validation

In this study, the observed data for (2001–2006) period was used for validation. The behavioral repeat test was performed by statistical indicators such as the coefficient of determination ($R^2$) and relative root mean square error (RMSEr).
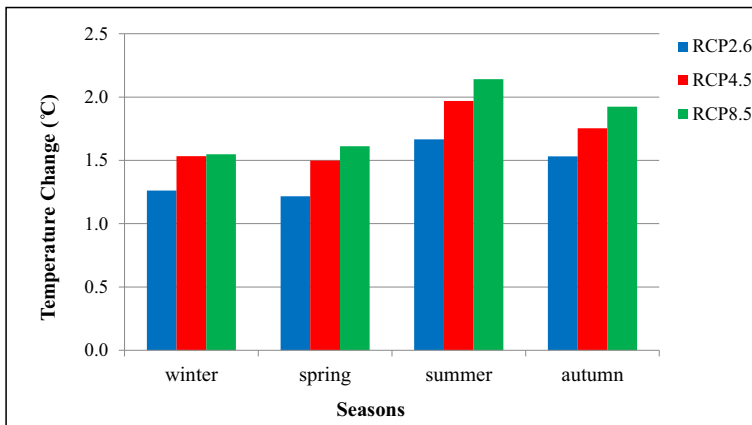


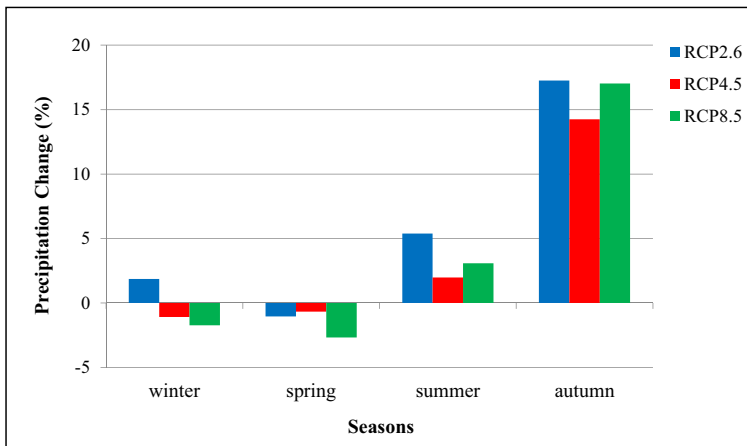**Fig. 5** The 30-year seasonal average of temperature change

**Fig. 6** The 30-year seasonal change in precipitation

The results of the behavioral repeat test for variables of population, domestic water demand, industrial water demand, and added value are presented in Table 3. According to Table 3, the system dynamics approach has good accuracy in simulating the different variables of the system. Based on the values obtained from the coefficient of determination, it can be concluded that the simulated trend by the model for different variables is highly correlated with the observed trend. Therefore, it can be concluded that the model is well calibrated to reconstruct the behavior of various parameters within the system.

Figure 7 shows the relationship between observed and simulated data for population, domestic water demand, industrial water demand and added value parameters. The calculated coefficient of determination ($R^2$) shows that the model simulated these variables with a high degree of reliability.

Also, the statistical tests, including Kolmogorov-Smirnov, Lilliefors and Shapiro-Wilk tests was performed on these variables (Table 4).

The results show, There is a significant correlation between the simulated and observed data and The model has a good ability to simulate various parameters.

The main purpose of this test was the evaluation of the model performance under extreme conditions. The results of the tests are presented in Figs. 8, 9, and 10. According to the results, the model simulate the expected trend in extreme conditions and this indicates the model's ability to simulate the sub-systems; behaviors properly under extreme conditions.

### 3.3 Climate Change Impacts on Socio-Economic Sub-System

The developed model was used to simulate the Hashtgerd Plain system under RCP2.6, RCP4.5 and RCP8.5 scenarios as well as Business as Usual (B.a.U.) hydrologic scenario as a reference

