Impact of Climate Change on Future Water Availability in Chitral River Basin using Regional Climate Models

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Abstract

The Chitral River, a vital tributary of the Indus River originating from the Hindu Kush Himalayan region, is a key source of water for domestic, agricultural, and hydro power needs in Pakistan. Its flow is predominantly governed by snowmelt, glacial runoff, rainfall, and groundwater baseflow, making it highly sensitive to climate change. This study investigates the impact of climate change on future water availability in the Chitral River Basin (CRB) using the Soil and Water Assessment Tool (SWAT) model and Regional Climate Models (RCMs) under RCP4.5 and RCP8.5 emission scenarios. Bias-corrected climate projections indicate significant warming in the basin, with temperature increases ranging from 2.34°C to 5.23°C by the late 21st century. Changes in precipitation are projected to range from 2.42% to 6%, varying across scenarios and timeframes. These shifts in climate variables are expected to alter the hydrological regime, with peak stream flow's anticipated earlier in the year, from June to July. Model simulations suggest an increase in mean annual flow by up to 19.24% under RCP4.5 and 20.13% under RCP8.5 during the mid-century (2041–2070). However, a decline in flows is projected in the late century due to diminishing glacial reserves, highlighting the transient nature of increased runoff driven by glacial melt. This research underscores the critical need for adaptive water resource management strategies to address the impacts of climate change. The findings provide valuable insights for policymakers, water resource managers, and stakeholders, emphasizing the importance of sustainable practices and integrated watershed management to ensure long-term water availability in the Chitral River Basin and downstream regions.

Keywords: Climate change; Chitral River; Regional Climate Models (RCMs); Soil and Water Assessment Tool (SWAT); Hydrological Modelling

1. Introduction

Water is indispensable for sustaining all life forms, and it plays a pivotal role in industrial development, agriculture, potable supply, and recreational activities [1]. However, only about 2.5% of the total global water is freshwater, and nearly 70% of that is sequestered in glaciers and polar ice sheets. This severely limits usable water, making its availability a critical issue, particularly under the looming threat of climate change [2]. Earth’s climate has historically alternated between glacial and interglacial states. In recent decades, however, the rate of warming has accelerated markedly. This has been characterized by rising atmospheric and ocean temperatures, increased melting of snow and ice, and a corresponding rise in sea levels [3–5]. As stated in the IPCC Sixth

Assessment Report (AR6), global average surface temperatures are projected to rise by 1.5°C between 2030 and 2035, a significant increase from the 0.75°C cited in the Fourth Assessment Report (AR4), thereby amplifying concerns around climate intensification [6]. In South Asia, average temperatures in coastal regions have risen by 0.6–1.0°C since the early 1900s, and in Pakistan, a rise of 0.6°C was recorded between 1901 and 2000 [7]. The increasing global population adds further stress to freshwater resources. Over the last 50 years, the world population has expanded from 3 billion to 6.5 billion, and projections suggest it could reach 8 billion by 2025 and 9 billion by 2050. Currently, irrigation alone accounts for roughly 70% of all freshwater withdrawals worldwide [8]. Pakistan, like many South Asian countries, is heavily dependent on snow and glacier-fed river systems. The Upper Indus Basin (UIB) in particular dominated by cryospheric processes supplies vital water through the Indus River and its network of tributaries [9]. Numerous investigations have focused on evaluating the hydrological consequences of climate change through the use of Regional Climate Models (RCMs). For instance, Andrea et al. (2014) utilized projections from the IPCC's Fifth Assessment Report across three Representative Concentration Pathways (RCP2.6, RCP4.5, and RCP8.5) and forecasted an advancement in snowmelt timing, intensified glacial melt, and a gradual decline in streamflow owing to thinning ice layers [10]. Similarly, Gerhard et al. (2014) predicted temperature rises of approximately 2.2 K during 2031–2060 and up to 3.5 K by 2070–2099, accompanied by a decrease in precipitation ranging from 12% to 35%, ultimately resulting in marked reductions in streamflow within the Upper Jordan River Basin [11]. In another study, Aijing Zhang et al. (2016) implemented the SWAT model to simulate hydrological behavior in the Heihe River Basin (HRB) and projected an increase in summer precipitation under future climate scenarios, with potential implications for regional irrigation practices [12]. For Pakistan's Upper Indus Basin (UIB), numerous studies have documented notable alterations in seasonal streamflow patterns, increased flood frequency, and reduced water availability. According to Asim Jahangir et al. (2020), peak flows are shifting earlier in the season (from May–June to July August), with their magnitude increasing by 50–100% [13]. Shabeh et al. (2019) examined the influence of glacial loss on the Jhelum, Kabul, and Indus rivers, concluding that a 25% reduction in glacier volume is plausible under a 1.5°C warming scenario [14]. Farooq et al. (2016), using GCMs and RCMs for the Naran Basin, projected changes in precipitation and sediment yield under warming trends [15]. Similarly, Shaukat Ali et al. (2015) indicated that under RCP4.5 and RCP8.5, streamflow could rise by 12–20% by 2100, although both pathways may overpredict precipitation and temperature in the UIB region [16,17].

Climate variability is already influencing water resources across Pakistan. The national average temperature has climbed by approximately 0.5°C per decade over the last 50 years [18]. Glacial retreat, particularly in Khyber Pakhtunkhwa (KPK), elevates the likelihood of flood hazards, while both surface and subsurface water reserves are rapidly depleting. In 2016, the per capita freshwater availability dropped below 1,000 cubic meters and continues to decline [18]. In light of these threats, evaluating future water availability using advanced modeling tools becomes essential for devising sustainable water management strategies.

1.1 *Objective of the Study:*

This research focuses on quantifying the implications of climate change on future water availability under various IPCC-endorsed Representative Concentration Pathways (RCPs). It analyzes past (1976–2005) and projected (2010–2100) water trends for the Chitral River Basin by applying Regional Climate Models (RCMs). The study draws on datasets from the Pakistan Meteorological Department and employs the SWAT model (with SWAT-CUP), bias correction (Quantile Delta Mapping), and multivariate statistical techniques (SPSS). The insights derived aim to support improved planning for water conservation and climate adaptation in Pakistan.

2. Study Area and Data Collection

2.1 Study area

The Chitral River Basin, situated in the Hindukush mountains of northeastern Pakistan, was chosen as the focus of this study. The Chitral River is a major indirect tributary of the Indus River, originating near the Baroghil Pass in the Hindukush Mountains. It flows from the Kunhar River, which is itself a tributary of the Kabul River in Afghanistan. A location map of the Chitral River Basin, along with the Digital Elevation Model (DEM), zonal classification, and key topographic features, is shown in Fig. 1. The uppermost part of the Chitral River, known as the Yarkhun River, is located between the towns of Mastuj and Chitral, and further downstream, it is referred to as the Chitral River. The river lies within the geographical coordinates of 35˚50' N and 71˚48' E (Gul, 2013; Ahmad et al., 2018). Five meteorological stations situated within or adjacent to the basin (Fig. 1) provided the observational data. The river is gauged at a flow gauge (FG) located in the town of Chitral (Figure. 1) on the river bridge.

