Journal of Himalayan Earth Sciences Volume 58, Number 2, 2025 pp. 129-146

Climate Inclusive Flood Inundation Modeling Using HEC-RAS: A Case Study of Panjkora River, Khyber Pakhtunkhwa, Pakistan

Hafsa Wadood[1*], Mujahid Khan[1], Shehla Nawaz[1], and Salman Khan[2]

[1] Civil Engineering Department, University of Engineering and Technology, Peshawar, Pakistan

[2] Creative Consulting Engineers, Peshawar, Pakistan

**Corresponding Author: hafsa.civ@uetpeshawar.edu.pk,*

Submitted Date: 02/05/2025 Acceptance Date: 12/09/2025 Publication Date: 30/11/2025

Abstract

Floods are among the most devastating climate-induced hazards, with severe socio-economic consequences, particularly in underdeveloped countries. Pakistan is highly vulnerable to climate change and has experienced several catastrophic flood events in recent decades. This study assesses future flood risks in the Panjkora River Basin, one of the major catchments in Khyber Pakhtunkhwa province, using hydrological and hydraulic modeling under different climate change scenarios. The Soil and Water Assessment Tool (SWAT) was employed to simulate hydrological processes using a 29-year weather dataset (1981–2010). Model calibration (1981–2002) and validation (2003–2010) demonstrated strong performance, with coefficient of determination (R^2) values of 0.731 and 0.721 and Nash–Sutcliffe efficiency (NSE) values of 0.72 and 0.71, respectively. Future projections were analyzed under Shared Socioeconomic Pathways (SSP 2–4.5, moderate emissions, and SSP 5–8.5, high emissions) for three periods: near future (2026–2050), mid-century (2051–2075), and late century (2076–2099). Flood inundation mapping was conducted using the Hydrologic Engineering Centre's River Analysis System (HEC-RAS). The results reveal a significant increase in flood inundation, particularly under SSP 5–8.5. Discharge is projected to increase by approximately 25% under SSP 2–4.5 and 27% under SSP 5–8.5 compared to the historical baseline. These findings underscore the increasing flood risks in the Panjkora River Basin under future climate change scenarios and highlight the need for adaptive water resource management and disaster risk reduction strategies in the region.

Key words**:** ARC-GIS; ArcGIS Soil and Water Assessment Tool (ArcSWAT); Shared Socioeconomic Pathway 2–4.5 (SSP2–4.5, medium stabilization scenario); Shared Socioeconomic Pathway 5–8.5 (SSP5–8.5, high-emission scenario); Soil and Water Assessment Tool–Calibration and Uncertainty Procedures (SWAT-CUP); Hydrologic Engineering Centre's River Analysis System (HEC-RAS).

1. Introduction

Comprehensive flood risk assessment and modelling have become quite important considering the global climate change phenomenon and its devastating impact on the socio-economic condition of underdeveloped countries. The Panjkora River Basin, located in the Khyber Pakhtunkhwa province of Pakistan, encompasses a large catchment area, steep hillsides, and rich forests. The river is a main watercourse covering the full basin and is highly vulnerable to floods brought on by glacier melting and monsoons. Apart from ensuring the preservation of the natural equilibrium, it offers the required water sources for farming and consumption. The hazard of floods in the study area is high due to the complex topography and extensive catchment area. During the monsoon season, the intensity of rainfall is very high, which results in excessive runoff. Resultantly, the risk of flooding increases in the study area. Considering the risk and vulnerability of agricultural land, infrastructure, and communities, flood risk assessment and management strategies are needed of the day (Garee et al., 2017; Ougahi et al., 2022).

Effective flood management strategies depend on one being fully knowledgeable of the hydrological dynamics of the Panjkora River Basin. However, hydrological modelling is complicated by the local weather consisting of numerous rainy and dry seasons with varying patterns. A complex ecosystem produced by the combination of terrain, land use, different types of soil, and meteorological variables requires to exact forecast and effective mitigation of flood dangers. This surrounds the demand for careful and in-depth research, as climate change is expected to cause frequent and severe flooding (Milly et al., 2008; Callaghan and Hughes, 2022) due to the changes in the hydrological patterns of the area. Bahadar et al. (2015) suggested that in the forecasting of future floods and their spatial inundation in the nearby floodplains, the incorporation of GIS, RS, and HEC-RAS plays an important role.

