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Hydrological responses to future climate change in semi-arid region of Iran (Golabar and Taham Basins, Zanjan Province)

Leila Nouri [a], Ghorban Mahtabi [a,*], Seyyed Hasan Hosseini [b], C. Venkata Siva Rama Prasad [c]

[a] Department of Water Engineering, University of Zanjan, Zanjan, 45371-38791, Iran
[b] Division of Water Resources Engineering, Faculty of Engineering, Lund University, P.O. Box 118, 22100 Lund, Sweden
[c] Department of Civil Engineering, Malla Reddy Engineering College, Secunderabad 500100, Telangana, India

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ABSTRACT

One of the most challenging and warning issues that have globally been introduced is the climate change and its effects on water resources. Climate change due to global warming has increased temperature and evaporation potential and has changed the precipitation pattern as well as precipitation amount in different seasons. The aim of this study is to assess the impact of climate change on the hydrological response of the basins of Golabar and Taham (in Zanjan province, Iran) in two future periods 2020–2030 and 2046–2065.10 different Global Climate Models (GCM) were analyzed to introduce novel selected model for future climate projections. The future climate parameters were simulated using the best climate model under the A1B and B1 emission scenarios. Two pessimistic and optimistic future climatic scenarios were defined based on the worst and the most desirable climate condition (using the temperature and precipitation data). The results showed that in the pessimistic scenario, the average annual temperature will rise 1.77 °C and 2.19 °C in Golabar and Taham basins, respectively. For the annual precipitation, reduction of 6.49 and 3.75 percent is shown for the Golabar and Taham basins, respectively. Also, in the average annual river flow, Golabar and Taham basins will experience a decrease of more than 25 percent in the future period (2046–2065). In the optimistic scenario, Golabar and Taham basins will experience 0.29 °C and 0.51 °C increase in the average annual temperature, respectively. In the annual precipitation, 3.6 and 7.01 percent increase is shown for the Golabar and Taham basins, respectively. In the average annual river flow, an increase of 7 % and 15 % would be expected in the future period (2020–2030) for the Golabar and the Taham basins, respectively.

1. Introduction

1.1. Background

In recent years, increasing the population and human activities, emissions of greenhouse gases, including carbon dioxide, have extremely increased and caused to changes in the ecosystem. Climate change due to global warming has increased temperature and evaporation potential and has changed the precipitation pattern as well as precipitation amount in different seasons. As a result, climate change affects the quality and quantity of water resources in different regions. So that some regions encounter the annual runoff reduction, increasing the flood flows relying on the storm, or early peak flow in spring. Another consequence of the climate change phenomenon and the increase of earth's temperature is the convert of snowfall pattern into rainfall. This will reduce the amount of flow in snow-affected rivers in spring and summer and will increase the runoff in autumn and winter. Therefore, changes in climate parameters can affect water resources by disrupting the common hydrological processes. The consequences such as changes in flow rates and changes in "timing of the main flow events" are among the major issues frequently mentioned in the researches. Hence, the assessment of climate change impact on water reservoirs is one of the most important research agendas around the world [1–5].

In the last decade, a lot of researches have been done on climate change and its effects on water resources using different methods and from various perspectives. Nkomozepi and Chung [6] investigated the effects of climate change on the water resources of the Geumho River in Korea. They used the statistical model and the General Circulation

* Corresponding author.
E-mail addresses: leilanouri22@yahoo.com (L. Nouri), ghmahtbi@gmail.com (G. Mahtabi), hasan.hosseini@tvrl.lth.se (S.H. Hosseini), cvsrprasad@mrec.ac.in (C.V.S.R. Prasad).

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Model (GCM) to predict the precipitation and temperature for three representative concentration pathways (RCPs). The results showed that climate change is likely to lead to a decrease in water resources in the Geumho river basin. Ning et al. [7] simulated runoff in the arid and semi-arid regions of China using distributed time variant gain model (DTVGM). The results showed that the future annual runoff had slowly decreasing trends during the period 2010–2100. Under the studied scenarios, the water resources situation of the study area will be extremely severe. Therefore, adaptive water management measures addressing climate change should be adopted to proactively confront the risks of water resources. Khajeh et al. [8] investigated the potential impacts of climate changes on the hydrological drought of the Zayandehrud basin in Iran. The data about climate change in HADCM3, INCM3 and NCCCSM models (A1B, A2, and B1 scenarios) were downscaled over 2011–2040 periods using the LARS-WG model. Generally, the results of the assessment of climate change demonstrated 1.5 °C rise in monthly temperature, fluctuation of rainfall over time, and a general 12.5 % decline of inflow to the reservoir.

Xuan et al. [9] investigated the impact of climate change on the hydrology of the Yarlung Zangbo River through using five Global Climate Models (GCMs) and the SWAT model under two Representative Concentration Pathways. Results showed that in the period 2069–2099, the total runoff at Nugesha and Nuxia stations will possibly decrease (with >60 % probability) while at Yangcun station increases are very likely (with >80 % probability). Chen et al. [10] quantified the climate and streamflow changes and their contribution to the corresponding annual variations at different time scales in a mountainous watershed in the Northeast of Tibetan Plateau. With a significant increase in temperature (>5.42 °C) in the late 21st century, the appearance of peak streamflow will shift forward from May to April. The seasonal streamflow will significantly increase except for that in summer, with the largest increase in spring contributing 38.1–59.5 % to annual increment. El Ouali et al. [11] evaluated the availability of water resources in The Upper Ziz basin known by its arid climate and strong climatic changes. The Statistical Downscaling Model (SDSM) method has been used to reduce the average rainfall and the temperature to predict future climate change related to various Representative Concentration Pathway (RCP) scenarios such as RCP 4.5 and RCP 8.5. Future precipitation showed an increasing trend in both scenarios. As for future mean temperature, it will recognize great seasonal variability, such as warming winter and spring and cooling summer and autumn. As a result, simulated future discharge will decrease by 26 % under RCP 4.5 and by 24 % under RCP 8.5 in the near future. Chen et al. [12] evaluated the hydrological responses to climate change for a data-scarce mountainous watershed in Taiwan. The study integrated short-term hydrological data with physics-based meteorological and hydrological models to measure the impact of climate change on future water scarcity in the Watershed. The results showed that precipitation, water percolation, and streamflow will decrease by about 10 % and increase by about 20–25 % in the dry and wet seasons, respectively. Mahdaoui et al. [13] studied the hydrological response to future climate change in the Bouregreg watershed, Morocco using GR2M model with considering the RCPs. Projections indicated a noticeable increase in mean temperatures, with expected rises of about 1.32 °C for RCP4.5 and 1.69 °C for RCP8.5. Also, precipitation levels were anticipated to experience significant reductions, decreasing by 33.74 % for RCP4.5 and 40.20 % for RCP8.5. These pronounced climate alterations are projected to lead to an annual decrease in streamflow. This reduction is estimated at 44.63 %, and for RCP8.5, it is even more significant at 64.30 %.

