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Evaluating the impacts of climate change projections on streamflow in the Panjshir watershed

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ABSTRACT

Climate change represents a critical global concern affecting water resources both quantitatively and temporally. Afghanistan ranks among the top ten most vulnerable countries to climate change, with its water supply heavily reliant on snowmelt. Situated on the southern slopes of the central Hindu Kush Mountains, the Panjshir Basin contributes a significant amount of water to the Kabul River. This study has utilized the Soil and Water Assessment Tool (SWAT) Model to assess the effects of climate change on streamflow within the relatively pristine target watershed. Initially, the recently (2008-2023) collected flow data were compared against the baseline period (1960-1980) revealing declines up to 10.77%. Subsequently, the SWAT model underwent configuration, calibration and validation using the observed data, and was then applied to project future streamflow under two climate scenarios – SSP2-4.5 and SSP5-8.5 – across three future periods: near-future (2031-2050), future (2051-2070), and far-future (2071-2100). The study's outputs point to a decreased streamflow under both scenarios – specifically 11.95% and 20.5% during the near-future interval, as well as 22.10% and 28.75% during the far-future interval, respectively, against the baseline. Moreover, the model shows a shift in peak discharge from June to April due to earlier snowmelt, which poses risks to agricultural water availability. Similar impacts are expected in nearby catchments in Afghanistan and high-altitude areas of the Hindu Kush-Himalayan system. The study's findings underscore the urgency of adaptive water management strategies, including developing water storage, improving irrigation efficiency, and employing climate-resilient agricultural practices to mitigate potential climate change impacts.

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1. Introduction

Climate change stands as one of the urgent and formidable issues facing our world in the 21st century, significantly altering hydrological cycles, ecosystems, and the broader environment (IPCC, 2023; Mengistu et al., 2021). Afghanistan, despite contributing only 0.19% to global greenhouse gas emissions, ranks the fourth most vulnerable country to climate change (Climate Change and Governance in Afghanistan, 2015; FAO, 2019; Mayar, 2021a; Sidiqi et al., 2023). Over the past decades, the country has witnessed a 1.8°C rise in mean annual temperature, resulting in earlier snowmelt and shifting precipitation patterns (Mayar, 2021b). These climate-induced changes impose profound effects on the water resources of the Kabul River Basin (KRB), which considerably relies on snowmelt from the Panjshir watershed (Akhtar et al., 2021, Azizi & Asaoka, 2020).

The KRB faces the mounting challenges of water scarcity driven by climatic variability. Prior research, such as Azizi & Asaoka (2020) and Sidiqi et al. (2023), have indicated snowmelt as the primary driver of water availability in the basin, making it highly sensitive to climate-driven changes in snow cover and meltwater timing. Studies by Akhtar (2017) and Mayar et al. (2020) emphasize the growing risk of imbalanced water resources with an increase in peak flow events and extended low-flow periods. Future climate scenarios, such as these analyzed by Ayoubi et al. (2024), further signal the effects of climate change on the KRB that could exacerbate water shortages during the critical summer months.

The Panjshir watershed, a key contributor to the KRB, remains under-researched compared to neighboring regions. The existing studies, such as Azizi & Asaoka (2020), Shokory et al. (2023), Azizi A.H. et al. (2024), Asharaf & Kulkarni (2023), and Akhtar et al. (2022), have either assessed snow cover changes and glacier recession in the larger KRB or focused on adjacent areas. Detailed analyses of the climate change impacts on streamflow variations and their implications for water resource management in the Panjshir watershed are lacking. This catchment's unique hydrological characteristics, including its minimal infrastructure and relatively pristine natural conditions, make it an ideal site for investigating the pure effects of climate change on streamflow. Unlike other regions where land use and urbanization heavily influence water availability, the Panjshir watershed offers a more controlled environment to isolate the impacts of climate variations from anthropogenic pressures. Given the target region's vulnerability, such an analysis is crucial for elaborating sustainable water management strategies.

The significant gap in meteorological records – particularly between 1980 and 2008 due to insecurity and civil conflict in the country – manifests one of the primary predicaments in the Panjshir watershed. In its turn, data scarcity limits accurate hydrological modeling. To address the gap, this study has integrated global climate datasets and remote sensing technologies, as recommended by Akhtar et al. (2021) highlighting the importance of coupling remote sensing data with hydrologic models in data-scarce environments. This methodology enhances the precision of streamflow forecasts as well as offers a better comprehension of the effects of climate change within the region.

The novelty of this manuscript lies in its localized analysis focusing specifically on streamflow variations in the Panjshir watershed under two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) over three time periods: near-future (2031-2050), future (2051-2070), and far-future (2071-2100). Unlike broader regional studies – often overlooking socio-economic factors such as future land use and cover changes, which can significantly affect hydrological predictions – this research avoids the uncertainty caused by anthropogenic impacts. By focusing on a watershed with pristine natural conditions, minimal infrastructure, and low likelihood of future human interventions, the analysis ensures more accurate predictions of climate-driven hydrological changes and offers insights essential for formulating adaption strategies aimed at effective water resource management in this vulnerable area.

2. Materials and methods

This study has adopted a three-phase approach (Fig. 1). The initial phase has encompassed selecting the study area and a suitable analytical model, as well as gathering relevant input data. The second phase has focused on model configuration using the required input data followed by calibration and validation to ensure output reliability. The third phase has incorporated introducing future scenarios and analyzing their outcomes for the three determined intervals. Each phase is described in detail below.

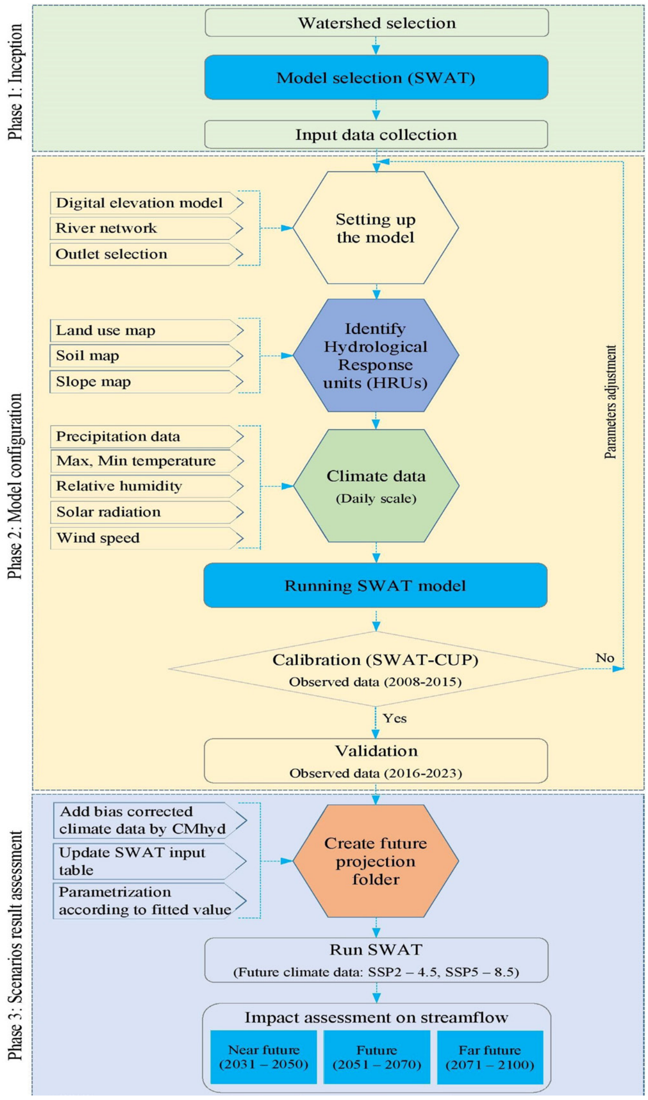

Figure 1. The study's tri-phasic methodology comprising the following stages: (1) selection of the study area and an appropriate model, and collection of input data; (2) model configuration using the required input data, and model calibration and validation; (3) introduction of future scenarios and analyzing model outcomes for the study area.

