

Climate Change Influence on Streamflow Projections Across the Chenab River Basin in Pakistan Under CMIP6 Scenarios

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Abstract

This study investigated the historical and projected climatic and hydrological patterns in the high-altitude Chenab River Basin for the 21st century. It has been observed that the average temperature (30.61 °C) for the 1981-2010 baseline period is expected to increase by 2.00 °C (2.65 °C) in the mid-century (2041-2070) and 2.82 °C (5.05 °C) in the late-century (2071-2100) under SSP 2-4.5 (SSP 5-8.5). Similarly, a 3.74% and 4.71% increase in precipitation is concluded for the mid and late centuries under SSP 2-4.5, while a 7.09% and 13.03% increase is recorded under SSP 5-8.5. Although average annual flows are projected to increase by 9.52–20.82% relative to the base period by 2100, a decline is expected in the late century compared to mid-century. This analysis reveals a significant rise in the peak flow's amplitude and an earlier accomplishment. As a result, hydrological extremes are likely to intensify. The optimal management of hydrological resources in the basin will require substantial modifications to the construction and maintenance of storage reservoirs, irrigation withdrawals, flood alleviation, drought control measures, and action plans.

Keywords: CMIP6-GCMs; SWAT model; Climate change; Extreme indices; Streamflow projections.

1. Introduction

Consistent with the Representative Concentration Pathways (RCPs) from CMIP5 (Coupled Model Intercomparison Project Phase 5) (van Vuuren et al., 2011), global temperatures are expected to rise by more than 2°C by 2100 (Grover et al., 2022). However, this temperature increase is expected to remain higher in Asia as opposed to other places in the world (Immerzeel et al., 2013). Numerous studies have documented rising warming trends (Bhadwal et al., 2019) and highly variable precipitation patterns (Pandey, 2016; Immerzeel et al., 2010) in the Hindu Kush–Karakoram–Himalaya (HKH) region of Asia. With 33,000 km² of glaciers and about 12,000 km³ of freshwater, this region is a crucial water and energy source for downstream areas, including Pakistan

(Solomon et al., 2007; Eriksson et al., 2009). The Indus River and its principal tributaries, such as the Chenab, have a leading role in sustaining this system. Around 56% of the people in Pakistan derive their livelihoods from the agriculture sector (Wescoat et al., 2000) and is highly dependent on irrigation, about 70% of which is supplied through the Indus Basin Project—one of the world's largest and most renowned irrigation networks (Kahlowan et al., 2007; Akhtar et al., 2008; Wescoat, 1991; Wescoat et al., 2000).

However, over the last few decades, a substantial glacial melting has been documented in the Hindukush-Himalayan belt (Gardelle et al., 2012, 2013; Käab et al., 2012, 2015), which has led to alterations in the flow patterns of the region's rivers, including the Chenab. It is, thus, essential to

examine the effect of climate change on the hydrological characteristics of the basins in the Himalaya region for long-term water resources management, which supports the lives of millions of people (Lutz et al., 2014).

Numerous studies have explored how future climate change may affect streamflow variability across river basins in Pakistan's Hindu Kush Himalayan (HKH) region. For instance, Dahri et al. (2021) conducted a study on the Indus River Basin (IRB), where the temperature rise (0.8-5.7°C) and decline in precipitation (11.9%) relative to the historical time frame are observed by the end of this century. The same study reveals an 11.4-62.9% increase in River Chenab flows by some climate models and a 13.2-51.3% decrease by others during 2021-2100, under different RCPs. In evaluating how the Chenab River Basin (CRB) is being affected by climate change, a 0.024-0.058°C increase in temperature is concluded in a study (Grover et al., 2022) with varying trends of increase and decrease in precipitation, rise in river flows, and a seasonality shift in discharge patterns. An increasing trend of future annual flows for the IRB is also reported (Gebre and Ludwig, 2014). In another study (Su et al., 2016) for the IRB, a 1.21-2.71°C rise in temperature is observed in the mid-21st century. The same study also showed an increase in precipitation, and, therefore, the possibility of a flood disaster is expected. To analyze streamflow variations for the entire IRB, one of the studies (Huang et al., 2016) reported a decreasing trend in precipitation and less availability of water in the coming years under different CMIP5 scenarios. For the Jhelum River Basin (JRB), Akhter and Ahanger (2019) concluded that at the end of the current century, the basin's temperature will accelerate by 1.43°C and 1.56°C, whereas the annual precipitation will decrease substantially by 30.88% and 35.32% under A1B and A2 scenarios, respectively, which will affect the streamflow variations. An increasing trend for the discharge in the JRB is predicted in a study (Munawar et al., 2021), in which a CMIP5 model is used to project the important climate parameters. In another study for the

Jhelum catchment (Jasrotia et al., 2021), the climate changes are analyzed from 2020 through 2100, using the Regional Climate Model version 4. Overall, the findings showed that precipitation estimates have a considerable impact on the Jhelum catchment's runoff.

Compared to CMIP5, climate change-related studies, based on the latest sixth phase of the Coupled Model Intercomparison Project (CMIP6) models, are limited. Such studies for the IRB (Kundeti et al., 2021; Mondal et al., 2021) and SREX region (Almazroui et al., 2021) indicate a rise in precipitation and temperature with varying flows. In one of the studies for Bangladesh (Kamruzzaman et al., 2021), it was reported that the CMIP6 models are more efficient in simulating the historical climate parameters, compared to CMIP5. Kim et al. (2020), in a study covering 41 sub-regions defined for the IPCC Sixth Assessment Report (AR6), reported that CMIP6 models provide improved representation and analysis of climate extreme indices compared to CMIP5 models. Similarly, CMIP6 models have demonstrated superior performance in predicting rainfall over South Asia (Shiru et al., 2022) and East Africa (Ayugi et al., 2021). Additional studies (Zhu et al., 2021; Li et al., 2021) further confirm that CMIP6 models outperform earlier CMIP phases, particularly in capturing rainfall events that directly influence streamflow dynamics. Therefore, existing hydro-climatic studies based on earlier phases of CMIP need to be revisited in light of the latest phase, as this is crucial for formulating effective climate change adaptation policies. Being a part of the world's highest mountainous region, the ridges of the CRB are blanketed with snow and glacial ice, which are ultimately vulnerable to climate change and are, therefore, affecting the hydrology of the region (Grover et al., 2022). However, this basin has received limited scientific attention regarding changes in climate parameters and their impacts on glaciers and snow cover, primarily due to limited geographical and climatic data. Only a limited number of hydro-climatic studies are available for the