In semi-arid regions, construction of dams is as an effective method for better managing of surface waters of basins that have the seasonal variations in river flow. However, future climate change causes to reduce in the quantity of the water resources and consequently dams. This issue is one of the challenges ahead in effective planning and managing the water resources [14,15]. Iran is one of the developing countries where more than 85 % of total water consumption belongs to agriculture. The findings of the intergovernmental panel on climate change [16] indicate that the developing countries due to the low flexibility in reforming economic structure and reliance on agriculture can be much more vulnerable to climate change. Over the past few decades, small and large dams have been constructed throughout the world to improve the management of surface water resources. However, most of these dams are located in basins that have not long-term measurements of the river flows. If enough data even are available, the effects of future climate change on the reservoirs inflows have not been considered. Therefore, the aim of this study is to assess the effect of the future climate change on the reservoir inflow of two dams in Zanjan province, Iran.

2. Materials and methods

2.1. Study area

The Golabar dam is in 50 km southwest of the Zanjan city and 3 km down the Golabar village on the Sojas River with longitude of 48° 19′ and latitude of 36° 19′. This dam is of great economic and agricultural importance for the region, so that 46 million m^3 of water will be supplied annually to the agricultural sections of the area. Taham dam is in 15 km northwest of the Zanjan city and 8 km down the Taham village with longitude of 48° 36′ and latitude of 36° 50′. The dam has been constructed at about 300 m down the junction of the two rivers of Taham and Golhrood, which forms the Sarimsaqlu River. The Sarimsaqlu River is one of the branches of the Zanjanrood River which itself is one of the branches of the Qizil-Uzan River. The main purpose of the construction of the Taham dam is supplying drinking water to the Zanjan city. Fig. 1 shows the Golabar and Taham basins as well as the nearest hydrometric stations on the main river.

2.2. Datasets (climate and runoff data)

The observed daily Climate data (rainfall and temperature data) and hydrometric data (records of river flow) of the Golabar and Taham dam basins were taken from the Zanjan regional water company. In order to use the rainfall and temperature data in the IHACRES rainfall-runoff model, a simple solution is to choose a station with sufficient and reliable data to provide a good representative of rainfall and temperature over the whole basin because of the inadequacy of data in many stations of the basins. For this purpose, the monthly averages of the temperature and precipitation data of the stations located in each basin were obtained for a common period. Correlation coefficients were calculated between the average values of the basins and the monthly values of each station. Then, the correlation between rainfall and runoff was assessed between the different stations in daily and monthly scales. Finally, by comparing the calculated correlations for each basin and the length of the data period, a representative station for temperature and a representative station for precipitation were chosen in each basin. Table 1 presents the representative stations and historic period (T_0) for both basins. Also, as is seen in Fig. 1, the representative hydrometric stations are located at the dam's upstream in the Golabar basin (Zarzar hydrometric station) and at the dam's downstream in the Taham basin (Paletti hydrometric station).

2.3. Methods

2.3.1. GCMs and emission scenarios

In order to predict the climate effects, the General Circulation Model (GCMs) are used. These mathematical models initially divide the earth's surface into networks of 1–4° with 5–20 vertical layers. Then, by considering the boundary conditions, these models dynamically solve the complete gas equations inside these networks for the air flow [17]. The GCMs determine the effects of changing concentrations of greenhouse gases on global climate parameters, such as rainfall, humidity,

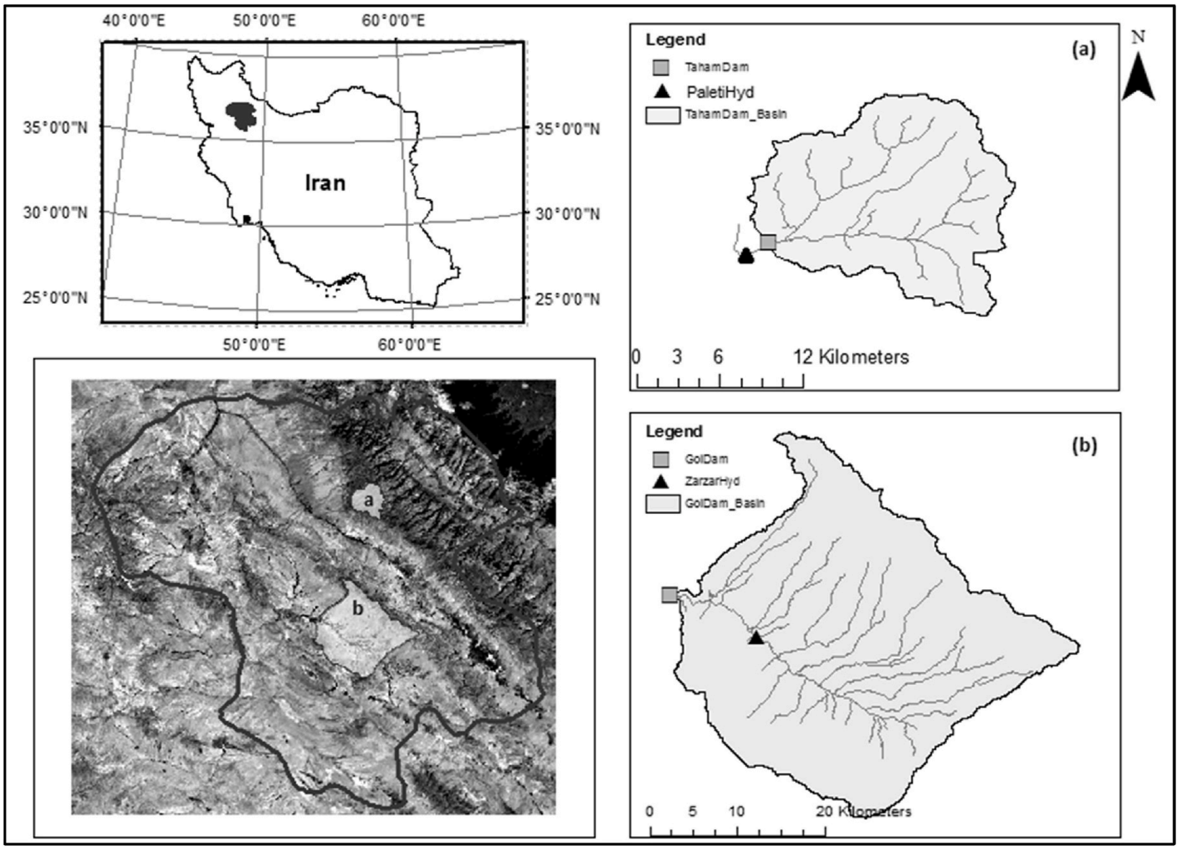

Fig. 1. Location of Zanjan Province in Iran and map of the basin areas for the (a) Taham, and (b) Golabar dams, including locations of the dams and the nearest hydrometric station to each dam.