2.1. Study area

Situated on the southern inclines of the central Hindu Kush Mountain Range, the Panjshir watershed is integral to the hydrological contribution to the Kabul River (Fig. 2), with its water used for domestic, irrigation and hydropower (in Naghlu, Sorobi and Darunta power stations) purposes in the basin's lower section. The Panjshir's catchment area is approximately 3,447 km² located between 69.24-70.03° longitude and 35.07-35.89° latitude. The watershed was selected for this investigation because it embodies nearly pristine natural conditions with minimal existing infrastructure affecting streamflow. According to Fig. 2b, bare land, permanent snow, irrigated agriculture, water bodies and built-up areas account for 88.1, 6.96, 3.75, 1.07, and 0.12% of the catchment, respectively. Additionally, rocky land with lithic Cryorthents and Haplocryids constitutes the majority of soil types within the target watershed (Fig. 2c). Furthermore, the likelihood of additional interventions potentially affecting streamflow in the basin in the near-future period is low. Thus, analyzing the local impacts of climate change can vividly reveal its actual consequences, which is crucial information for downstream water consumers. Moreover, the study's findings can be utilized to project climate change effects on adjacent areas.

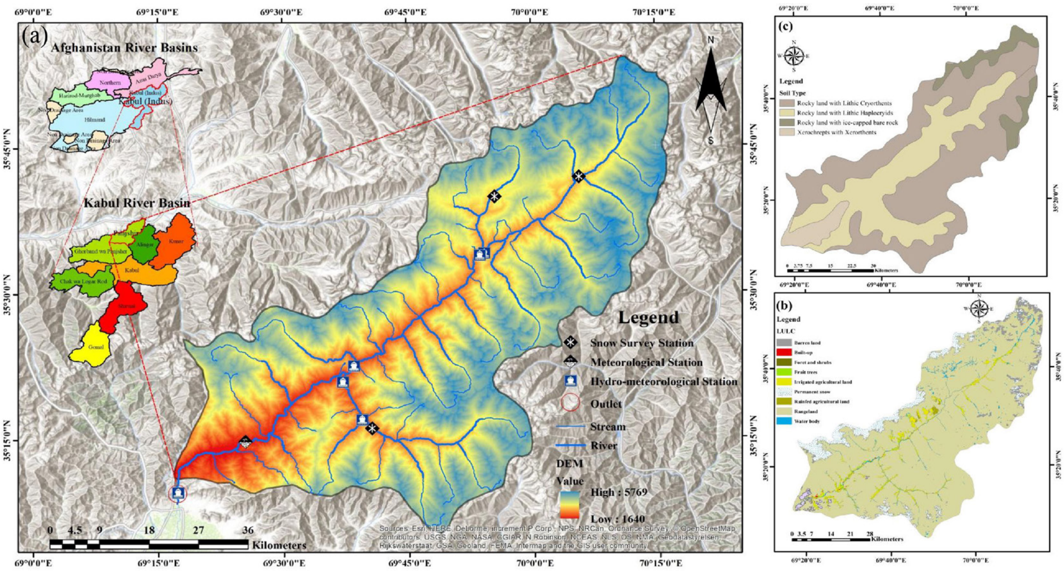

Figure 2. The Panjshir watershed, including (a) DEM topography, (b) land use and land cover map, and (c) spatial portrayal of soil types.

The climatic conditions in the target basin vary considerably in the course of the year. Fig. 3 depicts the monthly precipitation means, as well as maximum, minimum and mean temperatures for the study area. The maximum precipitation occurs during the winter and early spring seasons, especially in January, February, March and April, while the minimum precipitation is observed during the summer season, especially in June, July, and August. The melting of snow produces most of the river's discharge during the latter months of the year.

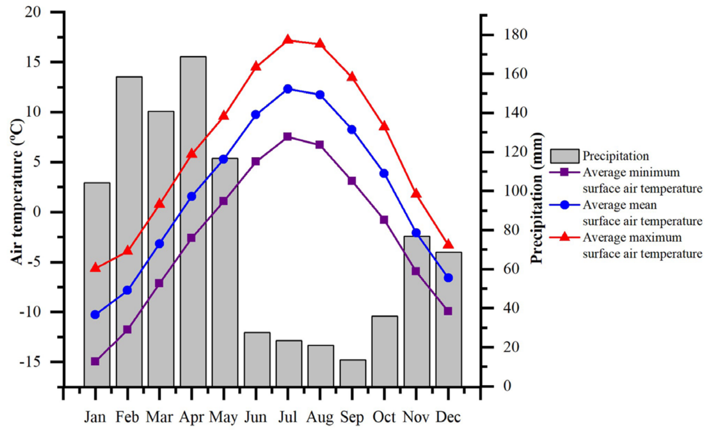

Figure 3. Mean monthly air temperatures and precipitation in the Panjshir watershed during 1981-2023 (based on the data from Afghanistan - Climatology, 2021).

The temperatures in the watershed depend on elevation. The maximum temperature of 39.45°C was registered at the Automatic Weather Station (AWS) in Dashtak, an area with the lowest altitude (1,787 m ASL) in the basin's middle section. The minimum temperature of -30.81°C was recorded at the Parian Snow Survey Station (SSS) in the high-elevation valley (2,929 m ASL) in the catchment's northeastern part.

The Panjshir watershed hosts nine observation stations (SSS, AWS, and hydro-meteorological) collecting hourly data and providing daily totals for precipitation (mm), maximum and minimum air temperatures (°C), mean relative humidity (%), total solar radiation (hours), and average wind speed (m/s). Table I contains further information about the installations.

Table I. Observation stations in the Panjshir watershed, their data recording periods and data types.

No	Station name	Record period	Collected data type	Type of station	Longitude	Latitude
1	Dara Hazara	2012-2023	P, T, RH, S and W	Snow Survey Station	69.676	35.269
2	Kootal Khawak	2012-2023	P, T, RH, S and W	Snow Survey Station	69.925	35.665
3	Parian	2012-2023	P, T, RH, S and W	Snow Survey Station	70.095	35.698
4	Dashtak-AWS	2012-2023	P, T, RH, S and W	Meteorolog-ical	69.423	35.247
5	Dewabi	2012-2023	P, T, RH, S and W	Hydro-mete-orological	69.618	35.348

Table I. Cont.

