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Investigating the uncertainty of atmospheric general circulation models in simulating the future runoff of Abu Al-Abbas Watershed, Khuzestan, Iran

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ABSTRACT

One of the most significant challenges in natural ecosystems is climate change, which greatly affects hydrology and the water cycle. This study aimed to examine the uncertainty of general circulation models in simulating runoff in the Abu al-Abbas Watershed in Khuzestan Province. For this purpose, the CMIP6 model scenarios SSP126, SSP245, SSP370, and SSP585 were used, and the minimum and maximum temperature and precipitation variables were simulated using the LARS-WG software. The IHACRES model was employed to simulate monthly discharge during the period 1992-2020. The results of evaluating the simulation of climatic data for future periods indicate the strong performance of the models utilized. The simulated climatic data for the future showed that the annual temperature and precipitation would increase by up to 3.5˚C and 93 mm in the most pessimistic scenario and by 1.2˚C and 0.9 mm in the most optimistic scenario. The results demonstrated that the CNRM model had the least uncertainty in the SSP126 scenario. Using this model, the monthly runoff for this watershed was simulated for the base period and future periods as 2021-2050 and 2051-2080; runoff is expected to increase by 20 to 25% during the period 2021-2050 and by up to 27% during the period 2051-2080.

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1. Introduction

In recent decades, the Earth's climate has been changing due to the expansion of industrial activities in human societies and possibly natural processes. Climate change, an atmospheric-oceanic phenomenon driven by increased greenhouse gases, leads to global warming and alters the hydrological behaviors of various regions. Global warming refers to the rise in Earth's temperature caused by human activities, distinct from natural variations (IPCC, 2023). This phenomenon can impact multiple systems, with water resources being one of the most affected (Najafian et al., 2017). Climate change can significantly alter the distribution of Earth's water resources, profoundly affecting agricultural production and related industries. Understanding these changes is crucial for future water resource planning. To study future climate changes, models are essential (Wilby and Harris, 2006).

Evaluating the impacts of climate change involves identifying three key aspects of uncertainty. First, there is uncertainty in general circulation models. Second, there is uncertainty in regional climatology, which includes uncertainties in statistical or dynamic downscaling methods. Third, there are parametric and structural uncertainties in various models used for impact assessment (Efron and Tibshirani, 1993). In most climate change studies, several general circulation models that have produced acceptable results are often used as climate scenarios. However, the uncertainty in analyzing the results of these models has not been adequately considered. In recent years, researchers have focused on sources of uncertainty related to general circulation models, downscaling methods, greenhouse gas emission scenarios, and various rainfall-runoff models in their studies. For instance, Iranshahi et al. (2022) examined the effects of climate change on temperature and precipitation in the Alishtar and Khorramabad regions. Their results indicated that, in both the near and far future, the maximum and minimum temperatures at the Alishtar and Khorramabad stations would increase compared with the observational period in all SSP scenarios, with the minimum temperature changes being greater than the maximum temperature changes.

Eslami and Ghanghermeh (2022) conducted a study to examine the Caspian Sea water level using climate models from the IPCC Sixth Assessment Report. The results indicated that under the SSP245 scenario, with moderate greenhouse gas emissions maintained at current levels until 2050 and reduced by 2100, the Caspian Sea water level will exhibit a steady decline. Conversely, under the SSP585 scenario, characterized by severe greenhouse gas emissions and a tripling of carbon dioxide levels by 2075, the Caspian Sea water level will remain stable until 2050 but will begin to decrease thereafter.

The results of climate change impact assessment studies are confronted with significant and unavoidable uncertainties. In this context, Abdolalizadeh et al. (2022) evaluated the accuracy of CMIP6 models in simulating temperature and precipitation in the Urmia Lake basin. This study assessed the precision of general circulation models from the IPCC Sixth Assessment Report in replicating the temperature and precipitation of the Urmia Lake watershed. The findings revealed a strong linear relationship between the corrected model data and observational stations for temperature, but a weak linear relationship for precipitation across the entire basin. The RMSE and NRMSE indices indicated high accuracy of the models in simulating monthly temperatures, while their accuracy in simulating monthly precipitation was relatively weaker. Among the models, CMCC exhibited the highest error. The spatial distribution maps of NRMSE for the monthly averages demonstrated that all four models simulated temperature with high accuracy, but the precipitation simulations in some areas of the basin lacked acceptable accuracy. Consequently, the accuracy of the studied models in simulating temperature was deemed good, whereas their performance in simulating precipitation, particularly in the CMCC model, was evaluated as weak.