CRB, and the primary datasets used in these studies are derived from CMIP5 models (Grover et al., 2022), satellite observations, or a combination of gridded global and satellite datasets (Ali et al., 2021a). To date, no such hydro-climatic study that is based on CMIP6 models has been conducted for the CRB. Thus, this study aims to analyze climate change-induced variations in river flows of the CRB based on CMIP6-GCMs across two different scenarios, i.e., middle-of-the-road (SSP 2-4.5) and fossil-fueled development (SSP 5-8.5). If the decrease in flow magnitudes in this study is observed toward the end of the century, it may be hypothesized that this decline is driven by reduced meltwater contributions resulting from rising temperatures. The technical insights generated by this study are intended to support policymakers in making informed and strategic decisions for the region.

2. Materials and methods

2.1 Study Area

The River Chenab originates in Himachal Pradesh, India, flows about 230 km to Jammu and Kashmir, and continues for another 276 km before entering Pakistan. In Pakistan, it flows from Marala to Trimmu Headworks, where it joins the Jhelum River, and about 75 km downstream, it merges with the Ravi (Mahmood and Rani, 2018).

The Chenab River Basin (CRB) consists of two main sections: the upper catchment, running from Himachal Pradesh to the Marala Headworks, and the lower catchment, extending from Marala to where the Chenab meets the Ravi River. The total basin area is 67,430.34 km², of which 26,526.92 km² constitutes the study area, located between 32°6'32"–34°13'6" N and 74°2'39"–77°46'55" E. Most of the study area lies in Jammu and Kashmir (70.71%), followed by India (27.87%) and Pakistan (1.42%) (Ali et al., 2021a).

The study area (Fig.1), situated between the middle Himalayan range, is distinguished by several glaciers and experiences moderate winter precipitation (Grover et al., 2020). Due to altitudinal variability (243–7005 m), the lower valleys experience high temperature, which becomes cooler and then progressively grows colder at higher elevations (Grover et al., 2022). As a result of climate change, this basin is probably going to be affected by changes in temperature and precipitation patterns. This might represent a potential risk to preserve the river flow, which would therefore have an impact on the existing and upcoming hydroelectric development projects in the study region.

2.2. Datasets

2.2.1 Climate Data

An assessment of 27 commonly used gridded precipitation datasets in the Upper Indus Basin (UIB) by Dahri et al. (2016) revealed that the fifth-generation ECMWF Reanalysis (ERA5) dataset provides the highest accuracy compared to other products. The superior performance of ERA5 for the UIB was further confirmed by Ahmad et al. (2025) and Baudouin et al. (2020). Accordingly, historical precipitation and temperature data for the Chenab River Basin (CRB), which forms part of the UIB, were obtained from ERA5 for the period 1981–2010.

Although larger ensembles are generally more effective at representing climate uncertainty, previous studies (Dahri et al., 2021; Hashmi et al., 2020; Iqbal et al., 2018) have shown that carefully selected smaller ensembles of 4–5 GCMs can sufficiently capture the range of projected changes for regional-scale impact assessments.

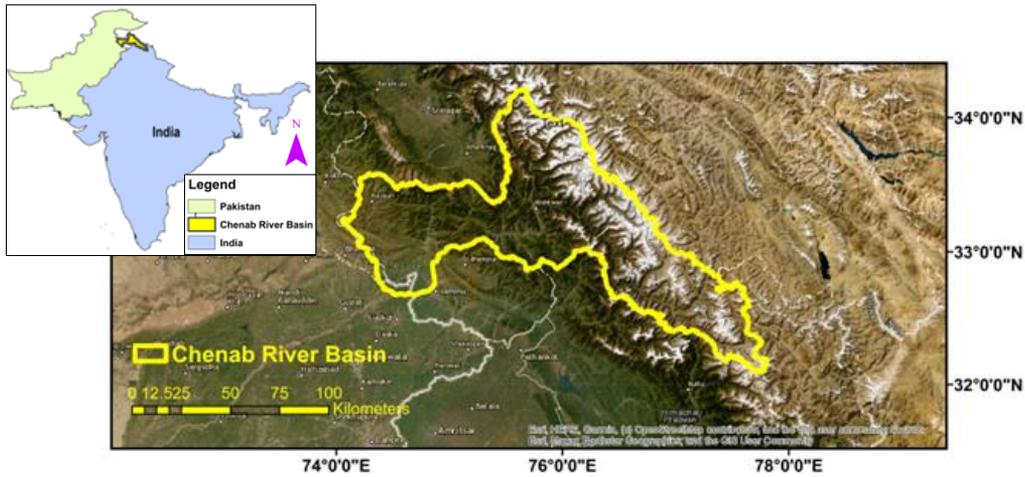


Fig. 1 Location of the study area on the world map

Accordingly, for the future period 2041–2100, five GCMs were selected for this study to capture wet, dry, cold, hot, and mean climatic conditions, following the approach of Dahri et al. (2021). These GCMs are GFDL-ESM4 (dry-cold), ACCESS ESM1-5 (wet-cold), MPI-ESM1-2-HR (wet-hot), NoRESM2-LM (average), and IPSL-CM6A-LR (dry-hot). The chosen models were downscaled to a uniform spatial resolution of $0.25^\circ \times 0.25^\circ$ and bias-corrected with ERA5 data for the SSP2-4.5 and SSP5-8.5 scenarios.

2.2.2 Streamflow Data

The discharge data from 1981 to 2010 at Maral Headwork is provided by the WAPDA (Water and Power Development Authority) in Pakistan and is shown in Fig. 2.