General Circulation Models (GCMs) under the Shared Socioeconomic Pathways (SSP 2-4.5 and SSP 5-8.5) are powerful tools to forecast the future climatic changes in a study Basin. SSP2-4.5 is a moderate scenario including some climate mitigating measures, while SSP5-8.5 is a high-emission, severe effect scenario (Field et al., 2012). These scenarios assist in producing accurate flood risk maps by enabling a thorough study of likely future flood events and facilitating in production of flood hazard maps. The Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012) model can mimic the effects of land use, climate change, and water management strategies on river basins during hydrological modelling (Neitsch et al., 2011; Arnold et al., 2012; Gassman et al., 2007). Neitsch et al. (2011) claim that the SWAT model was able to provide vital streamflow data that can be used in concert with the River Analysis System (HEC-RAS) (HEC, 2016) developed by the Hydrologic Engineering Center for constructing hydraulic models. Knowledge about the river geometry and flow data is two important parameters needed for HEC-RAS in developing a hydraulic model (Khan et al., 2020). Horritt and Bates (2002), Bates et al. (2010), and Brunner (2016) concurred in their research that HEC-RAS is essential for simulating water flow and producing floodplain maps. Khan et al. (2019) studied that the flood inundation maps developed by HEC-RAS help the line agencies in interventions and guide the local people to be prepared physically and mentally (Khan et al., 2019). The study conducted by Teng et al. (2017) and Moftakhari et al. (2017) observed that HEC-RAS successfully created flood inundation maps based on past data and predicted the future inundation under future climatic conditions. These maps offer an insightful analysis of how climate change will affect flood dangers in the Panjkora River Basin and the degree of flooding for different return periods. By means of the integration of SWAT and HEC-RAS, one may obtain a whole picture of the manner in which variations in land use, temperature, and precipitation could affect the behavior of floods in the region (Papaioannou et al., 2015; Budhathoki et al., 2021). Furthermore, a study of flood frequency lets one ascertain the probability of different flood magnitudes occurring during specific return times (Cunderlik and Burn, 2002; Kundzewicz et al., 2014). Similarly, Merz et al. (2007) and Di Baldassarre et al. (2010) created flood hazard maps using the flood frequency data and illustrated areas of the basin most likely to flood using HEC-RAS. Flood hazard maps, especially those incorporating climate change, are extremely helpful instruments for flood risk management and mitigation, as reported by Milly et al. (2008) and Field et al. (2012). These maps aim to provide exact visual representations of the flood extents under the SSP 2-4.5 and SSP 5-8.5 models. Resultantly, planners and legislators can spot important sites needing intervention (Van Alphan et al., 2009; Ward et al., 2011) and provide a forward-looking strategy in flood risk management (Ward et al., 2011; Jongman et al., 2014). This highlights the need for including estimates of climate change into assessments of the influence of characteristics of the surroundings, such as soil condition, forest-covered area, and precipitation values (Hirabayashi et al., 2008, 2013).

The current research work focuses on understanding the dynamics of future flood events of the Panjkora river basin using advanced hydrologic and hydraulic modelling methods. The study integrates these advanced modelling techniques to develop comprehensive flood risk assessments under the current climatic conditions and their future projections using SWAT and HEC-RAS. Lastly, the analysis of the SWAT and HEC-RAS models was coupled with GCM forecasts under the SSP 2-4.5 and SSP 5-8.5 for assessing the flood risk in the Panjkora River Basin using flood inundation maps. The quantification of flood risk is crucial for comprehending the spatial distribution of flood hazards to undertake necessary steps for safeguarding the infrastructure and livelihoods of the people living in the vicinity of the basin.