**Table 3** Statistical tests results of the selected variables of the system dynamics model

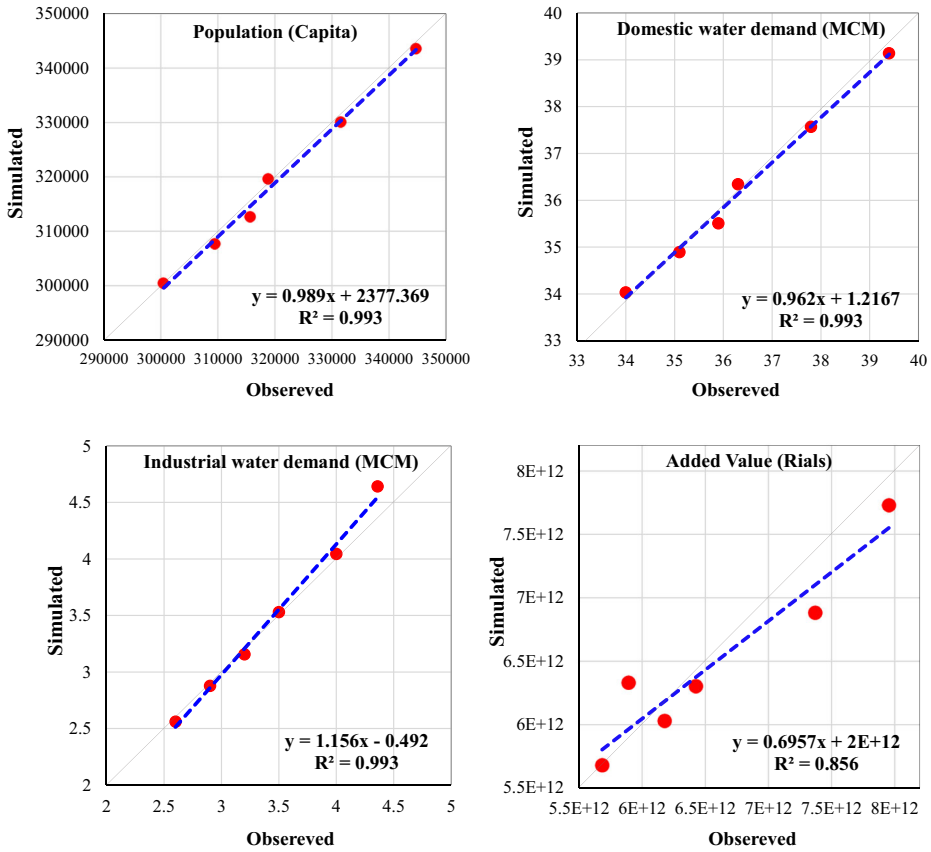| Statistical Characteristic | Population | Domestic water demand | Industrial water demand | added Value |
|---|---|---|---|---|
| $R^2$ | 0.993 | 0.993 | 0.955 | 0.856 |
| RMSEr | 0.562 | 0.686 | 5.977 | 5.812 |

**Fig. 7** The comparison of observed data and simulation results

**Table 4** Statistical tests results of Kolmogorov-Smirnov and Shapiro-Wilk for the selected variables

| Variable | | population | domestic water demand | industrial water demand | added value |
|---|---|---|---|---|---|
| Number | | 6 | 6 | 6 | 6 |
| Normal Parameters | Mean | 319,019.67 | 36.25 | 3.47 | 6.44E+12 |
| | STd.Deviation | 15,748.45 | 1.86 | 0.77 | 6.71E+11 |
| Most Extreme Differences | Absolute | 0.157 | 0.154 | 0.157 | 0.232 |
| | Positive | 0.157 | 0.154 | 0.157 | 0.232 |
| | Negative | −0.119 | −0.117 | −0.120 | −0.128 |
| Kolmogorov-Smirnov [c] | Statistic | 0.157 | 0.154 | 0.157 | 0.232 |
| | Asymp. Sig. (2-tailed) | 0.200[c,d] | 0.200[c,d] | 0.200[c,d] | 0.200[c,d] |
| Shapiro-Wilk | Statistic | 0.968 | 0.970 | 0.967 | 0.920 |
| | Sig | 0.876 | 0.892 | 0.874 | 0.507 |

*a* Test distribution is Normal

*b* Calculated from data

*c* Lilliefors Significance Correction

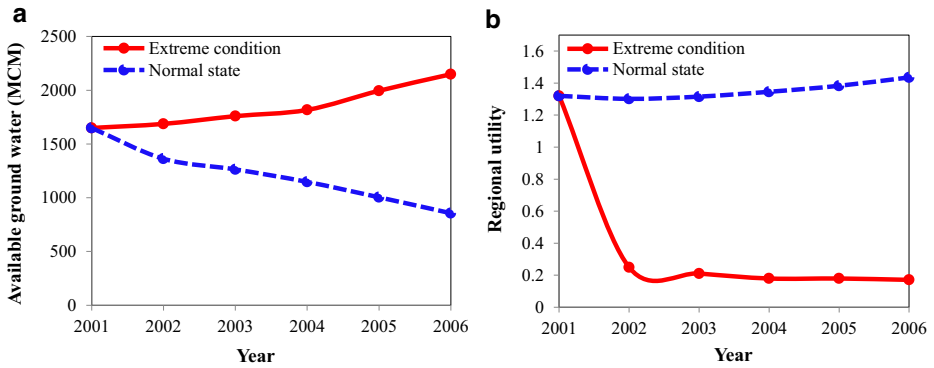*d* This is a lower bound of the true significance

**Fig. 8** Extreme Conditions Test results in the condition of economic recession (A) groundwater resources (B) regional utility

for comparison. The behavior of the key variables for the socio-economic sub-system including populations, domestic water demand, industrial water demand, and the regional utility are shown in Fig. 11.

The results show that temperature rise and precipitation reduction under climate change will lead to a decrease in regional utility of the basin. The low level of the regional' utility decreases the population growth, leading to lower domestic and industrial water demand values. The RCP2.6, RCP8.5, and RCP4.5 are the most optimistic, the most pessimistic and medium scenarios, respectively. The maximum and minimum levels of the regional' utility, population growth rate and the water demand are projected under the RCP8.5 and RCP2.6 scenarios respectively. Moreover, the results show that the RCP2.6 scenario simulates relatively wet conditions in the basin and the highest levels of the residents' utility will be expected under this scenario. The lowest plausible levels of regional' utility are expected under RCP8.5 as warm and dry conditions in the basin.