Table 1
The representative stations for the Golabar and Taham basins.

Basin	Representative station	Station type	historic period (T_0)
Golabar	Khandab	Rain gauge	2004–2014
	Khodabandeh	Synoptic (temperature)	2004–2014
	Zarzar	Hydrometric	2004–2014
Taham	Sarimsaqlu	Rain gauge	1981–2014
	Zanjan	Synoptic (temperature)	1981–2014
	Paletti	Hydrometric	1981–2014

temperature, and wind speed. Several General Circulation Model (GCMs) under SRES scenarios have been developed for future climate change projections. For example, HadCM3 is a coupled atmosphere-ocean GCM which has been developed in the Hadley Center for Climate Prediction and Research-Britain (HCCPRB). This model has been widely used in many of the climate change studies and is one of the existing models in the downscaling LARS-WG software database [16, 18]. In order to describe plausibly the future climate change, the greenhouse gas emission scenarios are used. These scenarios provide alternative imaginations about how greenhouse gases can be released in the future and about the related uncertainties. Use of two A1B and B1 scenarios (SRES scenarios) can help to identify the uncertainty range [19]. In this paper, the outputs of 10 GCMs for two different emission scenarios A1B and B1 were studied. Despite the significant increase in the resolution of General Circulation Models (GCMs), they cannot yet estimate climate outputs for small scales, which requires the use of models called downscaling models with the ability to convert the output of climate models to smaller spatial scales.

2.3.2. LARS-WG downscaling model

LARS-WG is a stochastic weather generator used to produce daily time series of precipitation, solar radiation, and minimum and maximum temperatures at a station for the present and future climate conditions [20]. The modeling of dry and wet periods, daily precipitation and series of radiation using this model is then based on utilizing separate semi-empirical distributions for each of these parameters [21]. In this study, the 5th edition of LARS-WG model is used that contains output information of various general circulation models. Also, the number of bins (intervals) used in the statistical distributions has been increased to 23 in this version [18]. showed that increasing the number of these bins can provide a better representation of the distribution of observational data. To generate data by the LARS-WG model, the characteristics of each station including name, location, and altitude, as well as the daily climate data in the observation period should be introduced as the input to the model. Then these data are analyzed by the LARS-WG model. Results of the model are including the statistical characteristics of the observational data (monthly and seasonal averages for the entire period) and the results of statistical tests, which indicate the ability of the model to rebuild the daily climate data. According to the statistical distribution governing the time series of the observational data, the model reproduces the climate data for the historic period. Then, the generated data, including the daily temperature and precipitation are compared with basic data. After analyzing the results of the assessment and confirming the ability of LARS-WG model to generate climate data, this model is used for downscaling statistical data of GCMs for the future periods using A1B and B1 scenarios, and finally, the daily values of the parameters were produced for the future periods. In this research, for both Taham and Golabar basins, the future climate periods of 2020–2030 (T_1) and 2046–2065 (T_2) were considered.

2.3.3. Rainfall-runoff model (IHACRES model)

IHACRES is a rainfall-runoff hydrological model, relating the regional precipitation to the runoff, is used in the basin scale. The IHACRES modeling process can be divided into two non-linear losses and linear (unit hydrograph) modules; the first of which converts rainfall into effective rainfall, and the second converts effective rainfall into the runoff [22,23]. In IHACRES (ver.2), the corrective method of [24] for calculating the effective rainfall uk is used. Accordingly:

$$u_k = [c(\varphi_k - l)]^p r_k$$

where, r_k stands for the observed rainfall at time k, and c, l, and p are parameters (mass balance, soil moisture index threshold, and non-linear response terms, respectively). Also, φ_k is a soil moisture index that is defined as:

$$\varphi_k = r_k + (1 - 1 / \tau_k)\varphi_{k-1}$$

In the above function, τ_k is drying rate that is stated as:

$$\tau_k = \tau_w \, exp(0.062 f (T_r - T_k))$$

where, τ_w, f, and T_r are parameters (reference drying rate, temperature modulation and reference temperature, respectively). In the second module, a linear unit hydrograph (UH) module converts effective rainfall to stream flow [22]. The more details of IHACRES modeling process can be found in the [23].

2.3.4. Evaluation indexes

Below are listed a few statistical criteria that were used for evaluating the performance of the hydrological modelling and the weather station-GCM climate data comparison. In the following equations, O_i and M_i stand for the observed and modelled values of the evaluated variable at time step i, and n is the length of the O-M data pairs.

- R^2 or the coefficient of determination:

$$R^2 = \left[\frac{n\sum_{i=1}^{n} O_i - \left(\sum_{i=1}^{n} O_i\right)\left(\sum_{i=1}^{n} M_i\right)}{\sqrt{n\sum_{i=1}^{n} O_i^2 - \left(\sum_{i=1}^{n} O_i\right)^2}\sqrt{n\sum_{i=1}^{n} M_i^2 - \left(\sum_{i=1}^{n} M_i\right)^2}}\right]^2$$

R^2 is unitless and can vary between and including 0 and 1. $R^2 = 1$ shows the best agreement (linear correlation) between O and M.

- *RMSE* or Root Mean Squared Error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - M_i)^2}{n}}$$

RMSE varies between 0 and inf, and $RMSE = 0$ indicates a perfect model. The unit of *RMSE* the same as the evaluated variable's (runoff for hydrological modelling, and precipitation or temperature for climate data comparisons). *RMSE* can be given in % if the above equation is divided by average of O (i.e., $\overline{O}$) or variation range of O. For the latter, for example, an $RMSE = 5$ % would mean that the magnitude of the average difference between the O-M data is 20 times smaller than the difference between max and min values of O.

- *NSE* or Nash-Sutcliff Efficiency:

$$NSE = 1 - \frac{\sum_{t=1}^{T} (O_i - M_i)^2}{\sum_{t=1}^{T} (O_i - \overline{O})^2}$$

NSE is unitless and varies between -inf and 1. Where $NSE = 1$ stands for the best O-M data agreement.