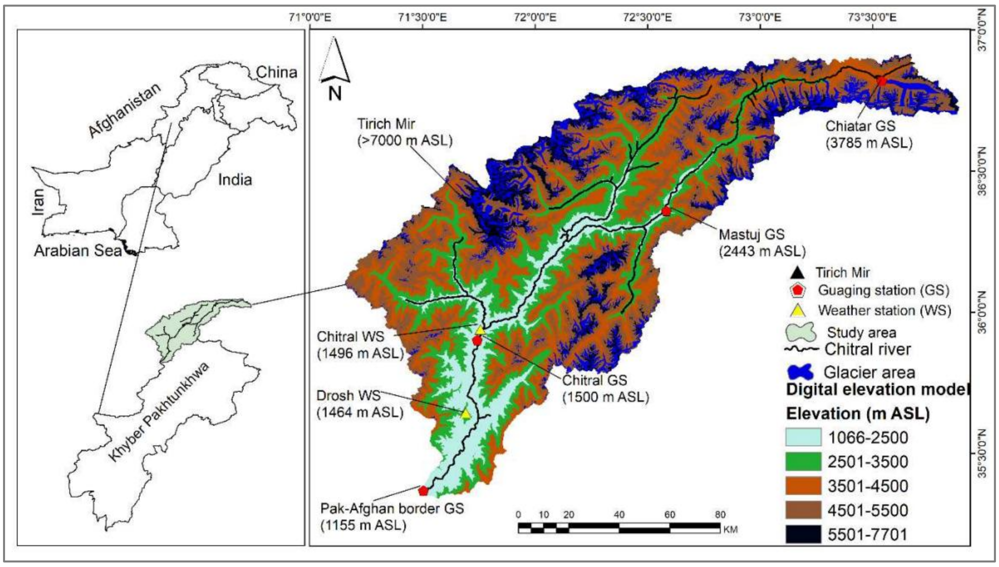


Figure.1. Location map and digital elevation model of the study area (Ahmad et al. 2021) [19]

The mean annual runoff of the river for 34 years of record (1964-1998) is 8670 Mm3. The maximum recorded discharge was 1586 m3/s on 16th July, 1973 and the minimum recorded discharge was 46 m3/s on 10th March, 1964. On July 8, 2019, a glacial lake outburst flood in the Golen Gol region of Lower Chitral caused widespread devastation. The flood, triggered by the sudden bursting of the Jam Ashpar glacier, destroyed five bridges, toppled power poles, and submerged roads and farmlands. According to the Khyber Pakhtunkhwa Provincial Disaster Management Authority (PDMA), the event caused significant damage to local infrastructure and livelihoods (Dawn, 2019).

2.2 Datasets

2.2.1 Hydro-Meteorological data

The upper most section of the Chitral River is known as Yarkhum River, between Mastuj and Chitral towns and downstream it is called Chitral River located between 35˚50 and 71˚48. A distributed network of meteorological stations spans the northern region, aiding basin-wide identification and analysis., maintained and recorded by two public sector entities namely the Pakistan Meteorological Department (PMD) and Water and power development authority (WAPDA). The meteorological observations from these stations include values of precipitation, maximum temperature and minimum temperature on a daily time-step required for a period of 30-years so as to substantiate impacts of climate change in this region of study. The observed time period selected for this study is 1976-2005 which unfortunately omits all of the Meteorological records maintained by Water and Power Development Authority (WAPDA) since its recording period started in the mid-1990s and therefore cannot be used in the present study owing to the constraint of 30 years observed data requirement for the three variables namely precipitation, maximum temperature and minimum temperature. An inventory of all the PMD stations used in this study so far are as given in Table 1.

Table 1. List of Meteorological Observatories in Chitral River Basin

Sr.#	STATION NAME	AGENCY	LATTITUDE	LONGITUDE	ALTITUDE (m.asl)
1	CHITRAL	PMD	35.85	71.83	1496
2	DROSH	PMD	35.57	71.78	1464

2.2.2 Spatial datasets CORDEX

The Coordinated Regional Climate Downscaling Experiment (CORDEX), initiated by the World Climate Research Program (WCRP), aims to develop a global framework of regional climate projections based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The project created worldwide projections of climate models on regional scales for analyzing impact studies. It created a pool/ensemble of climate model using dynamically and statistically downscaled GCM runs from the CMIP5 database with an initial resolution of 0.44 or 50 km. For this study, the selected Regional Climate Models (RCMs) and their GCM forcing data were obtained from the Earth System Grid Federation (ESGF), focusing on the South Asian domain. These datasets, formatted in netCDF, provide projections under different Representative Concentration Pathways (RCPs). Specifically, RCP 4.5 (4.5 W/m²) and RCP 8.5 (8.5 W/m²) (Table.2) scenarios were used, as they represent mid-range and high-end emission trajectories, respectively, and are considered the most plausible for long-term forecasting by 2100.

Table 2. RCMs Model Dataset

Institute	RCM	Driving GCM	Emission Scenario
CSIRO	CCAM	MPI-ESM-LR	RCP 4.5 & 8.5
SMHI	RCA4	EC-EARTH	Same as above
MPI-CSC	REMO2009	MPI-M-MPI-ESM-LR	Same as above

For the present study, the study of climatologically changes at fine resolutions on a global scale is made possible through the use of RCM datasets. GCM are used to dynamically downscale these RCM projections at a fine scale in order to perform impact-oriented studies. This research considers different RCPs to capture the range of plausible future climate outcomes. Given the similarities between RCP4.5 and observed CO_2 emission trajectories between 2005 and 2012, RCP4.5 was prioritized alongside RCP8.5, which represents more extreme warming scenarios. RCP2.6 was excluded due to its reliance on sustained and unrealistic global CO_2 reductions. Both RCP4.5 and RCP6.0 depict moderate climate futures, but RCP4.5 was selected due to its alignment with observed trends in emission rates (~1.5% annually) (Peters et al., 2012) [20].

2.2.3 Land use/Land cover data

LULC is the primary input data for SWAT modelling, as the variations in LULC can momentously affect runoff, Evapo-transpiration, and certain other parameters of the hydrological cycle (PRINCE, 2013) [21]. LULC data was obtained via the USGS Global Land Cover System, later reclassified to suit SWAT model categories with 1km spatial resolution, and further the data was then clipped according with shape file in order to get map of the desired land use for CRB. Based on land cover and Land use, the study area was divided into 6 major categories, which was then reclassified according to their hydrologic properties and SWAT requirement. For each land category, the model provides a unique four letter code. The division of these classes is shown in Table 3 and Figure. 2; where major classes were forest mixed, forest deciduous, range grasses and agricultural land-row crops etc.

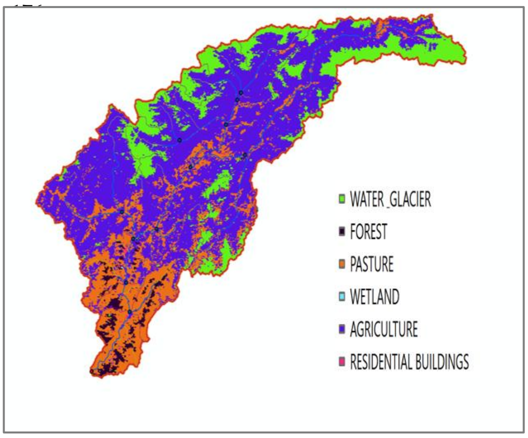


Figure.2. Land cover classes observed in CRB

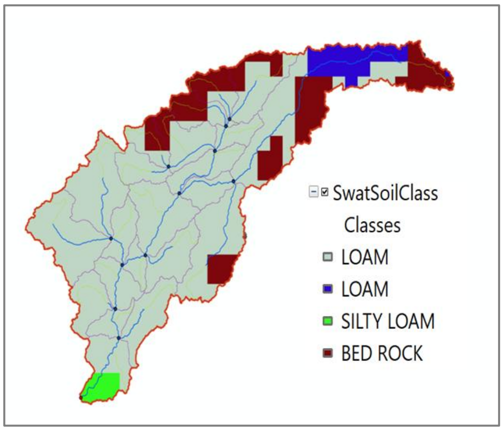


Figure.3. FAO Soil classification CRB

Table 3. Land Use Classification of Chitral River Basin with Percentage Area Covered

S. #	LULC Classes	SWAT Classes	% area covered
1	Water and Glacier	WATR	18.03
2	Forest	FRST	2.34
3	Pasture	PAST	20.25
4	Wetlands	WETL	0.022
5	Agricultural Land	AGRL	59.24
6	Residential Building	URHD	0.088

2.2.4 Soil Classification

The hydrological performance of soil is well described by its physical properties. Different soil physic chemical and textural properties are required for SWAT model like available water content, soil texture, bulk density, hydraulic conductivity and carbon content for each layer of different soil types. For this study, FAO/UNESCO soil data was used with projection based on UTM and 90m*90m resolution, and then applied in model in Hydrological Response Unit (HRU) analysis. After importing soil map to Arc SWAT interface, four different soils were delineated in the basin, details of which are summarized in Table 4. Similarly, Soil characteristics are also mentioned in Figure 3.