### 3.4 Climate Change Impacts on Agricultural Sub-System

The behavior of the main variables of the agricultural sub-system during the simulation period are shown in Fig. 12. The results show that agricultural water demand will increase due to
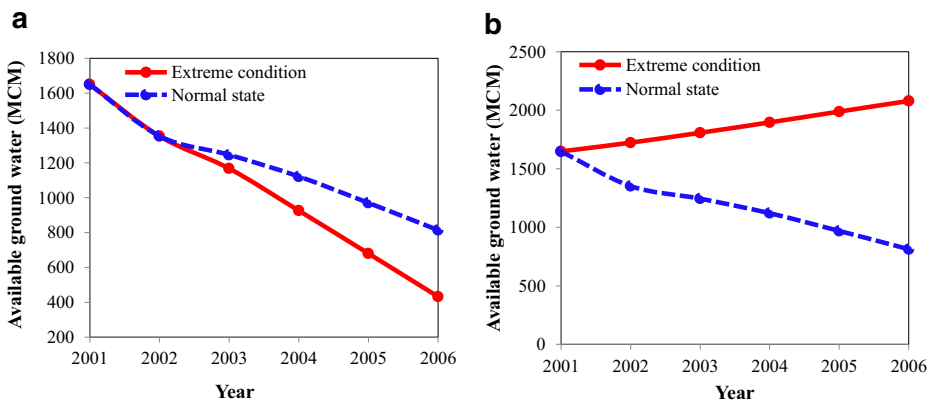


**Fig. 9** Extreme Conditions Test results in the condition of Non-withdrawals from (A) surface water sources (B) groundwater resources
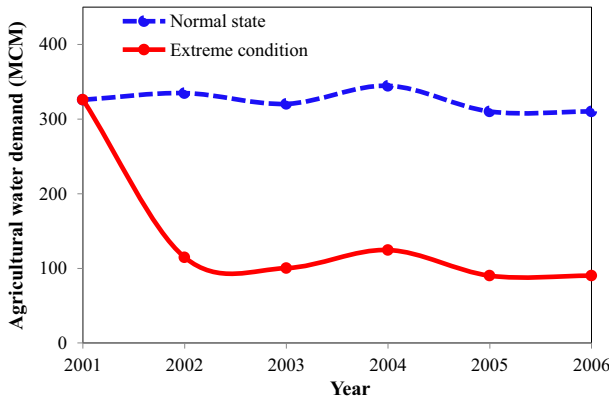
**Fig. 10** Extreme Conditions Test results in the economic recession condition

temperature rise under climate change scenarios. The maximum agricultural water demand is expected under the RCP8.5. Temperature rise will negatively affect the available water resources, leading to lower water allocation to the agricultural sector. Therefore, climate change will intensify the current water shortage in the basin (Fig. 12b). Therefore, the agricultural sector will experience significantly more severe water shortage under climate change.

Figures 13 and 14 illustrate the actual crop production and added value for the agricultural sector under climate change and B.a.U. scenarios. Due to the negative impacts of climate
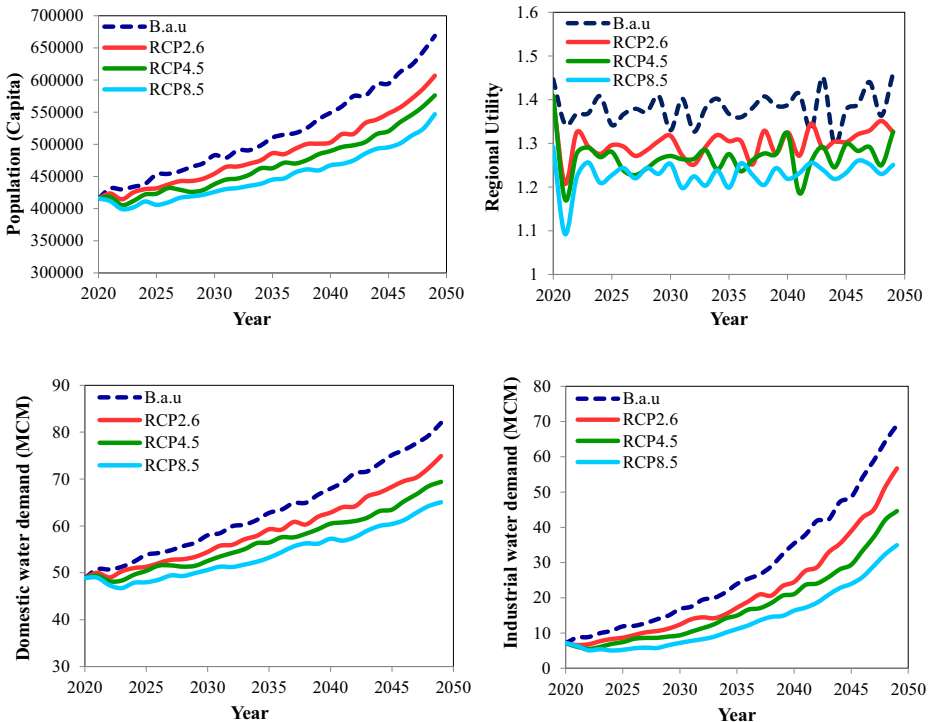