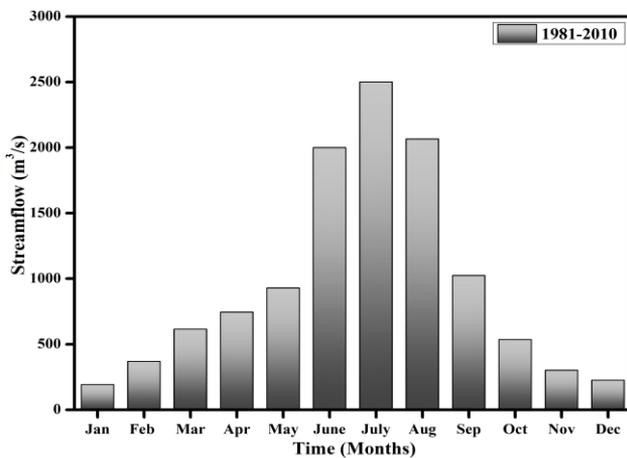


Fig. 2 Average monthly streamflow of River Chenab for the base period at Marala Headworks.

2.2.3 Geo-Spatial Data

Comprehensive terrain data, land use, and soil attributes of the study area are essential for watershed modeling using the Soil and Water Assessment Tool (SWAT). The drainage network and slope characteristics required by SWAT were derived from a Digital Elevation Model (DEM). For this study, a $30\text{ m} \times 30\text{ m}$ DEM was obtained from the CGIAR-CSI website (<http://srtm.csi.cgiar.org/>) on 12th November, 2022.

Additionally, a $5 \times 5\text{ km}$ global soil map was accessed from the Food and Agriculture Organization (FAO) website on 12th November, 2022. This dataset provides information on key soil properties such as depth, temperature, pH, and texture. Study-area-specific data were extracted from this map using the SWAT tool.

The study-area LULC data were retrieved on 15th November, 2022, from the USGS archive. This raster dataset of 30×30 meters offers details on different land covers within the basin.

2.3 SWAT–The Hydrological Model

The Soil and Water Assessment Tool (SWAT) is applied worldwide to model both surface and groundwater quantity and quality, assess the environmental impacts of land management practices, and evaluate how climate change influences both small- and medium-scale watersheds (Jakada and

Chen, 2020) and large mountainous basins (Taia et al., 2023). It has been extensively used for evaluating streamflow (Ahmed et al., 2020; Arnold and Fohrer, 2005; Awan et al., 2016; Haider et al., 2020), surface runoff (Diriba, 2021), agricultural watersheds (Donmez et al., 2020), and watershed management (Ahmadzadeh et al., 2022).

For watershed delineation, SWAT employs the Digital Elevation Model (DEM) to derive topographic and hydrological features of the study area. To simulate hydrological dynamics, the model requires accurate inputs on water abstraction, supported by climate data, LULC information, terrain characteristics, and watershed management practices. The basin is divided into sub-basins, which are further classified into Hydrologic Response Units (HRUs) based on homogeneous characteristics such as soil, slope, and land use, defined by user-specified thresholds. In this study, a threshold of 5% was applied to land use, soil, and slope, respectively. This discretization approach is particularly effective when field-scale simulations are computationally unfeasible, offering a reliable representation of hydrological variability in large watersheds. Detailed model configuration is provided in the ArcSWAT user manual (Winchell et al., 2010). The methodology of this study is summarized in Fig. 3.

2.3.1 Geo-spatial Inputs and Preprocessing

For the current study, the model of the CRB was prepared by classifying DEM, LULC, soil, and slope data, shown in Figs. 4a-d using the SWAT model. Table 1 provides detailed information on the area covered by different types of LULC, while the same information for different classes of soil is provided in Table 2.

Five different classes of slopes were selected during modeling, i.e., 0 to 20%, 21 to 40%, 41 to 60%, 61 to 80%, and 81 to 100% (Fig. 4d). Since the watershed's overall slope is steeper (Table 3), precise elevation specification is required to analyze the flow regimes within a snow-covered catchment properly.

Table 1: LULC classification of the Chenab River Basin.

Land Use Land Cover	Covered Area (km ²)	Covered Area (%)
Water Bodies	869.01	3.28
Forests	837.13	3.16
Shrublands	17.54	0.07
Savannas	539.87	2.04
Wetlands	6901.25	26.02
Grasslands	9738.54	36.71
Croplands	4.51	0.02
Built-Up	3298.44	12.43
Snow and Ice	200.80	0.76
Barren Land	4119.82	15.53

Table 2: Pedological classification of the Chenab River Basin

Soil Group	Soil Group Codes for SWAT	Covered Area (km ²)	Covered Area (%)
Sandy-Loam	Ao72-2b-3644	665.91	2.51
Clay-Loam	Be70-2-3a-3667	393.16	1.48
Clay	Be72-3c-3672	874.10	3.30
*Loam	Be78-2c-3679	5397.65	20.35
*Loam	Be79-2a-3680	1326.02	5.00
Sandy-Clay-Loam	I-B-U-3712	12685.68	47.82
*Loam	Lo44-1b-3799	1519.70	5.73
Glacier	Glacier-6998	3664.69	13.81

*Same type of soil with different characteristics

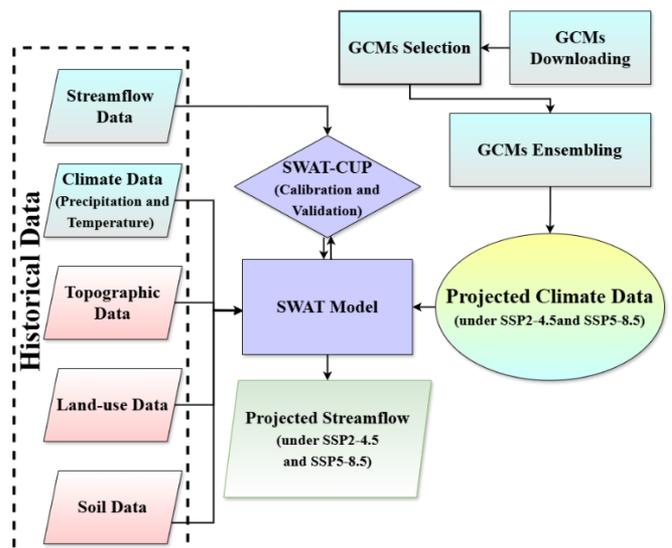


Fig. 3 Framework for simulating streamflow under climate change in the study area.