Dehghani et al. (2021) evaluated the uncertainty of regional climate models in Birjand County. This study assessed the accuracy and performance of these models. The results indicated that the average monthly index of the period exaggerated the efficiency of the models and methods, and the optimal model varied depending on the type of statistical index and the period considered. Ignoring uncertainties in study results can lead to unreliable and misleading outcomes. However, accounting for uncertainties makes the results more reliable and aids in better decision-making and precautionary measures (Khazaei et al., 2017). It is always possible that not all influencing factors are included in the model simulation. Therefore, the analysis is accompanied by uncertainty, and understanding the error or uncertainty of each model is essential for judging and trusting the results (Refsgaard et al., 2007).

Given the detrimental effects of climate change and the importance of water resource management, it is crucial to consider the impacts of this phenomenon on water resources. One method to examine the effect of climate change on water resources is to study the changes in streamflow at the basin outlet. Various models have been proposed to simulate the rainfall-runoff relationship, with the IHACRES model being one of them. This model, while providing appropriate responses, requires limited input data, which enhances its applicability for determining basin outflows (Ahmadpour et al. 2020). Numerous studies have highlighted the robust performance of this model and have utilized it to simulate streamflow changes under climate change conditions (Dehghanifard et al., 2022). Regarding the uncertainty of models and climate change scenarios, various researchers have conducted extensive studies. Many studies have also focused on examining the impacts of climate change on the hydrological phenomena of basins. This research aims to investigate the uncertainty of general circulation models, evaluate their performance in simulating climatic data under different scenarios, and simulate runoff under climate change conditions in the Abu Al-Abbas region of Baghmalek.

2. Materials and Methods

2.1 Study area

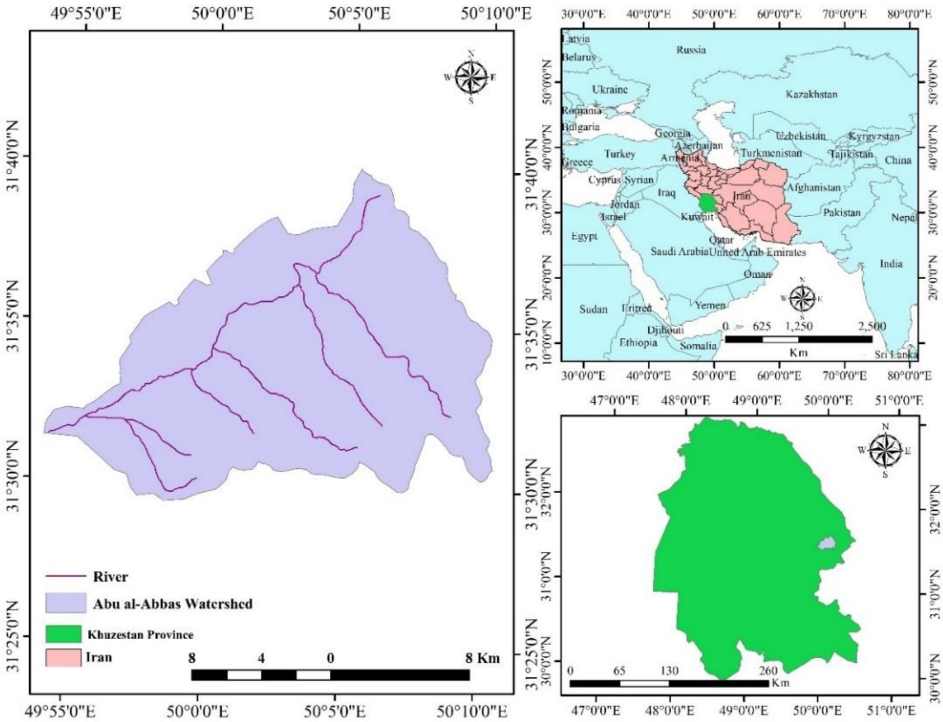
The Abu Al-Abbas Watershed is located in the east of Baghmalek County in Khuzestan Province, within the geographical coordinates of 31°28'23" to 31°40'14" N latitude and 49°59'26" to 50°5'12" E longitude, covering an area of 286.21 km². The elevation of this basin ranges from 691 m to 3283 m above sea level, with an average elevation of 1885 m. The Abu Al-Abbas River is the largest sub-basin of the Rood Zard River, which supplies water to a large portion of the agricultural lands in Baghmalek County. Fig. 1 shows the location of the study area. In the present study, due to the short statistical period and the deficiencies in data collection at other meteorological stations around the study basin, data from the Ramhormoz and Baghmalek meteorological stations were used for downscaling. Additionally, data from the Pol-e-Manjanigh station at an elevation of 675 m were used to calibrate the runoff model.

2.2 Climate change modeling

In this study, the latest version of the LARS-WG 6 model was utilized. LARS-WG, as a weather generator, can simulate daily weather variables for any duration based on a set of semi-empirical distribution frameworks. Initially, the model is calibrated, followed by validation using statistical tests and chart comparisons. For this purpose, statistical criteria such as the coefficient of determination (R^2), mean squared error (MSE), and root mean squared error (RMSE) were employed.