**Fig. 11** The behavior of the socio-economic sub-system under climate change scenarios
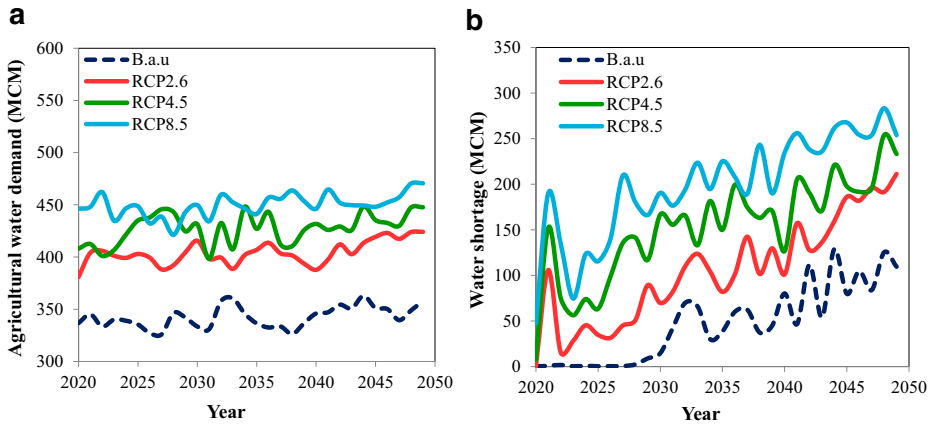
**a**



**b**

Fig. 12 The behavior of the main variables of agricultural sub-system under climate change

change on available water resources, the allocated water to the agricultural sector decrease in the future. On the other hand, the agriculture water demand in agricultural will also increase due to temperature rise. Therefore, the actual yield of products is reduced under climate change due to increase in water demand and reduction in allocated water to agriculture (Fig. 13). Agricultural added value will also decrease under climate change in comparison with the business as usual scenario (Fig. 14).
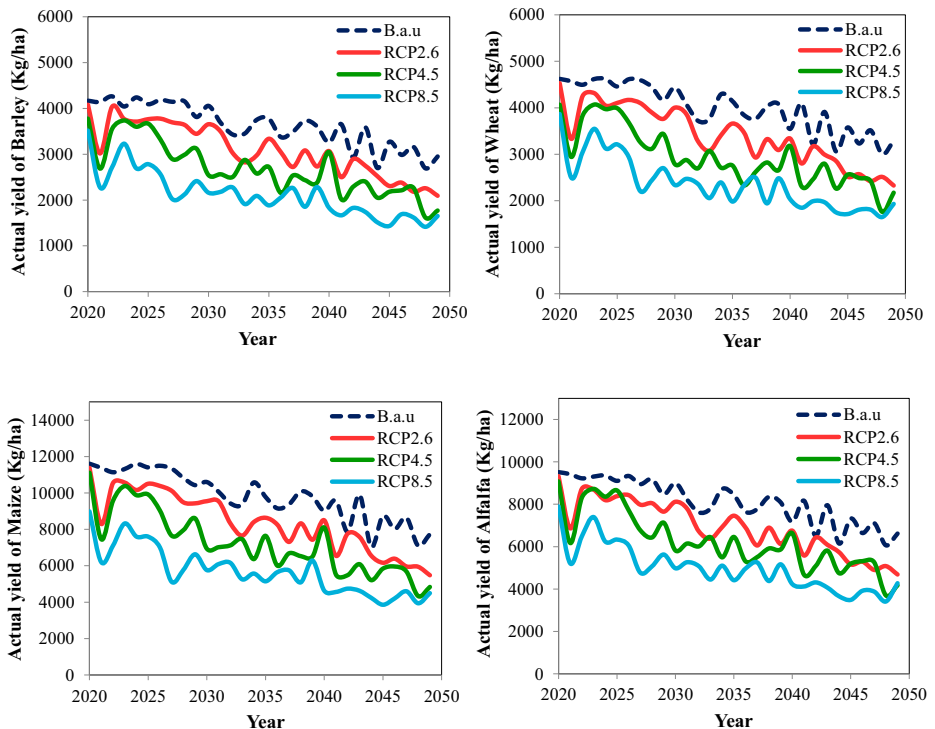


Fig. 13 The actual yield of the studied crops in the area under climate change in the future periods
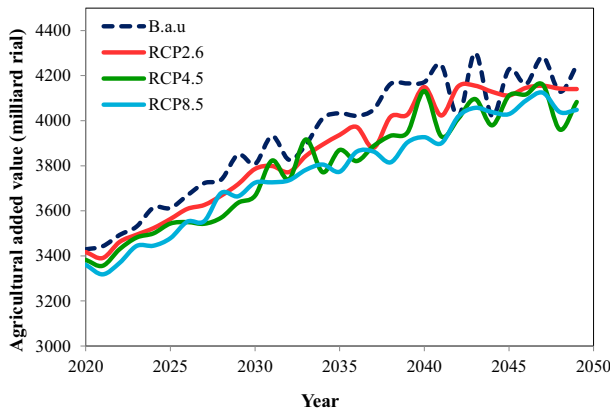
**Fig. 14** The behavior of agricultural added value under climate change in the future periods