3. Results and discussion

3.1. Rainfall-runoff model

At first, the IHADRES rainfall-runoff model was calibrated and verified for the study areas. The best input data set and the best calibration-verification period were selected based on the criteria such as the coefficients of Nash-Sutcliff and R2 and the RMSE values, obtained from the comparison between the observed and simulated runoff values. The results of the calibration-verification period for the rainfall-runoff modeling of Taham basin (Sarimsaqlo, rain gauge station, and Paletti, hydrometric station) are presented in Table 2. The selection of the calibration-validation periods was done based on reliable periods (the general compatibility between rainfall and runoff data), having the least missing data and, as much as possible, having the learning pattern of different events. According to Table 2, by comparing the values of the performance criteria, the period (1987–1988) and the period (1998 and 2002) have the best result of the calibration-verification periods. It should be noted that with a slight tolerance to achieve the best model by IHACRES, the most suitable controller structure of linear module was obtained by selecting the single exponential store (1,1).

3.2. Climate model selection

In order to evaluate the performance of GCMs in simulating the precipitation and temperature parameters, the simulated values of these parameters in a historic period were compared with the observed data. For this purpose, the data of monthly temperature and precipitation of 10 GCMs, containing the time series of climatic parameters for the historic periods of 1981–2003 and 2004–2010 (respectively, for the Taham and Golabar basins) was prepared through the CCCSN website (www.cccsn.ec.gc.ca). Then, the monthly mean temperature and rainfall were calculated. The performance of different GCMs in the simulation of the monthly temperature and precipitation data are shown in Table 3. According to Tables 3 and in the temperature simulation of both Golabar and Taham basins, the IPSLCM4 and HADCM3 models have the best performance and the CSIROM3.5 model has the weakest performance.

The performance of the GCMs in simulating precipitation shows that the HADCM3 model has the best performance for the Golabar basin and the CSIROMK3 model has a competitive performance. Also, the HADGEM1 and NCARCCSM3 models show the weakest performance for the basin. For Taham basin, the HADCM3 and CSIROMK3.5 models have the best performance; however, in this basin, the CSIROMK3 model also shows a competitive performance. The BCM2 has the weakest performance in the simulation of precipitation in this basin. In this research, to provide the same simulation procedure in both basins (to compare their results) and to assess the uncertainty of different climate models, in addition to using HADCM3 model, the precipitation outputs from the CSIROMK3 and temperature outputs form IPSLCM4 were used. Like in many previous studies (e.g. Refs. [25–27], the HADCM3 model also used in this study.

3.3. Absolute changes of temperature in the future periods

In this study, in order to investigate a more realistic change of future climate condition, the output of the GCMs were studied for the two pessimistic and optimistic scenarios based on the worst (the highest increase in temperature and decrease in precipitation) and the most desirable (the least increase in temperature and decrease in precipitation) climate condition, respectively. After generating data for the future and historic periods by LARS-WG, the average of absolute changes of temperature and relative changes of precipitation over the future periods were compared to the average of the historic period (Table 4). In both basins, it can be said that in the future T_1 (2020–2030) and T_2 (2046–2065) periods (based on both the GCMs and the emission scenarios), temperature will certainly increase relative to the historic

Table 2
Statistical results of IHACRES model in the prediction of daily flow values in Taham basin (Sarimsaqlo, rain gauge station and Paletti, hydrometric station).

Name of structure	Calibration				Validation			
	Period (years)	NSE	R2	RMSE (%)	Period (years)	NSE	R2	RMSE (%)
S1	1981, 1983	0.353	0.630	5.62	Remained	0.352	0.513	4.40
S2	1984, 1986	0.489	0.868	1.80	Remained	0.342	0.506	4.61
S3	1987–1988	0.523	0.656	2.96	Remained	0.448	0.643	4.44
S4	1990–1991	0.708	0.842	2.02	Remained	0.216	0.197	5.40
S5	1995–1996	0.759	0.907	1.41	Remained	0.366	0.568	4.63
S6	1998, 2002	0.571	0.825	1.47	Remained	0.426	0.609	4.02

Table 3
The performance of different GCMs in simulating the monthly temperature and precipitation data.

Watershed	Golabar				Taham			
Climate variable	Precipitation		Temperature		Precipitation		Temperature	
Criteria Models	RMSE (mm)	R	RMSE (°C)	R	RMSE (mm)	R	RMSE (°C)	R
BCM2	17.38	0.77	2.76	0.99	44.09	0.77	2.01	0.99
CSIROMK3.5	9.48	0.77	4.32	0.98	10.25	0.92	4.48	0.98
HADCM3	13.03	0.86	2.58	0.98	9.38	0.90	1.89	0.98
HADGEM1	26.17	0.68	2.65	1.00	22.46	0.77	2.31	1.00
NCARCCSM3	18.24	0.26	1.72	0.98	14.86	0.68	2.11	0.99
GFDLCM2.1	12.99	0.69	1.75	0.98	13.84	0.96	3.49	0.99
CNRMCM3	14.41	0.60	1.92	0.99	19.81	0.71	1.49	0.99
IPSLCM4	2.23	0.39	1.65	0.99	13.47	0.74	1.55	1.00
CGCM3T63	22.52	0.74	2.76	0.99	17.00	0.88	4.06	0.99
CSIROMK3	14.67	0.85	2.39	0.98	10.19	0.86	2.29	0.97

Table 4
Absolute changes in the temperature (°C) and relative changes in the annual precipitation (percentages) under the emission scenarios A1B and B1, in the future period (T_1 and T_2).

Future periods	T_1 (2020–2030)			T_2 (2046–2065)		
Climate scenarios	A1B			A1B		
	HadCM3	CSMK3	IPCM4	HadCM3	CSMK3	IPCM4
Golabar-Precipitation	−1.74	−3.40	–	−6.49	−2.95	–
Golabar-Temperature	0.29	–	0.31	1.77	–	1.68
Taham-Precipitation	3.27	−2.18	–	−3.75	−1.52	–
Taham-Temperature	0.51	–	0.64	2.19	–	2.10
Climate scenarios	B1 HadCM3	CSMK3	IPCM4	B1 HadCM3	CSMK3	IPCM4
Golabar-Precipitation	3.60	−3.79	–	−2.47	−1.19	–
Golabar-Temperature	0.32	–	0.27	1.46	–	1.24
Taham-Precipitation	7.01	−2.74	–	−3.60	0.83	–
Taham-Temperature	0.63	–	0.56	1.80	–	1.52

period. This increase of temperature in the T_2 (2046–2065) period is more considerable than the closer future period (T_1) for both basins. As a conclusion about the expected changes in mean temperature of both the Golabar and the Taham basins, it can be said that the most optimistic prediction belongs to the climate scenario of HadCM3-T_1-A1B (0.29 °C and 0.51 °C increase in temperature for the Golabar and Taham basins, respectively) and the most pessimistic prediction is related to the climate scenario of HadCM3-T_2-A1B (1.77 °C and 2.19 °C increase in temperature for the Golabar and Taham basins, respectively). Zarggami et al. [14] by studying the potential climate change of six synoptic stations in East Azerbaijan province, (nnorthwest of Iran), showed an average annual temperature rise of ~2.3 °C in the middle of the twenty-first century. Sayari et al. [28] studied the climate change impact on crops' production in the northeast of Iran using HadCM3 model under A2 scenario for two time periods (2011–2030 and 2080–2099). They reported that annual mean temperature will slightly increase (+5 %) under the near future conditions (2011–2030). Shahni Danesh et al. [29] assessed the impact of climate change on water resources in Iran using dynamic and statistical downscaling methods for the 21st century. According to the results, the temperature will rise between 0.6 and 0.8 °C in Zanjan province for 2010–2039. Cheshmberah and Zolfaghari [30] used the HADCM3 model data (under scenario A2 and B2) for prediction of future climatic parameters during 2020–2049 in different climatic zones of Iran for calculating reference evapotranspiration. The results showed that maximum and minimum temperature at Sanandaj station over the time period of 2020–2049 will increase 1.5 and 2.5 °C under A2 at and B2 scenarios, respectively.

