



Potential Impact of Global Warming on Climate and Streamflow of Adhaim River Basin, Iraq

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HIGHLIGHTS

- Connection between LARS-WG and SWAT models presented successful simulation for current and future climate and hydrological systems in ARB.
- ARB tend to become hotter and drier by 2080 due to global warming.
- Adaptation strategies should be applied in water resources management of ARB.

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ABSTRACT

Global warming induces to increase of greenhouse gases in the atmosphere and plays a crucial role in determining the future trend in climatology and hydrology of a watershed. This paper aims to investigate the implications of global warming on future climate and its consequents on streamflow of the Adhaim River Basin (ARB). For this purpose, the Long Ashton Research Station-Weather Generator (LARS-WG) and Soil and Water Assessment Tool (SWAT)-Based models were implemented. The climate and hydrologic records for the period 1990-2019 were used as a Reference Period (RP) and projected to 2080 under Representative Concentration Pathways (RCPs 2.6, 4.5, and 8.5) and five Global Climate Models (GCMs). The results show that the region of ARB tends to become hotter and drier with an increase in mean temperature by 1.2, 2.9, and 4.6 °C under the considered RCPs, respectively. However, precipitation tends to decrease from 366 mm/y in RP to 320.2, 302, and 300.5 mm/y by 2080 under the considered RCPs. Consequently, the streamflow will decrease to about 28, 26, and 24 m³/s by 2080 under the considered RCPs, respectively, compared with 28.96 m³/s in RP. Therefore, adaptation strategies are highly recommended to alleviate the negative impacts of climate change, and the implications of climate change on groundwater, water demand, and adaptation plans should be investigated in future studies.

1. Introduction

The concentration of greenhouse gases emitted in the atmosphere by anthropogenic activities is at a higher level than before [1]. These gases trap heat in the atmosphere instead of scattered space [2,3]. Temperature is a key driver of global climate [4,5]. Therefore, global warming has the main responsibility for changing the global climate [6,7,8]. Furthermore, climate change is an introduction to alteration of the hydrologic cycle [8]. The rapid increase in temperature means a high rate of evaporation from soil and water surfaces and transpiration from plants [9,10,11]. Moreover, climate change is also introduced as a spatiotemporal change in the patterns of precipitation and snowfall over a specific region [12,13,14]. Consequently, scientific research indicated that the streamflow of a watershed is highly alerted due to climate change [15,16,17,18].

IPCC, 2014 adopted the RCP 2.6, 4.5, 6, and 8.5 to describe greenhouse gases in the current century based on population, lifestyle, economic, land use conditions, energy consumption, and climate policy. The Coupled Model Intercomparison Project (CMIP) is a collaborative framework developed to improve the simulation of Global Coupled Models (GCMs) [19]. The five-phase of CMIP (CMIP5) has extra features over the old version in the simulation of the carbon cycle, forecasting the system in one decade step and determining the response of climate models [20].

Lelieveld et al. [21] analyzed long-term climate data recorded in the Eastern Mediterranean and the Middle East (EMME) region based on the regional climate model and A1B scenario of greenhouse emissions. The results indicated that the temperature tends to increase by 3.5–7 °C by the end of the current century. Therefore, a drier and hotter climate condition is expected in the studied region due to decreased precipitation and temperature rise. The increase in heat waves frequency and decrease in precipitation, in combination with population growth, will put water resources in the Middle East and North Africa (MENA)

under water stress [22]. Evans [23] stated that the region extended over Turkey, Syria, northern Iraq, and northeast Iran will suffer the largest decrease in projected precipitation under the A2 scenario of high greenhouse emissions. However, a small increase in precipitation over the southern Arabian Peninsula resulted from moving the inter-tropical climate zone to the north. Sowers et al. [24] reviewed the literature concerning on water resources of the MENA region. The analysis indicated that precipitation over MENA tends to decrease by 10-30% in the current century. Moreover, the water resources in Iraq will be under stress by the year 2025 due to climate change and population growth. Al-Faraj and Tigkas [25] examined the climate trend of the Diyala River basin, Iraq. The analysis indicated that precipitation tends to decrease with a rising temperature and evapotranspiration. As a result, the cumulative droughts affected streamflow for 1999-2001 and 2008-2009. Awchi and Kalyana [26] indicated that the frequency of drought events increased almost every decade in the northern region of Iraq due to the impact of climate change.

Stochastic climate models, joined with hydrologic models, are efficient tools to project future climate and evaluate the hydrologic response under climate change conditions [27,28]. Mohammed and Scholz [29] found that precipitation over the Lesser Zab River basin declined by 40 and 60% for drought periods recorded in 1998-2001 and 2006-2008, respectively. This reduction in precipitation can be induced by climate change which contributed to a decrease in the streamflow of Lesser Zab River up to 52-86% for studied extreme events. Using the Soil and Water Assessment Tool (SWAT) model, Khafaji and Al-Chalabi [30] projected the streamflow of Diyala River to the year 2050 using the SWAT model and five climate models of medium greenhouse emissions (A1B) scenario. The analysis shows that the streamflow of Diyala River will decline by 49 and 20% for Derbandikhan and Hemrin watersheds, respectively. The projected streamflow modeled by Hilo et al. [31] using the SWAT model and six Global Circulation Models (GCMs) indicated that the projected streamflow of Lesser Zab River tends to decline from 176.5 m³/s recorded in the period from 1980-2013 to 167 m³/s in the middle of the current century. Saeed et al. [32] applied the Long Ashton Research Station-Weather Generator model (LARS-WG) and SWAT models in Diyala River basin using weather data for 2080 under five GCMs. The results indicated that streamflow of Diyala River tends to decrease by 38.8, 47.9, and 52.8% under Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5, respectively, compared with observed streamflow recorded from 1990 to 2019.