2. Study Area

The Panjkora River Basin (Latitude: 34.76, Longitude: 71.79) is situated in the province of Khyber Pakhtunkhwa, Pakistan. It is hydrologically significant as defined by its unique environmental and topographical aspects. The basin defines itself with its steep slopes and strong topography; its heights range from the lowest plains to the highest altitudes of the Hindukush mountains (Ullah and Zhang, 2020). The highest mountain of the Hindu Kush is situated in this basin. It is covered by extensive forests with a wide spectrum of plant life, apart from the other remarkable topographical characteristics of the basin. This study intends to present an analysis by means of contemporary modelling techniques to improve knowledge of the hydrological behavior of the basin and provide suitable information for guiding flood management methods. The baseline for the research is created by means of meteorological data acquired from the Dir Station (Latitude: 35.20, Longitude: 71.85). It is situated inside the Panjkora River Basin and operates under the care of the Pakistan Meteorological Department. The meteorological data comprised daily temperature values and precipitation statistics for thirty years spanning from 1981 to 2010.

3. Methodology

This study intends to encompass a multi-step procedure for comprehensively assessing and controlling the flood risks in the Panjkora River Basin, as it is prone to recurrent floods due to its complex hydrological behavior and topography. The framework around which the research is carried out is the mix of several datasets incorporating topography information, land use and land cover data, data of soil characteristics, and climate data. Arc-GIS and Arc-SWAT tools allowed a reliable hydrological model for the Panjkora River Basin. The model is then rigorously calibrated and validated to guarantee its correctness and effectiveness. The model was modified to incorporate climate projections to evaluate the possibility of future modifications in the vulnerability to floods. Two different hypothetical climate scenarios were SSP 2-4.5: a moderate climate scenario and SSP 5-8.5: a high-emissions scenario encompassing greenhouse gas emissions and the likely influence of such emissions on the pattern of temperature and precipitation (Roy et al., 2021). Future estimates (2026–2099) could be compared against the historical climate data covering the years 1981–2010. The study sought to estimate how the probable future scenarios might affect the growth of flooding risks by means of simulating the response of the river basin to climate change.

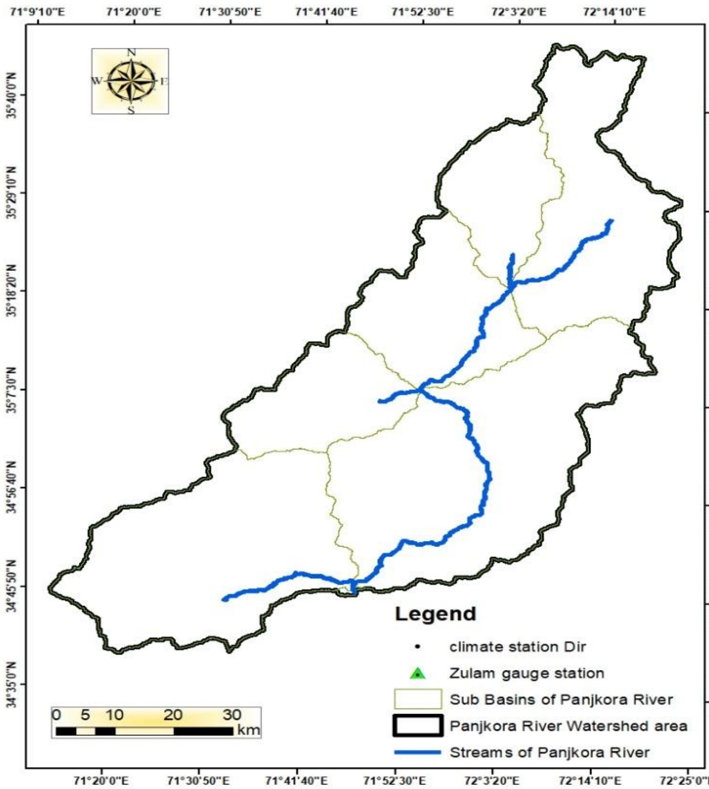


Fig. 1. Panjkora River catchment area (coordinates of Zulam gauge station, Lat: 34.76, Long: 71.79, climate station coordinates, Dir Climate Station Lat: 35.20; Long:71.85).