## 3.5 Climate Change Impacts on Water Resources Indicators

The impacts of climate change on water resources in the study area were evaluated under various scenarios by using water resources indicators (Table 5). Agricultural water demand will increase under climate change and cannot be fully satisfied (the value of the Rel index is zero and Vul index is greater than zero). According to the priority of water allocation in the study area, the water demand for domestic and industrial sectors are fully provided (the values of Rel and SI indices are equal to 1 and the Vul index is equal to zero), while the agricultural sector faces water scarcity and is more vulnerable to climate change (Vul index is greater than zero and Max. Deficit is relatively high).

The simulation results showed that, with no water resources management strategy, the study area will face the significantly growing water shortage under climate change. Therefore, it is necessary to implement appropriate management policies to ease the expected water crisis in the future and achieve sustainable development.

## 3.6 Adaptation Strategies to Climate Change

In order to adapt the water resources system of Hashtgerd Plain with climate change, effective policies should be adopted to improve the performance of the system in the long run. Regarding the water scarcity problems to moderating problems, water demand management is very important. It is also necessary to manage and control water demand in order to achieve sustainable development. The results show that urban and industrial water consumption is

**Table 5** Results of climate change impact on water resources indicators

| Scenario | Agricultural Sector | | | | Domestic and Industrial Sector | | | |
|---|---|---|---|---|---|---|---|---|
| | Max. Deficit | Vul Index | Rel Index | SI Index | Max. Deficit | Vul Index | Rel Index | SI Index |
| B.a.u | 0.36 | 0.20 | 0.33 | 0.56 | 0.00 | 0.00 | 1.00 | 1.00 |
| RCP2.6 | 0.50 | 0.27 | 0.03 | 0.23 | 0.00 | 0.00 | 1.00 | 1.00 |
| RCP4.5 | 0.57 | 0.36 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 |
| RCP8.5 | 0.60 | 0.44 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 |

**Table 6** five water demand management strategies as adaptation policies

| Adaptation policies | Acronym |
| --- | --- |
| Agricultural water demand management by improving irrigation efficiency | AW1 |
| Agricultural water demand management by reducing the cultivation area of high-consumption plants | AW2 |
| Agricultural water demand management by changing the cultivation pattern of high-consumption plants towards low-consumption plants | AW3 |
| Agricultural water demand management by improving irrigation efficiency and reduce the cultivation area of high-consumption plants | AW4 |
| Agricultural water demand management by improving irrigation efficiency and change the cultivation pattern of high-consumption plants towards low-consumption plants | AW5 |

effective on water resources, however, agricultural water consumption is the most important factor in consumption and water deficit in the basin. Demand management should be adopted to increase water use efficiency and reduce water loss during water use. In this study, five water demand management strategies as adaptation policies were evaluated to reduce the negative impacts of climate change, leading to sustainable of water resources management Presented in Table 6.
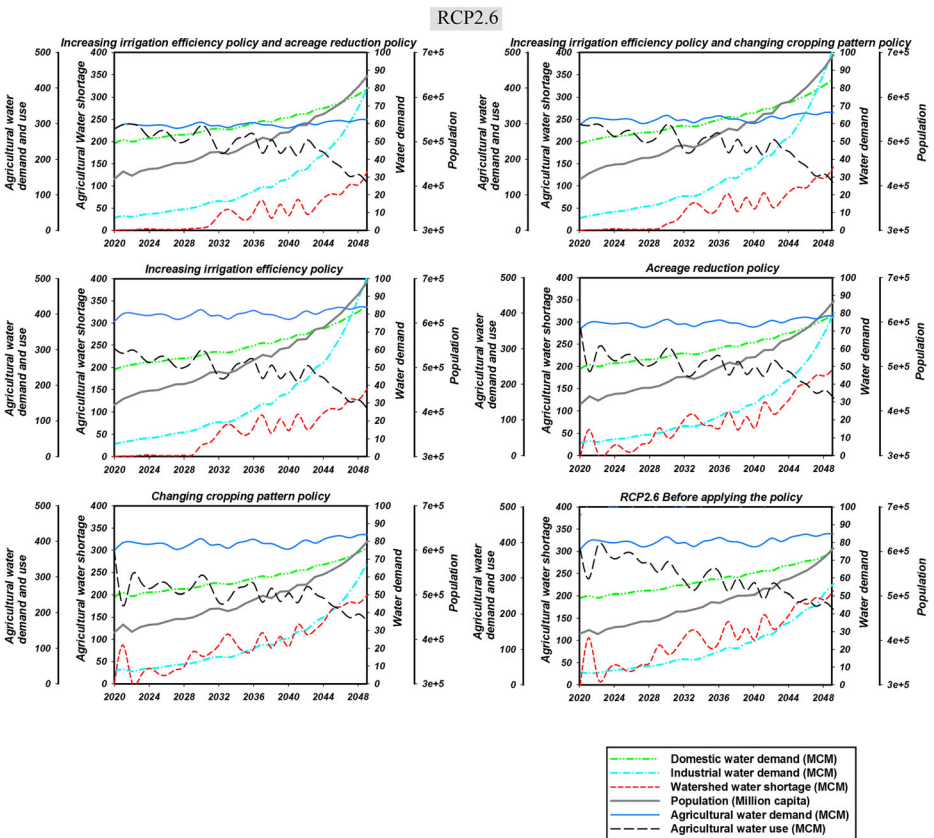