Adhaim River has little attention in regards to the impact of climate change on the water resources of the Adhaim River Basin (ARB). However, the future water resources of ARB need more understanding under global warming conditions to perform suitable plans for sustainable water resources management. Therefore, this paper aims to investigate the implications of global warming on the future trend of ARB climate and hydrological systems. It focuses on the basin's temperature, precipitation, evapotranspiration, and streamflow. For this purpose, the minimum and maximum temperatures (Tmin and Tmax) and precipitation (PCP) recorded in two climate stations in 1990-2019 as a reference period (RP) were projected into 2021-2040 (P1), 2041-2060 (P2) and 2061-2080 (P3) using LARS-WG under five GCMs and three RCPs. Furthermore, the current and projected climate data were utilized to implement a SWAT-based model for assessing the evapotranspiration and streamflow of the ARB.

Methods and

2. Materials and Methods

2.1 Study Area

The ARB has an area of 11600 km², one of Tigris River's tributaries. The ARB Figure 1 is located between the longitudes 43° 41' 9" to 45° 27' 31" E and latitudes 35° 42' 24" to 34° 33' 8" N in northern Iraq [33]. The river originates from highlands of 1800 meters above sea level (m.a.s.l.) and joins with Tigris river at 150 m.a.s.l in northern Baghdad City. The slopes of ARB range from 0 to 229 [34]. The barren land has dominated the basin, and agricultural lands are distributed in the northern and western parts of the basin [35]. The ARB is classified as an arid basin with temperatures between 6.7 and 50 °C [36], precipitation generally falls as rainfall in the range of 187-360 mm/y, and snowfall is very limited [37]. The streamflow of the river reaches zero from June to October. The streamflow is controlled by Adhaim Dam, constructed in 1999 [38]. Adhaim river is formed by the conjunction of Al-Zarka, Al-Kour, Kurei Chi, Jardai, and other small streams [39].

2.2 Data

The daily records of PCP for the period from 1/1/1990 to 31/12/2019 in Kirkuk meteorological station located in the coordinate; latitude 35°27'58.78"N and longitude 44°19'3.27"E (Station 1 in Table 1) were provided by Iraqi Meteorological Organization and Seismology (IMOS). In addition, the CFSR PCP data for the same period were downloaded from <https://swat.tamu.edu/> at a station located in the coordinate; latitude 35°11'11.36"N and longitude 44° 8'28.88"E (Station 2 in Table 1).

The Tmin, Tmax, wind speed, relative humidity, and solar radiation for Stations 1 and 2 were downloaded from Climate Forecasting System Reanalysis (CFSR). The CFSR weather data were recommended in SWAT applications in ungagged watersheds or missing data [40, 32].

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) of 90 m spatial resolution were used in SWAT for watershed delineation and determination of stream locations (downloaded from; <http://glcf.umd.edu/data/srtm/>, access date 30/4/2021). The Moderate Resolution Imaging Spectroradiometer (MODIS) land cover/use of 500 m spatial resolution (downloaded from; <http://gdex.cr.usgs.gov/gdex/>, access date 10/4/2021) and Food and Agriculture Organization (FAO) soil data of 1:500000 spatial scale (downloaded from; <https://www.fao.org>, access date 22/4/2021) were used in defining Hydrologic Response Units in SWAT [33]. Figure 2 shows the spatial data used in the SWAT model.

The observed daily streamflow at Adhaim Dam location was provided by National Center for Water Resources Management, Baghdad (NCWRM) from 1/1/1990 to 31/12/2019.

The average Tmin (Tmax) over ARB is shown in Table 1 within the range 3.6 and 25.1 °C (12.2 and 43.9 °C). The mean annual PCP for Stations 1 and 2 was 322.7 and 409.3 mm/y, respectively.