6	Keraman	2012-2023	P, T, RH, S and W	Hydro-mete-orological	69.656	35.283
7	Eomerz	2012-2023	P, T, RH, S and W	Hydro-mete-orological	69.640	35.375
8	Nazdik-e-Khawak	2012-2023	P, T, RH, S and W	Hydro-mete-orological	69.903	35.567
9	Khawak	2012-2023	P, T, RH, S and W	Hydro-mete-orological	69.894	35.564
10	Tangi-e-Gulbahar*	2012-2023	P, T, RH, S, W and Q	Hydro-mete-orological	69.288	35.159

Note: P – Precipitation, T – Temperature, RH – Relative Humidity, S – Solar Radiation, W – Wind Speed, and Q – Discharge.

*The Tangi-e-Golbahar Station at the Panjshir watershed's outlet is managed by the downstream Ghorband-Charikar Sub-Basin Administration.

The meteorological records of the observation stations in the study area have not been consistent and contain certain gaps. For instance, the Nazdik-e-Khawak Station lacks data for the months of October, November, and December of 2016. Additionally, gaps in rainfall and temperature data exist at intervals ranging from one to seven days. Furthermore, data gaps for wind speed and direction, solar radiation, and humidity were discovered for periods extending up to one to two months during 2014-2017. Two conventional protocols – Multiple Linear Regression (MLR) and Normal Ratio Method (NRM) – were employed to complete the daily meteorological datasets. Whereas MLR allows reconstructing the missing data by selecting nearby stations and determining the optimal sample size (Ambrosius, 2007), NRM is reported as simpler and more useful for detecting significant differences in normal annual climate data (Beven, 2020; Sadrianzadeh et al., 2023).

2.2. Model selection

Considering the study area location, altitude and available data, the Soil and Water Assessment Tool (SWAT) was chosen as the primary simulation model for evaluating the effect of climate change on streamflow in the target basin. SWAT is a highly esteemed semi-distributed physically-based continuous-time simulation model distinguished for its adaptability and dependability (Arnold et al., 2012). Developed and regularly updated by the United States Department of Agriculture, SWAT operates at daily time steps, making it suitable for various watershed scales and hydrological processes.

The suitability of SWAT for diverse geographical settings is evidenced by its widespread application in both small- to mid-sized basins and large mountainous regions worldwide (Sadrianzadeh et al., 2023). Notably, SWAT has demonstrated high efficacy in predicting the possible effects of climate change on river flow patterns, erosion rates, nutrient transport dynamics, and other critical environmental factors (Abbaspour et al., 2007; Arnold et al., 2012). Further technical details of the SWAT model can be found in Winchell et al. (2013).

SWAT's comprehensive capabilities made it the ideal choice for this study, enabling the assessment of complex hydrological phenomena and their responses to changing environmental conditions. Additionally, the model's ability for envisioning future possibilities offers crucial perspectives on how to tackle water resource management and devise strategies to adapt to the ever-changing climate landscape (Ougahi et al., 2022).

2.3. Input data

Calibration, validation and projection of hydrological models require topographic, land use, soil and hydro-climatic data. Table II provides an overview of the essential data used in the SWAT model under this study.

Table II. Key input data for the utilized SWAT model.

No	Data type and resolution	Characteristics	Sources
1	Digital Elevation Model (DEM) of 10 m resolution	Elevation	Copernicus Digital Elevation Model - Copernicus Contributing Missions Online, 2022
2	Land Use Land Cover (LULC) map of 30 m resolution	Land use and	FAO Map Catalog - Food and Agriculture Organization of the United Nations, 2020
3	The FAO/UNESCO Digital Soil Map of the World (DSMW) with the spatial resolution of 5x5 arc minutes and in geographic projection	Soil characteristics	FAO/UNESCO Soil Map of the World | FAO SOILS PORTAL | Food and Agriculture Organization of the United Nations, 1992
4	Historical (1960-1980) weather data of 0.5x0.5° (50x50 km) resolution	Precipitation, min and max temperatures	World Bank Group, 2021
5	Weather data from the observation stations listed in Table 1 along with the Climate Forecast System Reanalysis of 19.2 km resolution	Precipitation, min and max temperatures, solar radiation, relative humidity and wind speed	Ministry of Energy and Water (MEW) of Afghanistan; Fuka et al., 2014
6	Projected (2031-2100) daily weather data from the 6th Phase of the Coupled Model Intercomparison Project (CMIP6) available in a nominal (1.9× 2.5°) horizontal resolution configuration	Precipitation, min and max temperatures	CMIP6 Climate Projections. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 2021
7	Daily streamflow data	River discharge	Tangi-e-Gulbahar Station, MEW

To configure the SWAT model, static datasets pertaining to topography, soil types, land use (Fig. 2), and hydro-meteorological data are indispensable. Within the framework of this study, a digital elevation model (DEM) was utilized to characterize the geographical features and layout of the land. This DEM, obtained from the Copernicus Data Space Ecosystem website in October 2023 (European Space Agency, n.d.), provides elevation data at 10 m resolution. The DEM serves a critical role in the SWAT model, delineating watersheds and analyzing the patterns of the drainage network across the land surface. Consequently, features of the stream network, including primary and secondary streams and rivers – in addition to watershed metrics, including slope gradient and slope length – were extracted and integrated into the model.

The 2016 land cover dataset was received from the United Nations Food and Agriculture Organization (UN FAO) Geospatial Platform (Food and Agriculture Organization, n.d.). This dataset focusing on farms, orchards, and forests, is generated using Landsat Thematic Mapper (TM1) satellite imagery at 30 m resolution.

The soil data used under this study was sourced from the FAO/UNESCO Soil Map of the World (Food and Agriculture Organization, n.d.), with the spatial resolution corresponding to grid cells of approx. 10x10 km at the equator, facilitating detailed global soil analysis. The dataset employs a latitude-longitude coordinate system – a projection standard common for global datasets.

The historical temperature and precipitation data for the baseline period (1960-1980) with the spatial resolution of 0.5x0.5° (approx. 50x50 km) were obtained from the World Bank's Climate Change Knowledge Portal (World Bank, n.d.).

In addition, hourly climatic data on precipitation, air temperature, relative humidity, solar radiation and wind speed were harvested from the monitoring stations in the target catchment. The consistency and homogeneity of weather data were checked using double mass analysis.

For the future weather data, the General Circulation Model (GCM) data for three intervals of near-future, future, and far-future were collected in daily scale from the Community Earth System Model Version 2 (CESM2-USA) (Das et al., 2023; Simpson et al., 2020). This approach uses the bias-corrected dynamically downscaled output method by applying the Climate Model data for hydrologic (CMhyd) modeling software. The downscaling method uses the delta change approach commonly utilized in climate change impact research to improve precipitation and temperature data from GCM (Awotwi et al., 2021; Rathjens et al., 2016). This technique helps to correct any biases in GCM outputs for a given area. The process involves comparing future and current GCM simulations with recorded daily data, and then applying this difference to the current dataset to create a future projection (Das et al., 2023; Nepal et al., 2021). The corrected parameters are then used as input climate data to assess hydrological changes under future climate conditions.