3.4. Relative changes of annual precipitation in the future periods

In the Golabar basin, the HadCM3 model under the A1B emission scenario has predicted a decrease in precipitation for both periods relative to the historic period. However, under the B1 scenario, increase in the precipitation for the period T_1 and decrease of precipitation for the period T_2 has been predicted. For this basin, based on the CSIROMK3 model, precipitation is expected to decrease for both periods and the emission scenarios compared to the historic period. As a result, for the Golabar basin, it can be more certainly said that precipitation will decrease for the second period (2046–2065). In the Taham basin, based on the HadCM3 model under both emission scenarios, increase of precipitation for the period T_1 and decrease of precipitation for the period T_2 is predicted. However, according to the results of the CSIROMK3 model under the A1B scenario, precipitation will decrease for both periods. But, for the scenario B1, precipitation in the period T_1 will decrease and in the period T_2, will increase. Finally, it can be concluded that for both the Golabar and the Taham basins, the most optimistic prediction belongs to the HadCM3-T_1-B1 climatic scenario (3.6 and 7.01 percent increase in precipitation for the Golabar and Taham basins, respectively) and the most pessimistic prediction is related to the HadCM3-T_2-A1B (6.49 and 3.75 percent decrease in precipitation for the

Golabar and Taham basins, respectively). The result of Zarggami et al. [14] showed an annual precipitation reduction of ~3 % in East Azerbaijan province, Iran, in the middle of twenty-first century. Sayari et al. [28] also reported that annual precipitation in the northeast of Iran showed a 14 % decrease under far future conditions (2080–2099). In the following, random data of the pessimistic and optimistic scenarios were generated using the LARS-WG and introduced as inputs to the rainfall-runoff model. Then, the results of the corresponding outputs are presented in order to assess the effect of future climate change on the reservoirs inflow. Although the selection of the climate scenarios was based on the average annual changes of climatic parameters, a more detailed analysis of precipitation and temperature changes in different months is discussed below with consideration of change intervals.

3.5. Analysis of the range of climate scenarios changes

3.5.1. Temperature analysis

In Fig. 2, the changes in the mean monthly temperature of the Golabar and Taham basins in the future periods of 2020–2030 (T_1) and 2046–2065 (T_2) compared to the historic period (T_0) has been presented (for each month, from the left to the right: the base scenario, optimistic scenario and pessimistic scenario, respectively). According to Fig. 2, in both basins, the temperature increase is observed for almost all months. The only exception belongs to the optimistic scenario for the Golabar basin in March. The difference in temperature prediction between the climate scenarios in both basins in the warmest months (June–September) is more severe than in other months. Solaymani and Gosain [31] assessed the climate change impacts in the semi-arid Karkheh Basin (KB) of Iran using regional climate models (RCMs) under A2, B2 and A1B scenarios. They reported that the increase in temperature in the dry months (June, July and August) is greater than the increase in the wet months (January, February, March and April). In general, the behavior of different climate scenarios in both stations is similar and the temperature diagrams in both basins have many common points.

3.5.2. Precipitation analysis

In Fig. 3, the box-whisker plots show monthly changes in precipitation of Golabar and Taham basin in the future periods T_1 and T_2 compared with the historic period T_0 (for each month, from the left to the right: the base scenario, optimistic scenario and pessimistic scenario, respectively). In Fig. 3, the plot elements and the statistics are as follows: box boundaries represent the 25th and 75th percentiles; the line within the box marks the median and whiskers below and above the box indicate the 10th and 90th percentiles. Also, the black dot represents the mean of data. The range of changes in monthly precipitation for Golabar and Taham basins has also many common cases. The length of the box at both basins varies in almost the same way; the data variability in both basins is similar in different months. Thus, the highest precipitation is related to the early spring and the late autumn, and the highest standard deviation is in these two seasons. At both basins, the mean is higher or equal to the median in all months; that is, the skewness of the data distribution is positive. For both basins and in most months, the mean and most of the plot elements of the optimistic scenario are higher than those of the other two scenarios. Also, under the pessimistic scenario, the most reduction in the precipitation at both basins is related to the April, May, and June months. However, in the late autumn and the early winter, both the optimistic and the pessimistic scenarios show some increase in precipitation. Solaymani and Gosain [31] reported that in the Karkheh Basin (Iran), almost all the months during the rainy season show considerable reduction in precipitation except for the month of November. Osman et al. [27] expected future precipitation in central Iraq using seven General Circulation Models (GCMs) outputs for the periods of 2011–2030, 2046–2065, and 2080–2099. The results indicated a decreasing trend in March, April, and May for the future.

3.5.3. Reservoir inflow analysis

In Fig. 4, the range of monthly changes of reservoir inflow of the two Golabar and Tahm dams is presented for the future periods T_1 and T_2 compared to the historic period T_0. Similar to that observed for precipitation, here in both basins, the mean in all months is higher than the median (especially in the months with a relatively low precipitation), which represents an asymmetric distribution of flow data with positive skewness (indicating rare showers). In both basins, all months of the optimistic scenario show higher runoff compared with the base scenario which is aligned with the predicted precipitation changes. This result implicitly indicates that the increase of the predicted temperature under the optimistic scenario does not have a tangible effect on reducing the flow rates. The pessimistic scenario has shown a decrease in the runoff (except for the January and February in Taham basin) compared to both scenarios. The results showed that under the optimistic scenario, an increase of 7 % and 15 %, in the near period of 2020–2030, will be expected for the Golabar and Taham basins, respectively. Under the pessimistic scenario, the average decrease of annual flow into these two dams was calculated slightly more than 25 % relative to historic period (i.e. the periods 2004–2014 and 1981–2003 for the Golabar and Taham basins, respectively). Here it is worth noting that already, in the change of precipitation under a pessimistic scenario, months with the increase of precipitation were reported. Therefore, the expected significant increase in the temperature under the pessimistic scenario seems to have had a tangible impact on the decrease of flow rate, even in the months