Table 3: Slope classification of the Chenab River Basin

Slope Class	Slope Classification (%)	Covered Area (km ²)	Covered Area (%)
First	0-20	5969.45	22.50
Second	21-40	7321.66	27.60
Third	41-60	7033.80	26.52
Fourth	61-80	4732.38	17.84
Fifth	81-100	1468.88	5.54

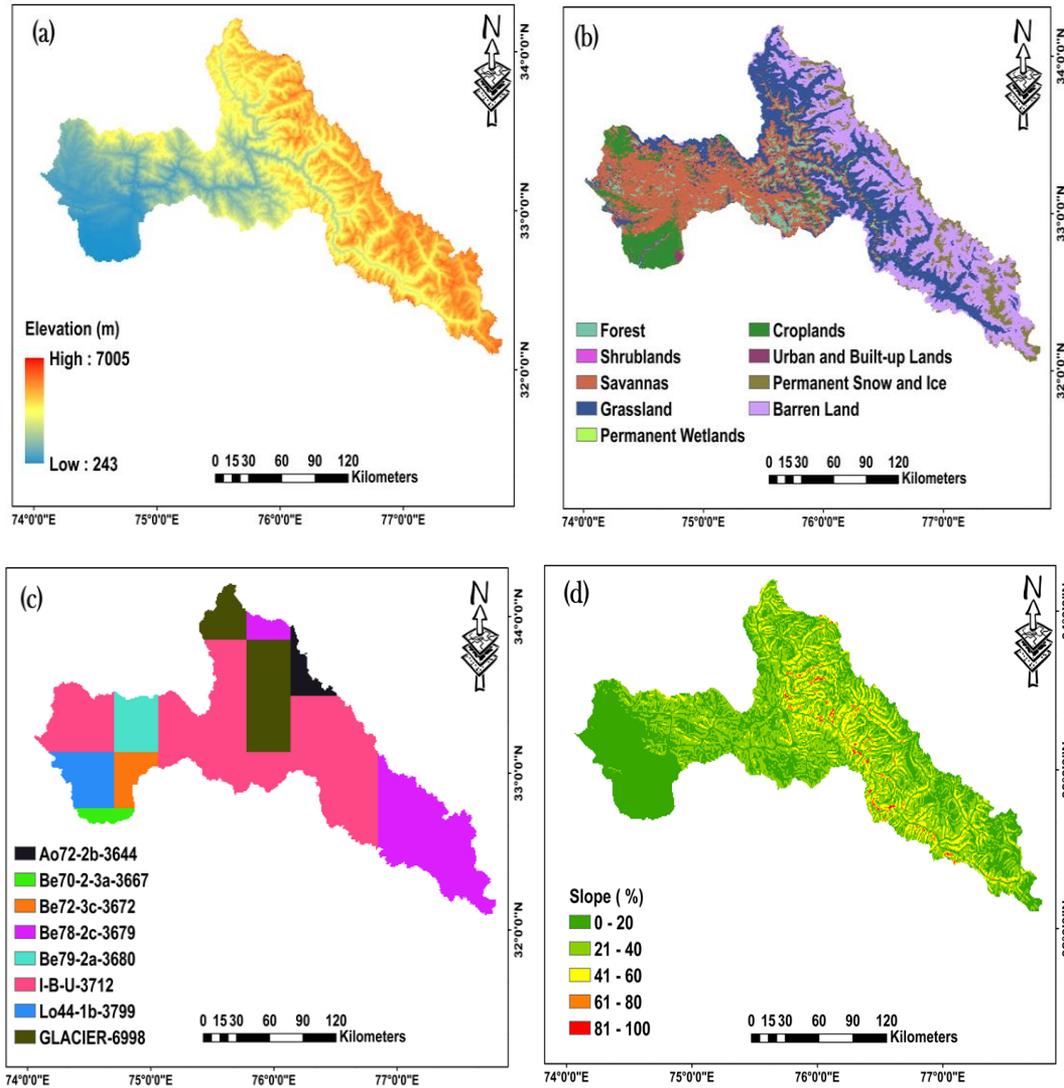


Fig. 4 (a) Digital Elevation Model (DEM) and the classification of (b) Land Use/Land Cover (LULC), (c) soil types, and (d) slope for the Chenab River Basin (CRB).

To explicitly account for elevation, the model’s option of defining elevation bands was utilized. In this study, the selected area was divided into 10 elevation bands, which also represent the upper limit allowed by the model.

2.4 Model Accuracy Assessment and Calibration-Validation Criteria

The SWAT model was calibrated and evaluated using the Soil and Water Assessment Tool–Calibration and Uncertainty Program (SWAT-CUP) (Abbaspour et al., 2015). Model performance

was assessed with multiple statistical metrics, including the P-factor, R-factor, Nash–Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and coefficient of determination (R^2), as described in the SWAT-CUP 2012 manual (Abbaspour, 2015). For streamflow prediction, a P-factor greater than 0.7 and an R-factor close to 1 indicate good model performance (Abbaspour et al., 2004), while NSE values above 0.65 are considered very good, whereas values below 0.5 suggest insufficient robustness (Narasimhan and Srinivasan, 2005). A PBIAS value less than 0.1 is considered excellent, with results remaining acceptable up to 0.15 (van Liew et al., 2007). Similarly, R^2 values between 0.75 and 0.85 indicate strong model performance (Moriassi et al., 2007). In hydrological model evaluation, performance criteria provide a single metric to indicate the agreement between simulated and observed streamflow (Gupta et al., 2009). In this study, the Kling-Gupta Efficiency (KGE) was used as the objective function with the SUFI-2 algorithm for automatic calibration. Simulation performance is classified as intermediate when $0.5 < KGE \leq 0.75$ and good when $KGE > 0.75$ (Thiemig, 2014).

Among the algorithms available in SWAT-CUP, SUFI-2 (Sequential Uncertainty Fitting, version 2) was selected for this study, as it allows simultaneous use of data from multiple gauge stations and efficient analysis of sensitive parameters (Abbaspour et al., 2007). Calibration was conducted for 1981–1995, and validation was performed using the same parameters and number of iterations for 1996–2010.

3. Results

According to the geographic data, nearly 42% of the study area is covered by forested areas, reflecting the highly fertile land (Table 2). This region is also found to be comprised of eight distinct soil types, with Sandy-Clay-Loam contributing the most and Clay-Loam contributing the least (Table 3).

Furthermore, about 77.49% of the CRB falls into slope categories ranging from Class II to Class V (Table 4), indicating that the watershed is predominantly steep, with altitude ranges from 243 m to 7005 m above the mean sea level.

