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Research Paper

Assessment ofClimate Change Impact on the Hydrology of the Kabul River Basin, Afghanistan

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ABSTRACT

Climate change and variability affect the availability and management of water resources and the hydrological cycle, especially in arid and semi-arid regions. This research was conducted to analyse the impact of climate change on the hydrology of the Kabul River Basin, Afghanistan by using the outputs of three General Circulation Models under two representative concentration pathway scenarios: RCP 4.5 and RCP 8.5. Future climate data (precipitation and temperature) obtained from the climate models were bias-corrected using the delta change approach. Maximum and minimum temperature and precipitation were predicted for the three future periods: 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099) against the baseline period 1961–1980. The mean annual temperature in the basin is projected to increase by 1.8 °C, 3.5 °C, and 4.8 °C in the 2020s, 2050s, and 2080s, respectively. The projected annual precipitation is expected to decline by approximately 53 to 65% for the whole river basin under both scenarios in the future period. The well-calibrated and validated Soil Water Assessment Tool (SWAT) was used to simulate the future streamflow in the basin. The mean annual streamflow is projected to increase by 50 to 120% in the future. This study provides valuable information for guiding future water resource management in the Kabul River Basin and other arid and semi-arid regions of Afghanistan.

Keywords: Climate change; Streamflow; RCPs. SWAT; Kabul River Basin

INTRODUCTION

In general, the warming trend of the earth has accelerated in the last fifty years but its distribution is not entirely uniform, as indicated by the 0.74 °C increase in global surface temperature in the last century (IPCC, 2007), but only a 0.39 °C increase from 1979–2011 in Central Asia (Unger-Shayesteh et al., 2013; Hu et al., 2014). Rivers fed predominantly by snowmelt and glaciers are the most vulnerable to climate change as these inevitably affect the hydrology cycle, runoff processes, and ultimately the availability of water resources (Ma et al., 2015; Shrestha et al., 2015).

Several studies have identified the pathways, likely impacts of climate variability, and hydrological changes, as well as the subsequent challenges to water resources management. Increased temperature may result in a rise in potential evapotranspiration and a decrease in the areal extent and volume of snowpacks in the mountains, thereby accelerating the hydrological cycle (Wang et al., 2012; Shrestha et al., 2014) and variability in streamflow. Annual streamflow may increase or decrease due to changes in precipitation and evapotranspiration

(Rind et al., 1990; Singh and Kumar, 1997; Albek et al., 2004; Shrestha et al., 2014). Seasonal variation (increase or decrease during spring and winter) occurs due to a shift in the timing of snowmelt, snow accumulation, and winter precipitation (Lettenmaier and Gan, 1990; Burn, 1994; Hagg et al., 2007). Climate variability and change may also affect public health through various direct or indirect pathways such as deteriorating water quality and subsequent increase in infectious diseases, impacting on the quantity and quality of agriculture yield, ecosystems, and services (Htut et al., 2014). Variations in streamflow and associated impacts are relatively higher in arid and semi-arid regions where most of the freshwater resources are fed by snow and ice.

Studies focusing on the climate change impacts on streamflow in the arid and semi-arid basins in different parts of the world generally agree that climate change affects streamflow and contributes to the availability and variability of water resources (Lai and Ye, 1995; Chen et al., 2005, 2006; Li et al., 2008; Wang et al., 2012; Raghavan et al., 2013; Chang et al., 2014). However, there are great variations in the impacts, depending upon physiography and climate, and it is hard to generalise their nature and extent. Wi et al. (2015) researched climate change and its implications on streamflow in the Kabul River Basin, Afghanistan for the 2050s under RCP 4.5 and 8.5 using GCMs. According to their results, the mean annual temperature at this basin is expected to increase by 2.2 and 2.8 °C under RCP 4.5 and RCP 8.5, respectively whereas precipitation does not show a clear trend. The analysis also proved that the streamflow will increase at the outlet of the basin (Dakah) and the evapotranspiration is expected to increase by 100 and 150 mm under both scenarios. It is, therefore, necessary to carry out separate studies on specific basins of interest, such as the Kabul River Basin (KRB) in Afghanistan, where reliable research has not yet been conducted.

General Circulation Model (GCM) outputs for future climatic conditions under various scenarios are generally used with fully calibrated and validated hydrological models to assess the climate change impacts on hydrology and water resources. However, due to the coarse resolution of GCMs, climate system sensitivity to greenhouse gas concentrations in the atmosphere, and availability of adequate phenomena, a high level of uncertainty exists in the predicted impacts (Stott and Kettleborough, 2002; Xu et al., 2013). In addition, the structural uncertainties within these models tend to produce inconsistent results when using the various GCMs (Maharjan and Babel, 2014). Two ways to reduce uncertainties caused by GCMs and emission scenarios are to use multiple GCMs (Xu et al., 2013; Shrestha et al., 2014) and downscale the output resolution to a specific location by establishing a statistical relationship between GCM outputs, climate variables, and local climate (Fowler et al., 2007; Maraunet et al., 2010). For this study, new climate scenarios and RCPs proposed by the IPCC's Fifth Assessment Report (AR5) are used. The RCP scenarios include the highest and lowest emissions of greenhouse gases (GHGs) examined by the climate modelling community, including mitigation measures that may be applicable in the future to control the emission of GHGs. The lowest emission scenario in the RCPs is consistent to stabilise the mean temperature to less than 2 °C. The RCPs also focus on emissions relevant to short-lived climate forces such as sulphate aerosols (van Vuuren et al., 2011).

The Kabul River Basin is one of five major river basins in Afghanistan, ranging in area from 70,900 km^2 to 262,342 km^2 (Kamal, 2004). It has been warming by 0.6 °C since 1960 at an average rate of around 0.13 °C per decade (SEI, 2009), facing a slight decrease in the mean annual rainfall at an average rate of 2% per decade for the same period. The Kabul River Basin, with parts of it extending to Pakistan, is the most important and populated river basin in the country and provides fresh water for drinking, agriculture, industry, and power generation. With an increasing population, as indicated by the growth rate of 4% per year from 2002–2007, the figure is expected to reach more than nine million in 2057 (based on the United Nations' projection); stress on hydrology and water resources is likely to increase further. Climate change is expected to aggravate the situation further.

There are currently no other studies available to predict the future climate and hydrology of the Kabul River Basin, Afghanistan using RCP scenarios. Therefore, the main objective of this study is to assess the impacts of climate change on the hydrology of the Kabul River Basin using the SWAT hydrological model under projected climate change scenarios from three GCMs in Coupled Model Intercomparison Project Phase 5 (CMIP5). The results of this study can be used for managing water resources under the impact of climate change.