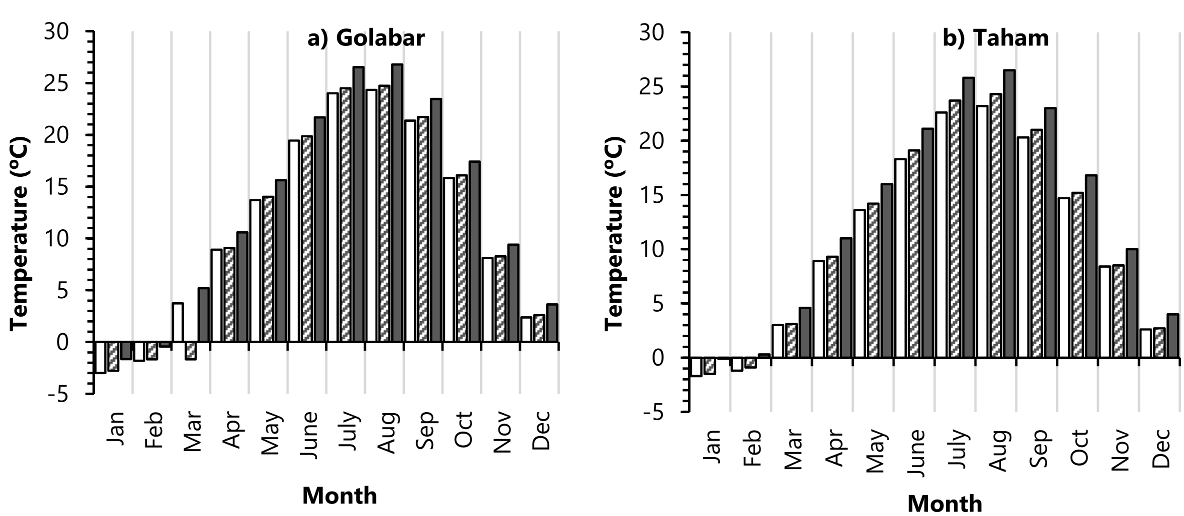

Fig. 2. Mean monthly temperature in Golabar (a) and Taham (b) basins in the periods T0, T1, and T2, at each month from the left to right, respectively.

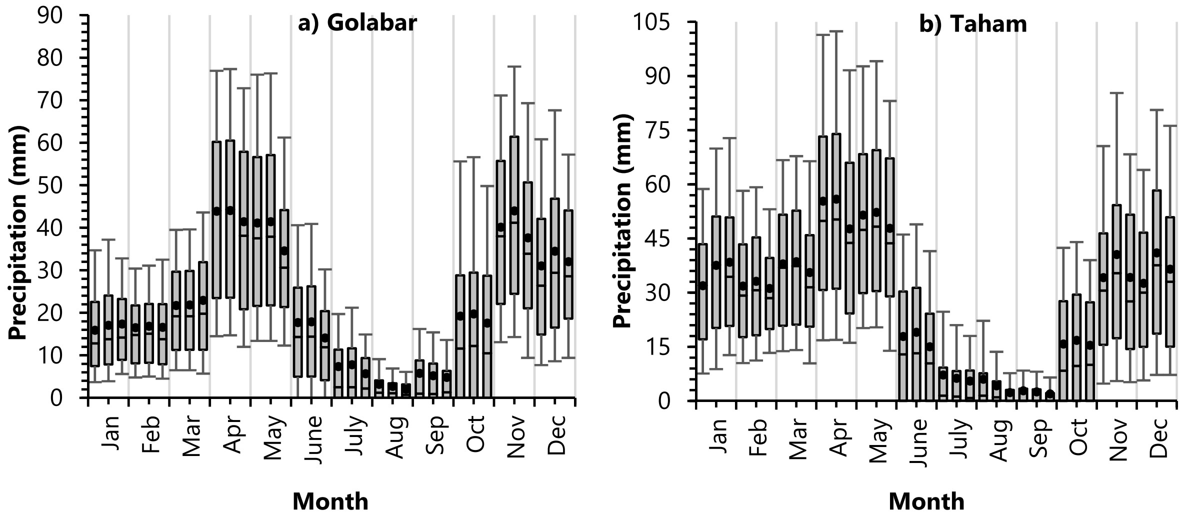

Fig. 3. Mean monthly precipitation in Golabar (a) and Taham (b) basins in the periods T0, T1, and T2, at each month from the left to right, respectively.

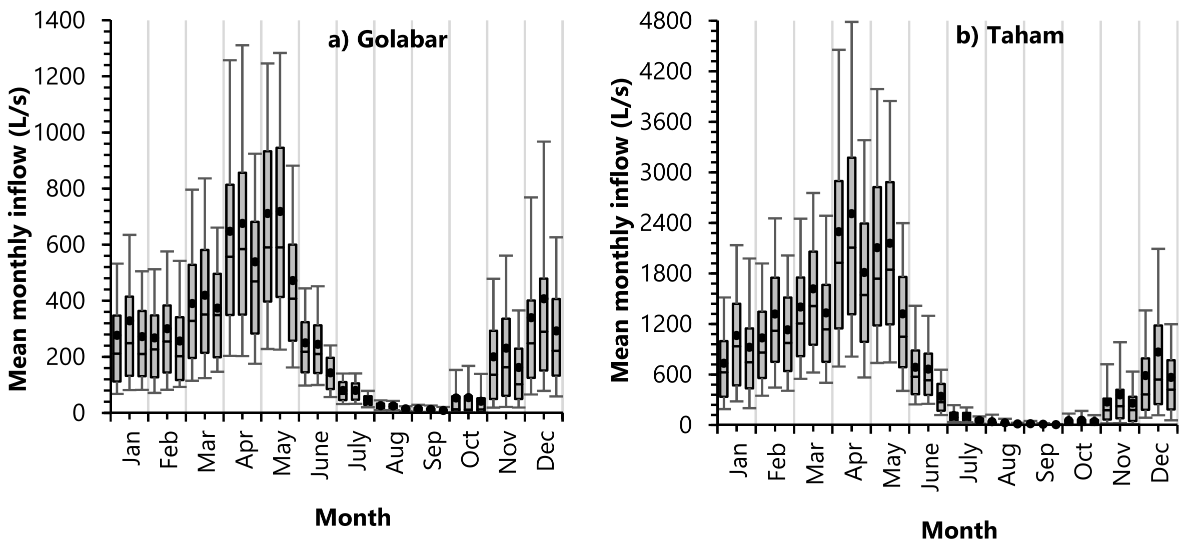

Fig. 4. Mean monthly inflow in Golabar (a) and Taham (b) basins in the periods T0, T1, and T2, at each month from the left to right, respectively.