After assessing the model's performance in simulating the behavior of climatic variables during the baseline period (1992-2020), meteorological data for future periods (2021-2050 and 2051-2080) and general circulation scenarios were simulated based on climate model data. This research incorporated the latest CMIP6 scenarios. Since these scenarios were not available at the time of writing, future climate scenarios were manually prepared based on past and future precipitation, maximum temperature, and minimum temperature data obtained from the climate change website and introduced to the model. Finally, using the SSP126, SSP245, SSP370, and SSP585 scenarios and the BCC, ACCESS-CM2, CNRM, CANESM5, FGOALS, GFDL, and INM models, future climatic parameters were simulated at the regional scale of the study area.

Fig.1 Location of study area



2.3 Uncertainty

In this study, two methods were used to examine and reduce the uncertainty of simulations: the Box-Whisker method and the non-parametric Bootstrap confidence interval method. Initially, outliers were identified and removed using the Box-Whisker plot. This method uses a rectangle with two lines on either side to depict the statistical parameters of the median, first, and third quartiles, and the minimum and maximum observed values for the parameter under study. The top and bottom of the rectangle represent the third and first quartiles, respectively, and the line inside the box represents the second quartile (median) (Rohani et al., 2017). The horizontal lines at the ends of the whiskers indicate the minimum and maximum data values. This plot allows for the interpretation of the central tendency, dispersion, and skewness of the data. Therefore, after downscaling, the simulated data with the LARS-WG model and various scenarios were plotted using the Box-Whisker method.

Subsequently, the Bootstrap method was used to examine the confidence interval of the simulated data over two periods. Bootstrap generates data under highly complex conditions without imposing any assumptions and naturally considers the empirical distribution of these data as an estimate of the original and unknown distribution (Rohani et al., 2017). Bootstrap is a resampling method and a subset of the Monte Carlo method, where samples are taken from the data with replacement, equal to the number of data points in each series. This process is typically repeated a thousand times, calculating a mean and variance for each iteration, and then the confidence interval for the thousand iterations is computed (Efron and Tibshirani, 1993).

2.4 Runoff simulation

After selecting the general circulation model and scenario with the least uncertainty, the future climatic data obtained were used to simulate rainfall-runoff for the upcoming period using the IHACRES model. The IHACRES model (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation, and Streamflow data) is an integrated conceptual model for simulating rainfall-runoff (Salimi et al., 2023). This model offers several advantages over other rainfall-runoff models, including lower input data requirements, a simple algorithm, and applicability to both gauged and ungauged basins. It can simulate rainfall-runoff using temperature, precipitation, and basin area data (Khalili et al., 2022). The method comprises two modules: a nonlinear loss module and a linear unit hydrograph module. Initially, rainfall is converted to effective rainfall using the nonlinear module at each time step, and then it is converted to surface runoff using the linear unit hydrograph module at the same time step (Hakami Kermani et al., 2021).

2.5 Runoff model performance

To evaluate the performance of the IHACRES model in simulating monthly runoff in the Abu Al-Abbas Watershed, various calibration periods were examined, and the period 1992-2001 was selected as the optimal calibration period. After determining the parameters, the model was validated for the period 2002-2020. The performance metrics used in this study include the Nash-Sutcliffe efficiency (NSE) and the coefficient of determination. The NSE is used to demonstrate the model's ability to simulate real data, ranging from -∞ to 1, with a value of 1 indicating perfect agreement between simulated and observed data. Eqs. (1) and (2) are used to calculate these coefficients (Eryani, 2022).

$$NSE = 1 - \left(\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right) \quad (1)$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}(O_i - \bar{O}) \times (S_i - \bar{O})\right)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \times \sum_{i=1}^{n}(S_i - \bar{S})^2} \quad (2)$$

Where, O_i and S_i represent the observed and simulated flow values, respectively, and $\bar{O}$ and $\bar{S}$ are the mean observed and simulated flow values, and n is the number of data points considered. The NSE index for flow simulation is considered satisfactory when it ranges between 0.36 and 0.75, and if it exceeds 0.75, the simulation results are considered good (Mojerloo et al., 2019; Eryani, 2022; Joorabian Shooshtari et al., 2022).

3. Results and Discussion

The validation results presented in Table 1 indicate that the correlation between observed and simulated data for maximum and minimum temperatures is higher than that for precipitation. This suggests that temperature variability is less pronounced than precipitation variability. One reason for the lower correlation in precipitation is the influence of various factors on precipitation (Abdolalizadeh et al. 2021). In a study by Abdolalizadeh et al. (2021) evaluating the accuracy of CMIP6 models for simulating temperature and precipitation in the Urmia Lake Watershed, it was also observed that the general circulation models from the IPCC Sixth Assessment Report (CMIP6) were more accurate in simulating temperature than precipitation.