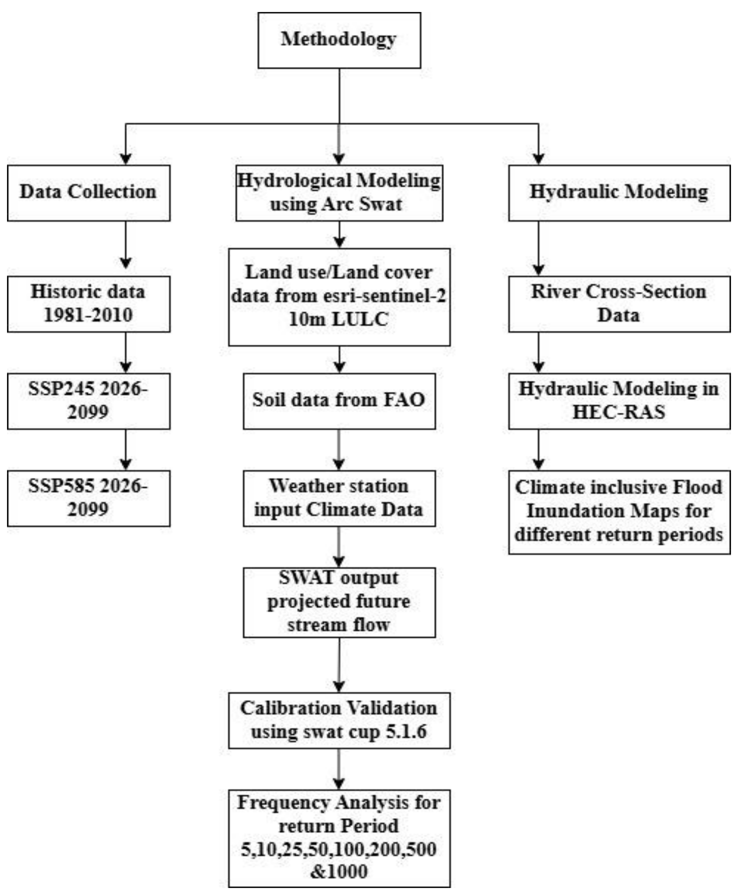


Fig. 2. Detailed Methodology steps of this study.

The Hydrology Division, Irrigation Department, Government of Khyber Pakhtunkhwa, Pakistan, is continuously compiling flow data from the gauge station installed on the Zulm bridge (latitude: 34.77, longitude: 71.79) situated on the Panjkora River. The flow data starting in 1981 and lasting through 2022 were utilized in the current study. This extensive dataset allows one to fully understand the hydrological aspects of the river using Arc-SWAT under various historical situations, which can be noticed in Figure 3.

A digital elevation model (DEM) of the study area was obtained from the United States Geological Survey (USGS), shown in Figure 5a, since it is one of the preliminary requirements for hydrological modeling to clearly define the watershed area. Important information, such as the drainage patterns, stream networks, as well as the exact watershed boundary determination, was acquired from the DEM, shown in Figure 5(a). The Hydrological Response Units (HRUs) lying within the selected watershed were analyzed, as they influence the runoff and streamflow values.

Figure 4b presents the data of land taken from the Land Sentinel-2 imagery provided by ESRI. The Food and Agriculture Organization (FAO) provided soil classification data, such as its texture, structure, and permeability, depicted in Figure 4c. These factors help in understanding the infiltration, runoff generation, and water retention capability of the soil. Furthermore, the SWAT model ran a baseline scenario using historic climate data ranging from 1981 to 2010. The precipitation data have been shown in Figure 5, while the important meteorological characteristics, including the greatest and lowest temperature values, have been shown in Figure 6. The model was also run for weather data of SSP 5-8.5 and SSP 2-4.5 covering the years 2026 to 2099.