3.1 Calibration – Validation Results

In this study, eight parameters were identified as the most sensitive and were therefore selected for calibration and validation (Fig. 5). The details of these parameters are provided in Table 4. The ranking of sensitivity was determined based on the absolute values of the t -statistic and the p -value. Among the calibrated parameters, the Runoff Curve Number (CN2) was found to be the most sensitive, while the snowpack temperature lag factor (TIMP) was the least sensitive. The optimal value of CN2 (80.367) was obtained after reducing its initial value (83.716) by 4%. In contrast, the calibrated value of TIMP required only a minor adjustment, with a 0.03% increase from its initial value. Further details regarding these parameters can be found in the SWAT-CUP_2012 User Handbook (Abbaspour, 2015).

After validation, the calibrated SWAT model was run for the mid- (2041-2070) and late-century (2071-2100) using the ensemble data of the selected models for two distinct scenarios of SSP2-4.5 and SSP5-8.5 to obtain the streamflow variations in River Chenab. The model's predictive accuracy was assessed using various statistical metrics (Table 5) and was found to align well with the observed data.

3.2 Projected Trends in Temperature and Precipitation

Based on the SSP 2-4.5 projections, precipitation in the Chenab River Basin is projected to increase by 3.74% in the mid-century and 4.71% in the late-century relative to the base period. Under SSP 5-8.5, the increase is more pronounced, at 7.09% and 13.03% for the same time horizons (Fig. 6).

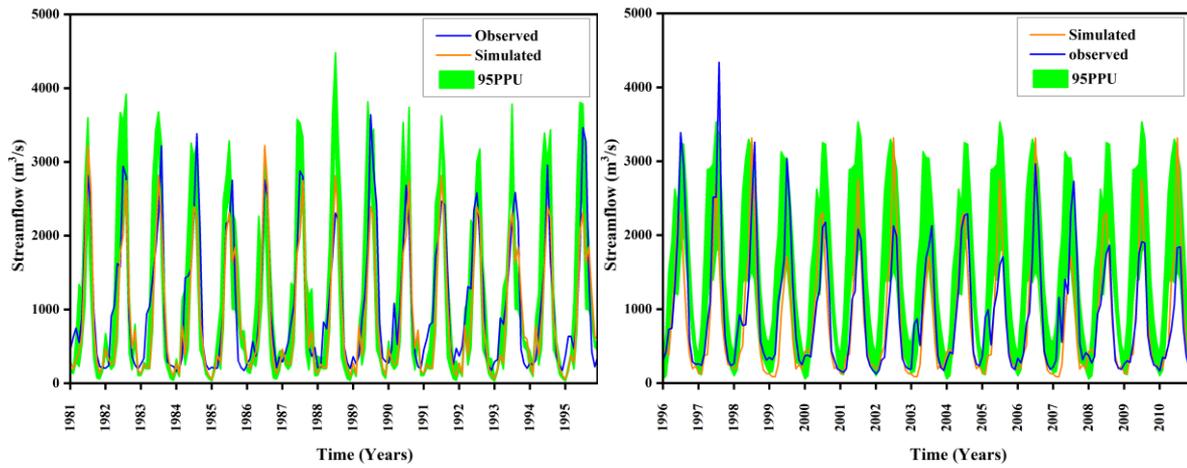


Fig. 5 Comparison of measured and modeled stream flows during the calibration (1981-1995) and validation periods (1996-2010).

Table 4: Details of the optimal parameter values.

Parameter	Description	Calibrated Range		Best Calibrated Value	Sensitivity Analysis		Sensitivity Ranking
		Minimum Value	Maximum Value		t-Stat	p-Value	
CN2	SCS runoff curve number	-0.05	0.05	-0.04	-109.19	0.00	1 st
SMFMX	Maximum melt rate for snow during the year	2.20	6.62	3.97	-32.15	0.00	2 nd
TLAPS	Temperature lapse rate (°C)	-8.00	-2.00	-6.20	-22.40	0.00	3 rd
SMTMP	Snow melts base temperature (°C)	-2.24	3.30	1.16	21.51	0.00	4 th
SFTMP	Snowfall temperature (°C)	-1.21	6.35	3.77	16.00	0.00	5 th
ESCO	Soil evaporation compensation factor	0.10	0.70	0.44	4.54	0.24	6 th
SMFMN	Minimum melt rate for snow during the year	1.57	4.71	4.07	1.16	0.36	7 th
TIMP	Snowpack temperature lag factor (°C)	-0.40	0.50	0.03	-0.12	0.90	8 th

Table 5: Model evaluation metrics.

Model Performance Indicator	Calibration (1981-1995)	Validation (1996-2010)
P-factor	0.75	0.92
R-factor	0.98	0.99
R ²	0.79	0.84
NSE	0.60	0.65
PBIAS	0.13	-8.22
KGE	0.72	0.89

However, precipitation patterns in the Western Himalayan region, encompassing the CRB and JRB, show not only considerable variability but also significant uncertainty. Dahri et al. (2021) reported both decreases (6–29.6%) and increases (17.1–48.1%) in precipitation for 1981–2020 across different GCMs. Hasson et al. (2019) observed a slight rise over northern high mountains, while Lutz et al. (2016) projected varying changes in median annual precipitation for the CRB. These differences mainly reflect the use of different datasets and baselines.

The average temperature for the study area, under SSP 2-4.5 projections, is expected to increase by 2.00 °C and 2.82 °C in the mid- and late-century, respectively, while a similar increase is noted as 2.65 °C and 5.05 °C under SSP 5-8.5 relative to the baseline period (30.61 °C). In a study on the CRB, Grover et al. (2022) projected a mean temperature increase of 0.72–1.08 °C under RCP4.5 and 1.17–1.74 °C under RCP8.5. Similarly, Dahri et al. (2021), in their assessment of the Indus River Basin (IRB), including the CRB as a

sub-basin, estimated a temperature rise of 0.8–5.7 °C by 2099. Most studies conducted for the CRB, either as an independent basin or as part of the Upper Indus Basin (UIB), consistently indicate a significant warming trend by the end of the century (Ali et al., 2021b, 2023a; Latif et al., 2021; Shah et al., 2020). The projected peak temperature increase identified in this study may intensify evapotranspiration and glacier melt, thereby significantly affecting future water resources.