**Fig. 15** The behavior of main variables of the system dynamics under RCP2.6 scenario and different adaptation policies

The behaviors of the main variables of the plain's water resources systems under adaptation strategies are shown in Figs. 15, 16 and 17. The values of water resources indices under the application of adaptation policies are presented in Table 7. The results show that the Hashtgerd Plain will face more severe water stress under B.a.U. scenario. Water stress has a negative impact on the yield of agricultural products which will affect the value added and the regional utility. The regional utility is also effective on population growth rates and as a result of the water demand for domestic and industrial sectors. With decreasing regional utility, the population growth rate will decrease and water demand in domestic and industrial sectors will decrease compared to the baseline period.

Improving irrigation efficiency (AW1) can ease the water crisis in the future period. Under this strategies, it is assumed that the net demand and cultivated area of crops will continue according to the current condition, however, agricultural water use efficiency will improve from 45% to 60%. The results show that water shortage in the agricultural sector will significantly decrease especially in the short run.

Increasing irrigation efficiency under climate change scenarios has reduced the agricultural water demand, leading to lower water scarcity in this sector. Therefore, improving irrigation efficiency has reduced the negative impacts of climate change on groundwater resources. With higher regional's utility and increasing population, the water demand domestic and industrial sectors will increase. The values of the Vul and Max. Deficit indices in Table 7 show that
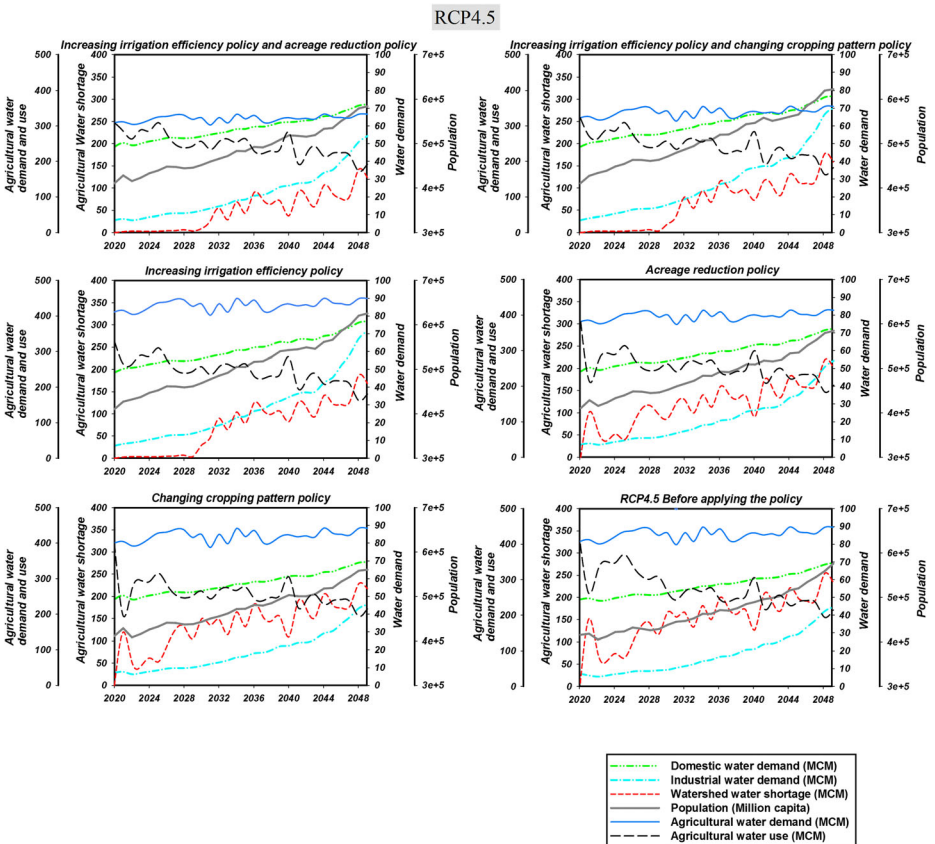