The river discharge values at the basin's outlet were recorded at the Tangi-e-Gulbahar Station registering daily and monthly discharge during 2008-2023 and during the baseline period.

2.4. Calibration and validation of SWAT-CUP

As a high-altitude catchment, the Panjshir faces challenges as to accurately simulating streamflow due to its complex hydrogeology. Determining sensitive parameters like hydrological, soil, meteorological, and groundwater factors is crucial for accurate estimation. Understanding the uncertainties associated with these parameters is essential for achieving agreement with recorded discharges. This study has used the Sequential Uncertainty Fitting (SUFI-2) algorithm to assess the relative sensitivity values, enabling the estimation of streamflow-relevant parameters. The SUFI-2 algorithm helps in estimating the target parameters effectively. To analyze the uncertainties, the SWAT-CUP tool was applied. The 95% prediction uncertainty (95PPU) – representing the proportion of optimal model solutions across a range of parameter values – is another output of this tool. Any one or more of the model's inputs could be the source of these uncertainties. The p-factor and the r-factor represent the model's uncertainty (Abbaspour et al., 2017). The percentage of real streamflow data that is accurately estimated in the model output is known as the p-factor (Almeida et al., 2018). The 95PPU's thickness is the r-factor (Idrizovic et al., 2020).

The SWAT-CUP calibration process entails iterative adjustments, including calculating a Hessian matrix, covariance matrix, and correlation matrix. Parameter ranges undergo reorganization, and settings are fine-tuned to center new ranges around the best simulation. The final results are subsequently assessed based on predetermined standards, aligning with model assessment guidelines for watershed simulations established by Moriasi et al. (2007). The three quantitative statistics in Table III were applied for the assessment within this study.

Table III. General reported ratings for Root Coefficient of Determination (R2), Nash-Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS).

Objective function	Very Good	Good	Satisfactory	Unsatisfactory
R2	75 < R2 ≤ 1	0.65 < R2 ≤ 0.75	0.5 < R2 ≤ 0.65	R2 ≤ 0.5
NSE	75 < NSE ≤ 1	0.65 < NSE ≤ 0.75	0.5 < NSE ≤ 0.65	NSE ≤ 0.5
PBIAS (%)	PBIAS < ± 10	±10 ≤ PBIAS ≤ ± 15	±15 ≤ PBIAS ≤ ± 25	PBIAS ≥ ± 25

The calibration and validation of the study area were conducted in its outlet station (Tangi-e-Gulbahar) for the periods of 2008-2015 and 2016-2023, respectively.

The validated SWAT configuration was subsequently employed to forecast streamflow in light of SSP2-4.5 and SSP5-8.5 climate change scenarios, from 2031 to 2100.

2.5. Climate change impact assessment

To assess the effects of climate change on streamflow, the mean discharge values of the three designated intervals were compared to the average baseline discharge. The net and relative differences were calculated. Furthermore, the monthly averaged values of discharge generated by the SWAT model using climate projected inputs were compared with the recorded monthly discharge means of the hydrograph at the outlet station.

3. Results

This section commences with outlining the comparative analysis of temperature and precipitation data from the years 2008 to 2023, alongside the three future intervals, in relation to the baseline period spanning from 1960 through 1980. Subsequently, it discusses the outcomes of the SWAT model calibration and validation for simulating streamflow in the study area. Next, it presents the findings regarding the effects of climate change scenarios on future streamflow. Lastly, the section describes the influence of climate change on monthly flow distribution.

3.1. Temperature and precipitation data analysis

The result of temperature variation is shown in Table IV and Fig. 4. The most significant increase of +6.74°C is expected in the far-future period under SSP5-8.5. In the same scenario, the temperature is anticipated to rise by an average of 2.86°C in the near-future and by 4.47°C in the far-future intervals, respectively.

For SSP2-4.5, an increase of +4.02°C in the far-future is anticipated. Similarly, temperature is projected to grow by an average of +2.53°C and +3.30°C in the in the near-future and the future intervals, respectively. The results of this study are consistent with the findings documented in the literature pertaining to the region. Notably, prior researches by Azizi & Asaoka (2020), Iqbal et al., (2018), and Sajood & Safi (2020) on climate change in the Himalayan basins demonstrate a pronounced escalation of temperatures during the winter months. Also, Sanjay et al. (2017) conducted a study utilizing regional climate models that indicated a rise in temperatures across the Hindukush and Karakoram regions. Their findings suggest that, under the SSP5-8.5 scenario, temperatures are anticipated to mount by 5.4°C in winter and 4.9°C in summer by the end of the 21st century.

Table IV. Temperature variation for the recorded and three future intervals compared to baseline.

Baseline period (1960-1980) mean, °C	Recorded (2008-2023)		Scenarios	Near-Future (2031-2050)		Future (2051-2070)		Far-Future (2071-2100)	
	Mean, °C	Anomaly, °C		Mean, °C	Anomaly, °C	Mean, °C	Anomaly, °C	Mean, °C	Anomaly, °C
-2.30	-0.91	+1.93	SSP2-4.5	0.23	+2.53	1.00	+3.30	1.72	+4.02
			SSP5-8.5	0.56	+2.86	2.17	+4.47	4.44	+6.74

Moreover, the visualization of annual mean temperatures for the baseline, recorded and future intervals under SSP2-4.5 and SSP5-8.5 climate scenarios indicates a consistent upward trend for the study area (Fig. 4).

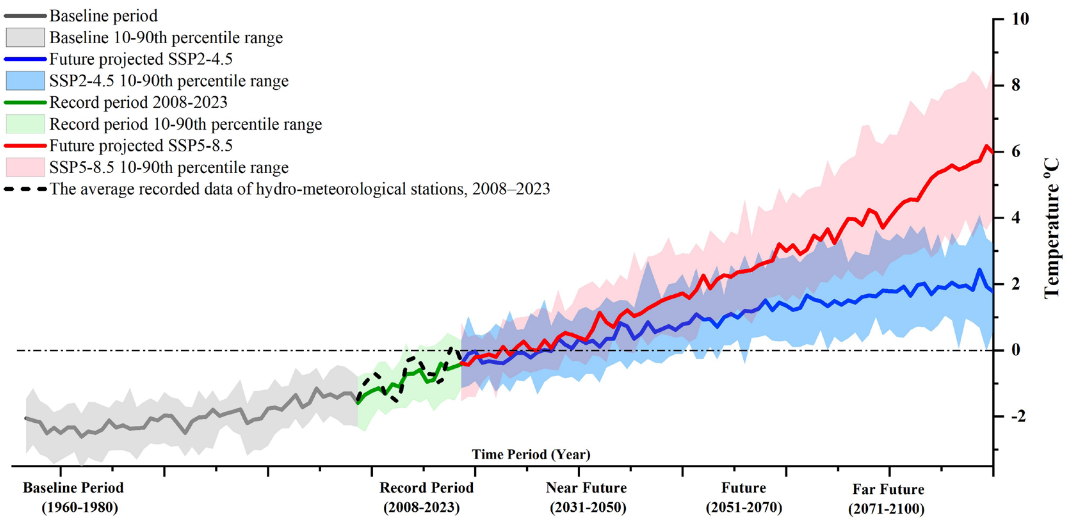

Figure 4. The projected mean annual surface air temperature in the Panjshir watershed under SSP2-4.5 and SSP5-5.8. The average recorded data of hydro-meteorological stations for 2008-2023 (green interval) is depicted in black dashed line showing its comparison with the data extract from the CESM2-USA model for the entire Panjshir watershed.

