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Studying the Impact of Climate Change on Spatiotemporal Variability of Blue and Green Water Resources

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Abstract

The present research was conducted to study the interaction of climate variability on the blue and green water (BW and GW) components in the Seymareh River basin (SRB) with the aid of the soil and water assessment tool (SWAT). Future climate scenarios for the period of 2020–2040 were generated based on the LARS-WG 6.0 model. According to the results, all climate change scenarios indicate an increase in precipitation in the range of 29 to 33%. Furthermore, the average monthly surface runoff was projected to increase approximately by 75%, 88%, and 98% under RCP 4.5, 6.0, and 8.5 scenarios, respectively. The results revealed that the SRB may witness a significant increase in BW due to the climate changes. Meanwhile, the magnitude of the GW indicator was different within the SRB, with minor changes. Identifying areas with high blue/green water potentials is effective in planning for rain-fed or irrigated agricultural in SRB.

Keywords: Blue water; Climate change; Green water; Seymareh River basin; SWAT

Introduction

Water is an essential natural resource for human beings, which has significant effects on the sustainable development of the environment and the stability of manufacturing activities. Nowadays, water resources all around the word are becoming increasingly vulnerable due to the increasing levels of societal demand. On the other hand, given the global warming and the rising frequency and intensity of extreme weather, the effects of climate change on the water resource is serious. Various river-basins all over the world are expected to experience undesirable effects of climate change on water resources and freshwater ecosystems (Abbaspour et al., 2009). Therefore, depicting the effects of climate change on various components of the water cycle is of great significance in the management of water as an indispensable resource.

Most hydrological systems consist of very complicated and heterogeneous processes which are not easily understood (Teshager et al., 2016). Furthermore, it is extremely difficult to measure all inputs, outputs, and states of hydrological processes and/or parameters in spatial and temporal scale due to spatial heterogeneity, temporal dynamics of hydrological forcing functions and processes, deficiencies in measurement methods, and limitations in times and costs (Mengistu et al., 2019). Knowledge about the internal renewable water resources provides valuable information in long term management and planning. Falkenmark (1995) introduced two main types of water: blue water (BW) and green water (GW). Blue water includes surface and groundwater runoff, and green water refers to precipitation that is stored in the root zone of the soil and evaporates, transpires, or gets incorporated by plants.

Distributed process-based hydrological models are suitable tools for determining the spatial and temporal information of the watershed area; they help understanding the hydrological processes and/or interactions between watershed features and the hydrological responses and support sustainable water resource planning, management, and decision-making procedures (Teshager et al., 2016; Franco & Bonumá, 2017; Mengistu et al., 2019). Over the recent decades, extensive researches have been conducted to study the spatial and temporal variations of the hydrological components, BW, and GW indicators, particularly in future climate change scenarios. The impacts of future climate on Iran's water resources were investigated using the calibrated soil and water assessment tool (SWAT) model for 1980 -2002 time horizon at a sub-basin level by Abbaspour et al. (2009). The future climate scenarios, A1B, B1, and A2, were generated by Canadian Global Coupled Model (CGCM 3.1) and downscaled for 37 climate stations. The effects of future climate scenarios on BW, GW, and wheat yield across the country were analyzed with the SWAT model. Rodrigues et al. (2014) illustrated analysis of the availability and use of BW and GW to represent water scarcity and vulnerability indicators at the basin scale in the Cantareira water supply system in Brazil. SWAT model was applied to depict the hydrological processes and derive the BW and GW footprint indicators against various water access levels for human activities during 23 years. The contrasting status of BW indicators was studied in their research based on different hydrological based methodologies to determine the monthly environmental flow requirements (EFRs), and the risk of natural EFR violation. Luo and Tao (2016) investigated the dynamics of GW and BW variables on the Heihe River basin in China based on the data from 1980 to 2009 to identify the controlling factors in each sub-basin. Farsani et al. (2019) evaluated the effects of climate change on the spatiotemporal distribution of water resources in order to analyze the water supply demand in the Bazoft watershed, Iran. SWAT model was applied to depict the changes of BW flow, GW flow, and GW storage for a future period (2010–2099) in comparison to a historical record (1992–2008). Veettil and Mishra (2018) studied the effects of both anthropogenic and climatic features on the spatiotemporal variability of water security indicators, such as BW scarcity, GW scarcity, Falkenmark index, and freshwater provision indicators in the Savannah River basin. Their results implied that the study area experienced a decline in BW due to the climate variability whereas GW was significantly affected by land use alternation. Zhu et al. (2018) examined the spatiotemporal distribution of GW in the Hai River basin based on the impacts of land use types. SWAT model was employed in their research for the determination of the relation between the soil and land use type with certain indices, such as maximum possible storage of green water, the green water footprint, and the available green water. The impacts of climate change on runoff, aquifer infiltration, renewable water resources, and drought intensity in the Salt Lake sub-basin, Iran, were assessed by Khalilian & Shahvari (2019). The calibrated and validated SWAT model projected the hydrological responses in watershed scale in a spatiotemporal framework based on various climatic scenarios. Huang et al. (2019) conducted a research to study the effects of climate and land use changes on crop GW and BW consumptions. A crop water use module, developed based on the global change assessment model and its hydrology module (Xanthos), was used to illustrate the effects of climate and land use changes on BW and GW footprints. The modeling results demonstrated the increase in global crop green water footprint and dominance of climate change over land use change on GW footprint. Furthermore, the global crop BW footprint would increase, specifically in areas with considerable irrigated land development.