Table 4. Soil Texture Classification of Chitral River Basin with Percentage of Particles

S. #	FAO Soil type	% area covered	Texture	Clay%	Silt%	Sand%
1	I-B-U-2c-3503	77.18	LOAM	26	30	44
2	I-X-2c-3731	4.91	LOAM	22	33	45
3	Xh18-bc-3870	1.69	SILT LOAM	21	54	26
4	GLACIER-6998	6.18	UWB	5	25	70

2.2.5 Regional circulation model base climate data

Climatic projections generated by General Circulation Models (GCMs) or Regional Circulation Models (RCMs) serve as crucial input data for evaluating climate change impacts. However, these models must be downscaled to achieve suitable resolutions, either through statistical or dynamical downscaling methods, or by embedding RCMs within larger GCM frameworks. After selecting RCPs, the next phase was addressing the two prime issues constraining the impacts studies: Firstly, the output of GCMs/RCMs may not be fine as necessary for local-scale and regional studies, and secondly, the output from GCM/RCM are supposed to contain biases of definite extent, as compared with observed data. Therefore, data of finer resolution and biases should be adjusted. Downscaling should be done by mean of statistical/dynamical method or with the help of RCMs, set in in a larger GCM (Khan, 2018) [22]. For this study, the RCM projections are available in CORDEX (NorESM1-M_RCA4). The Coordinated Regional Downscaling Experiment (CORDEX) has created fine-scale projections for different parts of the world, from which “CORDEX-South Asia” experiments cover the UIB. CORDEX-RCM model NorESM1-M_RCA4 is available and deliver dynamically downscaled dataset of 50 km resolution. Furthermore, data for the appropriate RCM group was downloaded, but the data is supposed to contain biases of definite extent, therefore, it needed bias correction, before use in modelling process. Conclusively, the RCM output was bias-corrected by “QDM” for RCP (4.5 and 8.5) for time lapses i.e. 2010-2039, 2040-2069 and 2070-2099 for the start, mid and late century respectively.

3. Methodology

3.1 SWAT Model Setup

The SWAT model operates as a distributed, physically-based tool developed to simulate long-term hydrological dynamics and sediment transport in watershed systems. Its primary goal is to assess the influence of land use, management practices, and climatic variables on processes such as water quantity, crop productivity, nutrient fluxes, and sediment yield. By partitioning watersheds into sub-units, the model enhances simulation detail and computational efficiency. It supports future scenario analysis using diverse input datasets, including land use, topography, climate, and soil data. SWAT modules address hydrological cycles, crop growth, water quality, and nutrient movement, all of which are validated in numerous case studies [23-25].

3.2 Watershed Delineation

Establishing watershed boundaries is a foundational step in SWAT-based hydrological modeling. In this study, the digital elevation model (DEM) was analyzed to extract topographic attributes, such as slope direction and accumulation, which are essential for defining stream networks and watershed edges. The DEM was projected using the UTM coordinate system (Zone N43), consistent with local geospatial standards in Pakistan. The catchment was segmented into 23 sub-basins based on elevation and hydrological flow paths (Figure. 4). Parameters such as stream delineation, outlet positioning, and inlet identification were systematically defined to produce accurate Hydrological Response Units (HRUs).

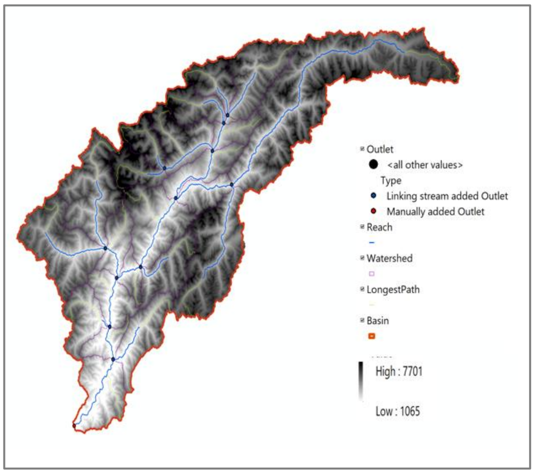


Figure.4. Watershed delineation of CRB

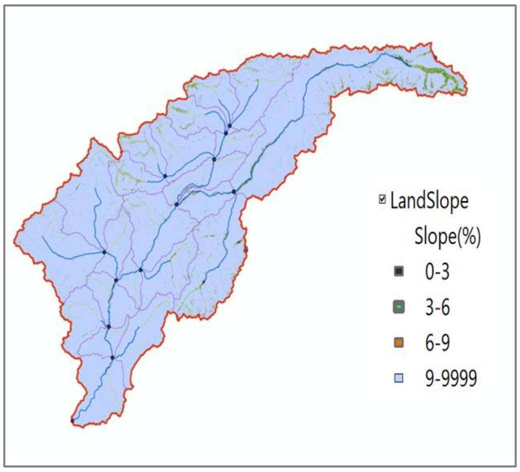


Figure.5. Land slope classification of CRB

3.3 Slope Classification and HRU Analysis

SWAT organizes spatial data into Hydrological Response Units (HRUs), which integrate slope, soil, and land use information within each sub-basin. Following watershed delineation, slope classes were derived from DEM elevations (Figure. 5) and Table 5, while land use and soil types were classified based on standardized SWAT input formats. These datasets were aligned under the UTM N43 coordinate system. HRUs were then created using the multi-slope method, allowing detailed spatial variability within sub-basins. SWAT can define HRUs either by unique land/soil combinations per sub-basin or by threshold-based filtering methods to reduce computational load.

Table 5. Soil Texture Classification of Chitral River Basin with Percentage of Particles

S. No	Slope Class	Upper-Lower limit	% age Area Coverage
1	Class 1	0-3	0.59
2	Class 2	3-6	1.36
3	Class 3	6-9	1.7
4	Class 4	9-9999	96.35

3.4 Data Analysis and data quality control

The statistically downscaled climate data were categorized into three 30-year intervals 2010–2039, 2040–2069, and 2070–2099 after which leap years were excluded to standardize the dataset for trend assessment and bias adjustment. The study incorporated outputs from three regional climate models (RCMs), each covering the aforementioned periods. These RCMs provided daily records of minimum and maximum temperatures as well as precipitation data relevant to selected meteorological stations. Compared to general circulation models (GCMs), these RCMs offer a finer spatial resolution (0.44° × 0.44°), enabling more localized climate projections. The model outputs are aligned with two Representative Concentration Pathways (RCPs): RCP4.5, reflecting moderate emissions, and RCP8.5, representing high emissions scenarios. These pathways are widely adopted for evaluating future climate trends as they incorporate a range of radiative forcing levels by 2100. A comprehensive list of RCMs and their associated GCMs is provided in Table 2.

3.5 Mann-Kendall trend analysis

To assess long-term trends in hydro meteorological parameters, the study applied the non-parametric Mann–Kendall (MK) trend test with a 5% significance threshold. The test was used to determine monotonic trends in variables such as river discharge, air temperature, and rainfall. Sen's Slope estimator (Sen, 1968) was utilized to quantify the magnitude of change over time, while Kendall's tau (τ) coefficient supported significance evaluation. A linear regression model was also employed to represent trends visually. Both seasonal and annual scales were examined to identify temporal patterns. The MK test, in combination with Sen's Slope, is widely used in climate-related research to detect non-linear but consistent shifts in environmental variables (e.g., Al-Safi and Sarukkalige, 2020; Pirnia et al., 2019).

3.6 Bias correction using Quantile delta mapping (QDM) and CMhyd Software

These climate datasets have inherent biases which if not addressed or removed could lead to unrealistic results. The Best Easy Systematic (BES) estimator is used for both temperature and precipitation. Although the BES method is good for temperature, its performance is low for precipitation. The Mean Monthly Correction Factor (MMCF) method is another such method used for precipitation bias correction but Bias correction of projected datasets against the observed data should employ a process that preserves its future peaks and does not average out the extreme values (Ali, Li, Congbin, & Khan, 2015) [29]. One such method employed that does not alter the future peaks is Quantile Delta Mapping method that is most frequently used in hydrological forecasting and projections. The QDM approach maintains the quantiles of projected changes while simultaneously removing systematic errors of quantiles of the projected series in comparison to the observed datasets. QDM bias correction in Table 6 applied on the two IPCC emission scenarios of their respective downscaled RCM datasets for the selected time slices i.e., 2010-2039, 2040-2069 and 2070-2099.