After confirming the model's performance in estimating climatic data during the baseline period, the output of the general circulation model under study was downscaled using the LARS-WG6 model to simulate changes in precipitation and temperature for the future periods 2021-2050 and 2051-2080. The simulated monthly precipitation for the period 2021-2050 varies significantly across models and scenarios. However, in most scenarios, summer and autumn precipitation increased (by 58% to 200%), while winter precipitation decreased (by 8% to 29%). Fig. 2 illustrates the changes in monthly precipitation under the SSP126 scenario for the two study periods. The conditions for the period 2051-2080 are similar, indicating that summer and autumn precipitation increased, while winter precipitation decreased. The results of this study align with those of Iranshahi et al. (2022). Najafian et al. (2017) also reached a similar conclusion in a study conducted in Kermanshah, it was found that precipitation fluctuations in the far future were greater than in the near future.

Table 1 Performance statistics values of LARS-WG model

Parameter	Maximum Temperature	Minimum Temperature	Precipitation
R^2	0.9991	0.9995	0.9813
RMSE	0.3149	0.2052	3.5934
NRMSE	1%	1%	4%

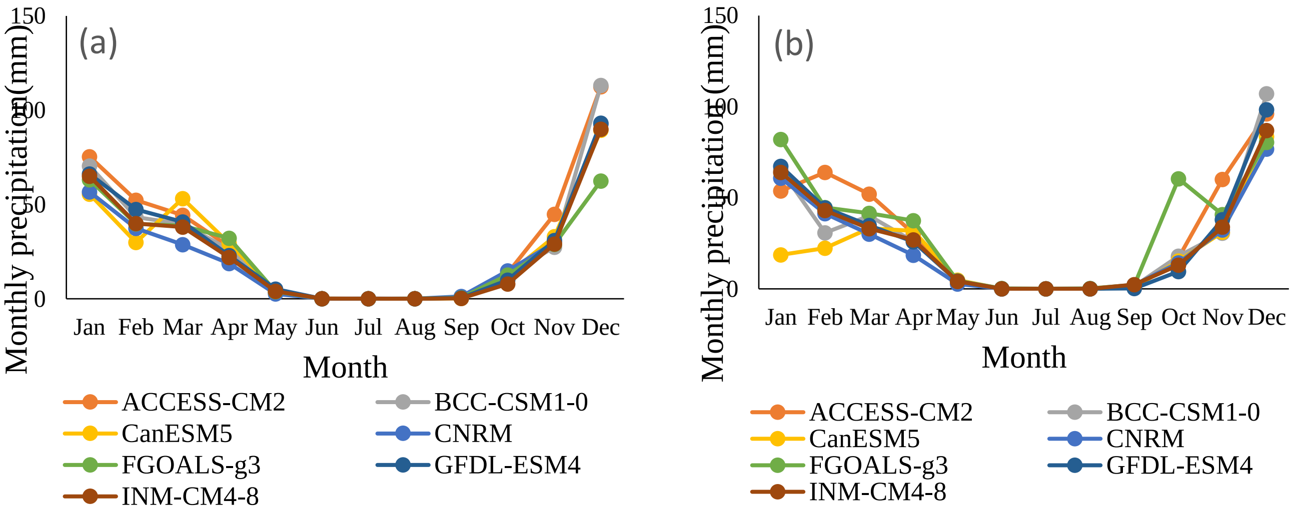


Fig. 2 Simulated monthly rainfall changes in different models under SSP126 scenario during the period of a) 2021-2050, and b) 2050-2080

The changes in monthly precipitation during the baseline period (1992-2020), the near future (2021-2050), and the far future (2051-2080) simulated by the CNRM model under the SSP126 scenario are illustrated in Fig. 3. The analysis indicates that the difference between simulated and observed precipitation is generally smaller in the first period compared to the second period. Minimum precipitation in June, July, August, and September is zero, while the highest precipitation occurs in January and December. During the period 2021-2050, summer and autumn precipitations are projected to increase by 80 and 17%, respectively, whereas spring and winter precipitations are expected to decrease by 190 and 12%, respectively. The most significant increase in monthly precipitation is predicted for October, with a 200% rise. Annual precipitation shows no significant change, with an increase of less than 1%. For 2051-2080, annual precipitation is projected to increase by only 2%. Winter and autumn precipitation are expected to rise by 1.0 and 18%, respectively, while summer precipitation is predicted to triple. However, spring precipitation is anticipated to decrease by 39%. The most notable changes in monthly precipitation are expected in July, September, and October, with increases ranging from 65 to 85%. Conversely, precipitation in May, March, and November is projected to decrease by 15 to 34%.