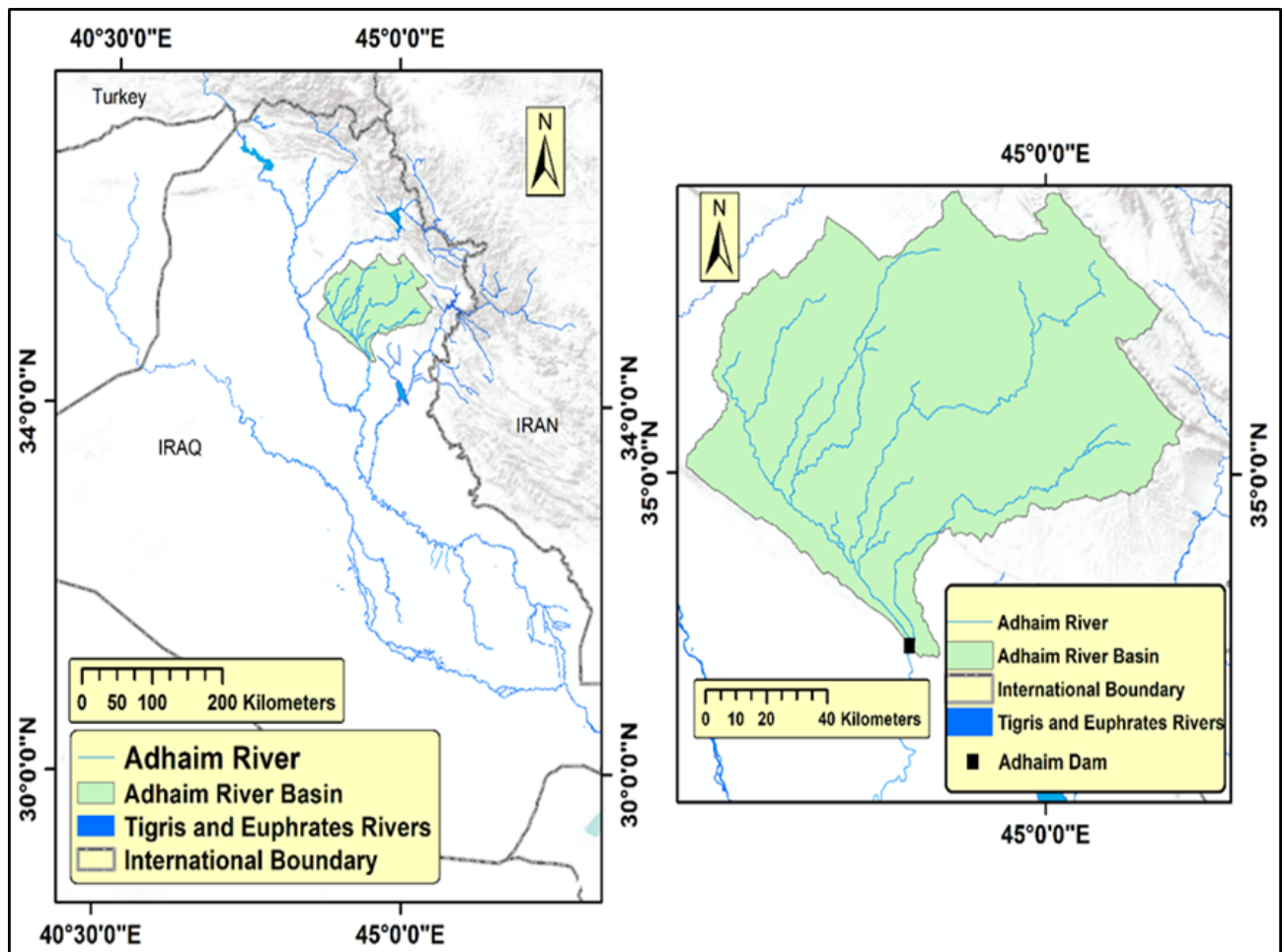


Figure 1: Location map for Adahim River basin

Table 1: The average recorded Tmin, Tmax, and PCP for ARB ((IMOS, 2021 and CFSR, 2021)

Month	Station 1			Station 2		
	Tmin (°C)	Tmax (°C)	PCP (mm)	Tmin (°C)	Tmax (°C)	PCP (mm)
Jan	3.8	12.5	62.0	3.6	12.2	82.1
Feb	4.6	14.8	53.2	4.3	14.3	70.2
Mar	7.5	20.3	44.6	7.3	19.8	63.8
Apr	13.1	27.5	36.6	12.7	26.9	45.6
May	18.5	34.4	18.1	18.3	33.9	19.7
Jun	22.4	40.7	3.9	22.4	40.3	4.0
Jul	25.1	43.9	0.3	25.0	43.7	0.0
Aug	25.1	43.5	1.5	25.1	43.2	1.5
Sep	21.1	38.7	0.3	21.2	38.3	0.3
Oct	16.8	31.2	13.4	16.8	30.8	15.2
Nov	10.1	21.1	36.5	10.0	20.8	45.9
Dec	5.5	14.7	52.3	5.3	14.4	61.0
Sum			322.7			409.3