DATA AND METHODS

Study area

The Kabul River Basin extends from 33° 29′ to 36° 6′ N in geographical width and from 67° 43′ to 71° 40′E of geographical length on the coordinates of Afghanistan (Fig.1). The basin is 700 km long, of which 560 km flows inside Afghanistan with a total drainage area of 67,370 km^2. Originating from the Paghman Mountains on the west and the Kohe Safi Mountains on the east, the river flows west to east and is the main source of freshwater. The Kabul River Basin represents 26% of the total water resources in Afghanistan with mean annual streamflow of 24 billion cubic metres. It covers 12% of the total area of Afghanistan and is regarded as the most important river basin in the country. The total population of the Kabul River Basin stands at 7,184,974 with a density of 93 per km^2, representing 35% of the country's total. The climate of the Kabul River Basin is categorised by cold winters with seven months of extreme precipitation (November to May), and hot summers with less or no precipitation and streamflow, except in those rivers and streams fed by melting snow or glaciers. Due to the variation of the elevation, precipitation varies considerably throughout the basin. Moreover, 72% of the total runoff is created by the melting of permanent snow. The Kabul River Basin eventually connects to the Indus River Basin in Pakistan.

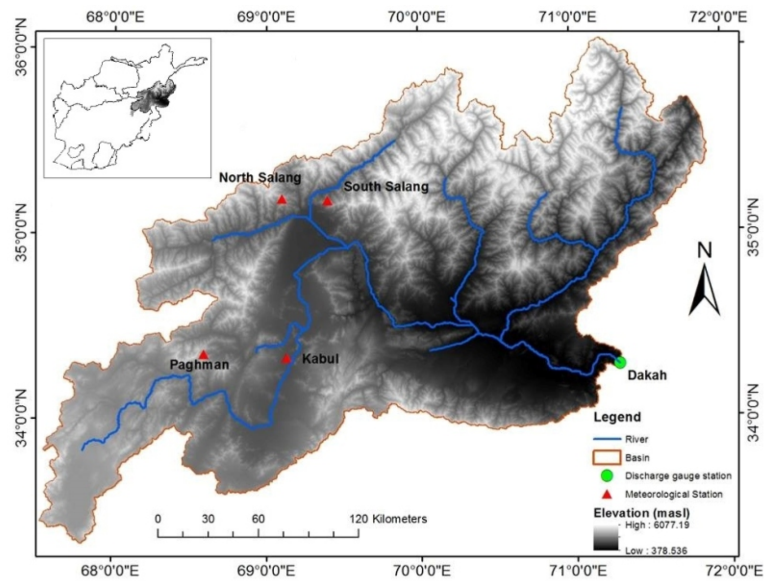


Fig. 1 Location map of the Kabul river basin with hydro-climatic stations

Hydro-climatic conditions of the basin

Historical monthly data for maximum and minimum temperature and precipitation was collected from the Department of Meteorology and Hydrology in Afghanistan. The period 1961–1980 was taken as the baseline for four meteorological stations inside the Kabul River Basin (Fig. 1). The monthly climatic data was changed to daily data using the MODAWEC model. The average annual maximum temperature, minimum temperature, mean temperature, and precipitation of the basin are 12, 2.6, 6.5 °C, and 690.3mm, respectively.

Table 1 : Characteristics of four climate stations used in the Kabul River Basin

Station	Avg Annual Precipitation (mm)	MeanT_{max} (°C)	MeanT_{min} (°C)	T_{mean} (°C)	Lat_N (°)	Lon-E (°)	Elevation (masl)
North Salang	990	4.23	2.82	0.70	35.19	69.1	3,366
South Salang	1036	6.47	0.11	3.17	35.18	69.4	3,172
Paghman	437	17.25	3.10	10.17	34.35	68.59	2,114
Kabul	299	19.74	4.60	12.18	34.33	69.13	1,791

Tmean mean temperature, Tmax maximum temperature, and Tmin minimum temperature Meteorological parameters: 1961–1980

The temperature in the Kabul River Basin varies according to the elevation and season. The maximum temperature falls in June, July, and August while the minimum temperature occurs in November, December, January, February, and March. The wettest month for the whole river basin is April, while June, July, August, and September are the driest.

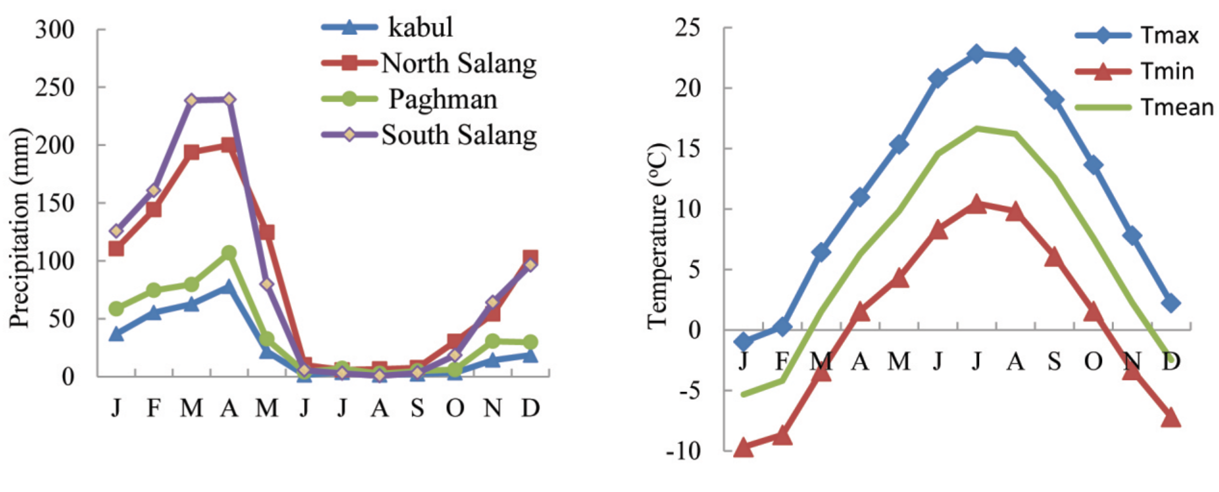


Fig. 2 Distribution of mean monthly Tmax, Tmin, and precipitation in the Kabul Basin at different meteorological stations for (1961–1980)

Mean monthly streamflow data for the Kabul Basin were collected (http://afghanistan.cr.usgs.gov/water) for one hydrological station located at the outlet of the basin. Available hydrological data for Dakah station covers the period from 1969–1978. A comparison of mean monthly streamflow indicates that the highest flow occurs during June and July, while the lowest flow can be seen in January, February, March, October, November, and December. On the other hand, since basin development has not occurred for 30 years, the increase in temperature may confirm the melting rate of snow peaks in the basin. Therefore, the melting snow peaks may cause an increase in the maximum runoff for 1980 compared to 1969 and 1975. The characteristics of the Dakah station are shown in Table 6.