Liang et al. (2020) determined the spatiotemporal variations of GW and BW at the rapidly developing Xiangjiang River basin in China according to climate change and anthropogenic activities. SWAT, as the semi distributed and process based hydrological model, demonstrated the influence of 1) BW scarcity from precipitation and population growth and 2) GW scarcity from agriculture and urban lands. In other words, the climatic features were found to affect the BW components in the river basin scale. Furthermore, the spatial shortages of BW and GW in the river basin scale showed that higher values in downstream reaches of the watershed. Mao et al. (2020) studied the interactions between GW and BW, focusing on the anthropogenic activities in an arid endorheic river basin in China. The knowledge about the interactions between GW and BW in the hydrological system was applied in integrated surface water and groundwater resource management and support of basin scale water resources management, addressing human nature water conflicts. A regional climate model (RCM), COSMO climate limited area model (CCLM), linked to the SWAT model, was applied by Mengistu et al. (2020) to assess the effects of climate change on the Upper Blue Nile (Abay) water system. They illustrated an increase in potential evapotranspiration by 27 % under RCP 8.5, an increase in surface runoff by 14 %, and a decrease in base flow by 30 % in comparison to the baseline scenario. Despite the increase in the surface runoff, the total water yield in the study area was estimated to decrease by −1.7 to −6.5 % and −10.7 to −22.7 % in RCP 4.5 and RCP 8.5 scenarios, respectively. Serur (2020) simulated BW and GW resources availability at the basin and sub-basin levels in the Weyb River basin in Ethiopia using the SWAT model. According to their results, the mean annual BW flow, GW flow, and GW storage exhibited an increase in the entire basin and in all the sub-basins under representative concentration pathway (RCP) 8.5/4.5/2.6 scenarios.

To our knowledge, the main attempt in modern water governance in watershed scale is to assess the effects of future climate change on water cycle. The scientific numerical hydrological models can help to define policy for the stakeholders and policy makers, which would result in more effective use of soil and water resources. In view of the changing pattern in climate features, it is desirable to investigate the spatiotemporal variability of water footprint indicators at river basin scales for water resource management and ecological conservation, especially in fragile watersheds. In this research, the integrated hydrological SWAT model (Arnold et al., 1998) was calibrated and validated (time horizon 2003 to 2016) to study the effect of climate change at a basin level for the Seymareh River basin (SRB), Karkheh, Iran. We investigated the changes of various components of water balance, including precipitation and evapotranspiration distribution, stream flow, soil moisture, and aquifer recharges. The spatiotemporal variability in water resources concerning BW and GW indicators was derived under RCP 8.5/6.0/4.5 scenarios. The proposed approach of this research could help in identifying areas with high BW/GW potentials to plan the rainfed or irrigated agricultural in river-basin scale. In addition, the current study would be effective in enhancing socio, economic, and environmental capital and sustainable development aspects.

Materials and Methods

Study Area Description

The study area is located in the southwestern Iran between 32° 40' to 34° 80' N and 46° 10' to 49° 30' E. It drains an area of about 28000 km2, out of which 11,700 km2 is located in Gamasiab sub-basin and 5700 km2 in Gharasou sub-basin and the remaining portion is located in Seymareh sub-basin. The study area, in terms of political divisions, includes Kermanshah, Ilam, Lorestan, Kordestan, and Hamedan provinces (Figure 1). The climate in the SRB is variable and characterized with cold/snowy winters and mild summers. The annual precipitation ranges from 247 mm to 700 mm. The temporal variation of rainfall is evenly throughout the year, but dry weather typically takes place between mid-summer to fall. Basin’s elevation ranges from less than 10 m above the sea level to more than 5500 m. Figure 1 represents the geographical location of SRB in Iran and the provincial areas located within SRB (MGCE, 2014).

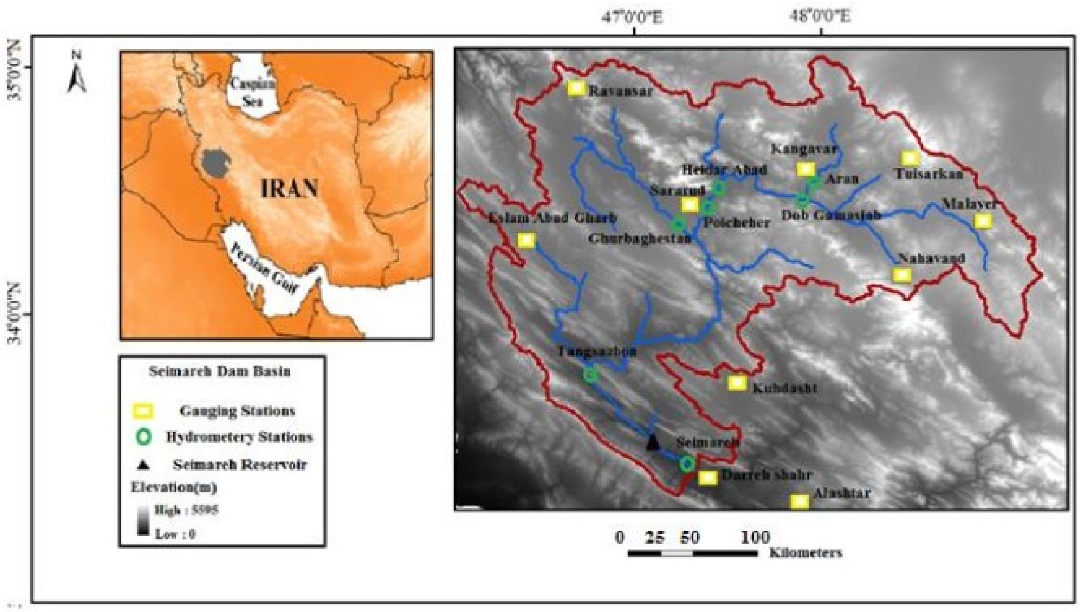


Figure 1: The geographic location of Seymareh River basin in Iran and the provincial areas in the study area