Similarly, the result of precipitation comparison is presented in Table V and Fig. 5. The mean precipitation for the baseline period is 425 mm in the study area. The recorded data for the parameter shows a 16% fall compared to the baseline. Precipitation is projected to decline further in accordance with SSP2-4.5 and SSP5-8.5 when compared to baseline values. Mean precipitation drops down to 347, 343, and 340 mm under the SSP2-4.5 scenario for the three intervals, respectively.

Similarly, 340, 336, and 331mm precipitation are expected under SSP5-8.5 for the three intervals, respectively.

Similar to temperature, Nepal et al. (2021) and Sajood & Safi (2020) have also documented the probability of rainfall deficit in the region. Furthermore, the analysis of annual mean precipitation for the baseline, recorded, and projected periods under SSP2-4.5 and SSP5-8.5 reveals a downward trend for the study area (Fig. 5).

Table V. Precipitation variation for the recorded and three future intervals compared to baseline.

Baseline period (1960-1980) mean, mm	Recorded (2008-2023)		Scenarios	Near-Future (2031-2050)		Future (2051-2070)		Far-Future (2071-2100)	
	Mean, mm	Anomaly, mm		Mean, mm	Anomaly, mm	Mean, mm	Anomaly, mm	Mean, mm	Anomaly, mm
425	357	-16	SSP2-4.5	347	-18.35	343	-19.29	340	-20.00
			SSP5-8.5	340	-20.00	336	-20.94	331	-22.11

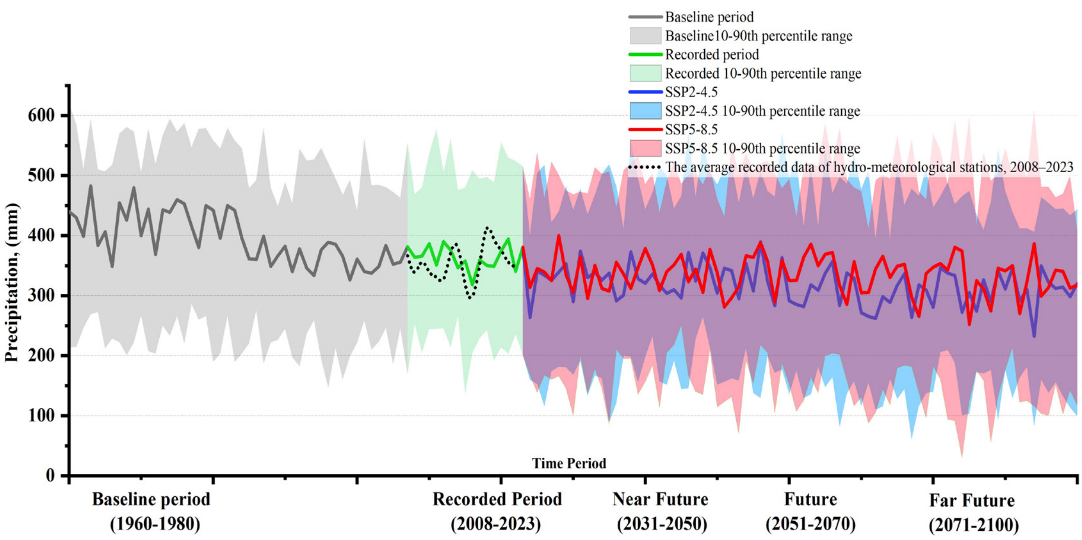

Figure 5. The annually averaged precipitation for the baseline and recorded data periods, and projected precipitation for the three future intervals in the Panjshir watershed under SSP2-4.5 and SSP5-8.5. The mean recorded precipitation of the Dara Hazara, Kootal Khawak, Parian, Da Dashtak-AWS, Dewabi, Keraman, Eomerz, Nazdik-e-Khawak and Khawak hydro-meteorological stations for 2008-2023 (green interval) is depicted in black short-dash line showing its comparison with the data extract from the CESM2-USA model for the entire Panjshir watershed.

3.2. Calibration and validation of simulated monthly streamflow

Hydrological models such as SWAT typically necessitate a “warm-up” period, defined as the duration the model runs before generating actual outputs, aimed at eliminating initial biases. For this study, the 2000-2007 period served as the “warm-up” phase to initiate hydrological parameters. The calibration employed the 2008-2015 streamflow data to estimate model parameter values, and parameter stability was tested during the 2016-2023 validation period. SWAT-CUP facilitated the calibration process, with the sequential SUFI-2 used for both calibration and validation. The calibration procedure involved adjusting 14 (fourteen) hydrological model parameters, including surface hydrology, groundwater hydrology, snowpack accumulation, snowmelt, and base flow. Table 6 illustrates these details of the initial and fitted parameter ranges across the target area. The maximum absolute t-statistic value observed during the calibration process signified the greatest sensitivity of a particular parameter. Under this research, the sensitivity analysis conducted using SWAT-CUP revealed that 14 out of the 19 (nineteen) parameters were the most sensitive. Following this identification, the calibration proceeded with the values of these 14 sensitive parameters while maintaining the default values for the remaining parameters throughout the calibration process. The ranking of the sensitive parameters, along with their initial, final, and fitted values, is presented in Table VI below.

Table VI. Calibration and validation of streamflow within the Panjshir watershed based on 14 identified sensitive parameters.

Sensitivity rank	Parameters	Description	Initial parameter range (Default)		Final parameter range		Fitted parameter range
			Min	Max	Min	Max	
1	R I __CN2. mgt	The SCS runoff curve number (CN) is a hydrological parameter utilized to estimate direct runoff from a rainfall event	-0.2	0.2	-0.002622	0.02936	-0.001023
2	R__SOL_ BD(..).sol	Moist bulk density refers to the mass of a given volume of material, including the moisture content present within that volume	0.9	2.5	2.390899	2.785307	2.634117

Table VI. Cont.