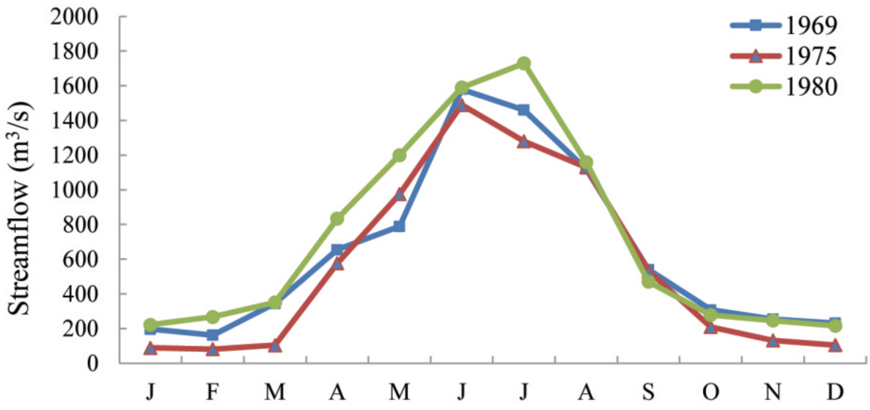


Fig. 3 Hydrographs of Dakah station in the Kabul River Basin (Source: Department of Hydrology, Kabul, Afghanistan 2014)

Spatial data used in the SWAT model

In this study, the 90 m resolution Digital Elevation Model (DEM) data from USGS was used to delineate the catchment, HRU, and derivation of stream slope and channel width. Besides, 300 m resolution of land use data was derived from the European Space Agency (http://due.esrin.esa.int/globcover) and reclassified based on the land cover system by Anderson et al. 1976. The land-use types of the study area were classified into seven groups: herbaceous vegetation (53.24%), agriculture (26.61%), permanent snow and ice (12.66%), forest (7.1%), bare land (0.31%), urban areas (0.01%), and water bodies (0.07%).

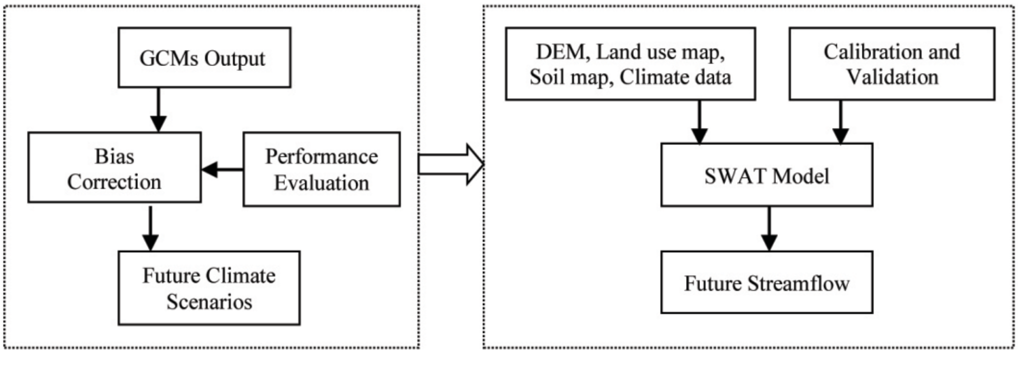


Fig. 4 Research methodology framework used in this study

Moreover, the soil map for the Kabul Basin and its properties was obtained from the DSMW (Digital Soil Map of the World) on a scale of 1:3000000. There are five types of soil in the study area: Eutric Combisols (0.1%), Litholic Gleysols (1.5%), Lithosols (76%), Calcaric Fluvisols (10.4%), and Haplic Acrisols (11.9%). In addition, the watershed was divided into 18 sub-basins and 122 HRUs using ARCSWAT based on land use, slope, and soil type. Corresponding to the HRUs and dependent upon the DEM used in this study, the total area was confirmed as 56,043 km^2.. The land use and soil definitions were provided by ArcSWAT 2012, using 2010 land use and soil maps.

Table 2 GCMs used in this study

Model	Resolution (long by lat)	Scenarios	Institution	Reference
CCSM4	1.25° X 0.9°	RCP 2.6 RCP 4.5 RCP 6.0 RCP 8.5	National Center for Atmospheric Research,USA	Gent et al., 2011
BCC-CSM1.1	2.8° X 2.8°	RCP 2.6 RCP 4.5 RCP 6.0 RCP 8.5	Beijing Climate Center, China Meteorological Administration	IPCC, 2007
MIROC5	1.40° X 1.40°	RCP 2.6 RCP 4.5 RCP 6.0 RCP 8.5	Atmosphere and Ocean Research Institute, Japan	IPCC, 2007

Methodology

This study mainly focuses on the projection of future climate using delta change method of bias correction and the assessment of its effect on the hydrology of the Kabul River Basin using SWAT hydrological model.

Climate change scenarios

Among 39 GCMs built into the CMIP5, three have been considered in this study (Table 2). These GCMs cover various resolutions, varying from 0.40° x 0.40° to 2.8° x 2.8° and their vintages are after 2010. Two RCP scenarios are used in this study: RCP 4.5 and the maximum and minimum temperature of RCP 8.5, representing future medium and high carbon emissions. The RCPs are four greenhouse gas concentration trajectories adopted by the IPCC for its Fifth Assessment Report (AR5) in 2014 (Table 3). The future time periods are divided into three as follows: 2020s, 2050s, and 2080s. The outputs of GCMs were used to project climate scenarios up to 2100 with respect to the baseline data (1961–1980). The meteorological future data was downloaded from the ESGF (Earth System Grid Federation) website and used for climate change projection. The output data (temperature and precipitation) of the models was downscaled using the delta change approach. The delta change method uses differences between simulated current and future climate conditions from General Circulation Models (GCMs) added to the observed (baseline) time series of climate variables.

$$T_f = T\,(GCM\,simulated)_f - T\,(GCM\,simulated)_p \quad (1)$$
$$P_f = PPT\,(GCM\,simulated)_f - PPT\,(GCM\,simulated)_p \quad (2)$$

Where, P is used for the present and F is used for the future time period. The future scenarios are then generated using equations 3 and 4.

$$F_s\,(T) = T\,(Baseline) + T_f \quad (3)$$
$$F_s\,(PPT) = PPT\,(Baseline) \cdot P_f \quad (4)$$

Where, $F_s(T)$ is for future temperature, $F_s(PPT)$ is for future precipitation, and PPT is used for precipitation.

In the Kabul River Basin, the GCM models were selected using statistical analysis. The statistical indicators: coefficient of determination (R^2) and root mean square error (RMSE) is the simplest and easiest methods of mathematical calculation. This study uses three GCMs to project future global data (2010–2099) for the four meteorological stations and the future mean changes in meteorological parameters corresponding to the baseline period (1961–1980). Therefore, the mean monthly values of R^2 and RMSE are developed among the meteorological parameters (maximum temperature, minimum temperature, and precipitation) of the models (GCMs) and the baseline data for the period 1971–1980. These values are then compared with the bias-corrected values of maximum and minimum temperature and precipitation for the same period. The value of R^2 is greater and RMSE is lower after bias correction. Thus, the three GCM models: CCSM4, MIROC5, and BCC-CSM1.1 can be used effectively in the Kabul River Basin.

Table 3 Summary of representative concentration pathways (RCP) scenarios

RCP	Description	Temp. anomaly (ºC)	CO_2 concentration (ppm)
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m2 in 2100	4.9	1370
RCP 6.0	Stabilisation without overshoot pathway to 6 W/m2 after 2100	3.0	850
RCP 4.5	Stabilisation without overshoot pathway to 4.5 W/m2 before 2100	2.4	650
RCP 2.6	Peak in radiative forcing at 3 W/m2 before 2100 and reaching 2.6 W/m2 by 2100	1.5	490 then declining

Impact of climate change on the hydrology

Hydrological modelling using the SWAT model

The SWAT model was selected for this study due to its worldwide use and validation (Gassman et al., 2007). In addition, it has been used for numerous climate change studies throughout the world (Fontaine et al., 2001; Eckhardt and Ulbrich, 2003; Chaplot, 2007; Guo et al., 2008; Schuol et al., 2008; Ficklin et al., 2009a, 2009b). SWAT is a hydrological/water-quality model developed by the US Department of Agriculture–Agricultural

Research Service (Arnold et al., 1998). The model is a continuous-time, spatially distributed simulator of the hydrological cycle and the transport of catchment-scale agricultural pollutants. It runs on either a daily or a monthly time step. A monthly time step was used for this study. The SWAT model's major components are weather conditions, hydrology, soil properties, plant growth, and land management, as well as the load and flow of nutrients, pesticides, bacteria, and other pathogens. A detailed description of SWAT can be found in Neitsch et al. 2005.