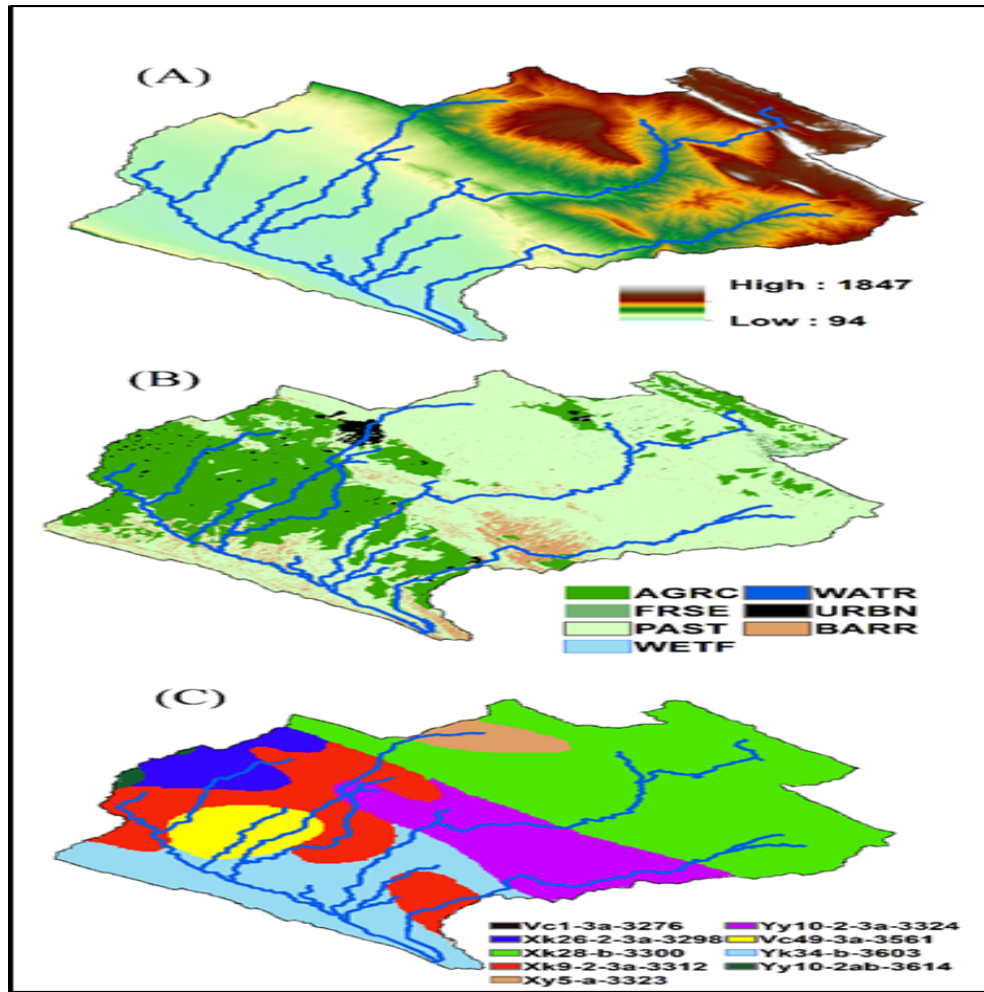


Figure 2: The Spatial data used in the SWAT model, A) SRTM DEM, B) Classified MODIS land cover/use, and C) Classified FAO soil data

2.3 Climate Change Prediction Model

The LARS-WG is an efficient model applied successfully in water resources applications [41,42]. The model statistically generates future weather time series based on records in a single station based on semi-empirical distribution. The model required Tmin, Tmax, PCP, and solar radiation as input data for simulation. LARS-WG simulates the precipitation by defining the wet and dry occurrence from input data. The Tmin and Tmax were simulated stochastically based on average and standard deviation of recorded temperatures using finite Fourier series. [43]. The sixth version of the LARS-WG model includes phase five of Coupled Model Inter-comparison Project (CMIP5) and the capability to project climate data into the year 2100 under the RCPs 2.6, 4.5, 6, and 8.5. The model is characterized by the ability to simulate extreme hydrologic events, possess the noises and errors in time series, fill the gaps in time series, interpolate the observation values located outside of the feasible range, and optionally to used specific GCMs [44, 45].

2.4 Hydrological Model

The United States Department of Agricultural (USDA) developed SWAT to simulate the hydrological process under various climate scenarios and land management. The model is semi-distributed since the watershed is divided into sub-basins based on topographic data. The watershed is further divided into Hydrologic Response Units (HRUs) based on grids of similar land slope, land cover/use, and soil data [46]. Finally, the water balance equation (Equation 1) is implemented in each HRU for surface runoff calculations.

$$W_f = W_b + \sum_{i=1}^t (P_{day} + Q_s - E_a - W_{se} - Q_g) \quad (1)$$

Where: W_f is the available final soil water (mm); W_b is the available soil water at the beginning at the time i (mm); P_{day} is the magnitude of precipitation at the time i (mm); Q_s is the magnitude of surface runoff at the time i (mm); E_a is the magnitude of evapotranspiration at the time i (mm); W_{se} is the magnitude of water entering the vadose zone from the soil profile at the time i (mm); Q_g is the magnitude of return flow at the time i (mm), and the t is the time (day).

The automatic calibration model called Calibration and Uncertainty Programs (SWAT-CUP) is traditionally used to calibrate SWAT simulation. In addition, the program optionally provides five mathematical techniques, the Sequential Uncertainty Fitting-2 (SUFI2), Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol), Particle Swarm Optimization

(PSO), and Markov Chain Monte Carlo (MCMC), for possessing of calibration and validation of results extracted from SWAT [47].

2.5 Methodology

The recorded Tmin, Tmax, and PCP in RP were projected into P1, P2, and P3 using the LARS-WG model. The model runs under the RCP 2.6, 4.5, and 8.5 of greenhouse emissions and five GCMs named Hadley Centre Global Environment Model-version 2 (HadGEM2-ES), Canadian Earth System-second generation Model (CanESM2), Beijing Climate Centre Institute of Atmospheric Physics (BCC-CSM1), Norwegian Earth System Model (NorESM1), and Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO-MK36). The observed weather and streamflow data of RP were used in calibration and validation of the SWAT model using 200 simulations and four trails in SWAT-CUP, based on parameters suggested by [48,34] and the SUFI-2 algorithm provided by SWAT-CUP. The projected Tmin, Tmax, and PCP were input into calibrated SWAT model to project future streamflow under the same climate conditions and periods used in LARS-WG. The results were analyzed, displayed in tables and figures, and then discussed with other researchers.

3. Results and Discussions

3.1 Future Trends in Climate Variables

Results of predicting Tmin, shown in Figure 3, indicated that the projected Tmin in ARB tends to increase in the future compared with Tmin recorded in RP. Under RCP 2.6, the lower increase was observed in January with 0.9, 3.9, and 4.5 % for P1, P2, and P3, respectively. However, the highest increase in Tmin was found at 11.5 (in February), 20.2 (in March), and 16.5 % (in December) for P1, P2, and P3, respectively. On the other hand, under RCP 4.5 (RCP 8.5), a lower rate of increase in Tmin is expected in August with 3.8, 7.5, and 9.9 % (5.3, 11.6, and 18.6 %), for P1, P2, and P3, respectively. In contrast, the highest increase in January was found with 19.7, 34.6, and 54.8 % (20.5, 51.8, and 80.4 % for P1, P2, and P3, respectively).