when the precipitation was unchanged or slightly increased. The effect of a significant increase in temperature is more important when it coincides with the reduction of precipitation. In fact, the similar trends between the two basins are a much more severe decrease in the runoff in the pessimistic scenario compared to the base scenario in the April, May, and June months, which were previously reported as the months with the most reduction in the precipitation. Therefore, it is expected that in these months, in both basins, the coincidence of precipitation decrease and temperature rise will be a reason for a significant decrease in runoff. Even an intense reduce in the flows of the early summer may also mean drying earlier than usual of the river. The results of Zarghami et al. [14] indicated that the average climate of East Azerbaijan province will convert from semi-arid to arid, and the permanent rivers will change to seasonal rivers. The results of Solaymani and Gosain [31] in the Karkheh Basin (Iran) showed that stream flow decreases considerably from January to September but increases from October to December. They also concluded that decreasing the river discharge might be related to increasing temperature and decreasing precipitation and anthropogenic changes in the study area. It seems that the rise in temperature not only increased evaporation and caused decreased runoff, but also accelerated melting snow [29,32], which causes an increased rate of runoff in the December, January and February months and a corresponding decrease in runoff April, May, and June months.

4. Conclusions

In this research, the effect of future climate change on the reservoir flows of two important dams of Zanjan province (Golabar and Taham dams) of Iran were investigated for the two periods of 2020–2030 (T_1) and 2046–2065 (T_2). For this purpose, the outputs of the selected climatic models which well represented the current climate in the basins were used under the two emission scenarios of A1B and B1. The LARS-WG model was used for downscaling of the outputs of the climate models. For estimation of the reservoir flows, the IHACRES rainfall-runoff model was used (by selecting the rainfall and temperature representative stations for each basin). The results of the mean values of temperature and precipitation for the representative stations showed that in the first and the second periods (T_1 and T_2), the temperature will certainly increase relative to the historic period for both models and the emission scenarios. However, this increase is more significant in the second period (T_2) than the near future period (T_1). In this study, in order to evaluate a more realistic change of future climate condition, the output of the selected climate models was studied based on the pessimistic scenario (the highest increase of temperature and decrease of precipitation) and the optimistic scenario (the least increase of temperature and decrease of precipitation) for the representative stations. In summary, in the mean annual temperature, the most optimistic and pessimistic predictions are related to the HadCM3-T_1-A1B and the HadCM3-T_2-A1B climate scenarios, respectively. Also, in the precipitation parameter, the most optimistic and pessimistic predictions belong to the HadCM3-T_1-B1 and the HadCM3-T_2-A1B climate scenarios, respectively. The results of the optimistic and the pessimistic scenarios showed that the uncertainty of climate scenarios (due to the emission scenarios and the climatic models) was relatively low for the temperature parameter but higher for the precipitation parameter. For this reason, the changes of precipitation values along with the reservoir inflow were reported as box plots. The changes of inflow in various months showed that although the uncertainty of the inflow rate in the rainy and relatively cold months (late autumn and early winter) is significant, the greatest difference in the inflow between the climatic scenarios belongs to the rainy and relatively hot months (i.e. spring months). Also, the main decrease in the reservoir flow of the two important dams of Zanjan province (Golabar and Taham) is expected in the middle of the current century, and especially in spring, due to the coincidence of a significant increase in temperature and the reduction of precipitation. According to monthly assessments, the most expected reductions of inflow were related to spring, and the slightest increases or the least change were related to the early and mid-winter. Therefore, the results of this study, along with the emphasis on the need for a revision of consumptions and development plans, recommend the assessment of the flexibility of these reservoirs (storage in months with high inflow or the least reduction in the inflow in order to compensate for a part of the shortcomings in other months) in the form of scenarios that are compatible with future climate change. Although this study considered a broad range of plausible future climate projections based on studying 10 GCMs, two emission scenarios, two future periods, and a downscaling technique using LARS-WG, doing the same study with the newer versions of the Coupled Model Intercomparison Project Phase (CMIP) and other downscaling techniques are recommended. Future studies can reveal, among other things, potential uncertainties due to the use of different versions of CMIP or the use of other downscaling models. With the study of hydrological models under plausible climate change projections, current and future management of reservoirs and downstream developments can improve.

CRediT authorship contribution statement

Leila Nouri: Methodology, Software, Writing – original draft. **Ghorban Mahtabi:** Conceptualization, Writing – original draft, Investigation, Project administration, Writing – review & editing. **Seyyed Hasan Hosseini:** Conceptualization, Methodology, Software. **C. Venkata Siva Rama Prasad:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

References

[1] H. Thodsen, The influence of climate change on stream flow in Danish rivers, J. Hydrol. 333 (2007) 226–238, https://doi.org/10.1016/j.jhydrol.2006.08.012.

[2] L. Li, H. Xu, X. Chen, S. Simonovic, Streamflow forecast and reservoir operation performance assessment under climate change, Water Resour. Manag. 24 (2010) 83–104, https://doi.org/10.1007/s11269-009-9438-x.

[3] Ch Ma, L. Sun, Sh Liu, M. Shao, Y. Luo, Impact of climate change on the streamflow in the glacierized chu river basin, central Asia, Journal of Arid Land 7 (4) (2015) 501–513, https://doi.org/10.1007/s40333-015-0041-0.

[4] W. Ba, P. Du, T. Liu, A. Bao, M. Luo, M. Hassan, C. Qin, Simulating hydrological responses to climate change using dynamic and statistical downscaling methods: a case study in the Kaidu River Basin, Xinjiang, China, Journal of Arid Land 10 (6) (2018) 905–920, https://doi.org/10.1007/s40333-018-0068-0.

[5] P.K. Rai, G.P. Singh, S.K. Dash, Projected change and variability assessment of Indian summer Monsoon precipitation in South Asia CORDEX domain under high-emission pathway, Pure Appl. Geophys. 177 (2020) 3475–3499, https://doi.org/10.1007/s00024-019-02373-3.

[6] T. Nkomozepi, S.O. Chung, The effects of climate change on the water resources of the Geumho River Basin, Republic of Korea, Journal of Hydro-environment Research 8 (4) (2014) 358–366, https://doi.org/10.1016/j.jher.2013.08.006.

[7] L. Ning, J. Xia, C. Zhan, Y. Zhang, Runoff of arid and semi-arid regions simulated and projected by CLM-DTVGM and its multi-scale fluctuations as revealed by EEMD analysis, Journal of Arid Land 8 (4) (2016) 506–520, https://doi.org/10.1007/s40333-016-0126-4.