SWAT model performance evaluation

The SWAT model was calibrated and validated by comparing observed and simulated streamflow values at Dakah hydrological station. The performance of the model was assessed using the coefficient of determination (R^2), percent bias index (PBIAS), and Nash-Sutcliffe efficiency (NSE). The formulas of these parameters are as follows:

$$R^2 = \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_{obs}^{mean}\right)\left(Q_i^{sim} - Q_{sim}^{mean}\right)}{\sqrt{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_{obs}^{mean}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Q_i^{sim} - Q_{sim}^{mean}\right)^2}} \quad (5)$$

Where, R^2 is the coefficient of determination, Q_i^{obs} is the i[th] observed flow, Q_i^{sim} is the i[th] simulated flow, Q_{obs}^{mean} is the observed mean flow, Q_{sim}^{mean} is the simulated mean flow and n is the total observed flow.

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2 \times 100}{\sum_{i=1}^{n} Q_i^{obs}} \quad (6)$$

Where, PBIAS is the percent bias between observed and simulated values. PBIAS measures the relative percentage error between simulated and observed values (Moriasi et al., 2007). The positive value denotes underestimation; a negative value indicates overestimation, and zero means optimal estimation.

$$NSE = \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_i^{sim} - Q_{obs}^{mean}\right)^2} \quad (7)$$

Where, NSE is the Nash-Sutcliffe efficiency. NSE measures the level of consistency in measured values with predicted values and generally ranges from – ∞ to 1 with NSE = 1 as the optimal value (Nash and Sutcliffe, 1970).

Results and Discussions

Projection of climate change scenarios

Temperature projections

To understand the changes in maximum and minimum temperature and precipitation in the future, projected values were considered in three future periods: the 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099) relative to the baseline period (1961–1980) under two emission scenarios (RCP 4.5 and RCP 8.5).

Table 4 represents the mean changes in maximum and minimum temperature annually and seasonally in the whole of the Kabul River Basin relative to the baseline period (1961–1980) under RCP4.5 and 8.5 scenarios. Afghanistan has four seasons, namely spring, summer, autumn, and winter. This section compares annual and seasonal changes over the entire basin. The results show increasing changes for all seasons under both scenarios except for spring in the 2020s. The winter season is the most affected, with the maximum temperature reaching 9.5 ˚C and a minimum 7.5 ˚C under the RCP8.5 scenario in the 2080s. The annual maximum temperature is expected to increase by 1.9 ˚C in the 2020s, 3.6 ˚C in the 2050s, and 5.1 ˚C in the 2080s under both scenarios, and minimum temperature is expected to increase by 1.8 ˚C, 3.3 ˚C, and 4.6 ˚C, respectively.

Table 4 Future mean seasonal and annual changes in maximum and minimum temperature (˚C) relative to the baseline period (1961–1980) under RCP4.5 and RCP8.5 scenarios in the Kabul River Basin

Period	RCPs	Annual		Spring		Summer		Autumn		Winter	
		Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
2020s	RCP 4.5	1.8	1.5	-1.6	-1.4	3.7	1.5	4.6	3.6	0.7	2.4
	RCP 8.5	1.9	2.0	-1.5	-0.9	3.8	3.9	4.8	4.3	0.7	0.7
2050s	RCP 4.5	3.1	2.9	0.6	0.3	3.3	3.5	5.2	4.8	3.4	2.9
	RCP 8.5	4.1	3.7	1.2	1.4	4.3	4.0	6.4	5.2	4.3	4.0
2080s	RCP 4.5	3.9	3.4	4.3	3.4	1.0	1.2	2.9	3.0	7.2	6.1
	RCP 8.5	6.2	5.7	6.6	5.1	3.3	4.3	5.4	5.7	9.5	7.5

Precipitation projection

The fluctuation in monthly precipitation over the Kabul River Basin under RCP4.5 and 8.5 scenarios is shown in Fig. 4. The wettest month has shifted from April to March. Besides, under both scenarios, fewer changes are observed in January, February, March, April, October, and December. Under both scenarios, April is the baseline for the greatest decrease in precipitation of approximately 60 mm in the 2050s and 80 mm in the 2080s. Precipitation only peaks during May in the 2020s, approaching 80 mm under the RCP8.5 scenario. Based on the historical period 1961–1980, the wettest month for precipitation is April at 173 mm and there are also rapid decreases in this month. These results show that most months can be under drought, causing water stress for the whole area in the future.

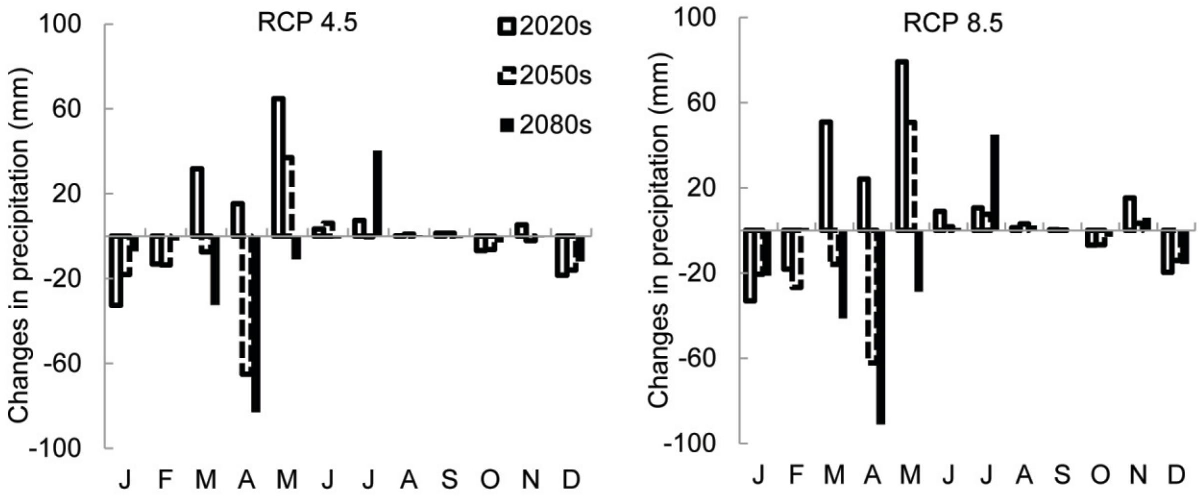


Fig. 5 Future mean monthly changes in precipitation relative to the baseline period (1961–1980) under RCP 4.5 and 8.5 scenarios in the Kabul River Basin

SWAT model calibration and validation

To perform the important process of hydrological modelling, the observed monthly streamflow for 1969–1978 was divided into two periods for calibration (1969–1973) and validation (1974–1978). The sensitive parameters (shown in Table 5) were checked by using the statistical indicators R^2, RMSE, and PBIAS. The total sensitive parameters were verified manually using the guidelines provided by Nietsche et al., (2005) to have a good model performance. The results from calibration and validation show that PBIASis very less and R^2 and NSE are within the limits showing 0.67 to 0.72.