Table 6. Bias-Correction for Different Time slice along Variables using QDM & CMhyd

RCM	IPCC emissions scenario	Time slice	Variable	Bias-Correction
CCAM	4.5 & 8.5	2010-2039 2040-2069 2070-2099	Prcp, Tmax & Tmin	Complete
RCA4	4.5 & 8.5	2010-2039 2040-2069 2070-2099	Prcp, Tmax & Tmin	Complete
REMO	4.5 & 8.5	2010-2039 2040-2069 2070-2099	Prcp, Tmax & Tmin	Complete

CMhyd was developed to simulate climate data that can effectively represent the locations of gauges used in a watershed model setup. Accordingly, climate model data were extracted and bias-corrected for each gauge location. CMhyd reads observed data in ASCII format. Each gauge's data is saved in individual files, organized through a location file. These location files specify precipitation and temperature data separately. The location file contains the relevant data file names and coordinates (LAT and LON) of the gauges. In the data files, the first line indicates the starting date of the time series, with subsequent lines representing daily records. Missing data (gaps) are represented by a no-data value (–99.9 or –99.0). The precipitation file provides one daily record (total daily precipitation in mm), and the temperature file contains daily maximum and minimum temperatures [°C]. This method determines the difference between current and projected GCM simulations and applies those changes to observed time series i.e., the CM Hydro Software bias correction framework, illustrated in Figure. 6. The correction adjusts observations according to the GCM or RCM response to climate change. For instance, if a GCM anticipates that temperatures will be 3°C warmer in the future, then 3°C is added to historical values to generate a new future climate time series. For rainfall, a percentage change is usually applied for example, if a 20% increase is projected, the past values are multiplied by 1.2. These delta adjustments may vary seasonally or monthly.

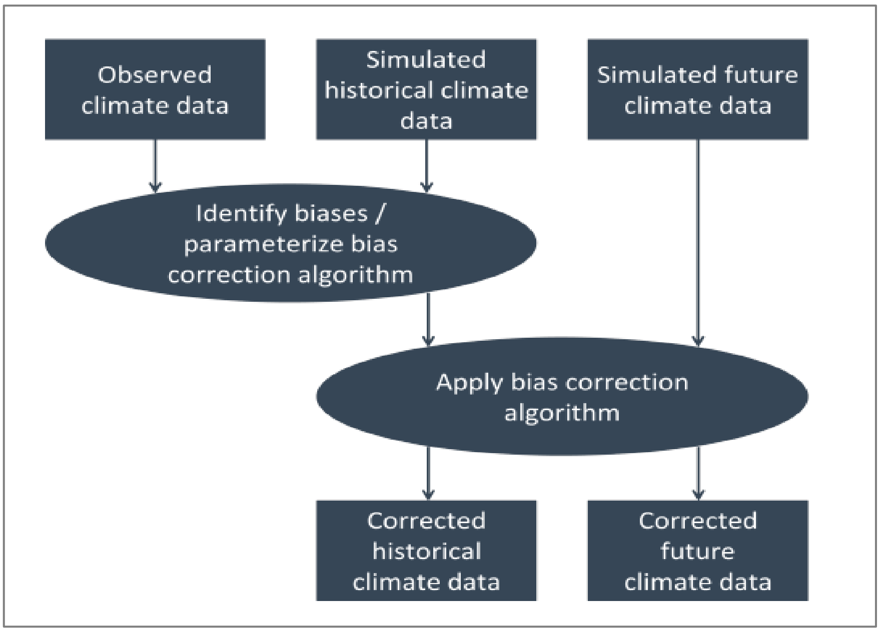


Figure 6: Bias correction framework of CMhyd software

3.7 Sensitivity analysis and comparison with other models/datasets

Sensitivity analysis plays a crucial role in identifying the most influential model parameters that require adjustment based on the specific characteristics of the study area. Given the inherent uncertainties in model input parameters, a systematic variation of these parameters was performed to enhance model accuracy and efficiency. This process ensures a better understanding of the system's hydrological behavior and the overall performance of the model. In this study, a local sensitivity analysis (one-at-a-time method) was implemented to determine the key parameters affecting streamflow simulation. These parameters were selected based on their impact on model output. To refine model accuracy, calibration and validation procedures were conducted to optimize the agreement between observed and simulated hydrological variables. Using daily discharge data from the Chitral River Station, the model was calibrated for the period 1977–1996 and validated using discharge records from 1997–2004 (Fig. 7 and 8). For calibration, the Sequential Uncertainty Fitting (SUFI-2) algorithm within SWAT-CUP v. 5.2.1.1 was applied [30,31]. The parameter ranges were assigned based on prior hydrological knowledge, sensitivity analysis results, and literature references. Model performance was quantified using two key uncertainty metrics: P-factor and R-factor, where the P-factor represents the proportion of simulated estimates falling within the 95% Prediction Uncertainty (95PPU) band, and the R-factor reflects the discrepancy between observed and simulated values. Beyond internal model calibration and validation, SWAT and RCM outputs were compared with other widely recognized hydrological models and climate datasets for further validation and to enhance the robustness of the results. The comparison was made using the GCM and RCM results in combination with observational data. The purpose of this comparison was to assess how well the SWAT model's outputs, when corrected for bias, align with outputs from models such as CCAM, RCA4, and REM (Table 6), as well as with datasets like the CMhyd-corrected climate data. This comparison allows us to evaluate the consistency of SWAT and RCM performance against other models, ensuring the credibility of the results across different model setups. Additionally, this comparison contributes to understanding how the simulated outputs behave in terms of future projections, as seen in Figure. 9. The validation results for period 1997-2004 as shown in Figure. 9 and Table 7.