[8] S. Khajeh, Sh Paimozd, M. Moghaddasi, Assessing the impact of climate changes on hydrological drought based on reservoir performance indices (case study: ZayandehRud river basin, Iran), Water Resour. Manag. 31 (9) (2017) 2595–2610, https://doi.org/10.1007/s11269-017-1642-5. .

[9] W. Xuan, Y. Xu, Q. Fu, M.J. Booij, X. Zhang, S. Pan, Hydrological responses to climate change in Yarlung Zangbo River basin, southwest China, J. Hydrol. 597 (2021) 125761, https://doi.org/10.1016/j.jhydrol.2020.125761.

[10] Z. Chen, R. Zhu, Z. Yin, Q. Feng, L. Yang, L. Wang, R. Lu, C. Fang, Hydrological response to future climate change in a mountainous watershed in the Northeast of Tibetan Plateau, J. Hydrol.: Reg. Stud. 44 (2022) 101256, https://doi.org/10.1016/j.jhydrol.2020.125761.

[11] A. El Ouali, Z. Dichane, A. Roubil, H. El Ouardi, A. El Hmaidi, A. Lahrach, Hydrological modeling and impact of climate change on water resources in the Ziz valley, central high atlas, Morocco, Ecological Engineering & Environmental Technology 24 (6) (2023), https://doi.org/10.12912/27197050/168335, 192-10.

[12] Y.H.R. Chen, H.W. Tseng, K.C. Hsu, S.Y. Chen, C.C. Ke, L.C. Chiang, Evaluation of hydrological responses to climate change for a data-scarce mountainous watershed in Taiwan, Journal of Water and Climate Change 14 (5) (2023) 1447–1465, https://doi.org/10.2166/wcc.2023.378, 2023.

[13] K. Mahdaoui, T. Chafiq, L. Asmlal, M. Tahiri, Assessing hydrological response to future climate change in the Bouregreg watershed, Morocco, Scientific African 23 (2024) e02046, https://doi.org/10.1016/j.sciaf.2023.e02046.

[14] M. Zarghami, A. Abdi, I. Babaeian, Y. Hassanzadeh, R. Kanani, Impacts of climate change on runoffs in East Azerbaijan, Iran, Global Planet. Change 78 (2011) 137–146, https://doi.org/10.1016/j.gloplacha.2011.06.003.

[15] B. Khaniya, C. Karunanayake, M.B. Gunathilake, U. Rathnayake, Projection of Future Hydropower Generation in Samanalawewa Power Plant, Sri Lanka, Eng. Appl. Artif. Intell. (2020), https://doi.org/10.1155/2020/8862067.

[16] IPCC, in: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (Eds.), Summary for Policymakers in Climate Change, The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2007.

[17] R.L. Wilby, C.W. Dawson, E.M. Barrow, SDSM—a decision support tool for the assessment of regional climate change impacts, Environ. Model. Software 17 (2002) 145–157, https://doi.org/10.1016/S1364-8152(01)00060-3.

[18] M.A. Semenov, P. Stratonovitch, Use of multi-model ensembles from global climate models for assessment of climate change impacts, Clim. Res. 41 (2010) 1–14, https://doi.org/10.3354/cr00836.

[19] K. Robert, H. Colin, A Review of Climate Change and its Potential Impacts on Water Resources in the UK, Official Publication of the European Water Association (EWA), UK, 2007.

[20] P. Racsko, L. Szeidl, M. Semenov, A serial approach to local stochastic weather models, Ecological Modeling 57 (1991) 27–41, https://doi.org/10.1016/0304-3800(91)90053-4.

[21] M.A. Semenov, R.J. Brooks, Spatial interpolation of the LARS-WG stochastic weather generator in Great Britain, Clim. Res. 11 (1999) 137–148, https://doi.org/10.3354/cr011137.

[22] A.J. Jakeman, G.M. Hornberger, How much complexity is warranted in a rainfall-runoff model? Water Resour. Res. 29 (8) (1993) 2637–2649, https://doi.org/10.1029/93WR00877.

[23] B.F.W. Croke, F. Andrews, J. Spate, S.M. Cuddy, IHACRES user guide, in: Technical Report 2005/19, second ed., iCAM, School of Resources, Environment and Society, The Australian National University, Canberra, 2005.

[24] W. Ye, B.C. Bates, N.R. Viney, M. Sivapalan, A.J. Jakeman, Performance of conceptual rainfall-runoff models in low-yielding ephermal catchments, Water Resour. Res. 33 (1997), https://doi.org/10.1029/96WR02840, 153-16.

[25] M. Hessami, P. Gachon, T.B.M.J. Ouarda, A. St-Hilaire, Automated regression-based statistical downscaling tool, Environ. Model. Software 23 (6) (2008) 813–834, https://doi.org/10.1016/j.envsoft.2007.10.004.

[26] E. Lioubimtseva, G.M. Henebry, Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations, J. Arid Environ. 73 (11) (2009) 963–977, https://doi.org/10.1016/j.jaridenv.2009.04.022.

[27] Y. Osman, N. Al-Ansari, M. Mawada Abdellatif, S.B. Aljawad, S. Knutsson, Expected future precipitation in Central Iraq using LARS-WG stochastic weather generator, Engineering 6 (2014) 948–959, https://doi.org/10.4236/eng.2014.613086.
[28] N. Sayari, M. Bannayan, A. Alizadeh, A. Farid, M.R. Hessami Kermani, E. Eyshi Rezaei, Climate change impact on legumes' water production function in the northeast of Iran, Journal of Water and Climate Change 6 (2) (2014) 374–385, https://doi.org/10.2166/wcc.2014.139.
[29] A. Shahni Danesh, M.S. Ahadi, H. Fahmi, M. Habibi Nokhandan, H. Eshraghi, Climate change impact assessment on water resources in Iran: applying dynamic and statistical downscaling methods, Journal of Water and Climate Change 7 (3) (2016) 551–577, https://doi.org/10.2166/wcc.2016.045.
[30] F. Cheshmberah, A.A. Zolfaghari, The effect of climate change on future reference evapotranspiration in different climatic zones of Iran, Pure Appl. Geophys. 176 (2019) 3649–3664, https://doi.org/10.1007/s00024-019-02148-w.
[31] H.R. Solaymani, A.K. Gosain, Assessment of climate change imp,acts in a semi-arid watershed in Iran using regional climate models, Journal of Water and Climate Change 6 (1) (2014) 161–180, https://doi.org/10.2166/wcc.2014.076.
[32] M.B. Gunathilake, Y.V. Amaratunga, A. Perera, I.M. Chathuranika, A. S. Gunathilake, U. Rathnayake, Evaluation of Future Climate and Potential Impact on Streamflow in the Upper Nan River Basin of Northern Thailand, Adv. Meteorol. (2020), https://doi.org/10.1155/2020/8881118.