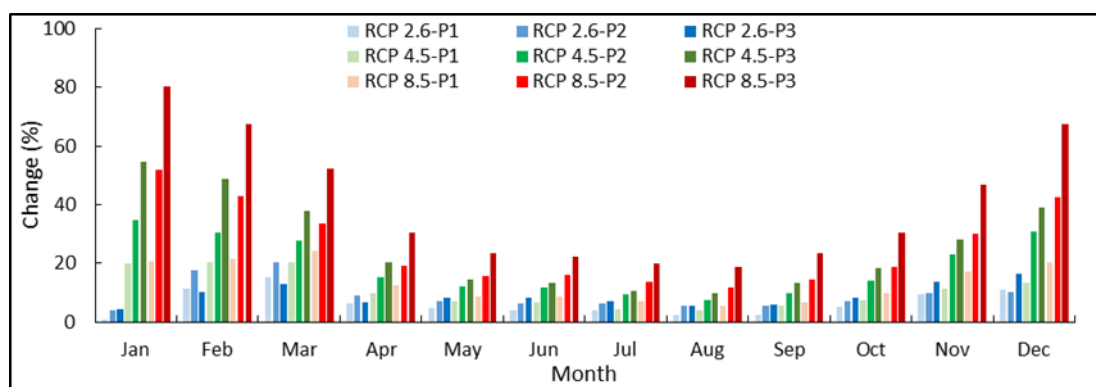


Figure 3: Future trends in Tmin

In Figure 4, a noticeable increase in Tmax over ARB can be seen. Under RCP 2.6, the lowest increase in Tmax for P1, P2, and P3 was 0.9 in December, 2.2, and 2.4 % in April, respectively. Moreover, the highest increase is expected to occur in February with 7.4, 9.6, and 9.5 % for P1, P2, and P3, respectively. Under RCP 4.5, the lowest (highest) rate of increase in Tmax was found in October with 2.9, 5.8, and 8.8 % (9.9, 15.5, and 20.8 % in February) for P1, P2, and P3, respectively. Under RCP 8.5, the lowest increase is expected at the rate of 3.6 (in October), 7.3 and 11.3 % (August) for P1, P2, and P3, respectively. However, the highest increase could reach 12.3, 18.9 (both in February), and 34.5 % (in January) for P1, P2, and P3, respectively.

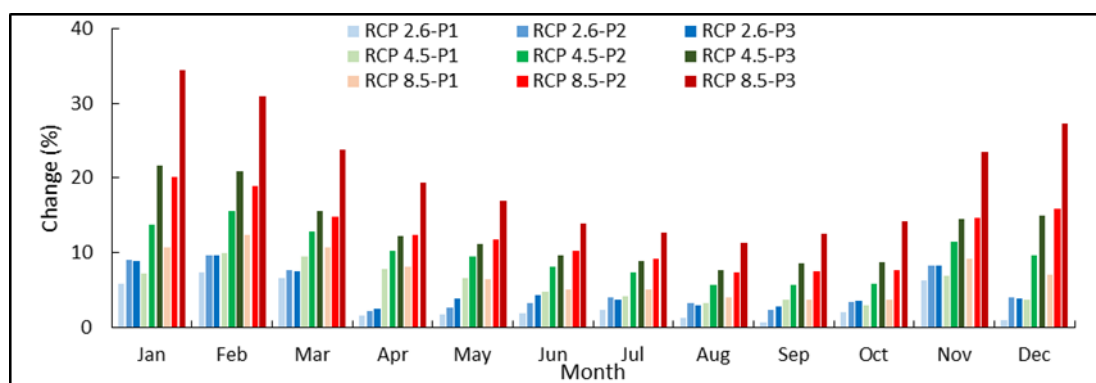


Figure 4: Future trends in Tmax

The results of projected Tmin and Tmax indicated that winter is accelerated towards warming more than summer. These results agree with Saeed et al. [49] Furthermore, according to the analysis presented by Zhang et al. [50], the results showed that temperature increased in winter at a rate compared with the increase in summer for MENA from 1950-2003.

Figure 5 shows the future trend in precipitation. It can be noticed that the projected precipitation, in general, tends to decrease over ARB. For example, under RCP 2.6, the highest decrease was found at 2.24, 2.5 (in December), and 3.65 % (in January) for P1, P2, and P3, respectively. Moreover, under RCP 4.5 (RCP 8.5), the highest decrease could reach 3.07, 2.97, and 4.88 % (1.85, 2.99, and 6.29 %) for P1, P2 (at P1 and P2 both in January) and P3 (at P3 in December), respectively. However, the figure shows a small increase in projected PCP over ARB under RCP 2.6 climate conditions with 3.09 % (in April) and 3.3 % (in November) for P2.

Results found by other researchers indicated that the projected precipitation over Iraq is expected to decrease by 5-30% [24,51]. However, the Inter-Tropical climate zone tends to move northward, which will generate fluctuation in precipitation as a small increase in precipitation over the southern and middle regions of the Arabian Peninsula [23]. These conditions will reflect the spatiotemporal distribution of water resources in ARB.