Seymareh River leaves Gamasiab sub-basin and flows through Gharasou and then Seymareh sub-basins through a series of deep valleys and canyons and joins Seymareh Reservoir. Gamasiab, Gharasou, and Seymareh sub-basins also contribute about 37 %, 23 %, and 43 % of the annual flow of Seymareh River. Roughly 9500 km2 of Seymareh River basin's total surface area is arable land and is devoted to horticulture (apple, grape and walnut) and field crop (wheat, barley and sugar beet) production. About 1700 km2 of this land is irrigated using traditional and modern techniques, and 7800 km2 of it is rain fed. The remaining land use of SRB includes forests, pastures, and rocks (totally 64 %) and barren lands, wetlands, and urban areas (less than 2 %) (MGCE, 2014). For modelling of the Seymareh river-basin, most (about 90 percent) horticulture and field crop productions are considered such as apple, grape and walnut, wheat, barley and sugar beet.

Data

To address the current project objectives, the required datasets were collected from multiple sources. The fundamental component of the datasets used for the model development included 1) the digital elevation model (DEM), obtained from the global U.S. geological survey's (USGS) public geographic domain database set at a spatial resolution of 90 m. The DEM was utilized to delineate the study area topographic characteristic; 2) the land use data sets were provided from USGS EROS Archive - Land Cover Products - Global Land Cover Characterization webpage; 3) the soil data was extracted from FAO/UNESCO global soil maps of the world; 4) the daily meteorological (precipitation and the minimum and maximum temperature) data from 2003 to 2016 were downloaded from national centers for environmental prediction (NCEP) climatic SWAT data website (https://globalweather.tamu.edu/); 5) the recorded stream flow data were obtained from the Basic Study Office of Iran water resources management company (IWRMC, 2017) for seven hydrometric stations from 2003 to 2016; 6) historical records on annual yields of horticulture and field crop productions were collected from 2000 to 2018 from the agricultural statistics and the information center of Ministry of Jahade-Agriculture (Ahmadi et al., 2019).

Hydrological Model

The soil and water assessment tool (SWAT) model is a continuous, long-term, physically-based, and semi-distributed hydrological model. SWAT model is able to assess the effects of climate and land management on the hydrological processes, sediment loading, pollution transport, and crop growth in watershed scales (Arnold et al., 1998). The SWAT model is useful for estimating BW and GW available at a basin scale (Veettil & Mishra, 2016; Schuol et al., 2008b; Abbaspour et al., 2015).

In the SWAT model, a watershed is partitioned into sub-basins that are further divided into a series of hydrological response units (HRUs). HRUs are uniform units that share unique combinations of soil and land use and are employed as the basis of the water balance calculation. The water components, sediment yield, and nutrient cycles are estimated in each HRU and then aggregated for the whole sub-basins in the watershed.

The SRB was divided into sub-basins, and then partitioned into unique HRUs. Five classes of slopes were defined for HRU delineation: 0 –5 %, 5-10 %, 10 –20 %, 20 –40 % and above 40 %. The number of HRUs was determined by adjusting the threshold of land use (5 %), soil (10 %), and slope (10 %), which resulted in 1723 HRUs under land use features of the study area. In this research, the surface runoff was illustrated with soil conservation service curve number (SCS-CN) using daily meteorological data and soil hydrologic group, land use and land cover features, and antecedent soil moisture. The potential evapotranspiration (PET) and actual evapotranspiration (AET) were simulated based on the Hargreaves Method and Ritchie Method, respectively. The leaf area index (LAI) and root development were simulated using the "crop growth" component of SWAT, which is the simplified version of the erosion productivity impact calculator (EPIC) crop model (Williams et al., 1984). Plant growth was determined according to leaf area development, light interception, and conversion of intercepted light into biomass, assuming a plant species specific radiation use efficiency. Phenological plant development was based on daily accumulated heat units, potential biomass, and harvest index. Plant growth could be inhibited by user specified temperature, water, nitrogen, and phosphorus stress factors (Neitsch et al., 2002).

Future Climate Data and Modeling Scenarios

Simultaneous past and future events of climate change are affected by a combination of external forcing, unforced internal fluctuations, and the response characteristics of the climate system. Due to human induced greenhouse gas emissions, the IPCC expects the average global temperature to change in future years (IPCC, 2014). It is crucial to understand how much change to the earth's climate system will affect future hydrological cycles and water components. To study the impacts of future climate changes on hydrological cycles, scenarios are created based on global circulation models (GCMs), considering certain boundary conditions (such as the solar constant) or physical parameters (such as the greenhouse gas concentration). To evaluate the effects of climatic scenarios on future (2020-2040) hydrologic events, GCM data have been used as an input to hydrologic models. However, such data cannot be applied directly since hydrologic models need local scale daily meteorological data as input (IPCC, 2014). Therefore, the GCM outputs should be converted to the appropriate spatial and temporal resolution using statistical downscaling tools, LARS-WG for instance.