Fig. 3 Rainfall diagram of the CNRM model under SSP126 scenario during observation and the future periods

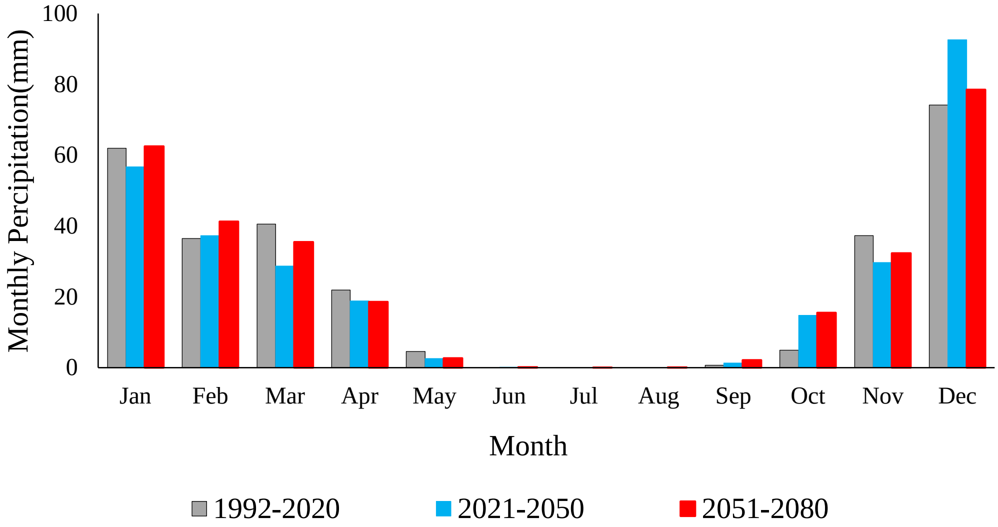
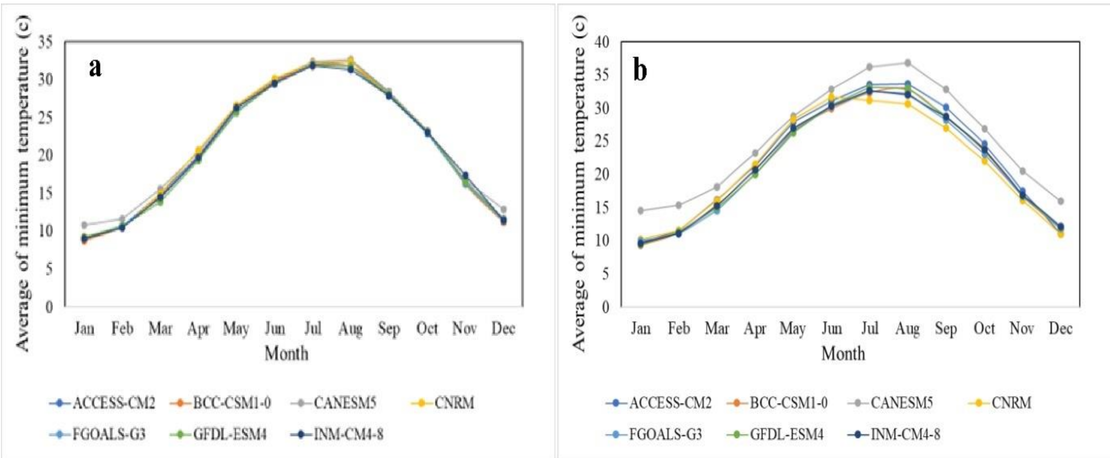


Fig. 4 The average of minimum temperature simulated in different models under SSP245 scenario during the period of a) 2021-2050 and b) 2050-2080



Overall, the results showed that in the two future horizons examined, the minimum and maximum temperatures increased in most general circulation models. The annual average temperature increased by 3.5°C in the most pessimistic scenario (SSP585) and by 1.2°C in the most optimistic scenario (SSP126). Fig. 4 shows the average minimum temperature simulated in various models under the SSP245 scenario, and Fig. 5 shows the average maximum temperature simulated in various models under the SSP585 scenario. However, the precipitation simulations showed significant fluctuations. The models and scenarios used in the precipitation simulation indicated that annual precipitation increased in all models and scenarios during the period 2021-2050. The annual precipitation in the ACCESS-CM2 model and SSP585 scenario showed the highest increase (33%), while the FGOALS model and SSP126 scenario showed the lowest increase (19%). In the period 2051-2080, the highest annual precipitation increase (34%) was related to the FGOALS model and SSP126 scenario, and the lowest simulated annual precipitation was related to the CanESM5 model and SSP126 scenario, with a 2% decrease compared to the baseline period.