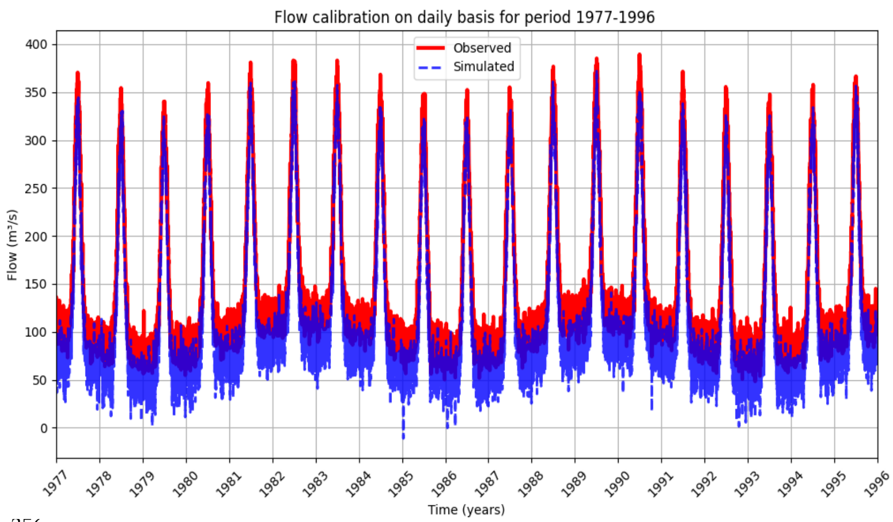


Figure 7: Flow calibration on daily basis for period 1977-1996

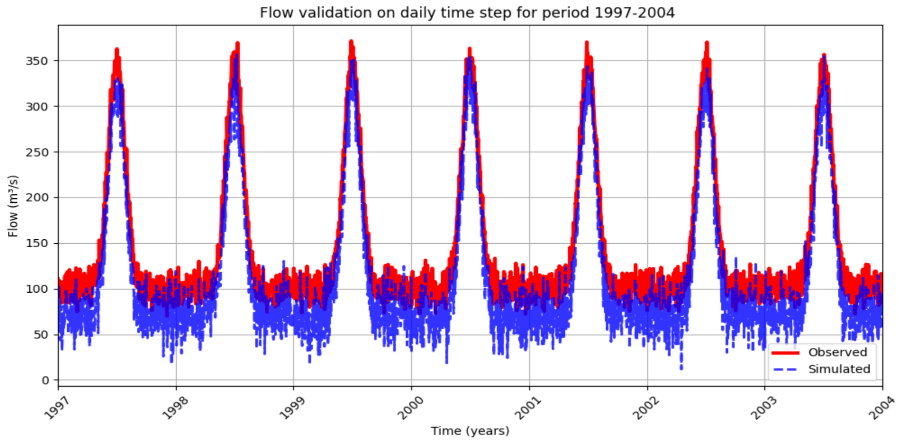
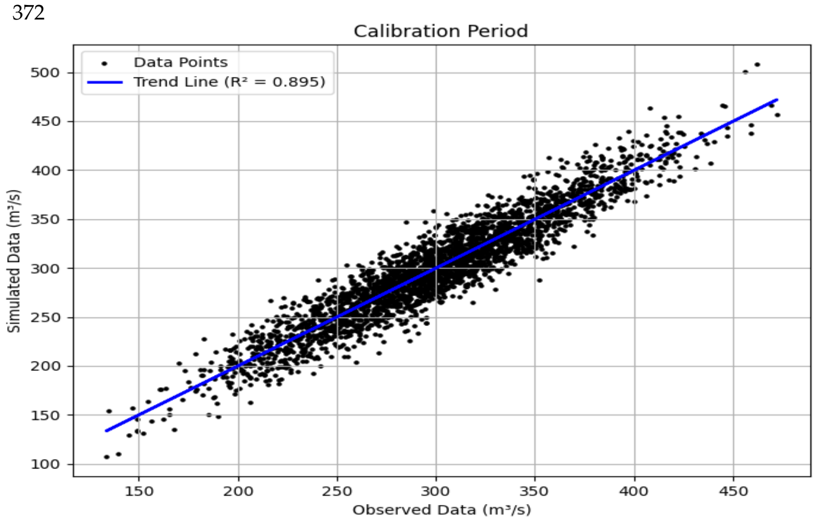
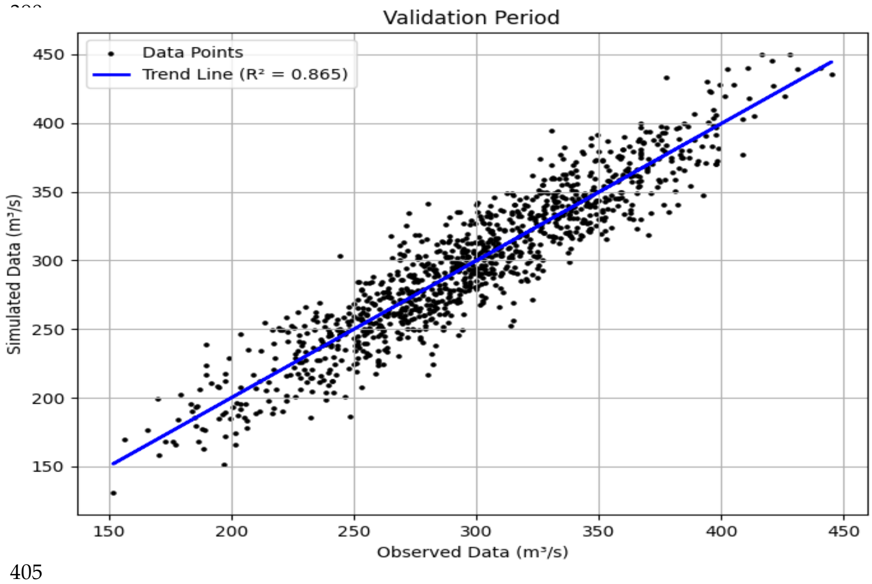


Figure 8: Flow validation on daily basis for period 1997-2004



(a)



(b)

Figure 9: Correlation between observed and simulated flow (a) Calibration (b) Validation

Table 7. Correlation results for Calibration and Validation period

Calibration period (1977-1996)			**Validation period (1997-2004)**	
Cofficients	**Simulated**	**Observed**	**Simulated**	**Observed**
Average flows (m3 /s)	293.5	274.3	307.7	242.8
r - factor	0.81		0.77	
p - factor	1.05		1.18	
R^2	0.89		0.86	

4. Results

4.1 Trend Analysis

The results for the trend analysis conducted for all the observed meteorological station datasets (TMAX, TMIN, and PRCP) situated in the respective basins using the non-parametric Man-Kendall test and associated magnitude quantification with the help of Sen Slope. All trends were determined over the examination time period 1976– 2005 with the level of statistical significance kept at 90%. The details of the result are listed below in the Table 8, 9 and Fig. 10, 11 for the observed stations.

Table 8. Man-Kendall Trend Test for Met. Stations for Chitral River Basin

Chitral Meteorological Station			
Tmax			
Time series	Z- Score	Sen Slope	Trend (90% Sig. Level)
Jan	2.57	0.11	Increase
Feb	2.07	0.09	Increase
March	2.50	0.13	Increase

Dec	1.89	0.07	Increase
Annual	2.64	0.05	Increase
IX-XI	1.75	0.03	Increase
XII-II	3.10	0.10	Increase

Chitral Meteorological Station			
Tmin			
Time series	Z- Score	Sen Slope	Trend (90% Sig. Level)
June	-3.25	-0.11	Decrease
July	-2.43	-0.07	Decrease
August	-1.96	-0.05	Decrease
Nov	-2.18	-0.04	Decrease
Annual	-1.68	-0.02	Decrease
VI-VIII	-3.14	-0.07	Decrease

Chitral Meteorological Station			
Prcp			
Time series	Z- Score	Sen Slope	Trend (90% Sig. Level)
June	2.21	0.29	Increase
Sep	1.84	0.27	Increase
Annual	2.07	5.25	Increase
IX-XI	2.21	0.77	Increase

Table 9. Man-Kendall Trend Test for Met. Stations for Drosh River Basin

Drosh Meteorological Station			
Tmax			
Time series	Z- Score	Sen Slope	Trend (90% Sig. Level)
Jan	2.00	0.08	Increase
March	1.86	0.08	Increase
XII-II	2.50	0.07	Increase

Drosh Meteorological Station			
Tmin			
Time series	Z- Score	Sen Slope	Trend (90% Sig. Level)
March	2.25	0.08	Increase
XII-II	1.96	0.05	Increase

Drosh Meteorological Station			
Prcp			
Time series	Z- Score	Sen Slope	Trend (90% Sig. Level)
April	1.74	2.12	Increase
Annual	1.93	6.27	Increase

The Mann-Kendall trend analysis for the Chitral River Basin (CRB) revealed a significant upward trend in both maximum temperature and precipitation across the annual scale, with parallel increases during autumn and winter. In contrast, a decreasing pattern was observed in minimum temperature, particularly during the monsoon season and over the overall annual time span from 1976 to 2005.