According to IPCC-V assessment report, cumulative emissions of CO2 mainly affect global mean surface warming by the late 21st century and beyond. Projections of greenhouse gas (GHG) emissions alter over a wide range, depending on both socio-economic development and climate policy. In this regard, four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions, and land use have been considered in the representative concentration pathways (RCP-s) (IPCC, 2014). In this study, we analyzed the effects of two intermediate scenarios (RCP 4.5 and RCP 6.0) and one scenario with very high GHG emissions (RCP 8.5) on the hydrological cycles.

LARS-WG, as a credible stochastic weather generator tool, could be used for the projection of weather data at a local site, under both current and future climate conditions. This tool provides a means to extend the weather time series simulation of unobserved locations through the interpolation of the weather generator parameters obtained from running the models at neighboring sites (Semenov, 2020). This model can serve as a computationally inexpensive tool to generate multiple year climate change scenarios at the daily time scale, which considers changes in both mean climates and climate variability. The LARS-WG 6.0 incorporates climate projections from the CMIP5 ensemble described in the IPCC Fifth assessment report. The model incorporates the process of generating synthetic weather data into three distinct steps: model calibration, model validation, and generation of synthetic weather data (Semenov, 2020).

While using LARS-WG, model calibration consists of calculating the relevant statistical parameters for each meteorological variable from the observed historical data. These parameters or the once modified based on future climate change scenario are then used to stochastically generate realistic climate data corresponding to the present or future climate scenario, respectively. For the first set of experiment, mean of observed daily precipitation as well as daily maximum and minimum temperatures are used to extract the statistical parameters of the current climate. For precipitation, these parameters consist of monthly histogram intervals and frequency of events in each interval for dry and wet spell lengths, as well as precipitation amounts. On the other hand, temperature is modeled in LARS-WG by using Fourier series which can be constructed with parameters such as mean value, amplitude of the sine and cosine curves and phase angle. Both maximum and minimum temperatures are modeled more accurately by con- sidering wet and dry days separately; therefore, the temperature parameters for wet and dry days are derived separately. The weather generator also uses parameters corresponding to average autocorrelation values for minimum and maximum temperature derived from observed weather data. After the observed weather data is analyzed in this way, the derived statistical parameters are used to generate synthetic weather data representing the current climate. (Dibike & Coulibaly, 2005).

Calibration Set up and Analysis

In this research, the ArcView GIS interface for SWAT 2012 (Winchell et al., 2013) was configured and parameterized to depict the hydrological processes in Seymareh River basin. In the SWAT model set up, the watershed was delineated into 33 sub--basins with the main outlet in Seymareh Reach inflow. The daily precipitation data and the minimum and maximum temperature data were obtained from national centers for environmental prediction (NCEP) climatic SWAT data website. The hydrologic SWAT model was calibrated and validated at the sub-basin level based on monthly observed discharges at seven stations across the river basin, and annual crop and garden production yields. The combinations of river discharge and crop and garden yields in the calibration processes result in a more accurate approximation of both runoff and evapotranspiration and therefore, soil moisture and deep aquifer recharge. SWAT calibration and uncertainty program (SWAT-CUP) was applied to calibrate the SWAT model parameters. Adjusting the model parameters would result in model accuracy to better depict the hydrological process of the study area. In this research, the SWAT simulation of SRB consists of the warming up period (2003-2004), the calibration period (2005-2012), and the validation period (2013-2016). As the SWAT model involves extensive parameters, a sensitivity analysis was accomplished to identify the main parameters across various hydrologic regions.

The SUFI-2 algorithm in the SWAT-CUP program was used in the SWAT model parameter adjustion. The whole uncertainties (parameter, conceptual model, input, and so forth) of the simulation were included in the parameter ranges as the algorithm attempts to involve the 95% prediction uncertainty of the measured data. Two indices quantify the goodness of calibration/ uncertainty performance, the P-factor, and the R-factor. In order to compare the observed and simulated monthly discharges and annual crop yields, the coefficient of determination (R^2), Nash-Sutcliffe efficiency coefficients (NS), and percent bias (BIAS) were used as the criteria to evaluate the accuracy of the SWAT model performances.

Blue and Green Water Calculation

“Blue water” is generally defined as “the sum of river discharge and deep groundwater recharge.” (Abbaspour et al., 2009). Based on modeling framework, BW is estimated by combining both water yield and groundwater storage. The amount of water leaving the HRU and inflowing to the main channel is illustrated as water yield. Groundwater storage is defined as the difference between the total amount of water recharging to aquifers (GW_RCHG) and the amount of water from the aquifer entering the main channel flow (GW_W). “Green water” consists of resource and flow as soil moisture and actual evaporation-transpiration, respectively (Abbaspour et al., 2009; Veettil & Mishra, 2016). In this study, these two different sources of water were determined based on SWAT model results and the effects of climate changes on each source were evaluated.