Table 5 Calibrated parameters and their optimal values used in the SWAT modelling of Kabul River Basin

Parameter	Description/Units	Range	Optimal Value
$SFTMP_{(basin)}$	Snowfall temperature (ºC)	1	-0.59
$SMTMP_{(basin)}$	Snowmelt base temperature (ºC)	1	2.87
$SMFMX_{(basin)}$	Maximum melt rate for snow during the year (mm/c-day)	4.5	10
$SMFMN_{(basin)}$	Minimum melt rate for snow during the year (mm/c-day)	4.5	1
$SNO50COV_{(basin)}$	Snow water equivalent corresponding to 50% snow cover	0.5	0.99
$SECO_{(basin)}$	Soil evaporation composition factor	1	0.06
$EPCO_{(basin)}$	Plant uptake composition factor	1	0.649
$ADJ\_PKR_{(basin)}$	Peak rate adjustment factor for sediment routing in the sub basin (tributary channel)	1	1.87
$MSK\_COI_{(basin)}$	Calibration coefficient used to control the impact of the storage time-out constant for normal flow	0.75	6.8
$MSK\_CO2_{(basin)}$	Calibration coefficient used to control the impact of the storage time-out constant for low flow	0.25	1
$MSK\_X_{(basin)}$	Weighting factor controlling the relative importance of inflow and outflow rate to determine water storage in reach segment	0.2	0.3

Parameter	Description/Units	Range	Optimal Value
SOL_AWC (soil-sub-basin)	Available water capacity for the soil layer (mm/mm)	0.28	0.31
PLAPS (sub-basin)	Precipitation lapse rate (mm/km)	100	-59
TLAPS(sub-basin)	Temperature lapse rate (°C/km)	0	-4.5
CANMAX(hru-sub-basin)	Maximum canopy storage (mm)	0	12.1
ESCO(hru-sub-basin)	Soil evaporation composition factor	0.95	0.395
EPCO(hru-sub-basin)	Plant uptake composition factor	1	0.13
CH_N2 (routing-sub-basin)	Manning's "n" value for the main channel	0.014	0.2115
CH_K2(routing-sub-basin)	Effective hydraulic conductivity in the main channel alluvium (mm/h)	0	78.875
GW_DELAY (GW-sub-basin)	Manning's "n" value for the main channel (days)	0	409.259
ALPHA_BF(GW-sub-basin)	Base flow alpha factor (days)	0.048	0.057
GW_REVAP (GW-sub-basin)	Ground water revap coefficient	0.02	0.134
REVAPMN (GW-sub-basin)	Threshold depth of water with shallow aquifer for revap to occur (mm)	750	7.245
RCHRG_DP(GW-sub-basin)	Deep aquifer perculation fraction	0.05	0.361
GWQIMN(GW-sub-basin)	Threshold depth of water required in the shallow aquifer before return of flow can occur (mm)	1000	12.744

Table 6 Performance of SWAT for simulation of streamflow by using monthly data

Discharge station	Lat N(°)	Long E(°)	Alt (m)	D. Area (km^2)	Calibration (1969–1973)			Validation (1974–1978)		
					R^2	NSE	PBIAS	R^2	NSE	PBIAS
Dakah	34°14'	71°02'	420	67.73	0.71	0.67	16.3	0.63	0.72	-4.45

Note: R^2, Coefficient of determination; NSE, Nash-Sutcliffe Efficiency; PBIAS, Percent bias

During the calibration and validation period, the model underestimated the peak discharge in some months of 1971, 1972 and 1974 (Fig. 6). The differences between the baseline and simulated peak values are very high in 1971, 1972, and 1976, which may be caused by an error in the observed streamflow data at Dakah station. This overestimation for 1976 and underestimations for 1971, 1972, 1974, and 1978 are due to data error during the baseline and calibration and validation periods. At that time, the civil war and lack of security in Afghanistan meant that the government could not collect hydrological and meteorological data. In addition, there were no trained staff or adequate facilities available to operate this station and some data is missing. Consequently, the sensitive parameters explained in Table 5 are used in the SWAT model to predict the future streamflow in the Kabul River Basin.

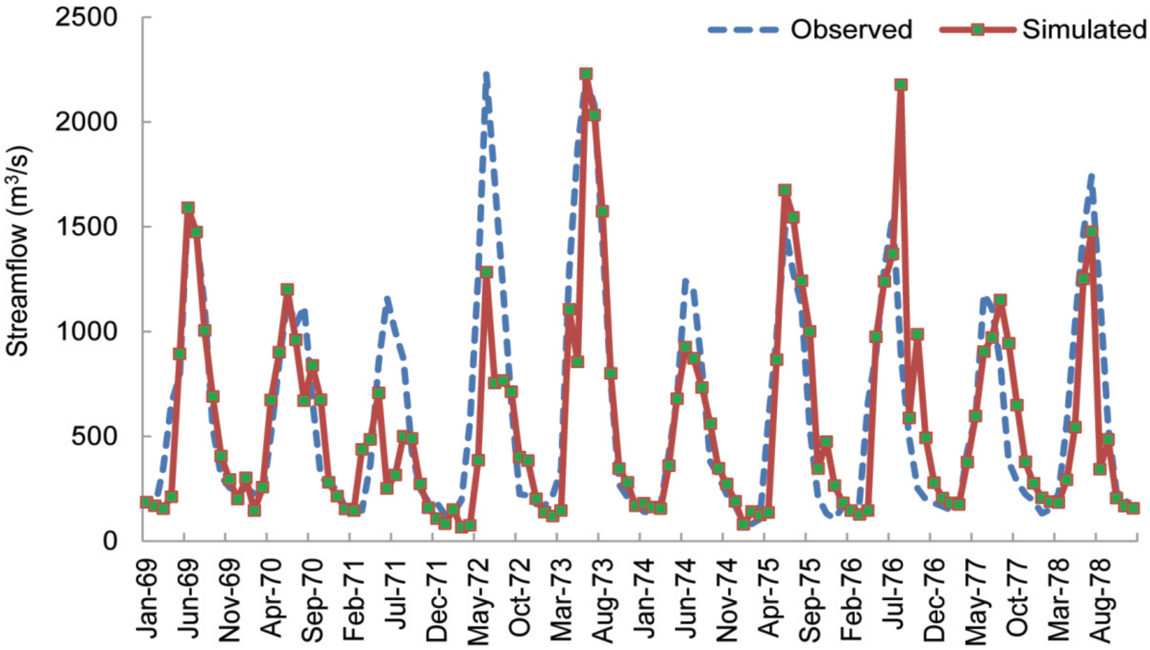


Fig.6 Comparison of observed and simulated monthly streamflow at Dakah station for calibration (1969–1973) and validation (1974–1978) periods in the Kabul River Basin