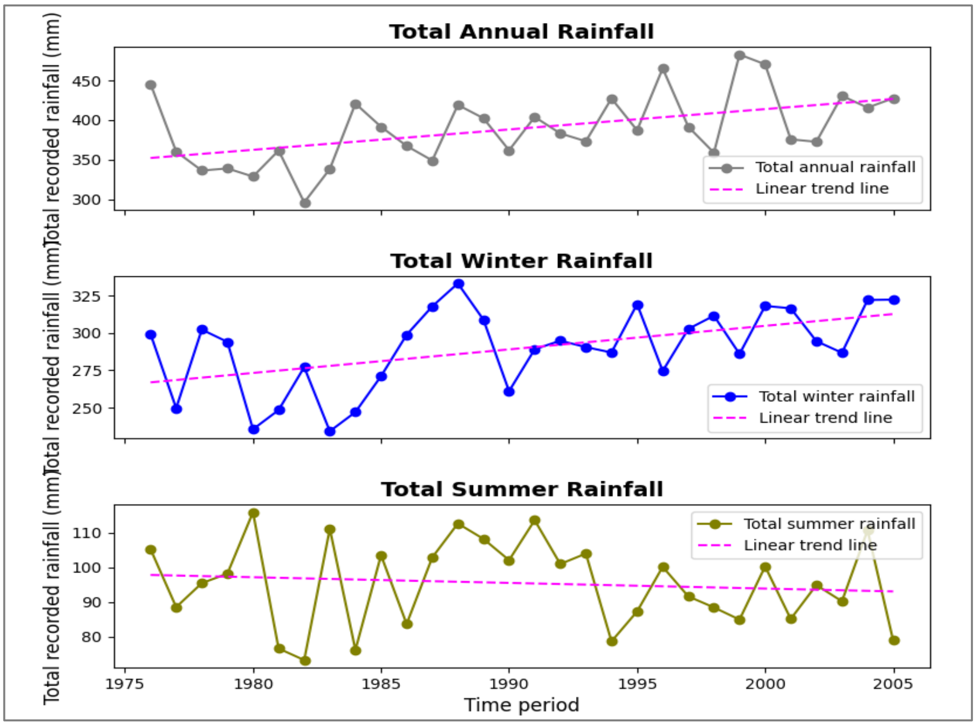


Figure 10: Trend analysis of total annual and seasonal rainfall recorded in CRB

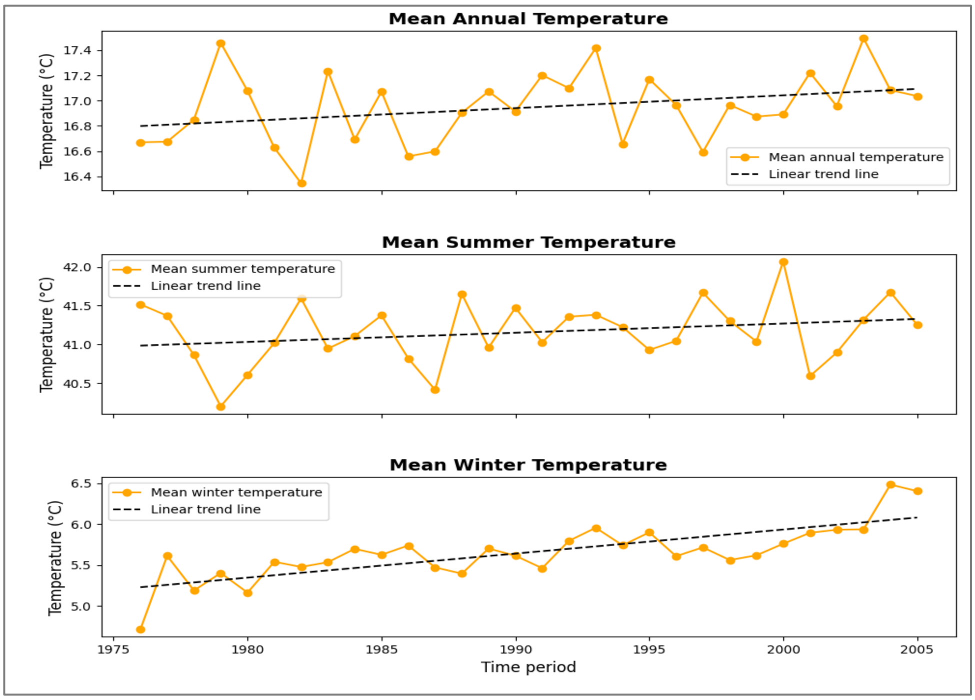


Figure 11: Mean annual and seasonal temperature trends over the period of 1976–2005 in CRB

4.2 Limitations of RCMs and Bias Correction Techniques

While the RCMs provide a higher spatial resolution for climate projections, they are inherently dependent on the Global Climate Models (GCMs) used for boundary conditions. These GCMs themselves carry a degree of uncertainty, which propagates through the RCM outputs, resulting in biases. These biases can lead to discrepancies when comparing simulated data with observed data. Additionally, RCMs typically have a resolution ranging from 50-100 km [32]. Although they offer a more localized representation of climate, this resolution is often insufficient to capture small-scale variations in climate, particularly in regions with complex terrain like the Chitral River Basin. Localized topographical features, such as mountain ranges, can significantly influence precipitation and temperature patterns, which might not be fully represented in RCM projections. Another key limitation lies in the bias correction methods. In this study, we used the CMhyd bias correction framework, which assumes that past biases in the RCM or GCM outputs will remain consistent in the future. This assumption may not always hold, particularly when future climate dynamics diverge from past trends. While methods like quantile mapping (QDM) and delta change are effective at adjusting the mean and seasonal variability, they may fail to capture extreme events or rapid shifts in climate variability that are critical for hydrological modelling [33]. Moreover, the process of bias correction is typically focused on annual averages and seasonal trends. However, short-term variability and extreme weather events are often underrepresented in bias correction methods, leading to potential limitations in their application for flood forecasting or drought prediction. Finally, despite efforts to correct data gaps, the issue of missing data or incomplete records remains a challenge in both the RCM outputs and the observational datasets. Gaps in temperature or precipitation records can influence the accuracy of both the raw RCM simulations and the final bias-corrected outputs.

4.3 Projection in stream flows

Bias-corrected inputs from the CORDEX RCM NorESM1-M_RCA4 were employed to simulate three future periods: 2020–2039, 2050–2069, and 2080–2099. For individual case, the future hydrology was assessed for annual average and seasonality for three periods. Estimates were derived as percentage deviations from the baseline period (1976–2005). The results are summarized in Table 10 and graphically shown in Fig. 13 to Fig. 18. From results, it is clear that the projected variations in flow fairly shows a steady increase in First, mid and late centuries for all future climate scenarios as compared with baseline period (1976-2005). In RCP4.5, comparing with reference period, anticipated changes in mean annual flow amount to 7.42%, 11.83%, and 11.08% for the early, mid, and late 21st century intervals. Similarly, this increase in mean annual flow is 8.16%, 9.24% and 12.76% under RCP8.5 for start, mid and late century respectively. Under this scenario, flow volumes initially rise with temperature induced glacier melt, followed by a long-term decline for the region as examine in Table 10.

Table 10. Probable Changes in Flow in First, Mid and Late Century for Chitral River Basin

Difference in Flows for different RCMs Mean annual Observed Flow (1976-1996) = 274.3 m3 /s						
RCMs	**2020-2039**		**2050-2069**		**2080-2099**	
RCPs	(4.5)	(8.5)	(4.5)	(8.5)	(4.5)	(8.5)
CCAM	148.12-135.2	125.09-112.25	130.63-120.26	127.96-121.83	126.57-118.4	121.8-117.92
	(-8.72%)	(-10.26%)	(-7.93%)	(-4.77%)	(-6.46%)	(-3.8%)
RCA4	106.73-98.81	122.53-112.53	129.5-114.18	122.7-111.36	128.51-114.26	131.03-114.3
	(-7.42%)	(-8.16%)	(-11.83%)	(-9.24%)	(-11.08%)	(-12.76%)
REMOO	177.2-143.92	188-153.75	178.41-44.96	170.57-140.31	167.4-135.29	154.54-135.21
2009	(-18.78%)	(-18.21%)	(-18.74%)	(-17.74%)	(-19.18%)	(-12.50%)

4.3.1 Stream flow projection using CCAM RCM

The CCAM Regional Climate Model result for both methods show a variation in Flows. For Delta change the values reaches to the observed Flows at the gauge station. But in both cases the resulting flows for RCP 4.5 and RCP 8.5 in comparison with Observed Flows decrease as shown in Figure 12 and 13.

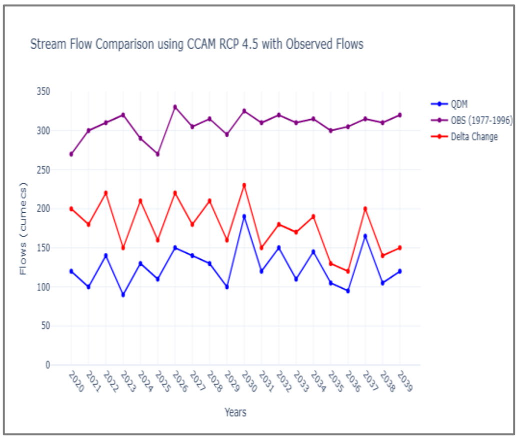


Figure. 12. Streamflow projections RCP4.5

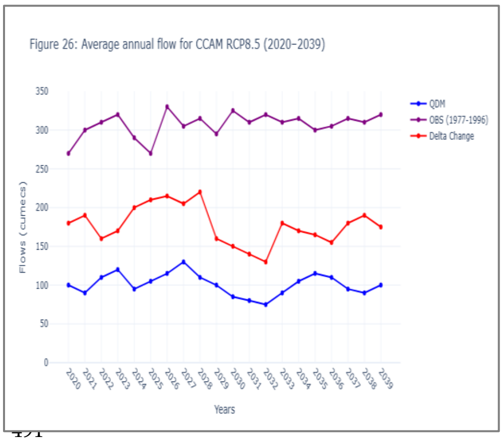


Figure. 13. Streamflow projections RCP8.5

4.3.2 Stream flow projection using RCA4 RCM

The RCA4 Regional Climate Model result for both methods show a little variation in Flows. For Delta change and QDM the resulting outflows is similar but the graph is below the Observed Flows as illustrated in Figure 14 and 15. But in both cases the resulting flows for RCP 4.5 and RCP 8.5 in comparison with Observed Flows decrease.