This was done to provide approximations of the future climate prediction. The SWAT simulations help one to grasp how streamflow and flood dangers of future warming scenarios vary in the basin (Gebrechorkos et al., 2020), including predicted fluctuations in temperature and precipitation into the model. Similarly, weather data corresponding to the SSP 2-4.5 and SSP 5-8.5 pathways were used (precipitation and temperature) covering the period from 2026 to 2099 for future climate scenarios. These scenarios provided projections of future climatic conditions, allowing for the generation of future flow outputs.

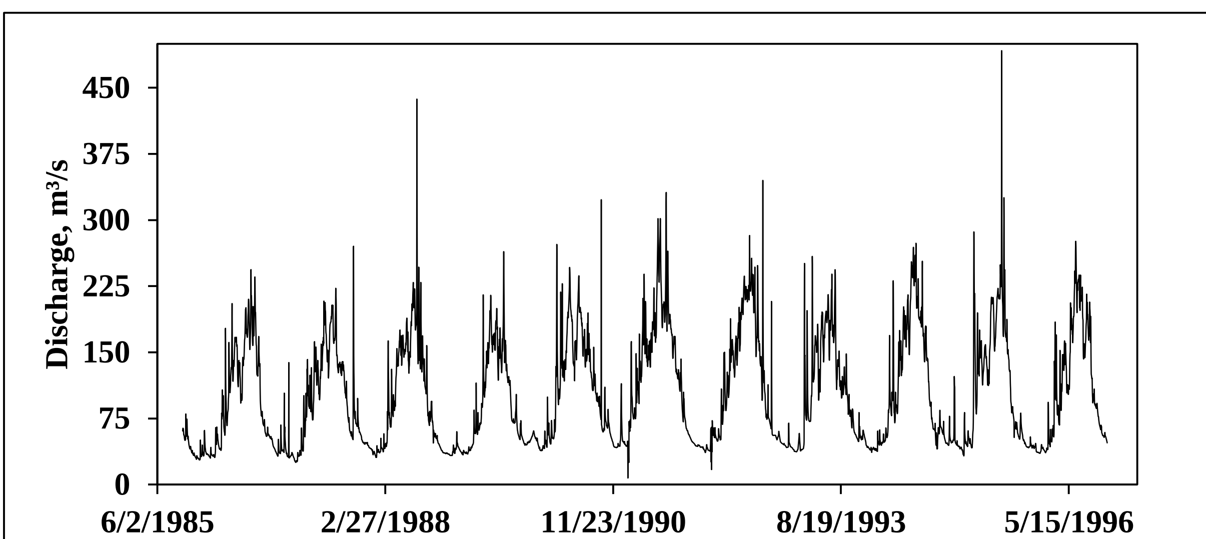
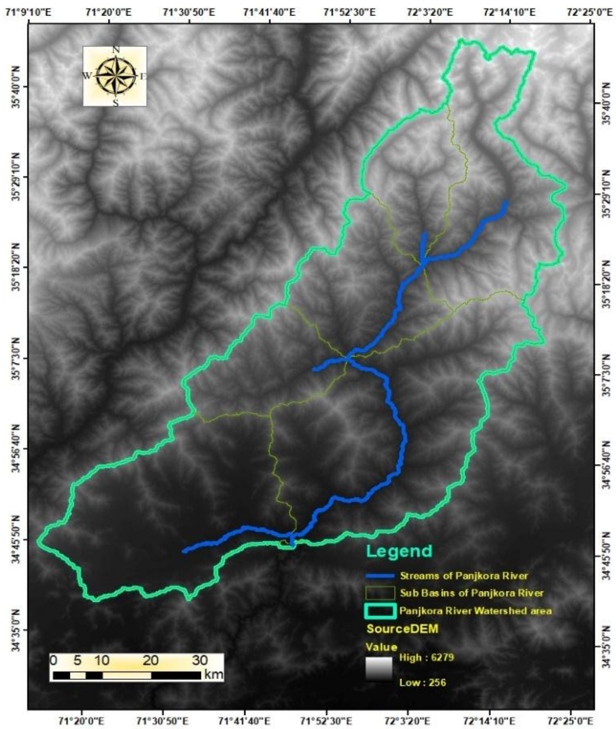
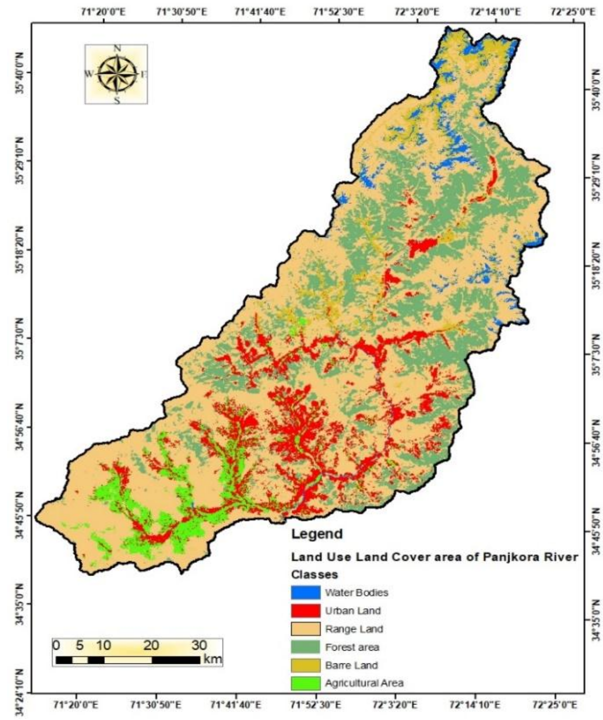