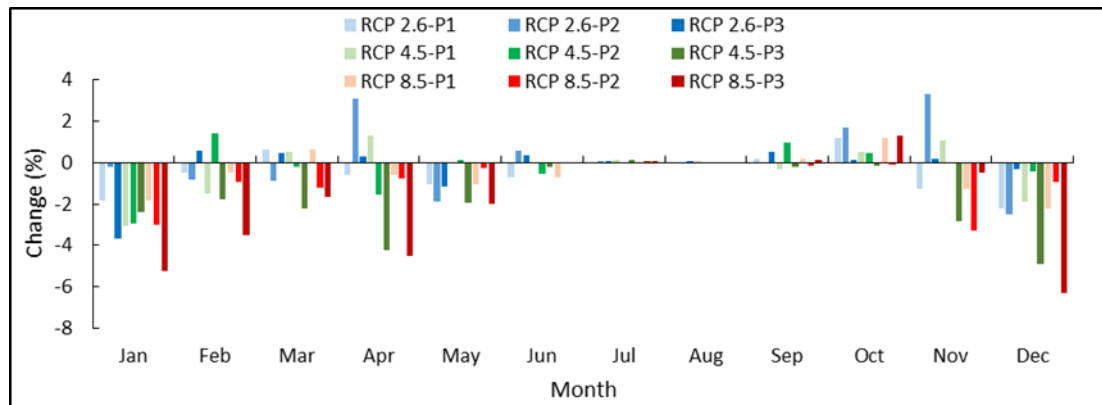


Figure 5: Future trends in PCP

3.2 Sensitivity Analysis, Calibration, and Validation of SWAT

The results of the sensitivity analysis possessed by SWAT-CUP are introduced in Table 2, showing that the calibrated streamflow is highly sensitive to CN2 over other hydrologic parameters. For example, the groundwater parameters (GW_DELAY, ALPHA_BF, GWQMN, and GW_REVAP) have the second sensitivity rank. On the other hand, the SOL_AWC, HRU_SLP, and OV_N are the less sensitive parameters to the calibrated streamflow.

Table 2: Sensitivity analysis of calibrated hydrologic parameters

Rank	Parameter Name	Description	t-Stat	P-Value	Initial (final) range	
1	CN2.mgt	SCS-curve number	-17.76	0.00	-0.5 (-0.07)	0.5 (-0.14)
2	GW_DELAY.gw	Groundwater delay	0.63	0.53	30 (53)	450 (235)
3	ALPHA_BF.gw	Baseflow alpha factor	1.11	0.27	0 (0.4)	1 (0.73)
4	GWQMN.gw	Threshold depth of water in the shallow aquifer	-1.19	0.24	-0.5 (-0.3)	0.5 (-0.4)
5	GW_REVAP.gw	Groundwater re-evaporation	0.34	0.73	-0.5 (-0.2)	0.5 (-0.5)
6	SOL_AWC(..).sol	Soil available water capacity	1.24	0.22	-0.5 (-0.4)	0.5 (0.49)
7	HRU_SLP.hru	HRU slope	1.23	0.22	-0.5 (0.23)	0.5 (0.2)
8	OV_N.hru	Overflow Manning coefficient	-0.12	0.91	-0.5 (0.2)	0.5 (0.52)

The calibrated streamflow in arid and semi-arid watersheds showed high sensitivity to CN2 and groundwater parameters. These parameters are the most controlled in simulated streamflow than other parameters in arid and semi-arid watersheds [52,53].

Figure 6 shows that the Nash Sutcliffe efficiency (NS) and coefficient of determination (R²) were maximized for calibration processes to reach 0.7. For the validation processes, the NS and R² reached 0.74 and 0.75, respectively. These are acceptable and very good ranges for calibration and validation of the SWAT model, as stated by [54].