3	V II _ALPHA_ BF.gw	Base flow duration (days)	0	1	0.275385	0.462421	0.290971
4	V__GW_ DELAY.gw	The duration of groundwater delay (days)	0	5000	301.447449	411.613831	409.77774
5	V__ REVAPMN.gw	The minimum water depth in the shallow aquifer required for the process of "revap" to take place (mm)	0	500	346.93869	387.392426	381.324371
6	V__GWQMN. gw	The minimum water depth in the shallow aquifer necessary for the occurrence of return flow (mm)	0	5000	1449.18627	1827.23437	1808.33203
7	V__EPCO. bsn	Plant uptake compensation factor	0	1	0.65896072	0.759128	0.72073
8	V__ESCO. bsn	Soil evaporation compensation factor	0	1	0.373935	0.449257	0.432937
9	V__CH_ N2.rte	The Manning's “n” coefficient for the primary channel	-0.01	0.3	0.405958	0.4911	0.421567
10	V__SMTMP. bsn	The base temperature for snowmelt (°C)	-5	5	-2.325753	-0.990815	-2.036516
11	V__SMFMX. bsn	Maximum melt factor (mm°C/day)	0	10	0.331243	1.352857	0.859077
12	V__SMFMN. bsn	Minimum melting rate (mm°C/day)	0	10	-0.558261	0.908463	0.150656
13	V__TIMP.bsn	Snowpack temperature lag	0	1	-0.135017	0.015669	0.003112
14	V__SURLAG. bsn	Surface runoff lag time	0.05	24	20.29987	24.46167	20.507959

Note: I R_ - an existing parameter value is adjusted by multiplying it by (1 + a specified value); II V - the existing value is substituted with the new value.

The Kling-Gupta Efficiency (KGE) – chosen as the objective function for calibrating the SWAT model at the Tangi-e-Gulbahar outlet – achieved a value of 0.81 after multiple iterations. Additionally, the Nash-Sutcliffe Efficiency (NSE) was recorded at 0.69, while the mean square error (R^2) was noted at 0.70. These classifications have been considered “good” according to the criteria established by Moriasi et al. (2007).

The calibration and validation results of the SWAT model at the outlet of the study area are shown in Fig. 6. During the calibration phase, the mean simulated streamflow was recorded at 46.50 ± 48.33 m^3/s, in comparison to the mean observed streamflow of 47.20 ± 52.70 m^3/s for the same timeframe. The calibration yielded p- and r-factors of 0.64 and 0.89, respectively. It is noteworthy that during the validation phase, there was a significant enhancement in the p-factor, which increased up to 0.64, signifying that 64% of the observed data points were effectively encompassed within the simulations. Accordingly, the r-factor grew from 0.89 during the calibration phase up to 0.94 in the validation phase, indicating a significant improvement in the model's ability to simulate monthly streamflow. Furthermore, the KGE improved from 0.81 in the calibration phase to 0.82 in the validation phase. Conversely, the NSE declined from 0.69 during calibration to 0.66 during validation. The increment of KGE and NSE suggest notable enhancement in the model's predictive accuracy for streamflow. During the validation period, the mean simulated streamflow was recorded at 51.61 ± 52.94, while the observed streamflow was 49.74 ± 48.90, demonstrating a close alignment between the two. Additional statistical information can be found in Table VII.

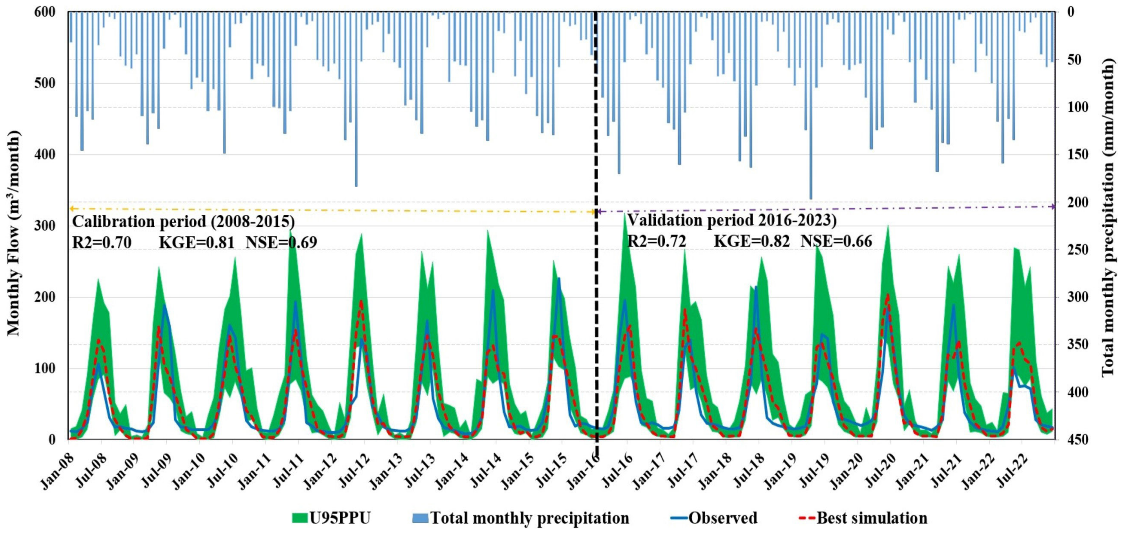

Figure 6. The results of calibration (2008-2015) and validation (2016-2022) of the Panjshir River flow simulation at the catchment's outlet station of Tangi-e-Gulbahar (*U95PPU: 95% Prediction Uncertainty).

Table VII. Sensitive parameters employed for the calibration and validation of streamflow within the Panjshir watershed.

Period	p-Factor	r-Factor	R2	NSE	PBIAS	KGE	Mean_SimI (Mean_Obs) (m^3/s)	StdDev_SimII (StdDev_ Obs) (m^3/s)
Calibration	0.64	0.89	0.70	0.69	1.5	0.81	46.50 (47.20)	48.33 (52.70)
Validation	0.65	0.94	0.72	0.66	-3.8	0.82	51.61 (49.74)	52.94 (48.90)

Note: II Mean of simulated and observed values; IV Standard deviation of simulated and observed values.

The relationship between the simulated and observed streamflows is illustrated in scatter plots for both the calibration and verification periods, as shown in Fig. 7. The results indicate that the NSE values range from 0.50 to 0.75. In contrast, during the validation phase, the NSE values also fell within the range of 0.50 to 0.75. As stated by Knoben et al. (2019), when using the mean streamflow as a reference point, a model output within the range of -0.41 < KGE ≤ 1 is deemed "reasonable", indicating that the model developed within the framework of this study exceeds the benchmark. In accordance with this standard, the KGE values recorded were 0.81 during the calibration phase and 0.82 during the validation phase, thereby confirming the model's performance as satisfactory.