3.2 Projected Changes in Streamflow and Seasonality

The findings of the current study indicate that mid- and late-century stream flows of the River Chenab are higher under SSP5-8.5 than under SSP2-4.5 (Fig. 8). The flows are usually found to be higher when monsoon rainfall aligns with snowmelt-driven runoff in the summer season. However, during winter, when precipitation predominantly occurs as snow, stream flows typically reach their lowest levels.

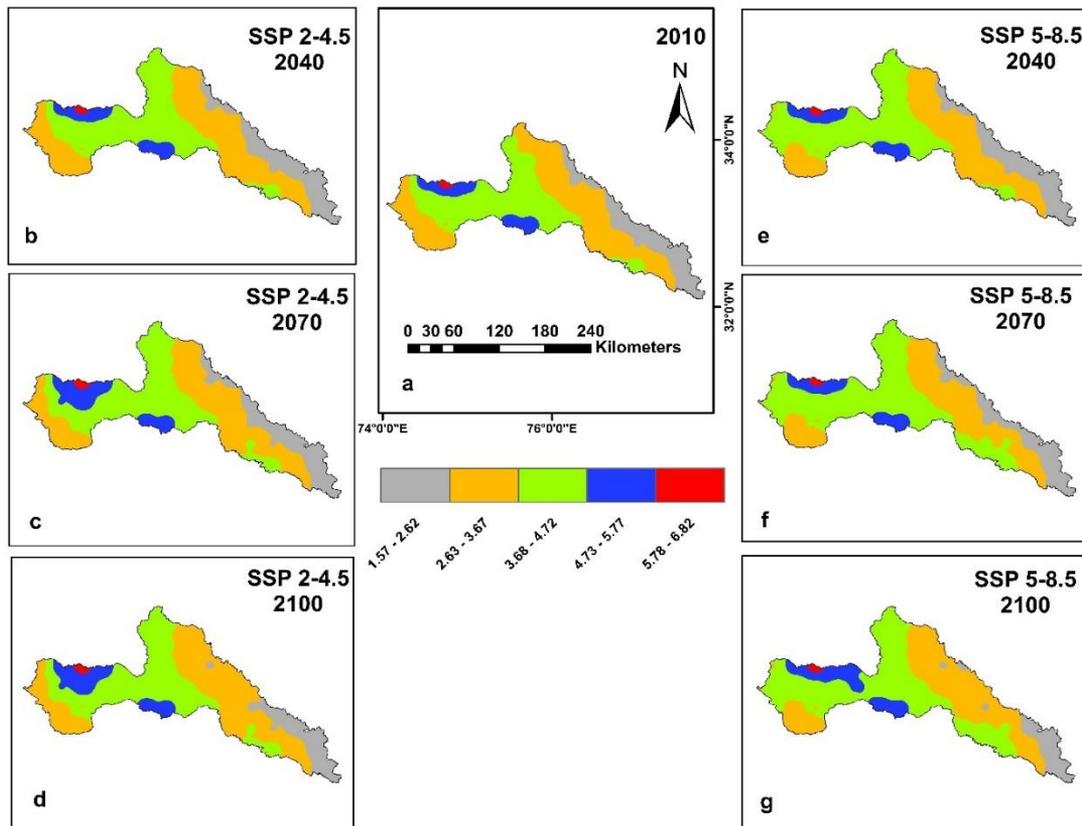


Fig. 6 Projected increase in precipitation (mm) under SSP 2-4.5 from (a) 2010 to (b) 2040, (c) 2070, and (d) 2100, and under SSP 5-8.5 from (a) 2010 to (e) 2040, (f) 2070, and (g) 2100.

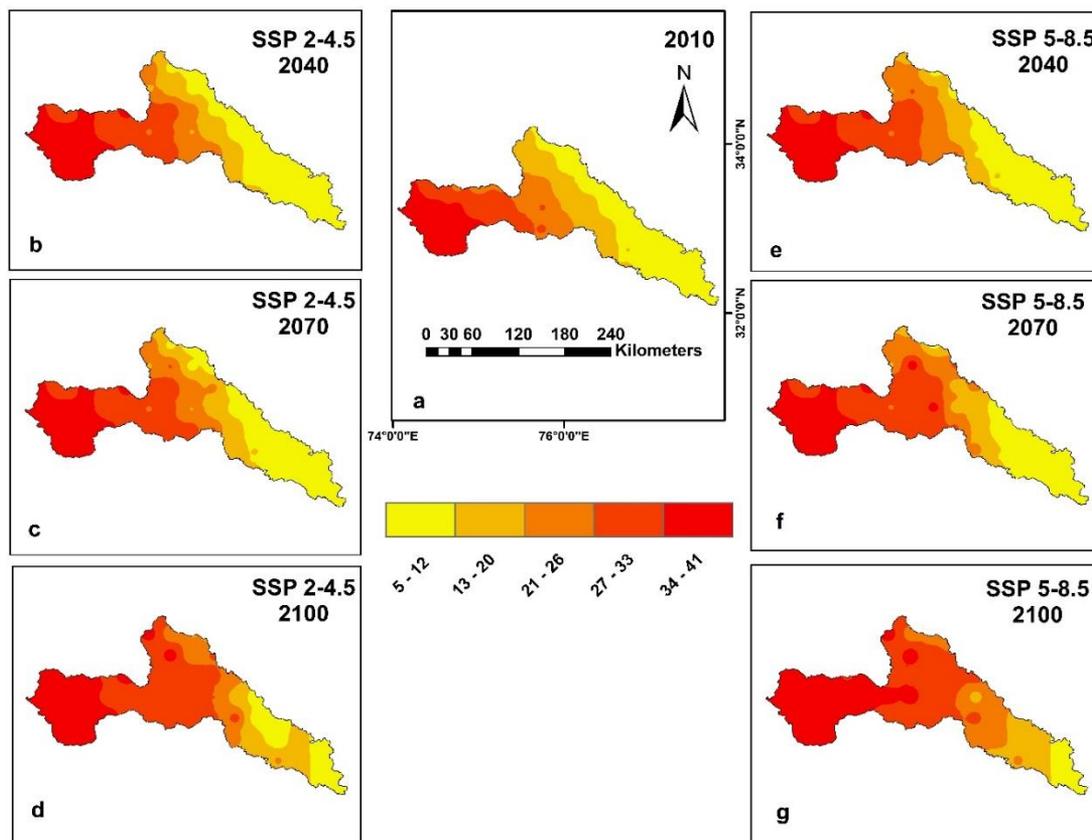


Fig. 7 Projected increase in temperature ($^{\circ}\text{C}$) under SSP 2-4.5 from (a) 2010 to (b) 2040, (c) 2070, and (d) 2100, and under SSP 5-8.5 from (a) 2010 to (e) 2040, (f) 2070, and (g) 2100.