Impacts of climate change on hydrology

Changes in mean monthly and annual streamflow

To understand streamflow changes in the future, the projected values of meteorological parameters (temperature and precipitation) from four meteorological stations inside the Kabul Basin for three future periods (2020s, 2050s, and 2080s) were inputted into the SWAT model. The mean monthly simulated streamflow at Dakah station for the three future periods with respect to the baseline period (1969–1978) is shown in Fig. 7. The simulated streamflow for the 2020s peaked in June under RCP4.5 as well as for the remaining future periods and baseline. Under RCP8.5, the 2020s and 2080s simulated streamflows peaked in August and for the other periods in June. There are more higher peaks under RCP8.5 than RCP4.5 (approximately 400 m^3/s higher). Similar trends are seen for the 2020s, 2050s, and 2080s from September to December under RP4.5 and during September and October under RCP8.5. Under RCP4.5, the simulated future streamflow in the Kabul River Basin for June peaks higher than the baseline at roughly 300 m^3/s for the 2020s, 280 m^3/s for the 2050s, and 200 m^3/s for the 2080s. On the other hand, for the RCP8.5 scenario, an increase of 600 m^3/s is shown for August, 400 m^3/s for June, and 600 m^3/s in August also. These results show that the streamflow peaks are shifting from June to August for the 2020s and 2080s under RCP8.5.

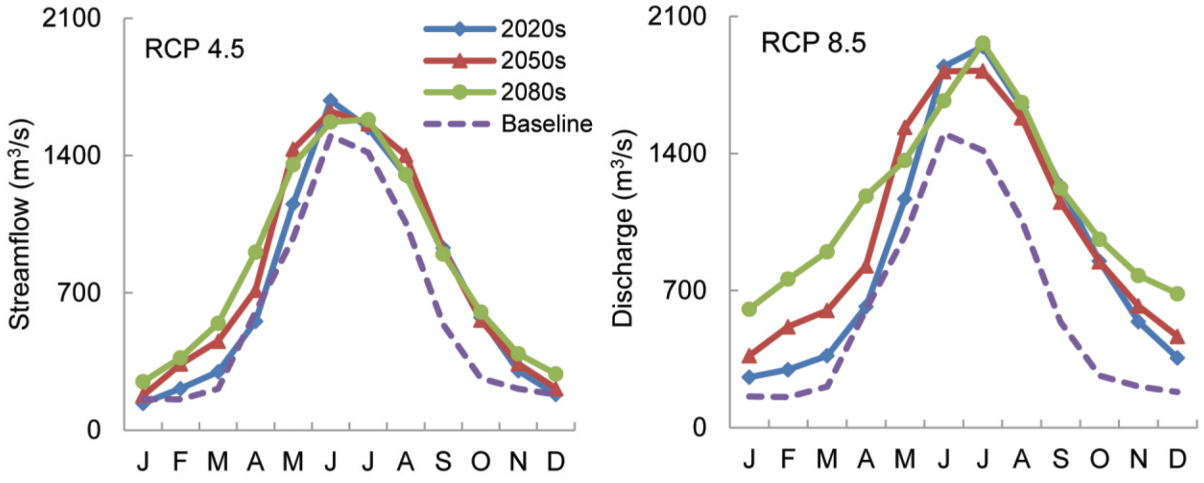


Fig. 7 Simulated mean monthly streamflow at Dakah station during the baseline (1969–1978) and three future periods (2020s, 2050s, 2080s) using the multi-model mean of projection under RCP4.5 and 8.5 scenarios

Table 7 shows the percentage change in simulated streamflow relative to the baseline period (1969–1978) under RCP4.5 and 8.5 scenarios at Dakah station. The greatest changes can be seen in February under RCP8.5 by 384% and 159% for RCP4.5. The largest decreases occurred in January (-13%) and April (-8%) under RCP4.5 for the 2020s only. In December, the streamflow changes under the two RCPs are different: 96% in the 2020s, 157% in the 2050s, and 277% in the 2080s under RCP8.5, and 0.7, 17, and 58% for RCP4.5. respectively.

Table 7 Percentage change in mean monthly streamflow for the future period of 2010–2099 relative to the baseline period (1969–1978) under RCP4.5 and RCP8.5 at Dakah station

Month	Baseline (m^3/s)	% change in Streamflow					
		RCP4.5			RCP8.5		
		2020s	2050s	2080s	2020s	2050s	2080s
January	158.5	-13.4	12.1	56.4	62.4	132.0	282.0
February	156.7	35.3	115.1	135.7	89.1	228.9	384.0
March	210.8	41.4	115.3	158.6	74.3	183.7	326.4
April	603.2	-8.1	18.4	50.4	2.4	37.0	96.2
May	981.1	17.5	45.9	37.9	19.1	56.2	39.1
June	1,501	11.9	8.2	4.6	22.8	21.1	11.2
July	1,414.9	8.9	10.4	11.9	37.5	28.7	38.8
August	1,058.8	22.7	32.4	23.1	54.5	49.4	56.8
September	538.7	72.6	71.0	66.6	129.0	113.8	127.2
October	264.9	117.1	111.9	127.2	221.1	219.9	263.4
November	210.8	43.9	61.0	85.1	156.5	194.9	268.5
December	181.8	0.7	16.6	57.8	96.3	156.7	276.5

Uncertainty in the projection of streamflow is inherent in climate change and water resources study. This section explains the uncertainties in streamflow projection by using box and whisker plots as shown in Fig. 8. The bar represents the median values, with the upper limits of the whiskers projecting the highest streamflow. Under RCP4.5, the streamflow will increase by 430 m^3/s in the 2020s, 440 m^3/s in the 2050s, and 390 m^3/s in the 2080s. On the other hand, under RCP8.5 it will be 700 m^3/s, 630 m^3/s, and 700 m^3/s, respectively. The streamflow changes for RCP8.5 are greater than those of RCP4.5 in all periods: 230 m^3/s in the 2020s, 180 m^3/s in the 2050s, and 300 m^3/s in the 2080s when checking the upper ends of the whiskers. The median values for streamflow changes are not very high but their projections are extremely significant at approx. 620 m^3/s for RCP8.5 and 400 m^3/s for RCP4.5 in the future period 2010–2099.