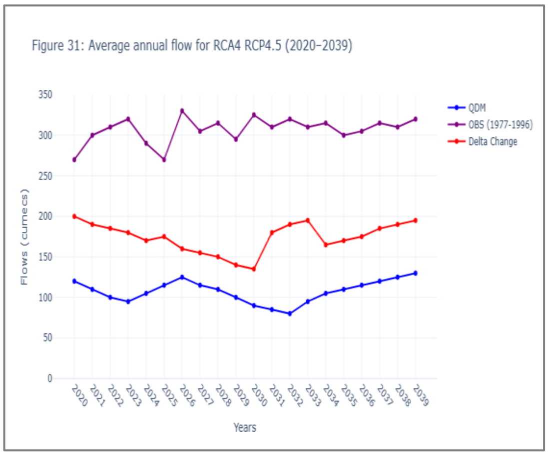


Figure. 14. Streamflow projections RCP4.5

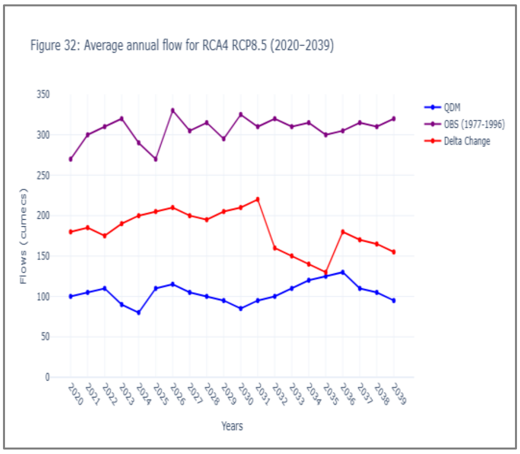


Figure. 15. Streamflow projections RCP8.5

4.3.3 Stream flow projection using REMOO 2009 RCM

The REMO Regional Climate Model result for both methods show a big difference in Flows. For Delta change and QDM the resulting outflows show a variation but the graph is below the Observed Flows. But in both cases the resulting flows for RCP 4.5 and RCP 8.5 in comparison with Observed Flows decrease. The substantial gap between modelled and observed values underscores the critical need for model calibration and highlights the REMO model's conservative nature in projecting hydrological responses to climate change. These outcomes further reinforce the importance of applying multiple RCMs and bias correction strategies to capture the full spectrum of possible future hydrological behaviors in mountainous watersheds as shown in Figure 16 and 17.

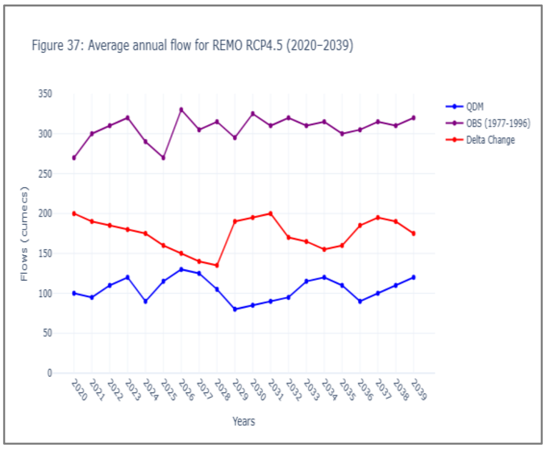


Figure. 16. Streamflow projections RCP4.5

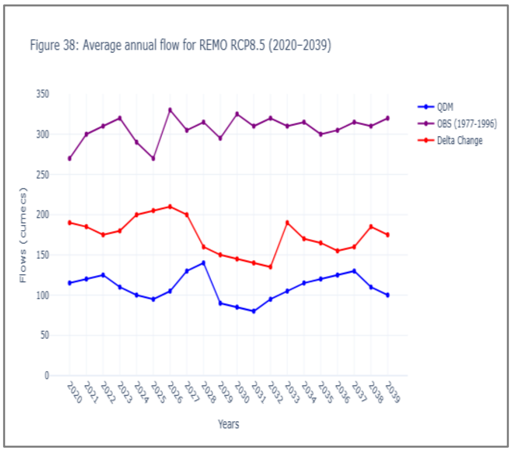


Figure. 17. Streamflow projections RCP4.5

4.4 Comparative Analysis with Similar Studies in the Upper Indus Basin

The projected climate changes in the Chitral River Basin (CRB) closely align with findings from several studies in the Upper Indus Basin, demonstrating similar trends in temperature and precipitation increases under RCP4.5 and RCP8.5 scenarios. In this study, our findings indicate a steady rise in seasonal temperatures, aligning well with earlier projections by Shah et al. (2020), who reported a temperature rise of 2.36°C to 3.50°C under RCP4.5 and 2.92°C to 5.23°C under RCP8.5. This increase in temperature is also reflected in Anjum et al. (2019), who found a similar rise in temperature in the region, supporting the warming trends seen in our projections. Furthermore, precipitation in the CRB is projected to increase during both the annual and seasonal timescales, aligning with results from Shah et al. (2020), who observed an annual precipitation increment ranging from approximately 2.4% to 2.5% in RCP4.5 and up to 6.0% in RCP8.5 projections, and from Anjum et al. (2019), who noted similar increases in winter precipitation in the Upper Indus Basin. These trends in temperature and precipitation changes are consistent with our findings in the CRB, confirming that climate change impacts are likely to affect both regions similarly. In terms of streamflow projections, the CRB shows an increase in mean annual flow of 7.42% to 12.76% for the first, mid, and late century projections under RCP4.5 and RCP8.5. This increase in streamflow is largely driven by the rising temperatures and glacier melt in the region, which has been similarly observed in previous studies. For instance, Shrestha et al. (2015) and Tahir et al. (2011) found that the Upper Indus Basin is projected to experience increased streamflow as a result of climate change, mainly due to the melting of glaciers and increasing temperatures. Our study's projections of streamflow increase for the first century are consistent with these findings, which emphasize the role of climate-induced changes in hydrological behavior in the region.

5. Discussion

The findings underscore a significant influence of climate change on future water availability in the Chitral River Basin. Projected precipitation patterns and temperature variations, simulated through RCMs, indicate shifts in hydrological behavior. While increased temperatures may lead to glacier melt and temporarily elevated flows, long-term reductions in snowpack and altered rainfall regimes pose risks to sustainable water resources. These results are consistent with previous studies conducted in Himalayan and Karakoram basins, reinforcing concerns about regional water security. The study's projections support proactive planning for climate adaptation and integrated water management policies. Further research incorporating socio-economic drivers and land use changes could enhance the robustness of future scenarios.

6. Conclusions

The Chitral River, a significant tributary of the Indus River, plays a vital role in supporting regional water availability, largely influenced by snowmelt, rainfall, and groundwater inputs. This investigation employed the SWAT model to evaluate the potential influence of climate change on the Chitral River Basin (CRB), particularly analyzing streamflow responses under the RCP4.5 and RCP8.5 emission scenarios. The findings indicate a considerable increase in both temperature and precipitation, which substantially alters streamflow dynamics. For the mid-21st century period (2041–2070), average annual flow is expected to increase by 19.24% under RCP4.5 and 20.13% under RCP8.5, with peak discharges observed during June and July, primarily driven by elevated snowmelt rates. These outcomes suggest an urgent need for improving flood risk management, enhancing water storage infrastructure, and establishing early warning systems to address surplus runoff. By contrast, during the late-century period (2071–2100), the upward trend in streamflow persists but at a slightly reduced rate, reaching 16.78% and 15.86% under RCP4.5 and RCP8.5 respectively. This attenuation is likely due to reduced snow accumulation and altered precipitation trends. These projections underscore the need for long-term strategies, including efficient water resource planning, climate adaptive agricultural techniques, and sustained water use practices to ensure agricultural productivity and mitigate drought conditions. The dynamic nature of hydrological shifts calls for further research on the long-term consequences of glacier recession, altered snowmelt patterns, and extended dry periods to better inform adaptive water security planning in the region.