Average annual flows for the study area, according to the SSP 2-4.5 scenario, are anticipated to increase by 13.60% (during mid-century) & 9.52% (during late-century), while for SSP 5-8.5, this increase is found as 20.82% and 15.4% concerning the base period (Table 7). Mean monthly flows are also observed to increase over the years except for the July-September months for both the time-slices, with ensemble-mean tendency shift from July to June (Fig. 9).

Under SSP 2-4.5 (SSP 5-8.5), the flows in the monsoon season (July-Sep) are likely to decrease by 5.03-12.14% (0.04-7.95%) and 7.96-14.99 % (4.04-13.42%) during the periods of mid- and late-century, respectively. A certain increase in average flows before and after the monsoon seasons is evident throughout under both scenarios (Table 6). The study also indicates that the percentage change in winter flows is greater than in summer flows for both time periods under both scenarios (Table 6). During mid-century, winter and summer flows are projected to increase by 27.42% (35.83%)

and 10.27% (19.6%), respectively, relative to the baseline under SSP2-4.5 (SSP5-8.5). For the late century, winter flows are expected to rise by 22.09% (26.85%) and summer flows by 6.48% (14.94%) under SSP2-4.5 (SSP5-8.5).

4 Discussion

The previous section provided a detailed summary of the projected changes in temperature, precipitation, and streamflow under SSP2-4.5 and SSP5-8.5 for both mid-century and late-century. This study indicates that average annual flows are expected to be higher during the mid-century (2041–2070) than in the late-century (2071–2100). The reduction in flow magnitudes in the late century can be attributed to the gradual decline in meltwater contributions (Wijngaard et al., 2017) and the likely intensification of evapotranspiration caused by rising temperatures, which may offset gains from precipitation or glacier melt (Ali et al., 2023b; Gordon et al., 2022; Kapnick et al., 2014; Kilroy, 2015; Wijngaard et al., 2017).

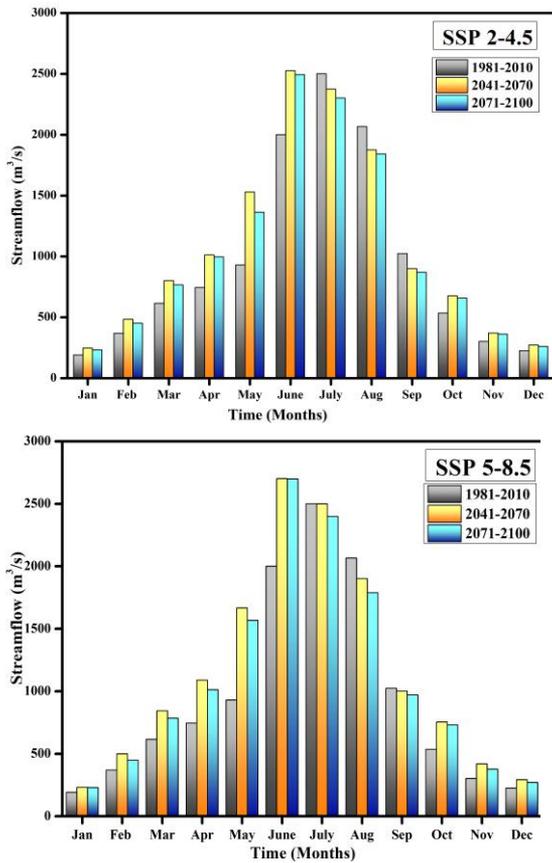


Fig. 8 Historic and projected average monthly flows of the study area.

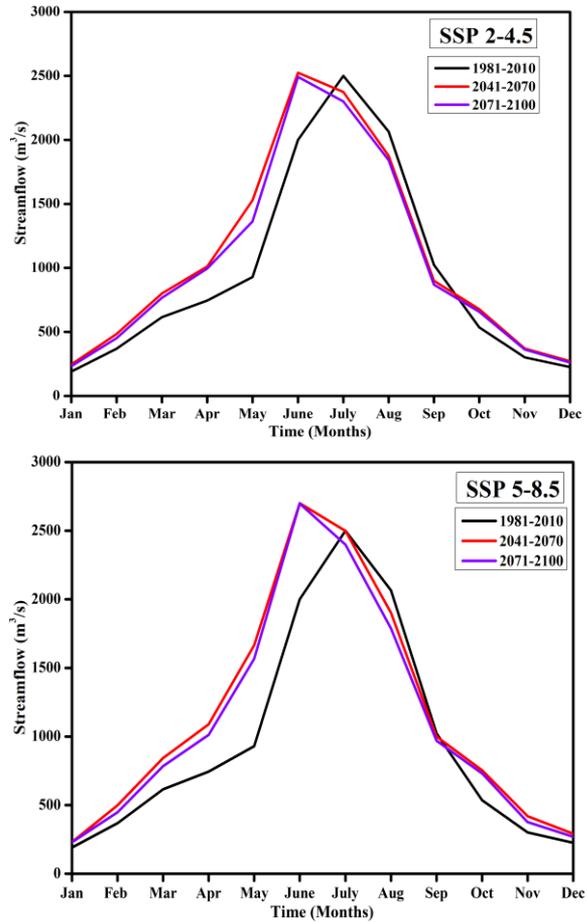


Fig. 9 Early shifting of peak flows in the mid and late centuries

Table 6: Projected changes (%) in average monthly (J-D), annual (Y), and seasonal (S & W) flows relative to the baseline period (1981–2010)