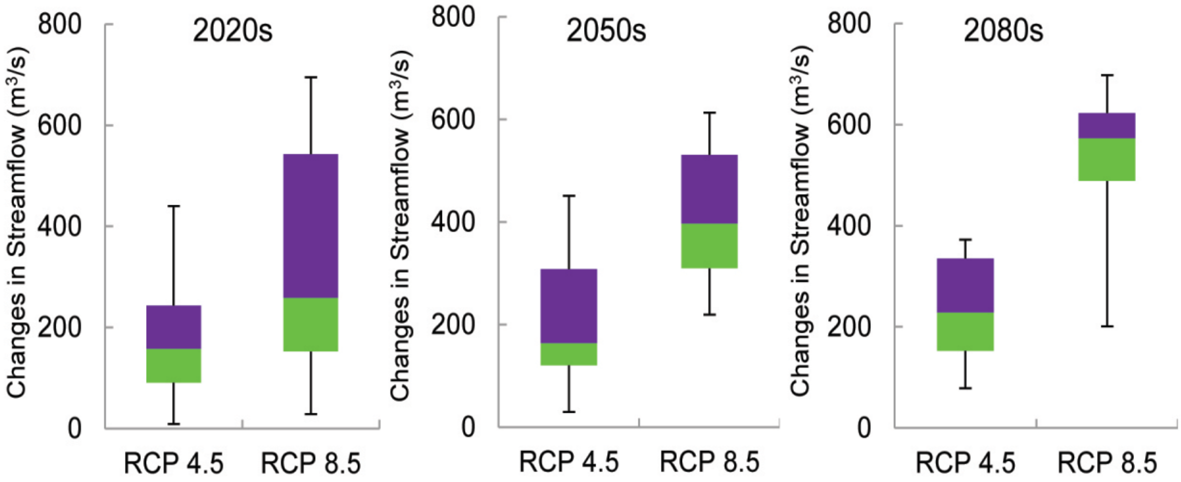


Fig. 8 Changes in annual mean streamflow for the 2020s, 2050s, and 2080s relative to the baseline period (1969–1978) at Dakah station

Changes in mean monthly and annual streamflow due to GCMs

Comparison between all three GCMs showed that streamflow will change in the future. Increases and decreases in streamflow for the future periods (2010–2099) under all GCMs are not the same. As shown in Fig. 9, the CCSM4 model projected increasing streamflow in every month for all three periods under RCP8.5, but it decreases in the months of January, February, March, April, and December of the 2020s under the RCP4.5 scenario. Peak flow changes in August of the 2050s under RCP4.5 and May under RCP8.5. In the future (2010–2099), the streamflow peaks in August (to almost 1500 m^3/s) for RCP4.5, and September (to 1000 m^3/s) for RCP8.5. Besides, the MIROC5 model projected decreasing streamflow for May, June, and July under both scenarios for the three periods. The greatest decreases in flow approach -900 m^3/s under RCP 4.5 for the 2080s and -600 m^3/s under RCP8.5 for the 2050s in the month of June. The greatest increases in flow are projected to be + 600 m^3/s for the 2050s and +800 m^3/s for 2080s under both scenarios in the month of March. Moreover, the BCC-CSM1.1 model projected increasing streamflow for most months under both scenarios. Under RCP4.5, the streamflow peaks in March approaching 690 m^3/s in the 2080s and 1700 m^3/s for RCP8.5. These streamflow changes are very different among the RCPs; the flow change is 180 m^3/s under RCP4.5 but 700 m^3/s under

RCP8.5 in January. The largest decrease in streamflow is seen in July under RCP4.5 but RCP8.5 showed no decline.

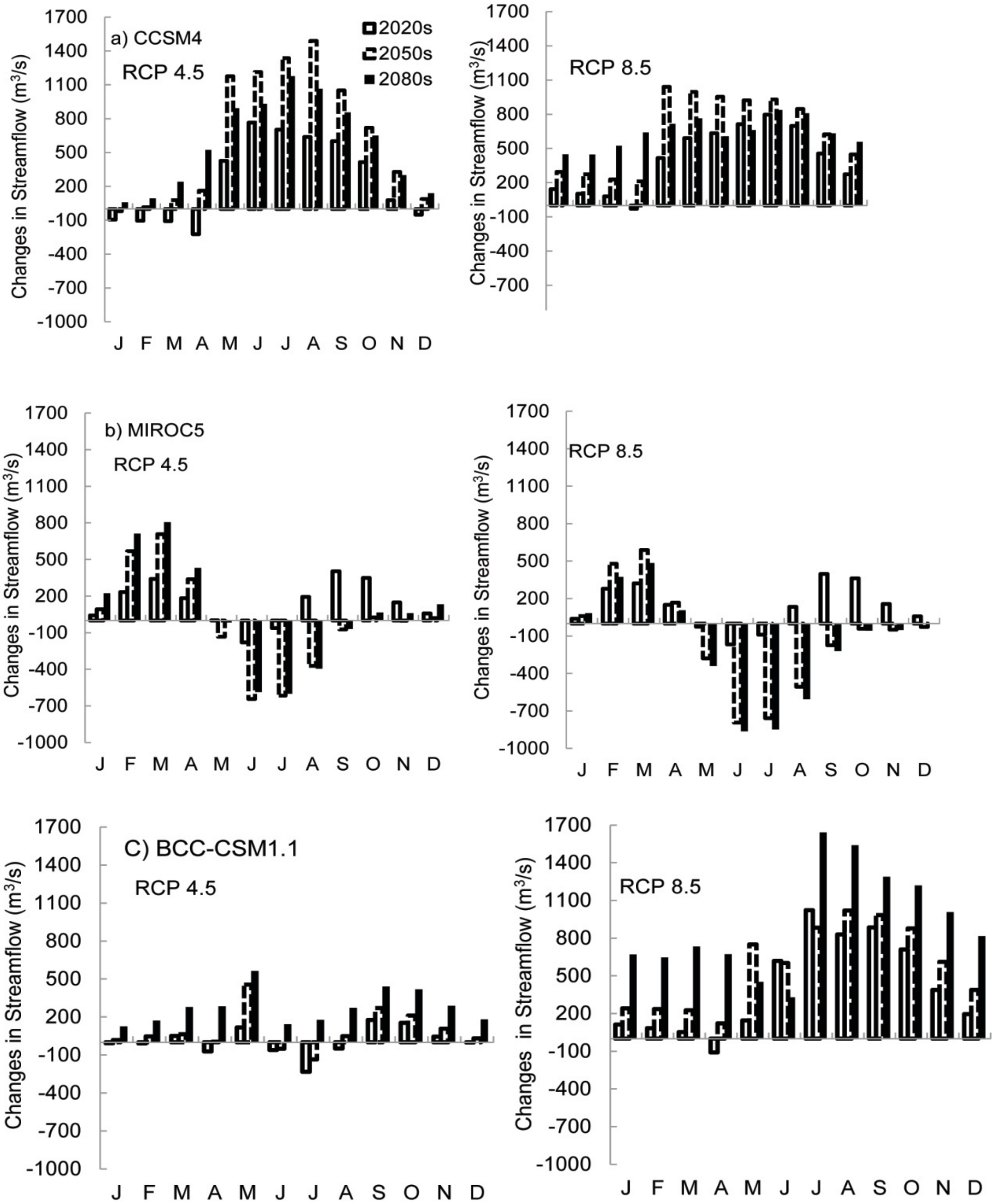
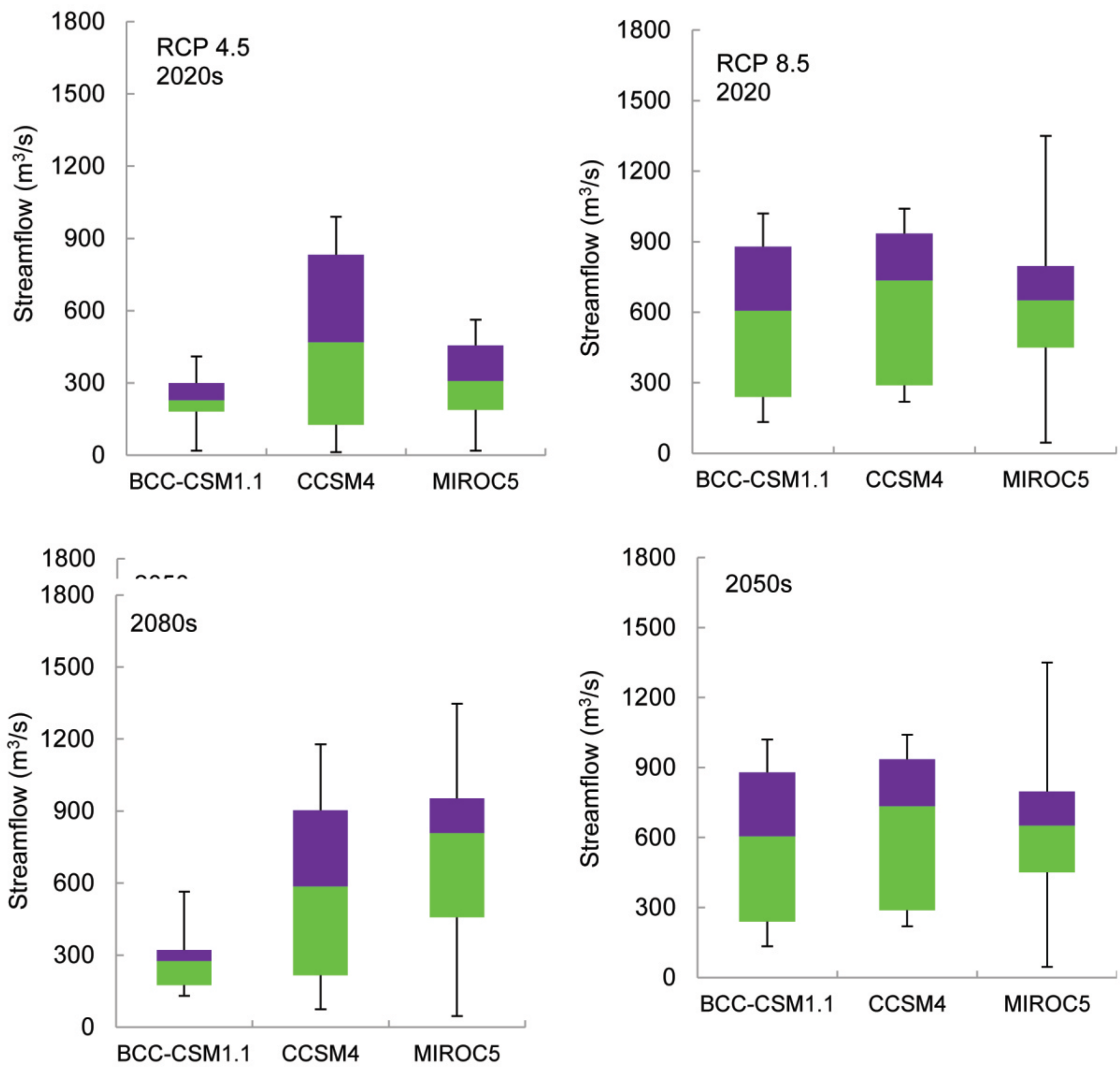