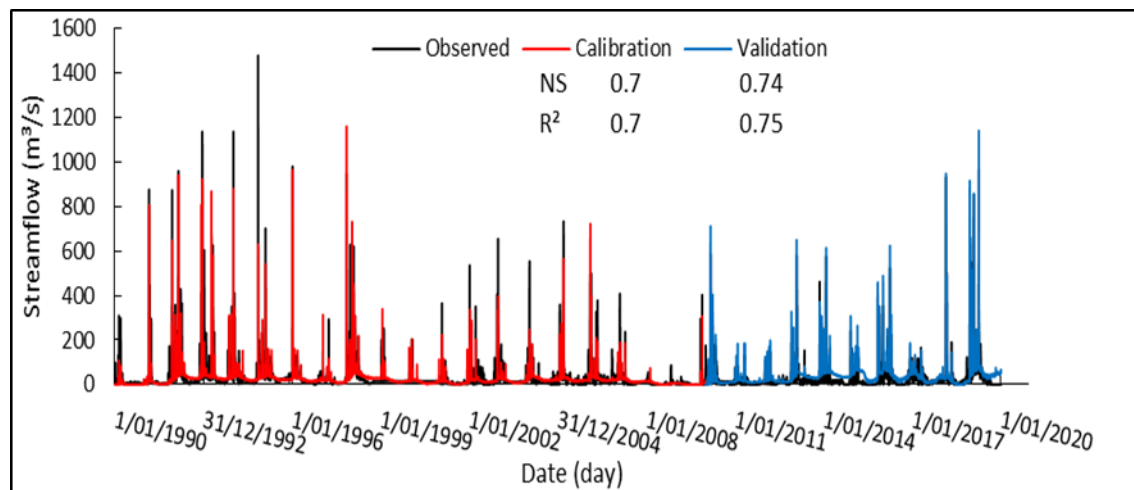


Figure 6: Calibrated and validated streamflow of ARB

3.3 Future Trend in Evapotranspiration

Figure 7 shows the mean annual evapotranspiration in RP of 2198.7 mm/y, with the highest and lowest rate in July and January with 317.7 and 53.4 mm, respectively. The consequents of increased temperature and the projected evapotranspiration also tend to increase. Under RCP 2.6, the highest (lowest) rate of increase was found in March (September) with 4.4, 5.4, and 4.9 % (0.5, 1.9, and 2 %) for P1, P2, and P3, respectively. Under RCP 4.5, the increase is expected with 6.1 in March and 8.4 and 11.6 % in February for P1, P2, and P3, respectively. However, the lowest increase could be observed in August with 2.1, 3.9, and 5 for P1, P2, and P3, respectively. Under RCP 8.5, the highest increase in projected evapotranspiration was found at 7.1 in March, 10.4 in February, and 18 % in January for P1, P2, and P3, respectively. In contrast, the lowest increase is expected to occur in August with 2.6, 5.1, and 7.6 % for P1, P2, and P3, respectively.

The highest evapotranspiration rate in central Iraq is recorded in July and August [55]. Therefore, the evapotranspiration tends to be accelerated in winter months more than in summer months due to the temporal variation of increase in projected temperature. The evapotranspiration showed high sensitivity to global warming with an annual increase of 92 mm/y in the eastern Mediterranean Region [56].

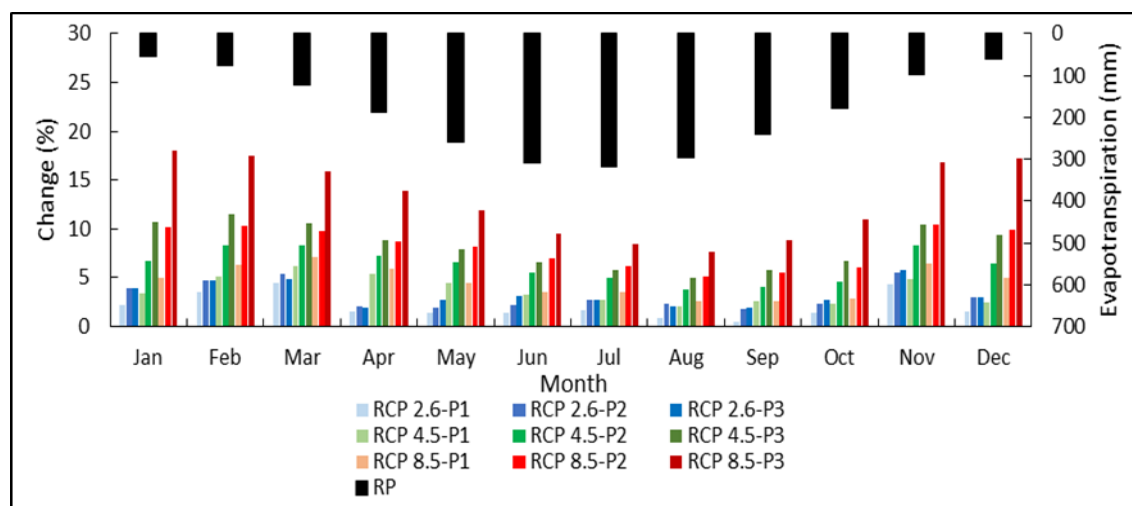


Figure 7: Future trend in evapotranspiration for ARB

3.4 Future Trends in Streamflow

The predicted future trend in projected streamflow for ARB is shown in Figure 8. To eliminate the variation among the GCMs, the average of these models was considered in the analysis of future streamflow[57,58]. It is worth noticing that the annual streamflow in RP of 28.96 m³/s magnitude, with a peak, reaches 63.6 m³/s in February. Therefore, under RCP 2.6, the average annual streamflow tends to decline with 28.58, 28, and 27.86 m³/s for the P1, P2, and P3, respectively. Under RCP 4.5, the average annual streamflow is expected to decrease with 27.55, 26.66, and 25.54 m³/s for the P1, P2, and P3, respectively. Moreover, Under RCP 8.5, the average annual streamflow tends to drop to 24.81, 24.3, and 23.68 m³/s for the P1, P2, and P3, respectively.

The presented results in Figure 8 show no significant shifting in projected peaks under all considered scenarios and future periods. This is because the rainfall dominates ARB, and the snowfall is very limited. Therefore, snow parameters were not observed in calibrated hydrologic parameters in SWAT (see Table 2). Chiew [59] indicated that the streamflow is sensitive to rainfall in arid regions. Other researchers found that the peak of streamflow is highly related to snowmelt under climate change conditions [60,61,62][32].