Results and Discussions

Calibration and Validation of SWAT Model

Due to extensive tunable parameters in SWAT model, a sensitivity analysis was accomplished to identify the main parameters across various hydrologic regions. In the sensitivity analysis, we initially selected 17 parameters integrally related to streamflow and another four parameters related to crop and garden growth. Afterwards, to consider the spatial variations in soil and land uses, the selected parameters were further differentiated. This led to 268 scaled parameters, for which we performed a sensitivity analysis.

Hydrometric Stations	Calibration				Validation			
	NS	R^2	P-factor	R-factor	NS	R^2	P-factor	R-factor
Aran	0.63	0.75	0.7	1.41	0.62	0.71	0.71	1.36
Heidarabad	0.69	0.73	0.68	1.26	0.68	0.74	0.69	1.3
Doabgamasiab	0.56	0.7	0.69	1.63	0.54	0.68	0.72	1.54
Polcheher	0.63	0.68	0.72	1.11	0.59	0.66	0.74	1.05
Ghurbaghestan	0.64	0.67	0.73	1.21	0.62	0.65	0.68	1.26
Tangsazbon	0.62	0.63	0.75	1.02	0.61	0.62	0.73	1.12
Seymareh	0.6	0.62	0.72	0.96	0.59	0.64	0.68	1.07

Table 1: Calibration and validation performances relevant to hydrometric stations of Seymareh River basin

Given the spatial distribution of these hydrometric stations, the results (Table 1) illustrated that the R2 value in the downstream station was lower than that of the upstream station. Reviewing the simulation results of the annual yield of horticulture and field crop production in comparison with historical records (Figure 2) implied appropriate depictions of river basin status with the aid of the SWAT model. The correlation coefficient of field data and SWAT model resulted in crop and horticultural performance in the river basin was over 0.99. In view of the results presented in Table 1 and Figure 2, the performance of the seven control stations and annual production yield attained the requirement, meaning that the SWAT model was well established for Seymareh region and could be used for further analysis.

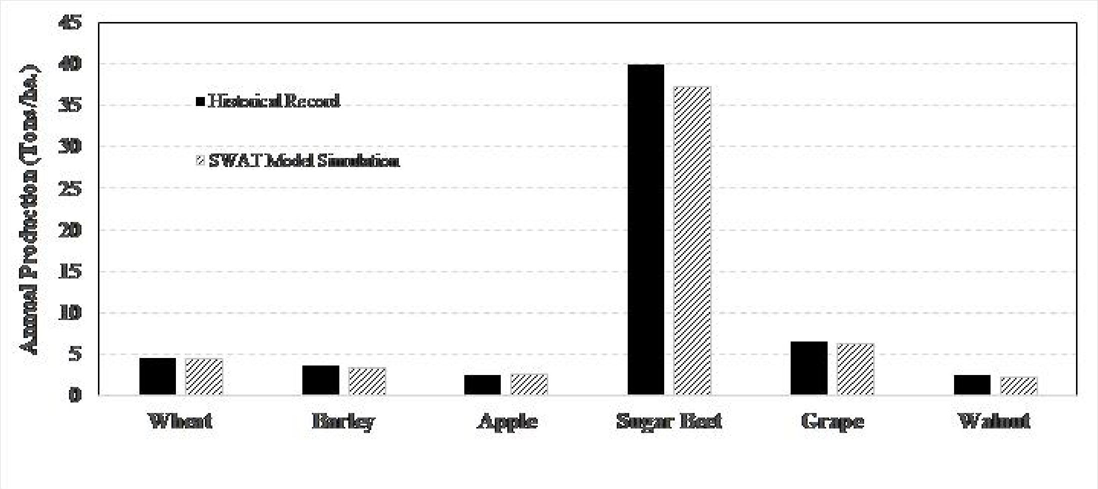


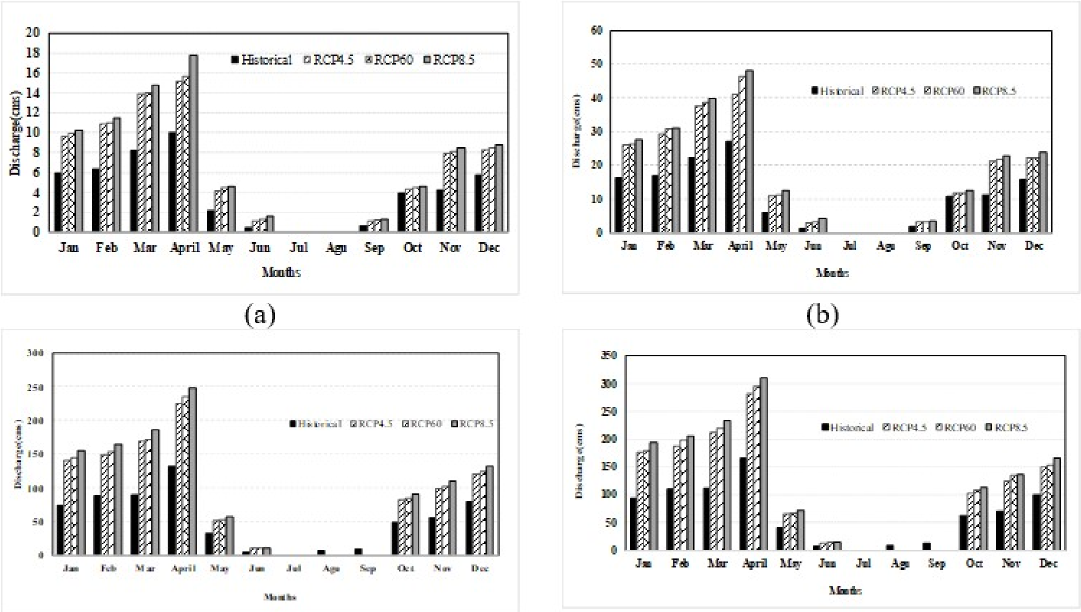
Figure 2: Comparison of historical records and SWAT model results on annual yield of horticulture and field crop production