Author Contributions: Conceptualization, methodology, validation A.K.; data visualization, formal Analysis Gul., Z.K., H.A.; writing original draft, Gul. and M.L.; writing—review and editing M.L., H.A. and Z.K; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CRB	Chitral river basin
RCM	Regional climate model
DEM	Digital elevation model
SWAT	Soil and Water Assessment Tool

References

[1]. Shah, M. I., Khan, A., Akbar, T. A., Hassan, Q. K., Khan, A. J., & Dewan, A. (2020). Predicting hydrologic responses to climate changes in highly glacierized and mountainous region Upper Indus Basin. Royal Society open science, 7(8), 191957.

[2]. Duran-Encalada, J. A., Paucar-Caceres, A., Bandala, E. R., & Wright, G. H. (2017). The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region. European Journal of Operational Research, 256(2), 567-581.

[3]. Rosenzweig C, Casassa G, Karoly DJ, Imeson A, Liu C, Menzel A, Parry ML. 2007 Assessment of observed changes and responses in natural and managed systems. In Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth Assessment report of the intergovernmental panel on climate change, pp. 79–131.

[4]. IPCC. 2007 Climate change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change (eds RK Pachauri, A Reisinger). Geneva, Switzerland: IPCC.

[5]. Verweij W, Van der Wiele J, Van Moorselaar I, Van der Grinten E. 2010 Impact of climate change on water quality in the Netherlands. RIVM rapport 607800007.

[6]. IPCC Sixth Assessment report: 20 March 2023.

[7]. Khalid, S., Qasim, M., & Farhan, D. (2013). Hydro-meteorological characteristics of Indus River Basin at extreme north of Pakistan. J Earth Sci Clim Change, 5(1).

[8]. Gupta, S. K. (2011). Modern hydrology and sustainable water development. John Wiley & Sons.

[9]. Hewitt, K., & Young, G. J. (1993). The Snow and Ice Hydrology Project: a Pakistan- Canada research and training programme. IAHS Publications-Publications of the International Association of Hydrological Sciences, 218, 49-58.

[10]. Soncini, A., Bocchiola, D., Confortola, G., Bianchi, A., Rosso, R., Mayer, C., ... & Diolaiuti, G. (2015). Future hydrological regimes in the upper indus basin: A case study from a high-altitude glacierized catchment. Journal of Hydrometeorology, 16(1), 306- 326.

[11]. Smiatek, G., Kunstmann, H., & Heckl, A. (2014). High-resolution climate change impact analysis on expected future water availability in the Upper Jordan catchment and the Middle East. Journal of Hydrometeorology, 15(4), 1517-1531.

[12]. Zhang, A., Liu, W., Yin, Z., Fu, G., & Zheng, C. (2016). How will climate change affect the water availability in the Heihe River Basin, Northwest China?. Journal of Hydrometeorology, 17(5), 1517-1542.

[13]. Khan, A. J., Koch, M., & Tahir, A. A. (2020). Impacts of climate change on the water availability, seasonality and extremes in the Upper Indus Basin.

[14]. Hasson, S., Saeed, F., Böhner, J., & Schleussner, C. F. (2019). Water availability in Pakistan from Hindukush–Karakoram–Himalayan watersheds at 1.5 C and 2 C Paris Agreement targets. Advances in Water Resources, 131, 103365.

[15]. Azim, F., Shakir, A. S., & Kanwal, A. (2016). Impact of climate change on sediment yield for Naran watershed, Pakistan. International Journal of Sediment Research, 31(3), 212-219.

[16]. Ali, S., Li, D., Congbin, F., & Khan, F. (2015). Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. Environmental Research Letters, 10(1), 014007.

[17]. Dierauer, J. R., Allen, D. M., & Whitfield, P. H. (2018). Exploring future water demand and climate change impacts on water availability in the peace region of British columbia, Canada. In The Water-Energy-Food Nexus (pp. 45-54). Springer, Singapore.

[18]. Qamar Uz Zaman Chaudhry, Climate Change Profile of Pakistan, 2017.

[19]. Ahmad S, Israr M, Liu S, Hayat H, Gul J, Wajid S, Ashraf M, Baig SU, Tahir AA. 2018. Spatio-temporal trends in snow extent and their linkage to hydro-climatological and topographical factors in the Chitral River Basin (Hindukush, Pakistan). Geocarto Int. 1–24. DOI: 10.1080/10106049.2018.1524517.

[20]. Peters, G. P., Davis, S. J., & Andrew, R. (2012). A synthesis of carbon in international trade. Biogeosciences, 9(8), 3247-3276.

[21]. PRINCE, L. (2013). Impact of climate change in Krishna western delta using swat hydrological model (Doctoral dissertation, ACHARYA NG RANGA AGRICULTURAL UNIVERSITY, GUNTUR).

[22]. Khan, A. J., & Koch, M. (2018). Selecting and downscaling a set of climate models for projecting climatic change for impact assessment in the Upper Indus Basin (UIB). Climate, 6(4), 89.

[23]. Neitsch SL, Arnold JG, Kiniry JR, Williams JR. 2011 Soil and water assessment tool: theoretical documentation—version 2009. Texas Water Resources Institute Technical Report No. 406. 17 Agricultural Research Service (USDA) & Texas Agricultural Experiment Station, Texas A&M University, Temple.

[24]. Marcinkowski P, Piniewski M, Kardel I, Szcześniak M, Benestad R, Srinivasan R, Okruszko T. 2017 Effect of climate change on hydrology, sediment and nutrient losses in two lowland catchments in Poland. Water 9 156. (doi:10.3390/w9030156).

[25]. Jha MK. 2004 Hydrologic modeling and climate change study in the Upper Mississippi River Basin using SWAT. Retrospective theses and dissertations, 951. Iowa State University Digital Repository. (https://lib.dr.iastate.edu/rtd/951).

[26]. Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development 1. JAWRA Journal of the American Water Resources Association, 34(1), 73-89.

[27]. Kendall, M., Gibbons, J., 1990. Correlation methods. Oxford: Oxford University Press.

[28]. Pirnia, A., Darabi, H., Choubin, B., Omidvar, E., Onyutha, C., Haghighi, A.T. (2019). Contribution of climatic variability and human activities to stream flow changes in the Haraz River basin, northern Iran. Journal of Hydro-environment Research, 25, 12-24.

[29]. Ali, S., Li, D., Congbin, F., & Khan, F. (2015). Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. Environmental Research Letters, 10(1), 014007.

[30]. Abbaspour Kc, Yang J, Maximov l, Siber R,Bogner K, Mieleitner, Srinivasan R. 2007Modelling hydrology and water quality in thepre-alpine/alpine Thur watershed using SWAT.J. Hydrol.333,413-430.(doi:10.1016/j.jhydrol.2006.09.014).

[31]. Abbaspour KC. 2013 SWAT-CUP 2012.SWATcalibration and uncertainty program-a usermanual.

[32]. The RCM Fallacy: Why Regional Models are Not a Definitive Source ... (2023). https://www.jupiterintel.com/blog/the-rcm-fallacy-why-regional-models-are-not-a-definitive-source-for-climate-impact-projection.

[33]. What is bias correction? - Copernicus Climate Change. (n.d.). https://climate.copernicus.eu/sites/default/files/2021-01/infosheet7.pdf.

[34]. Soriano, E.; Mediero, L.; Garijo, C. Selection of Bias Correction Methods to Assess the Impact of Climate Change on Flood Frequency Curves. Water 2019, 11, 2266. https://doi.org/10.3390/w11112266.

[35]. Anjum MN, Ding Y, Shangguan D.2019Simulation of the projected climate changeimpacts on the river fow regimes under CMlP5RCP scenarios in the westerlies dominated belt,northern Pakistan.Atmos. Res. 227,233-248.(doi:10.1016/j.atmosres.2019.05.017).

[36]. Shrestha M, Koike T, Hirabayashi Y, Xue Y, WangL, Rasul G, Ahmad B. 2015 Integratedsimulation of snow and glacier melt in waterand energy balance-based, distributedhydrological modeling framework at HunzaRiver Basin of Pakistan Karakoram region.J. Geophys. Res. Atmos. 120,4889-4919(doi:10.1002/2014JD022666).

[37]. Tahir AA, Chevallier P, Amaud Y, Neppel L,Ahmad B. 2011 Modeling snowmelt-runoffunder climate scenarios in the Hunza Riverbasin, Karakoram Range, Northern Pakistan.J. Hydrol. 409,104-117.(doi:10.1016/j.jhydrol.2011.08.035).