Fig. 9 Mean monthly streamflow changes in the future period of (2010–2099) relative to the baseline period (1969–1978) by different GCMs

Uncertainty in annual streamflow changes due to GCMs

Uncertainties in the projected changes of mean annual streamflow using three GCMs under the RCP4.5 scenario with respect to the baseline period at Dakah station are shown in Fig. 10. The CCSM4 GCM projected more flow changes than the other two GCMs in the 2020s and 2050s and MIROC5 for the 2080s. The BCCCSM1.1 projected the least changes relative to the baseline data and can be assumed to provide a good performance projection under RCP4.5 in the Kabul River Basin. The difference between the highest and lowest flow can be the baseline in MIROC5 for both the 2020s and 2050s and BCCCSM1.1 for the 2080s, while BCCCSM1.1 and CCSM4 show the least projected changes. The highest projected change is almost 1700 m^3/s and the least 1100 m^3/s in the future under RCP8.5. The BCCCSM1.1 projected the least amount of changes under RCP4.5 but CCSM4 predicted more for RCP8.5. Comparing the two GCMs, CCSM4 is a higher resolution model but projected the most flow changes under RCP4.5.



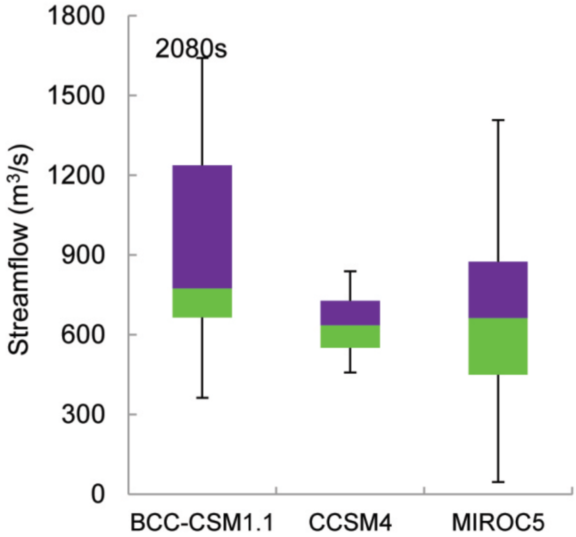


Fig. 10 Changes in mean annual streamflow according to GCMs under RCP 4.5 and RCP 8.5 relative to the baseline period at Dakah station

Conclusions

This study assessed the climate change impact on streamflow in the Kabul River Basin in Afghanistan. The outputs of three GCMs were bias-corrected using the delta change approach for future climate scenarios (2010–2099) at the basin level. All three GCMs showed good performance after bias correction. Forecasted future climate data from three GCMs under two Representative Concentration Pathways; RCP 4.5 and RCP 8.5 was applied to the SWAT model to evaluate the potential streamflow changes in the Kabul River Basin for three future periods: early-century (2020s), mid-century (2050s), and late-century (2080s).

It is projected that the mean annual maximum and minimum temperature will increase in the future for the whole basin under both scenarios in all three future periods. The highest increase of mean annual temperature is projected for the winter and spring seasons under both RCPs. The mean maximum temperature will increase from 2.9 °C to 4 °C and the minimum temperature 2.7 °C to 3.7 °C in the future period 2010–2099 under both scenarios. In contrast, the mean annual precipitation will be reduced from 53 to 65%, corresponding to the baseline period for the Kabul River Basin.

Analysis of the outputs of the SWAT hydrological model showed that the streamflow is expected to increase at the outlet of the Kabul Basin in the future. The increase in streamflow can be attributed to the melting of snow and ice as 72% of the total runoff is contributed by the melting of permanent snow and ice in the basin.

Although all three GCMs were bias-corrected before application to the study area, uncertainties are always associated with future climate data and thus, this study is no exception. Besides, due to the lack of land-use change, uncertainties also exists within the SWAT model calibration. Therefore it is recommended to include the changes in land use together with other development issues for the estimation of changes in streamflow in future. The findings of this study will be useful to water resources planners and policymakers when considering the effect of climate change on streamflow.

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