Fig. 16 The behavior of the main variables of the system dynamics under the RCP4.5 scenario and different adaptation policies
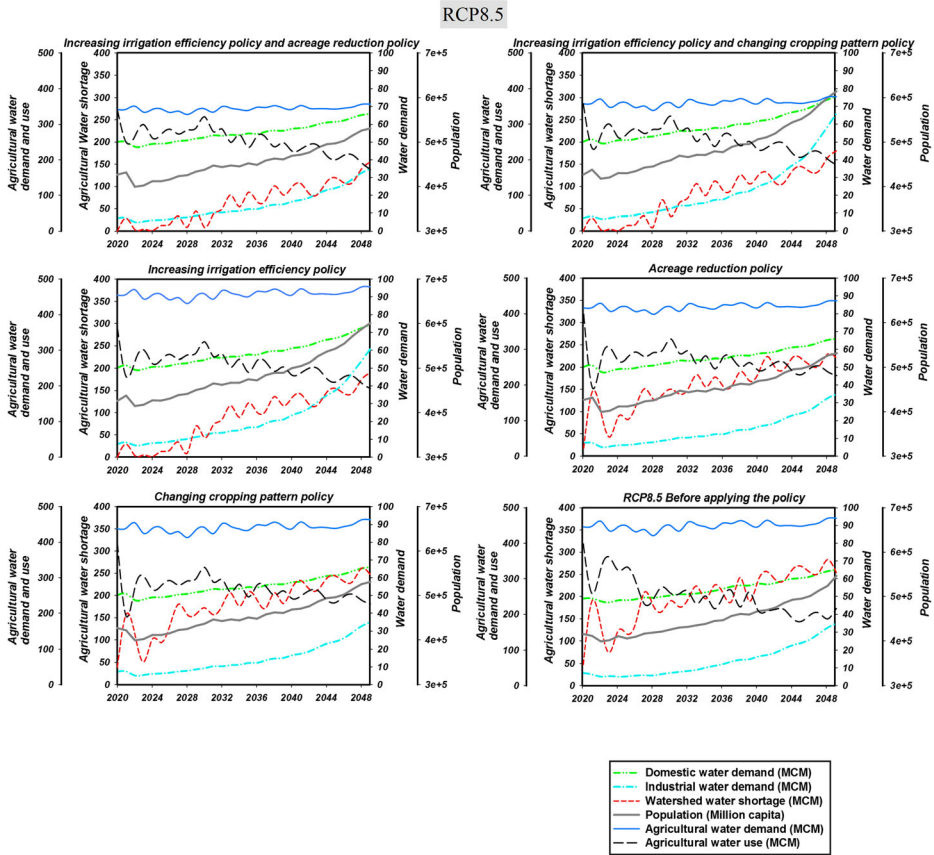
**Fig. 17** The behavior of main variables of the system dynamics under the RCP8.5 scenario and different adaptation policies

improving irrigation efficiency (AW1) in agriculture could reduce the vulnerability of the agricultural sector to climate change by reducing the negative impacts of water scarcity.

According to the high water consumption in the agricultural sector of Hashtgerd, it is very important to apply water consumption management policies. In this study, two cropping pattern strategies, including the reduction of the cultivation area of high-consumption plants (AW2) and changing the cultivation pattern from high-consumption toward low-consumption plants (AW3) were evaluated.

In the policy of reducing the cultivation area of high-consumption plants (AW2), the maize and wheat cultivation areas were reduced by 50% and 30%, respectively. In the policy of changing the cultivation pattern from high-consumption plants toward low-consumption plants (AW3), it is assumed that the cultivation area of maize is reduced by 50% and this area is allocated to barley which needs less irrigation. Figures 15, 16, and 17 show that the decrease in cultivated area (AW2) and the change in the cropping pattern of high-consumption plants (AW3) in the Hashtgerd Plain have led to a significant reduction in the agricultural water demand, leading to lower water deficit in the Hashtgerd plain.

By applying these policies, the reliability of water resources in agricultural sector will increase under climate change impacts (Table 7). Additionally, the vulnerability of the

Table 7  The values of the selected indices under different adaptation policies during 2020–2049

| Adaptation Policies | Scenario | Max. Deficit Index | Vul Index | Rel Index | SI Index |
|---|---|---|---|---|---|
| Future period under climate change without \applying adaptation policy | RCP2.6 | 0.50 | 0.27 | 0.03 | 0.23 |
| | RCP4.5 | 0.57 | 0.36 | 0.00 | 0.00 |
| | RCP8.5 | 0.60 | 0.44 | 0.00 | 0.00 |
| Agricultural water demand management by improving irrigation efficiency | RCP2.6 | 0.47 | 0.17 | 0.33 | 0.52 |
| | RCP4.5 | 0.54 | 0.22 | 0.27 | 0.46 |
| | RCP8.5 | 0.52 | 0.25 | 0.13 | 0.36 |
| Agricultural water demand management by reducing the cultivation area of high-consumption plants | RCP2.6 | 0.52 | 0.21 | 0.03 | 0.23 |
| | RCP4.5 | 0.55 | 0.31 | 0.03 | 0.22 |
| | RCP8.5 | 0.55 | 0.38 | 0.00 | 0.00 |
| Agricultural water demand management by changing the cultivation pattern of high-consumption plants towards low-consumption plants | RCP2.6 | 0.50 | 0.23 | 0.03 | 0.23 |
| | RCP4.5 | 0.54 | 0.33 | 0.03 | 0.22 |
| | RCP8.5 | 0.59 | 0.40 | 0.00 | 0.00 |
| Agricultural water demand management by improving irrigation efficiency and reduce the cultivation area of high-consumption plants | RCP2.6 | 0.44 | 0.20 | 0.33 | 0.53 |
| | RCP4.5 | 0.44 | 0.22 | 0.27 | 0.49 |
| | RCP8.5 | 0.45 | 0.22 | 0.13 | 0.39 |
| Agricultural water demand management by improving irrigation efficiency and change the cultivation pattern of high-consumption plants towards low-consumption plants | RCP2.6 | 0.45 | 0.16 | 0.33 | 0.54 |
| | RCP4.5 | 0.52 | 0.20 | 0.27 | 0.47 |
| | RCP8.5 | 0.50 | 0.23 | 0.13 | 0.37 |

agricultural sector will be decreased. As a result, the regional's utility, and water demand in domestic and industrial sectors will increase.