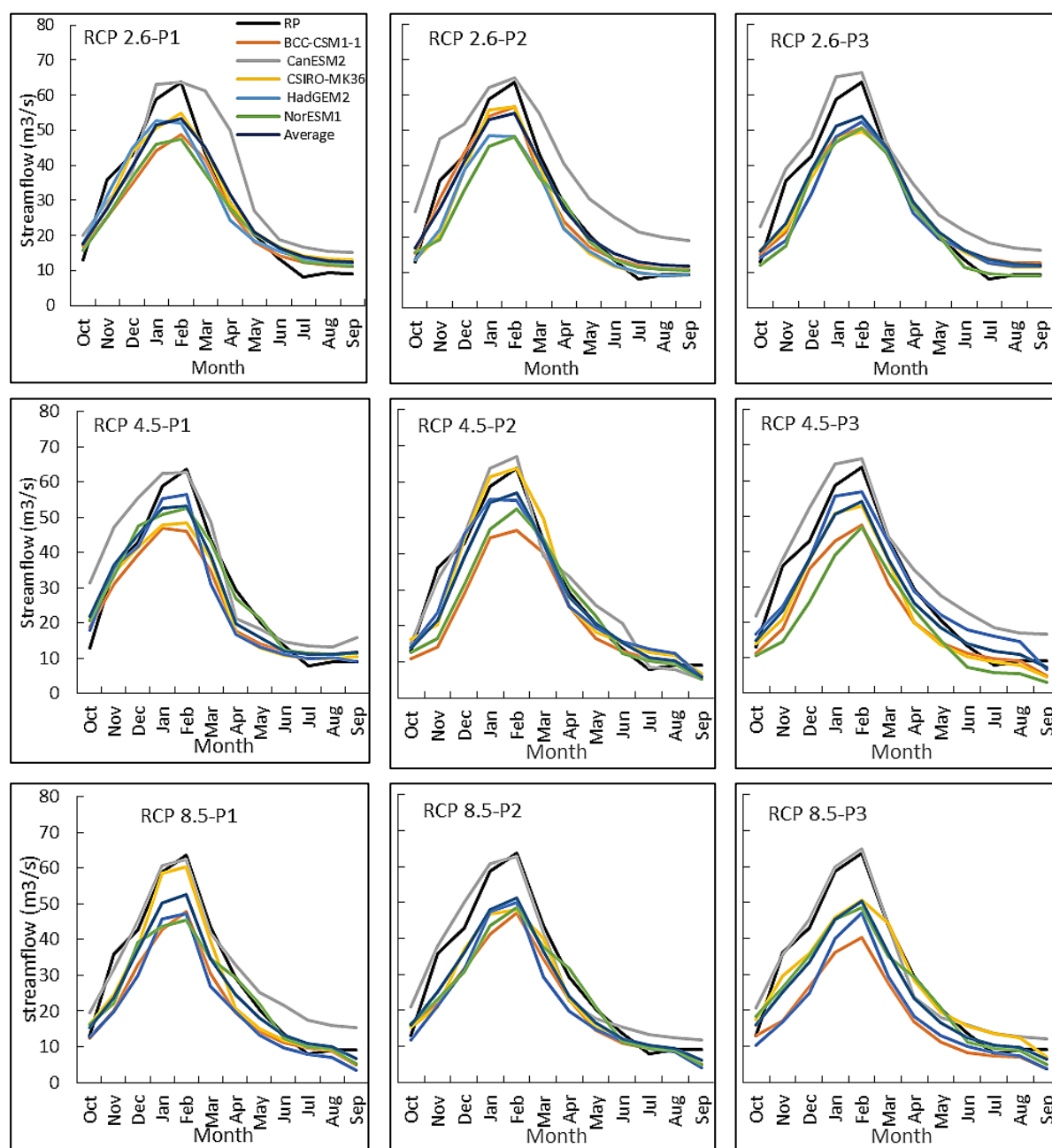


Figure 8: Future trend in streamflow of ARB

4. Conclusion

This paper investigates the climate conditions and streamflow in ARB for three future periods of 20 years starting from 2021 under various global warming scenarios. This investigation is performed under three RCPs, which are 2.6, 4.5, 8.5, and five GCMs. The LARS-WG and SWAT were used to conduct this investigation.

The results show that ARB tends to become drier and hotter by 2080 due to climate change induced by global warming. By 2080, the mean temperature will rise by 1.2, 2.9, and 4.6 °C under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. The consequence of temperature rise is increasing the evapotranspiration over ARB from 2198.7 mm/y in RP to 2262.9, 2324.1, and 2445 mm/y by the year 2080 under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. Furthermore, the average annual precipitation decreases from 366 mm/y to 320.2, 302, and 300.5 mm/y by 2080 under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. Therefore, the streamflow will decline from 28.96 m³/s in RP to 27.86, 25.54, and 23.68 m³/s by 2080 under RCP 2.6, RCP 4.5, and RCP 8.5, respectively.

The paper presented an integrated analysis of climate change's impact on future ARB streamflow in response to various global warming scenarios. However, a remarkable decrease is expected in projected streamflow with no monthly shifting can be observed as the ARB is located in the arid region of Iraq, and there is no considerable snowmelt contribution with streamflow. The paper also showed that the streamflow for arid watersheds is extremely controlled by CN2 and groundwater parameters.

The main finding of this paper indicated that the ARB would be under water stress due to climate change. Furthermore, the expected population growth and expanded agricultural and municipal water demands will exacerbate the stress rate. Therefore, adaptation strategies are highly recommended to accommodate the negative impacts of climate change. These strategies should be adopted by decision-makers, including reforming water resources management agencies, justification of the water priorities among water consumers, improving water use efficiency, and evaluating the responses of water consumers to each other when applying adaptation plans.

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Author contribution

Methodology Fouad H. Saeed, Mahmoud S. Al-Khafaji, and Furat Al-Faraj; Software Fouad H. Saeed; Formal Analysis Fouad H. Saeed, Mahmoud S. Al-Khafaji, and Furat Al-Faraj; Writing-Original Draft Preparation, Fouad H. Saeed; Writing-Review & Editing Fouad H. Saeed, Mahmoud S. Al-Khafaji, and Furat Al-Faraj. "All authors have read and agreed to the published version of the manuscript."

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

"The authors declare no conflict of interest."

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