The results of the uncertainty analysis (Fig. 6) indicated that among the seven models studied and four scenarios, the CNRM model and SSP126 scenario exhibited the least uncertainty due to their narrower bandwidth. Additionally, the uncertainty bandwidth in the second period (2051-2080) showed more variation compared to the first period (2021-2050). The uncertainty bandwidth for monthly minimum and maximum temperatures ranged from 0.26 to 0.5 °C, while for monthly precipitation, it ranged from 0.5 mm to 33 mm. For the monthly precipitation parameter in the ACCESS-CM2 model, the widest bandwidth in SSP126 during the first period was in January and December (27.3 and 43.7 mm, respectively), and in the second period, it was in February and December (33.4 and 53.2 mm, respectively). In SSP245, the widest bandwidth in the first period was in January and December, and in the second period, it was in January and November. In the other scenarios, January and December continued to have the widest bandwidth. The range of uncertainty for the precipitation parameter is greater than for the temperature parameter, indicating that the uncertainty in simulating precipitation data is higher than for temperature. Fig. 6 shows the uncertainty charts for the CNRM model under the SSP126 scenario for precipitation and temperature during the period 2021-2050. The CNRM model and SSP126 scenario had the least uncertainty, and the data from this model were used to simulate future runoff.

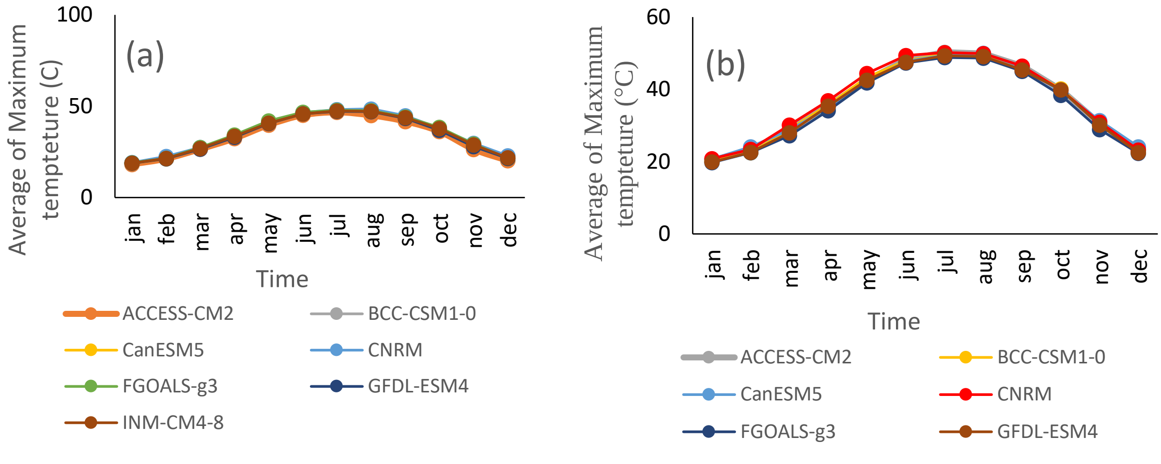


Fig. 5 The average of maximum temperature simulated in different models under SSP585 scenario during the period of a) 2021-2050 and b) 2051-2080

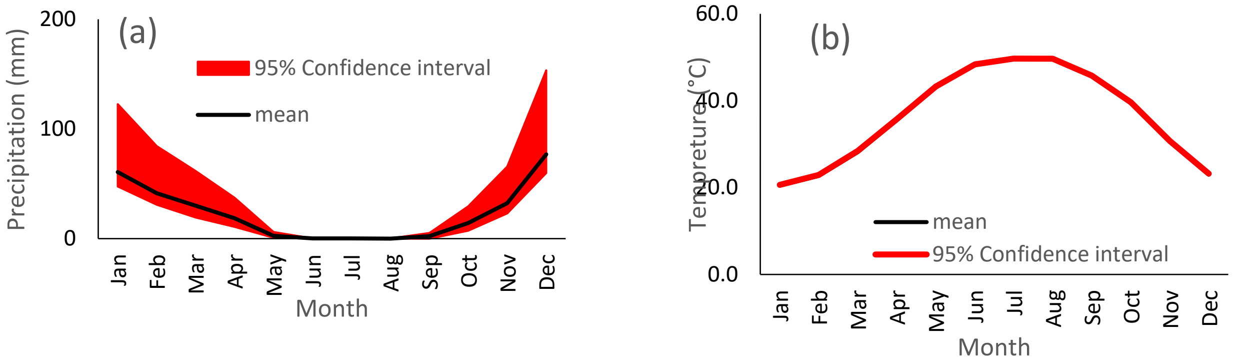


Fig. 6 Computed 95% confidence interval on the precipitation (a) and temperature (b) projected under CNRM model and SSP126 scenario during the period of 2021-2050

Table 2 Results of efficiency of IHACRES model in the calibration stage

R squared	R^2	Bias	NSE
0.93	0.66	0.01	0.69

Subsequently, monthly discharge was simulated using temperature, precipitation, and discharge data from the period 1992-2020 and the IHACRES model. The model's performance was evaluated using efficiency coefficients. The results of the IHACRES model performance evaluation are presented in Table 2.