Effective management of the water crisis should be based on combined policy of improving irrigation efficiency and reducing the cultivation area of high-consumption plants (AW4) and the combined policy of improving irrigation efficiency and changing the cultivation pattern of to low-consumption plants (AW5) were examined. Application of the combined policies has led to a reduction in the agricultural water demand and water shortage in the agricultural sector under climate change impacts. The values of water resource indices under these policies (Table 7) show that the water resources reliability in agricultural sector increase under the combined policies AW4 and AW5. The values of Vul and Max. Deficit in agricultural sector decrease under the combined policies in the future period. The Rel index also indicates an increase in the system's ability to provide various secrors with sufficient water. Generally, two combined management policies (AW4 and AW5) will make water resources more adaptive to future climate change and ease the water crisis in the agricultural sector of the Hashtgerd plain.

# 4 Conclusions

This study aims to evaluate the impacts of climate change on agricultural, water resources and socio-economic activities of Hashtgerd Plain. A system dynamics model was developed to take into account the impacts of climate change and other social and economic stimuli in water resources planning and management. In this study, 19 AOGCM models were used under three RCP2.6, RCP4.5, and RCP8.5 scenarios. Climatic data processing showed that temperature will increase under climate change. The maximum and minimum temperature will be under

RCP8.5 and RCP2.6, respectively. The results showed that the autumn, spring and winter seasons will experience minimum temperature increase in the future period. The monthly rainfall changes will not show a general trend in the future. In general, the Hashtgerd Plain will face warmer and drier conditions under climate change in the future period.

According to the complex nature of water resource systems, policy-making should be based on a holistic insight into hydrologic and socioeconomic activities. In this research, a comprehensive model based on the system dynamics approach was developed to investigate the interactions of water resources, agriculture, and socio-economic sub-systems. The simulation results show that the agricultural sector is the more vulnerable sector to climate change than the domestic and industrial sectors. Moreover, the negative impacts of climate change on the availability of water resources will lead to more sever water shortages. Intensified water scarcity leads to lower regional' utility, the population growth rate and the industrial and domestic water demands relative to the B.a.U scenario. Additionally, the severe water shortage in the agricultural sector will intensify water stress leading to over withdrawal of groundwater resources under climate change. Therefore, appropriate managerial approaches should be adopted to minimize the negative impacts of climate change.

Analysis of different adaptation policies in this study showed the studies management strategies can reduce the water stress under climate change impacts in the future period. The results indicate that improvement of irrigation efficiency coupled with changing the cultivation pattern (AW5) will significantly reduce the agricultural water shortage in Hashtgerd plain. Therefore, policy making and water resources managers should focus on the improvement of water productivity in agricultural sector by encouraging the farmers to cultivate low water requirement crops under expected warmer and drier condition in the future.

The developed model is an integrated model based on system dynamics approach to long term planning and management of water resources system by capturing the hydrologic, social, and economic issues which is similar to Scarborough et al., 2015, Duran-Encalada et al., 2017. But, this model captures the dynamic feedbacks between climate change and various sub-systems at watershed scale. Gohari et al. (2013) developed an integrated model based on the system dynamics approach to evaluate adaptation strategies to climate change. Concomitantly with Gohari et al. 2013, the climate change impacts will intensify water shortage by reducing water availability and increasing water demand, with potential to restricting watershed development and population growth. Due to climate change and water scarcity, the agricultural sector is more vulnerable than other sectors and the lack of systemic thinking and lack of consideration feedback relations between hydrological, socio-economic and agricultural sub-systems in the long term will lead to the failure of management policies. Therefore, policy must be made to reduce the negative effects of climate change on the agricultural sector.

The developed model facilitates investigation of the root causes of the basin's persistent water scarcity problem. This will, in turn, help avoid quick-fix structural solutions and/or it will increase the successes of such projects by identifying unintended side-effects that can be thoroughly analyzed in the planning phase of water resources development projects in the basin. This will contribute to efficient investment of funds to mitigate water resources problems in the basin. Furthermore, our vision is to improve the foundational systems thinking knowledge, and its application in other parts of Iran and the world to contribute to regional and global sustainability. The developed model can be appropriate to apply in practical projects and also academic researches. This model can help to establish system thinking theory as the practical base for water resources planning and management to solve the current environmental problems of the other regions at regional and global scales.

## Compliance with Ethical Standards

**Conflict of Interest**   None.

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