Downscaling Climate Variables

The downscaled meteorological data from LARS-WG agreed relatively well with the recorded historical data in all the 11 control stations. The downscaled temperature in all the meteorological stations had R2 values in the range of 0.96–0.99. The R2 and NS coefficient, calculated between the downscaled rainfall data (simulation with the LARS-WG) and the measured data, indicated entirely satisfactory results for all the regions in the study area.

Impacts of Climate Changes

The differences between the historical and projected precipitation with different emission scenarios were calculated and compared for the period of 2020 to 2040 and 2003 to 2016, respectively. According to the obtained findings, all climate change scenarios indicated an increase in the precipitation in the study area in the range of 29 to 33 %.



(a) (b)

(c) (d)

Figure 3: Monthly average surface runoff in historical and various climate change scenarios in a) Aran, b) Doab-Gamasiab, c) Tange-Sazbon, and d) Seymareh hydrometric stations

Driven by the daily precipitation, the data associated with the minimum/maximum temperature from the LARS-WG under RCP 4.5, 6.0, and 8.5 scenarios, the parameterized SWAT model estimated the surface runoff in spatial and temporal scales in the context of climate change at Seymareh River basin (Figure 3). In the future period (2020 to 2040), the average monthly surface runoff derived from the climate change scenarios was predicted to increase approximately by 75 %, 88 %, and 98 % under RCP 4.5, 6.0, and 8.5 scenarios, respectively. The results revealed that climate changes associated effects on the base flow in Seymareh River basin was negligible. Reviewing the climate change effects, more dry period extensions were observed, particularly in downstream parts of Seymareh River basin.

The analysis of the hydrological status under climate change scenarios of IPCC-V assessment report revealed intensification of surface runoff, especially in the wet seasons of the year in Seymareh River basin. However, the surface runoff intensification in the upstream parts of Seymareh River basin seems more evident than that in the downstream parts (Figure 3).

Monthly average values of the various hydrological components, extracted from the results of SWAT model from 2003 to 2016, may be applied to quantify blue and green water general balance and examine the temporal agricultural patterns throughout the basin. In river basin management, access to information about the spatiotemporal distribution of GW and BW flows may provide appropriate evaluations of the proportionality relation between the hydrological components and the horticulture and/or field crop patterns. Figure 4 represents the monthly average hydrological components (precipitation, GW, and BW flows) in the study area in the base period (2003 to 2016). Uneven temporal distribution of precipitation significantly affected the temporal pattern of GW and BW flows in the study area. The hydrological model results indicated that the proportionality between blue and green water flow fractions remains almost the same throughout the study area.

The decreases in precipitation and then BW flows from July to October (Figure 4) were manifested in the framework of the lowest surface runoff on the warm seasons in various hydrometric stations around Seymareh River-basin.

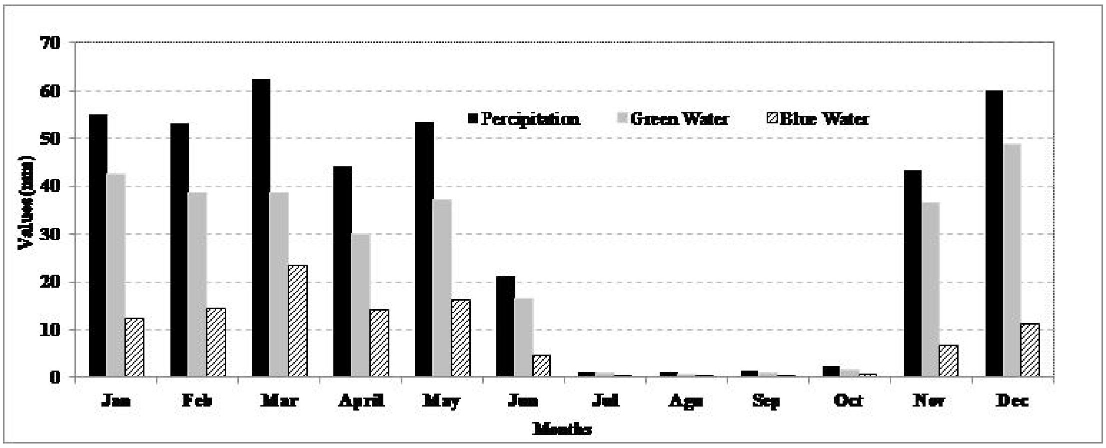


Figure 4: Monthly variation of precipitation, GW, and BW in the historical scenario in the Seymareh River basin in the base period

Detail analysis of the hydrological responses in Seymareh River basin to various climate change scenarios of IPCC-V assessment report (Figure 5) illustrated different patterns in GW, BW, GW flow, and GW storage. The BW and soil water components (GW storage) derived from the climate change scenarios were observed to increase by 77 %, 79 %, and 100 % and 20 %, 25 %, and 4 % under RCP 4.5, 6.0, and 8.5 scenarios, respectively. However, the ET (Evapotranspiration as GW flow) and GW as the hydrological indicators in the RCP4.5, 6.0, and 8.5 scenarios, altered respectively to (-13 %, -4 %, and -3 %) and (-7 %, 1 %, and -2 %), respectively.