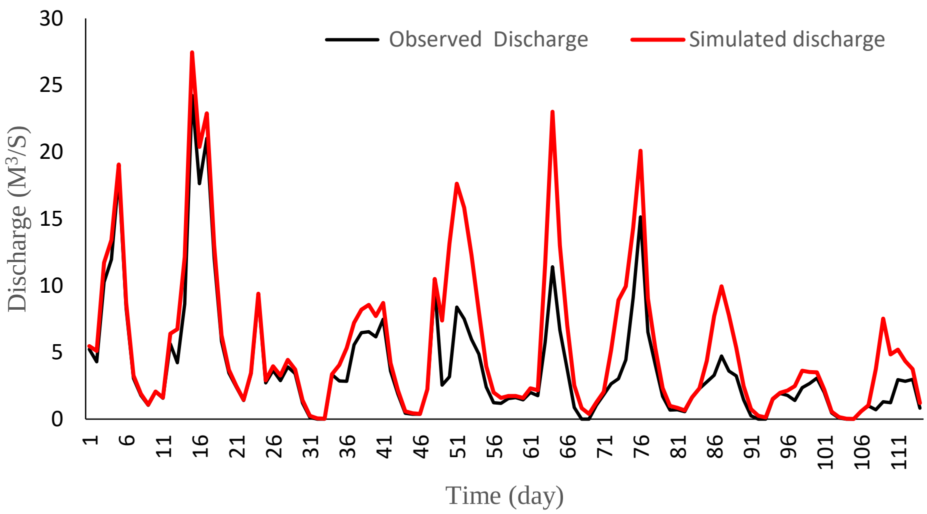


Fig. 7 Time series of observed and modeled runoff in IHACRES model during the base period

Additionally, Fig. 7 shows the simulated and observed discharge values in the study area. As indicated by the chart, the model was able to simulate the flow trend well. Given the Nash-Sutcliffe efficiency coefficient of 0.69 and the coefficient of determination of 0.66, this model was able to simulate the monthly discharge in this basin with acceptable accuracy. Numerous studies have confirmed the acceptable performance of this model in simulating runoff. Studies by

Mojerloo et al. (2019) on the effects of climate change on the discharge of the Tajan Watershed and Dehghanifard et al. (2022) in the Jarreh basin are among these studies. These studies also confirmed that the model was able to simulate base flow and minimum discharge well but did not perform as well in simulating peak flows.

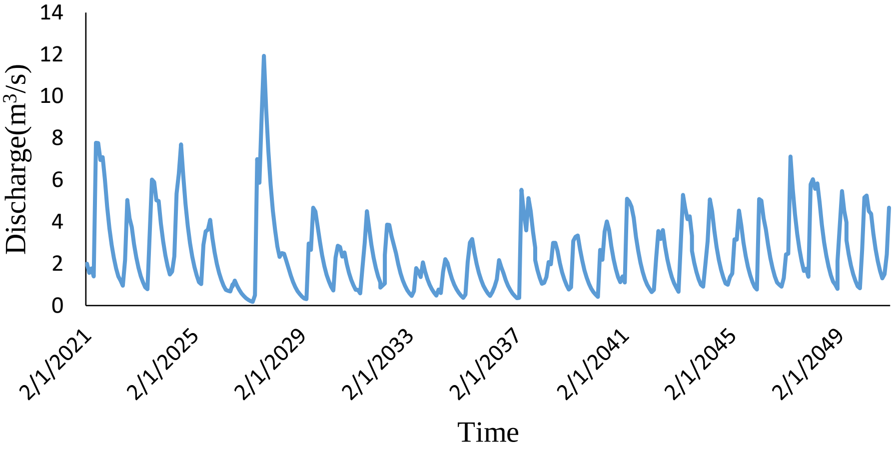


Fig. 8 Modeled runoff time series with CNRM in IHACRES in 2021-2050

After calibrating the IHACRES rainfall-runoff model and confirming its acceptable performance, the future monthly runoff of the basin was simulated using precipitation and temperature data generated by the LARS-WG6 and CNRM models. The results of the monthly discharge simulation for future years (Figs. 8 and 9) showed that the average monthly discharge in the period 2021-2050 will increase compared to the long-term past average. Additionally, in the period 2051-2080, the average discharge, especially in October and December, will increase significantly compared to the baseline period average, which can be attributed to increased precipitation in these months. The runoff in the period 2051-2080 also shows a greater increase compared to the period 2021-2050. Overall, runoff in the first period increased by 20% to 25% in different months, and in the second period, it will increase by up to 27%. Given the predicted greater increase in precipitation in the period 2051-2080 compared to 2021-2050, a further increase in river discharge is not unexpected.