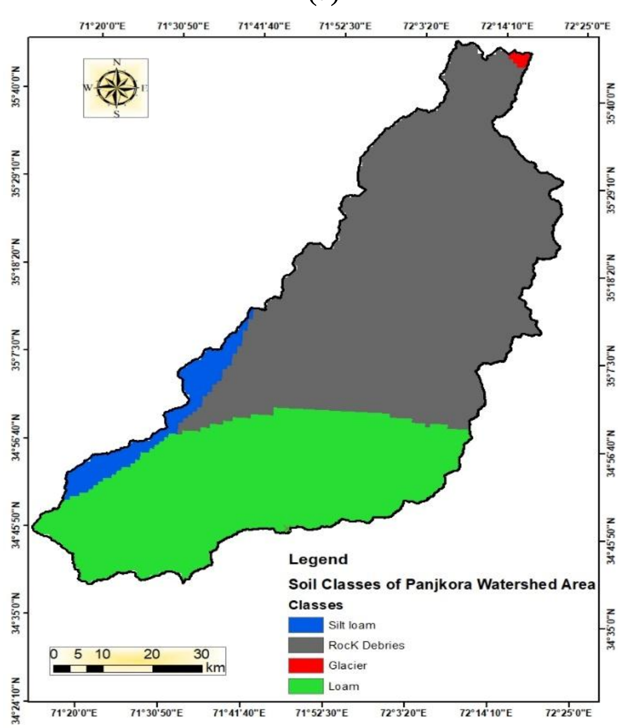
Fig. 3. Panjkora River flow data at Zulam gauge station.



(a)



(b)



(c)

Fig. 4. Panjkora River characteristics: **a)** Results of watershed (Panjkora River) delineation, **b)** land use and land type (the legend on the map describes different types of land in the study area, which is further clarified by colors, and **c)** soil classification as per FAO.