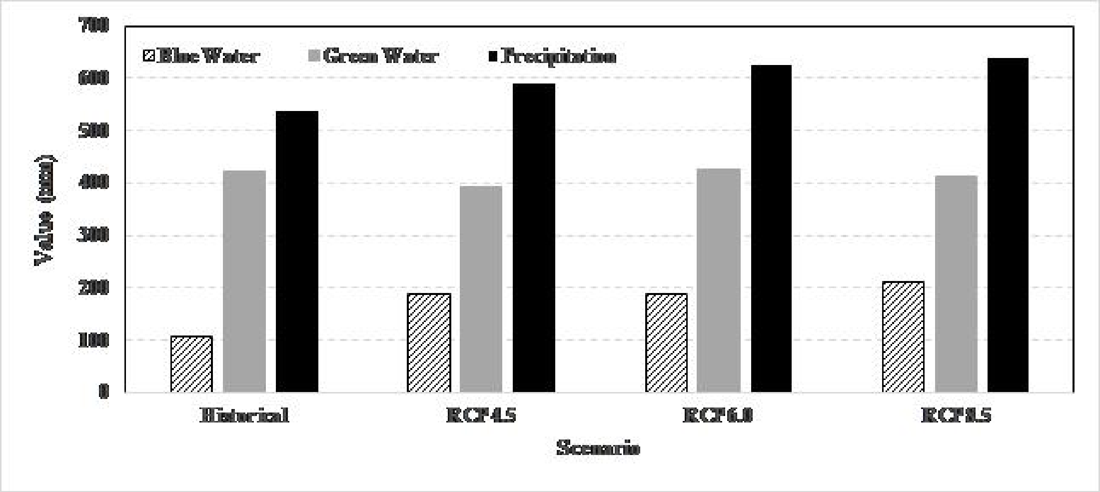
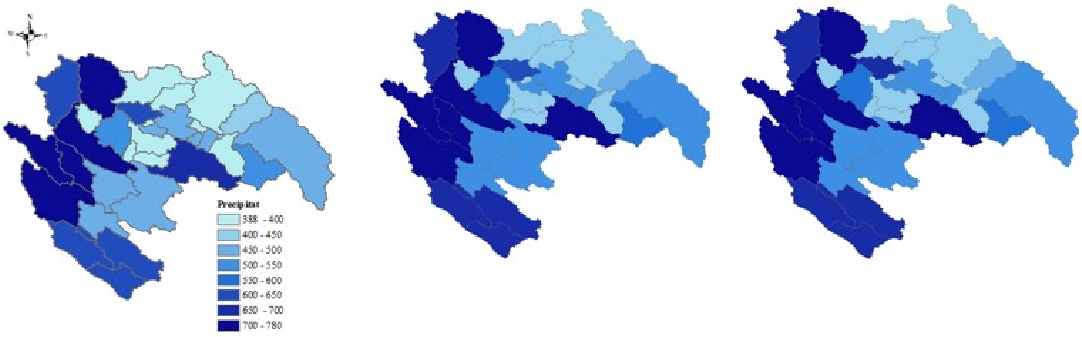


Figure 5: Variation of the precipitation, GW, and BW in the historical scenario in comparison to various climate change scenarios of IPCC-V Assessment Report in the Seymareh River basin



a b c

Figure 6: The spatial distribution of precipitation in the a) historical, b) RCP 4.5, c) RCP 8.5 scenarios

The spatiotemporal variations of precipitation, BW, and GW are of great importance for water resources management and planning. Figure 6 (a, b, c) depicts the annual changes of precipitation under historical, RCP 4.5, and RCP 8.5 in spatial scale. The spatial distribution of precipitation in the study area changed based on climate change scenarios (RCP 4.5, 6, and 8.5). According to RCP 4.5 and RCP 8.5 scenarios, several regions with precipitation in the range of 450-550 mm in the historical scenario moved to the range 550-650 mm. Furthermore, due to climate change scenarios, the precipitation in the lower sub-basins in the SRB increased significantly.

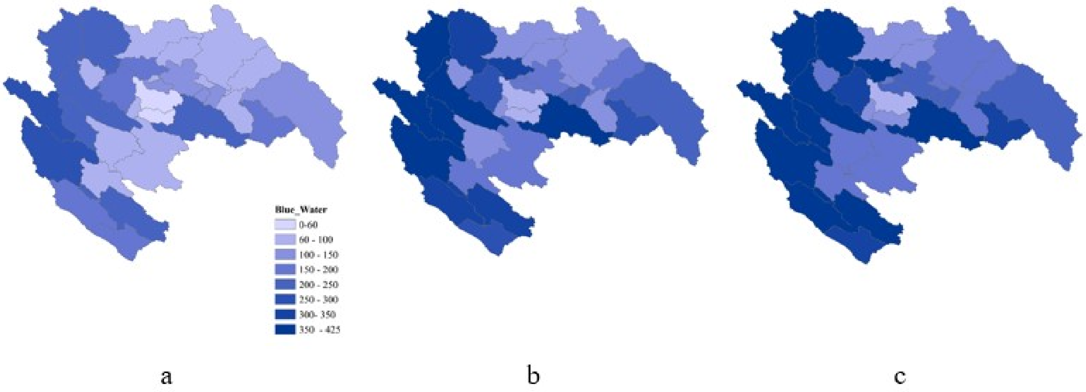


Figure 7: The spatial distribution of blue water in the a) historical, b) RCP 4.5, c) RCP 8.5 scenarios