Other studies, such as those by Haji Ghasemi et al. (2020) in the Mazlaghan River basin, Zarei et al. (2020) in the Halilroud basin in Kerman Province, and Aghajanzadeh et al. (2019) in the Zarrineh River basin, have also confirmed the projected increase in runoff in future periods.

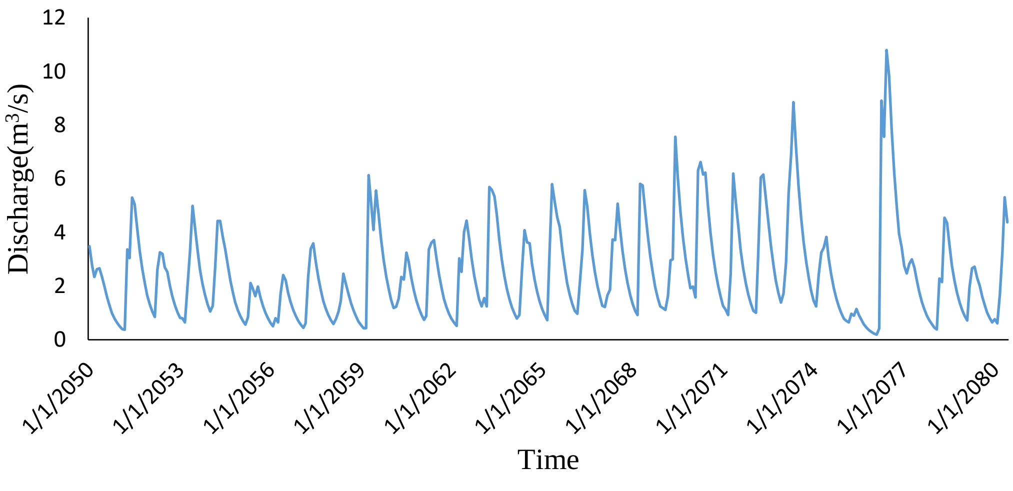


Fig. 9 Modeled runoff time series with CNRM in IHACRES in 2051-2080

4. Conclusion

Based on the research results, the following general conclusions are presented:

1. The good performance of the LARS-WG6 model in simulating climate data for the 1992-2020 period.

2. In the two future periods, 2021–2050 and 2051–2080, the monthly minimum temperature increased by 0.2 °C to 9.8 °C, and the monthly maximum temperature increased by 0.8 °C to 2.9 °C. The average annual rainfall increased by approximately 14% in the 2021-2050 period and 16.5% in the 2051-2080 period compared to the base period across all models and scenarios.

3. Among the models BCC, ACCESS-CM2, CNRM, CANESM5, FGOALS, GFDL, and INM, the CNRM model and the SSP126 scenario showed less uncertainty compared to

the other models. Additionally, during the second period (2051–2080), the models demonstrated greater uncertainty compared to the first period (2021–2050).

4. The IHACRES model demonstrated acceptable capability in simulating monthly discharge in the study area and can be used to simulate future monthly discharge.

5. The average monthly discharge is projected to increase by 20% in the 2021-2050 period and by 27% in the 2051-2080 period compared to the long-term historical average, which corresponds with the months showing increased monthly rainfall.

Given the impacts of climate change and future discharge variations in the Abu Al-Abbas watershed, it is recommended to implement management plans aimed at mitigating the negative effects of flooding and extreme discharges in the basin. This study has solely addressed the impacts of climate change, and it is suggested that the effects of land-use changes be evaluated alongside climatic changes in future research.

Statements and Declarations

Acknowledgment

This article is part of the results derived from the first author's master's thesis at the Agricultural Sciences and Natural Resources University of Khuzestan.

Data availability

The data used in this research are provided in the text of the article.

Conflicts of interest

The author of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

K. Tahmasebi: data collection, software, modeling, drafting the initial version, accuracy evaluation; Z. Khorsandi Kohanestani: conceptualization, drafting the initial version, research design, software, modeling, responding to review, accuracy evaluation, visualization; S. Joorabian Shooshtari: conceptualization, drafting the initial version, research design, software, modeling, responding to review, accuracy evaluation, visualization.

AI Use Disclosure

During the preparation of this manuscript, the authors used ChatGPT for language translation. All content has been carefully reviewed and revised by the authors, who take full responsibility for the final version of the manuscript.

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