	SSP 2-4.5												SSP 5-8.5																	
	J	F	M	A	M	J	J	A	S	O	N	D	Y	S	W	J	F	M	A	M	J	J	A	S	O	N	D	Y	S	W
2041-2070	29.08	31.06	30.29	35.89	64.44	26.25	-5.03	-9.21	-12.14	26.41	22.81	20.79	13.60	10.27	27.42	21.03	35.38	37.12	46.21	79.23	35.05	-0.04	-7.95	-2.29	40.86	39.01	29.41	20.82	19.60	35.83
2071-2100	21.64	22.53	24.60	33.66	46.64	24.61	-7.96	-10.81	-14.99	22.75	20.22	15.85	9.52	6.48	22.09	19.98	21.39	27.56	35.84	68.49	34.91	-4.04	-13.42	-5.22	36.34	24.87	19.79	15.40	14.94	26.85

For the CRB and JRB, Dahri et al. (2021) observed a similar pattern, with an initial increase in streamflow during the mid-century followed by reductions in the late-century. Other studies, however, report varying outcomes. Haider et al. (2020) projected a rise in streamflow for the Jhelum

River Basin (JRB) by 87.62% during 2040–2069 and 97.17% during 2070–2099, while Munawar et al. (2021) reported an increase of 5.5–8.6% during 2020–2060 but a reduction of 3–7.1% during 2061–2099. Similarly, several studies focusing on the HKH region (Ali et al., 2015; Azizi and Asaoka, 2020;

Shah et al., 2020) have highlighted a tendency toward declining stream flows in the distant future.

The projections of this study also reveal interesting contrasts between the two scenarios. Due to increased precipitation and enhanced glacier/snowmelt driven by higher temperatures, streamflow is consistently higher under SSP 5-8.5 than under SSP 2-4.5. Comparable findings have been reported in other studies for the CRB (Dahri et al., 2021; Grover et al., 2022) and for other basins across the HKH region (Jasrotia et al., 2021; Hashmi et al., 2020; Akhtar et al., 2022), showing greater flow increases under more extreme scenarios. Nevertheless, model-based differences remain evident. Haider et al. (2020), for example, found that some CMIP5-GCMs projected higher flows under RCP 4.5 than RCP 8.5, while others projected the opposite.

Seasonal flow patterns in this study indicate that future increases will be more pronounced in the winter season (October–March) compared to the summer season (April–September) (Table 6) and is evident from other studies also (Ali et al., 2015; Krishnan et al., 2019; Sanjay et al., 2017) Monthly-scale analyses show that flows are expected to increase in most months across both scenarios, except during the monsoon season (July–September), where reductions are projected. This decline may point to a weakening of future monsoon precipitation. Supporting this, Grover et al. (2022) projected decreased monsoon rainfall during 2036–2065 and 2066–2100, while pre-monsoon (April–June) and post-monsoon (October–November) precipitation was expected to increase. Similarly, Dahri et al. (2021) reported reductions in monsoon streamflow for the CRB of 1.7–57.3% during 2021–2060 and 0.8–77.4% during 2061–2100. Additional studies (Hasson et al., 2015; Huang et al., 2016; Khattak et al., 2011) have also noted cooling during the monsoon season alongside warming during winter and spring months in the Upper Indus Basin (UIB). These findings suggest that rising temperatures, combined with higher precipitation, will drive stronger winter

streamflow increases in the Chenab River Basin compared to summer flows in the future. The early shift (from June) in peak flows observed by this study may also be due to the enhanced temperature and earlier glacier/snow melts.

Overall, the results of this study align with previous research and emphasize that the primary drivers of climate-induced hydrological change in the CRB are rising temperatures, changes in precipitation, and accelerated glacier and snowmelt. However, factors beyond climate change signals may contribute to the projected streamflow responses, for example, hydrological model structural uncertainty, the size of the GCM ensemble, uncertainties associated with ERA5 precipitation in high-altitude regions, and possible artifacts introduced through the bias-correction procedure. These factors may influence the magnitude and direction of the projected changes.

5 Conclusion and Recommendations

For the complex high-mountain Chenab River Basin, this study highlighted and validated considerable uncertainties associated with CMIP6-GCM projections. The Soil and Water Assessment Tool (SWAT), one of the most widely used hydrological models, was applied using selected temperature and precipitation datasets to simulate future hydrological regimes under both moderate and extreme climate change scenarios. Consequently, the study provides distinct projections of climate change and its hydrological implications.

Historically, the basin has already experienced fluctuating river flows, accompanied by a slight rise in temperature and precipitation. However, future estimates remain highly erratic and uncertain. Climate parameters are projected to rise almost linearly over the twenty-first century, while forecasts of River Chenab inflows, though speculative, generally exhibit increasing tendencies under both scenarios.

Seasonal analysis suggests substantial increases in river inflows during the winter (October–March) and pre-monsoon (February–June) periods. This

enhanced water availability during the Rabi season (November–May) could reduce reliance on storage reservoirs for supplemental releases. Furthermore, the lower riparian provinces of Sindh and Baluchistan may particularly benefit from increased flows during the early Kharif season (April–June), which coincides with the onset of cropping and often faces irrigation shortages. Since peak flows strongly influence return periods, the observed increase in mean and seasonal flows suggests that extreme flows and consequently return periods are also expected to increase.

In summary, under the severe climate change scenarios considered in this study, the Chenab River Basin is expected to exhibit unexpected and highly variable hydrological responses. The projected changes in seasonal and annual streamflow may have potential implications for drought management, flood control, reservoir operations, and irrigation water abstractions, but dedicated operational modeling and risk-based analyses are required to translate these projections into actionable management strategies.

In the present study, uncertainty analysis using SWAT-CUP with the SUFI-2 algorithm was limited to the model calibration stage, and uncertainties associated with GCM projections were not propagated through the hydrological model to simulate future streamflow. This limitation is acknowledged and identified as a key direction for future research. Specifically, future work will focus on fully propagating GCM-related uncertainties through the hydrological modeling framework to better quantify projected climate change impacts. In addition, a more comprehensive assessment of uncertainty bounds and inter-model variability is recommended to enhance understanding of the range and variability of projected monthly streamflow.

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Author's Contribution

AK provided the concept and methodology; TM worked on methodology, formal analysis, data curation, and writing the original draft; MK was involved in the formal analysis; MA contributed to the article structuring, review & editing.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

Data will be provided upon request.

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