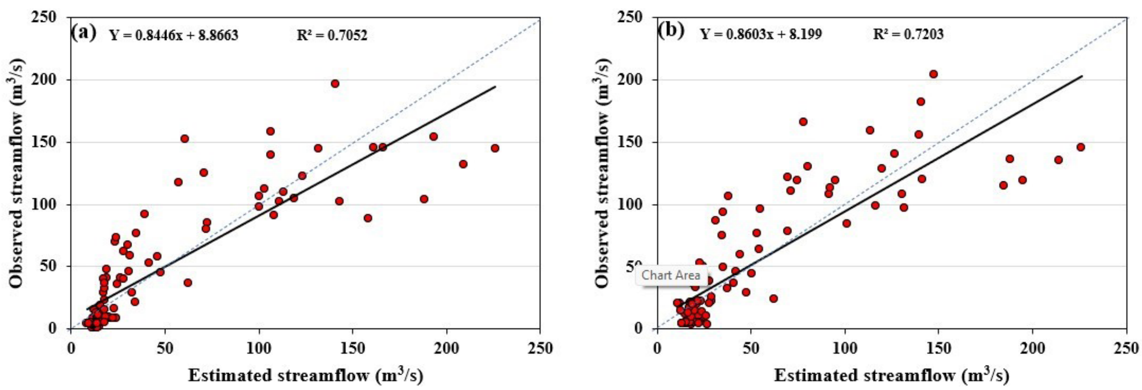

Figure 7. Correlation of mean monthly observed streamflow during (a) calibration and (b) validation for the Panjshir watershed river flow simulation using SWAT model.

3.3. The impacts of climate change on streamflow

The findings regarding streamflow variation for the recorded period, as well as for the three future intervals in comparison to the baseline period, are presented in Table VIII and illustrated in Fig. 8. A considerable decrease in the streamflow of the basin for both scenarios, with a more pronounced reduction for SSP5-8.5, is predicted. The comparison with the baseline shows a reduction of 28.75% at the far-future interval in the worst case. The average streamflow for the baseline period was 54.70 m3/s. Under SSP2-4.5, the model predicts 48.16, 46.83, and 42.61 m^3/s streamflow in the near-future, future, and far-future intervals, respectively, i.e. 11.95 14.38 and 22.10% reduction of streamflow compared to baseline, respectively. Similarly, the discharges of 43.45, 41.40, and 38.97 m^3/s are modelled for SSP5-8.5 in the near-future, future, and far-future intervals, corresponding to 20.56, 24.13 and 28.75% reduction, respectively.

Table VIII. Streamflow variation for the recorded and three future intervals compared to baseline.

Baseline period (1960-1980 mean, (m^3/s)	Recorded (2008-2023)		Scenarios	Near-Future (2031-2050)		Future (2051-2070)		Far-Future (2071-2100)	
	Mean, (m^3/s)	Anomaly, (%)		Mean, (m^3/s)	Anomaly, (%)	Mean, (m^3/s)	Anomaly, (%)	Mean, (m^3/s)	Anomaly, (%)
54.7	48.81	-10.77	SSP2-4.5	48.16	-11.95	46.83	-14.38	42.61	-22.10
			SSP5-8.5	43.45	-20.56	41.40	-24.13	38.97	-28.75

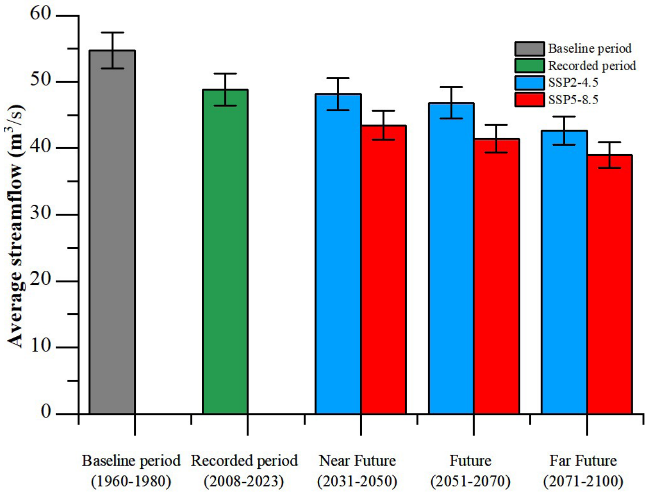

Figure 8. Streamflow variation for the recorded and three future intervals under SSP2-4.5 and SSP5-8.5 at Tangi-e-Gulbahar outlet of the Panjshir watershed.

Moreover, Fig. 9 illustrates the projected annual streamflow at the outlet of the study area in the near-future, future, and far-future intervals. In addition to the downward trend, the projected flow variations under SSP2-4.5 and SSP5-8.5 may indicate the probable dry (drought) and wet (flood) years. This figure also shows the increased frequency and severity of dry and wet years, particularly under the SSP5-8.5 climate scenario.

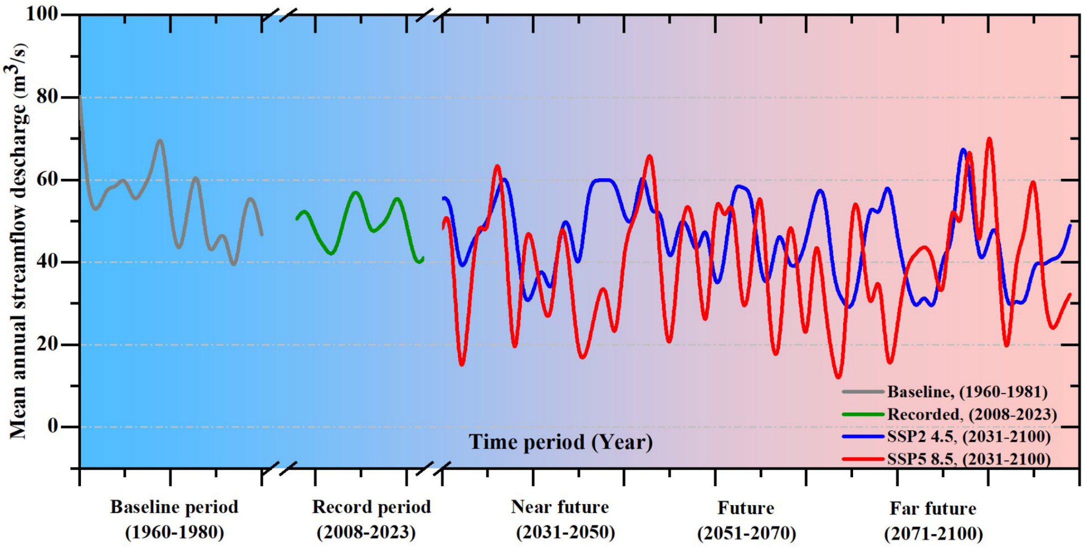

Figure 9. Mean annual fluctuations in streamflow in response to climate change at Tangi-e-Gulbahar outlet of the Panjshir watershed.

3.4. The effect of climate change on streamflow hydrograph

Fig. 10 illustrates the monthly average streamflow hydrographs and participations for the recorded data and the results of SWAT model based on two climate scenarios for the three intervals in the target basin. The analysis indicates that the highest flow rates during the recorded period are observed in June, coinciding with the melting of the majority of accumulated snow in the upstream catchment section as temperatures rise. Nevertheless, projections based on climate change scenarios suggest a shift in the timing of peak flow from June to April, with the most significant effects anticipated under SSP5-8.5 in the far-future interval. Additionally, Fig. 10 demonstrates an increment in the flow peak under SSP5-8.5 for all three intervals. This alteration can be attributed to a partial transition from snowfall to rainfall, with variations in the intensity and consistency of precipitation affected by climate change. This phenomenon is a result of higher temperatures and earlier snowmelt. Moreover, as per Fig. 10 the streamflow decreases during the summer months, when agriculture requires considerable water for irrigation. In addition, the hydrographs likewise show a considerable extension of low flow duration under SSP5-8.5, particularly in the far-future interval.