The spatial variations of BW across the SRB area under historical, RCP 4.5, and RCP 8.5 scenarios could be seen in Figure 7 (a, b, c), respectively. The hydrological analysis in the spatial scale in SRB demonstrated a significant increase in blue water across all the sub-basins. The analysis on the BW contents shows that the long term minimum and average spatial changes of Seymareh River basin in the RCP 4.5 scenario were 45 % and 65.5 %, respectively. The standard deviation of the long term spatiotemporal changes of BW in various sub-basins in RCP 4.5 scenario was 9 % compared to the historical scenario. The analysis on the similar statistical spatiotemporal indices in RCP 8.5 scenario demonstrated an increase in the average and minimum changes in BW of various sub-basins to 60 %, 85 % and 60%, respectively, in comparison to the historical scenario.

Figure 8 (a, b, c) exhibits the spatial variations of GW across the SRB area respectively under historical, RCP 4.5, and RCP 8.5 scenarios. The hydrological analysis in the spatial scale in SRB presented insignificant changes of green water across all the sub-basins. Additionally, the GW component in climate change scenarios decreased in some sub-basins compared to the historical scenario in SRB.

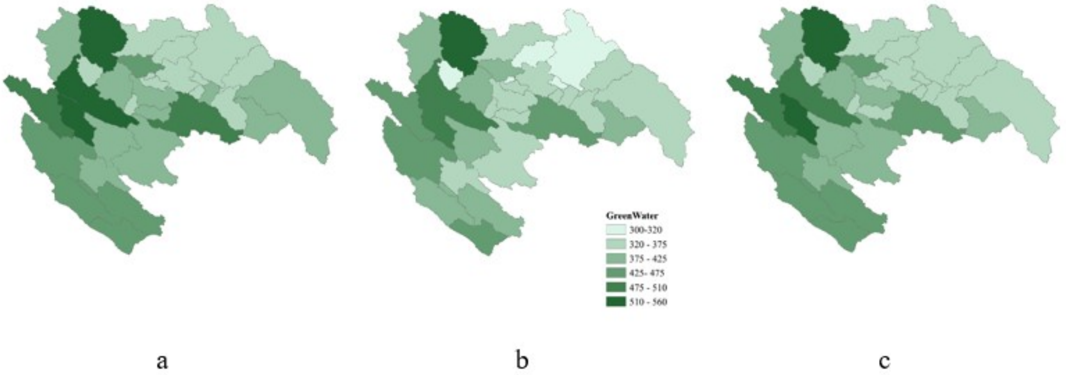


Figure 8: The spatial distribution of green water in the a) historical, b) RCP 4.5, c) RCP 8.5 scenarios

The long term average spatial changes of GW contents in various sub-basins in RCP 4.5 and 8.5 scenarios were -7.4 % and -1.9 %, respectively. Furthermore, the standard deviations of the spatial changes of GW contents in various sub-basins in RCP 4.5 and 8.5 scenarios were 0.84 % and 0.18 %, respectively. According to the results (Figure 8) and the spatial analysis, the reductions of GW contents in all the sub-basins of Seymareh River basin occurred in both RCP 4.5 and 8.5 scenarios.

Concluding Remarks

In this research, the spatiotemporal impacts of climate change on the hydrological components, precipitation, GW, and BW, were studied utilizing the SWAT model. The knowledge on the hydrological components as an essential subject in the river basin water resources management and planning was derived based on the physically based distributed hydrological model. The SWAT model in the SRB was calibrated and validated based on the measured streamflow in seven hydrological stations and the yield of agricultural and horticultural products in 2003 to 2016. The spatial analysis on the precipitation, GW, and BW demonstrated further water availability in the western parts of SRB.

Future climate scenarios for periods of 2020–2040 were generated based on the LARS-WG 6.0 model, which projected the future climate status from the CMIP5 ensemble described in the IPCC Fifth assessment report. In the climate change scenarios, higher flow discharges would be experienced in the hydrological stations, especially in the wet seasons whereas the dry seasons would be extended. According to the results, the climate change scenarios influenced the precipitation more substantially compared to other meteorological components in the SRB. The analysis on meteorological components demonstrated that in the climate change scenarios, the projected annual precipitation and ET would increase and decrease, respectively, relative to 2003-2016 as the baseline periods. The significant spatiotemporal changes of BW were principally anticipated due to climate change scenarios whereas the effects of climate change scenarios on GW were insignificant. In other words, the BW was mainly affected by precipitation and positively correlated with it.

This study would help regional watershed managers and national policy makers to make more accurate and reasonable decisions concerning water resources planning and protection in the SRB. Future research is recommended to include more water quantity and quality indicators as water security indicators. Moreover, studying further effects of future land use scenarios on the hydrological components in the corresponding hydrological response units (HRU) of SRB would be interesting; this might help to get insights into the spatial variation of each variable.

Data Availability

The data that support the findings of this study are cited in the reference section. Direct requests for these materials may be made to the corresponding author.

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Conflicts of interest/Competing interests

There are no real or perceived financial conflicts of interest for the authors.

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