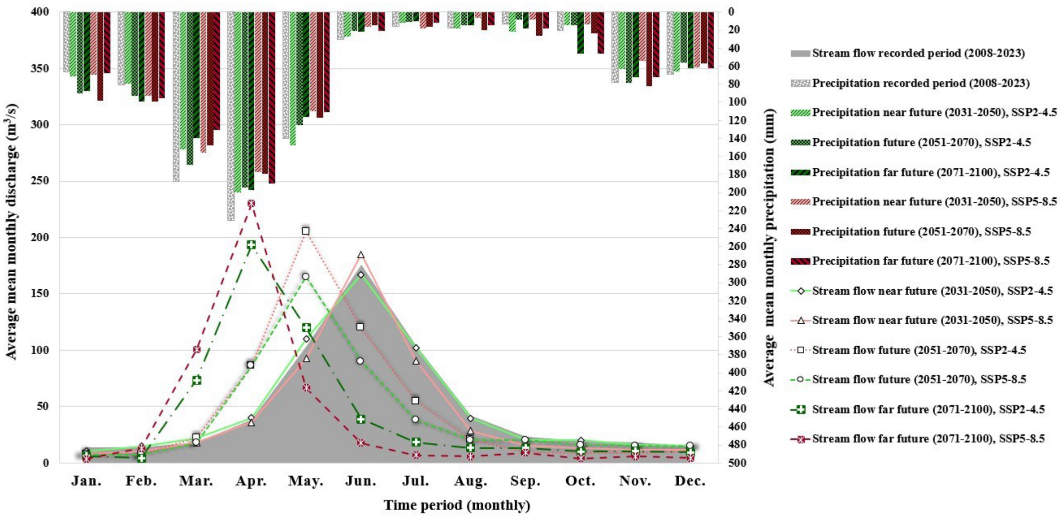

Figure 10. Hydrographs representing monthly streamflow of the recorded period compared with these generated by the SWAT model under SSP2-4.5 and SSP5-5.8 for all three intervals.

4. Discussion

The results of this investigation substantiate the considerable influence of climate change on the hydrological dynamics in the Panjshir watershed, specifically regarding streamflow and alterations in its seasonal patterns. The projections indicate substantial decreases in streamflow for both climate scenarios, SSP2-4.5 and SSP5-8.5, with reductions becoming more pronounced over time. The far-future interval shows the most alarming drops, with 22.10% streamflow reduction under SSP2-4.5 and 28.75% reduction under SSP5-8.5 against the baseline period. This is consistent with the global trends reported for other high-altitude basins, where climate change leads to reduced snowmelt contributions and altered precipitation patterns.

The observed decrease in streamflow is closely linked to both lower precipitation or more frequent dry years (droughts) and temperature rise in study area. The higher temperatures, especially under SSP5-8.5, provoke greater evaporation and a shift from snow to rain, reducing the snowpack and, consequently, the amount of meltwater feeding the streams. This phenomenon is further reflected in the changes in terms of peak flows, which are predicted to shift from June to April under SSP5-8.5. This shift could have serious implications for water resource management, particularly for agriculture highly water-dependent during the summer months.

The calibration and validation of the SWAT model, utilizing historical data, exhibited commendable performance, achieving a KGE of 0.81 during the calibration phase and 0.82 during the validation phase, respectively. These values indicate the model's robustness in simulating streamflow under current and future conditions. However, the model's limitations, such as uncertainties in input data (due to the lack of long-term consistent records for certain climatic variables) and the inherent uncertainties of future climate projections, should be acknowledged.

As suggested by the projections of more frequent dry and wet years under SSP5-8.5, the potential for increased streamflow variability adds further complexity to water management in the target basin. This increased variability could exacerbate flood risks during wet years and drought stress during dry years. Thus, adaptive management strategies – such as promoting efficient irrigation practices, establishing priority-based water allocation systems, building small-scale storage facilities, using drought-resistant crops, and implementing community education programs on sustainable water use – are required to mitigate these impacts, particularly for agriculture and hydropower generation, which are critical sectors for the country's economy.

The lack of consistent meteorological and hydrological data across all elevations in the Kabul River Basin manifested a significant constraint of this research. The data in the KRB are primarily available from the 1960s to the 1980s, with a large gap between 1980-2008 caused by the instability in the country. Efforts were made to address these challenges during the model configuration using common scientific approaches. Additionally, the complexity of climate systems, particularly at regional and local scales, means that future climatic changes may deviate from the obtained projections. Furthermore, socio-economic factors like land use changes, which are expected to be minimal, and future water management policies, which are not accounted for in the models, could further influence the actual climate impacts in the study area.

While the study's findings are directly relevant to the Panjshir and Kabul Basins, other catchments in Afghanistan – such as the Amu Darya headwaters located in the northern side of the Hindu Kush, as well as the Harirud-Murghab and Northern basins – are also likely to experience similar climate change impacts. Lower precipitation and earlier snowmelt may affect regions with comparable elevations and climatic conditions. Besides, studies in other parts of the greater Himalayan region, such as the Upper Indus Basin (Immerzeel et al., 2010) and the Ganges headwaters (Nepal & Shrestha, 2015), have identified parallel trends of declining snowpack, reduced streamflow, and seasonal shifts under high-emission scenarios. These patterns reinforce the findings of the present study and underscore the vulnerability of snow-dependent river systems to mounting temperatures and altered precipitation. Nonetheless, each basin has distinct hydrological and climatic features, and further localized modeling is essential for designing effective and context-specific adaptation strategies.

5. Conclusion

This research illustrates the substantial effects of climate change on streamflow within the Panjshir watershed playing a vital role in the hydrology of the Kabul River. Employing the SWAT model alongside future climate projections derived from the SSP2-4.5 and SSP5-8.5 scenarios, the study's findings indicate a persistent decline in streamflow throughout all anticipated intervals. Streamflow reductions are projected to range from 11.95 to 22.10% under SSP2-4.5 and from 20.56 to 28.75% under SSP5-8.5 by the end of the century. Furthermore, climate change is expected to cause a temporal shift in the streamflow hydrograph, with peak flows transferring from June to April in the SSP5-8.5 scenario and in the far-future interval. This could disrupt seasonal water availability and exacerbate drought conditions during critical agricultural periods. Moreover, surrounding basins in Afghanistan and other high-altitude areas of the Hindu Kush-Himalayan Mountain Range are likely to face comparable impacts from climate change.

The study's findings emphasize the need for immediate adaptation strategies to mitigate the potential adverse climate-induced effects on water availability for agriculture, domestic use, and hydropower in the region. Additionally, the increased streamflow variability under both scenarios, including more frequent dry and wet years, highlights the importance of developing flexible and robust water resource management infrastructure and policies. Further research should focus on improving the accuracy of regional climate projections, including socio-economic factors and land use changes, to enhance the predictive capacity of hydrological models in similar contexts.

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