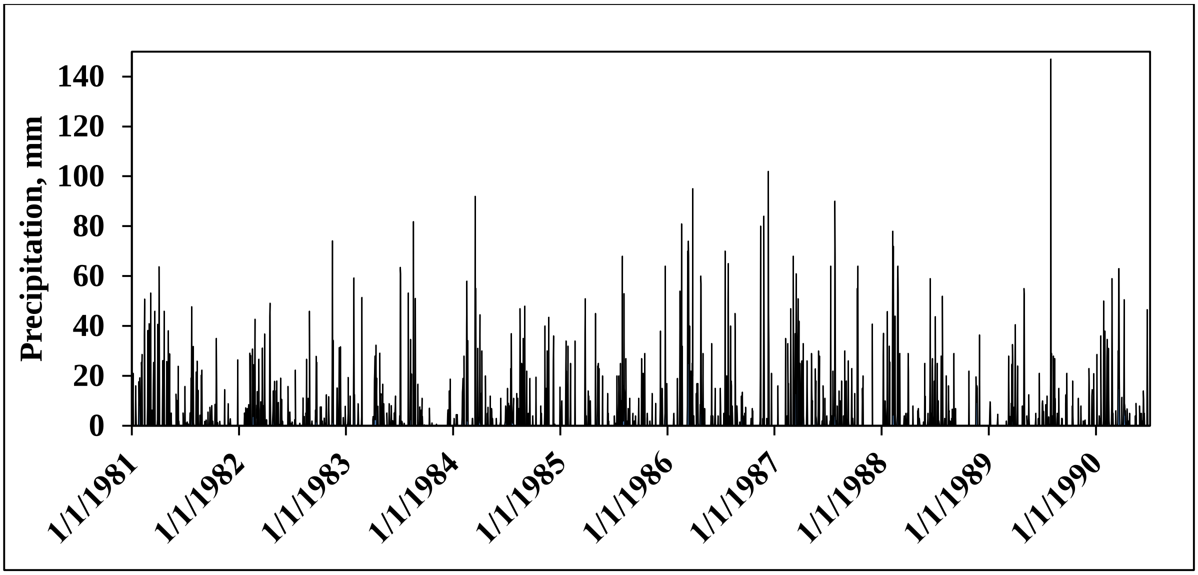


Fig. 5. Precipitation values from 1981 to 2010 at the Dir Meteorological station.

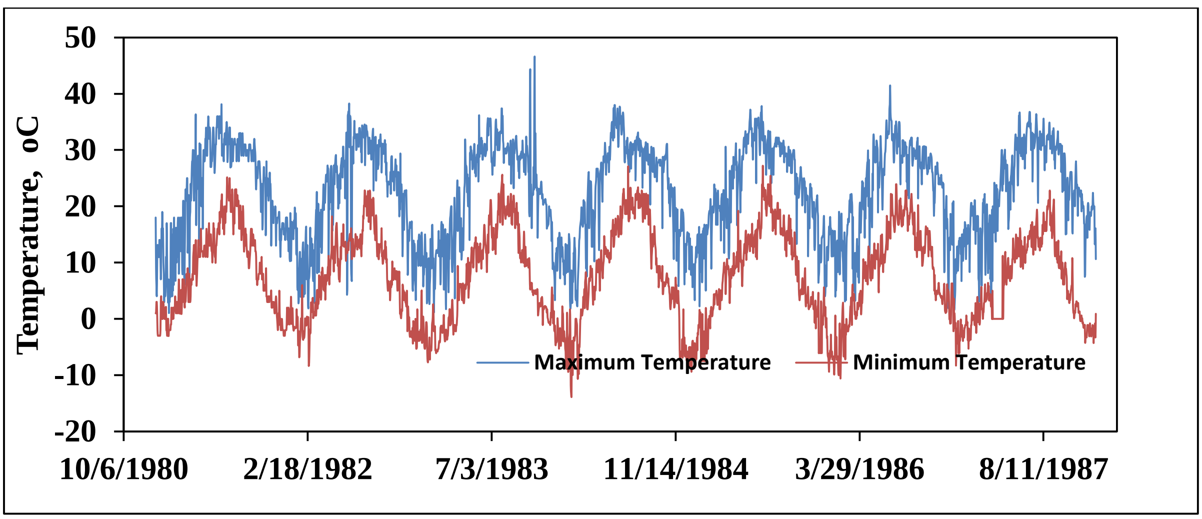


Fig. 6. PMD minimum and maximum temperature data.

The initial SWAT outputs were developed for the historical base period (1981-2010), providing a comprehensive baseline of the basin's hydrological behavior. These outputs included daily, monthly, and annual streamflow data, which are crucial for understanding historical water flow patterns and calibrating the model. For future projections, the SWAT model was used to simulate streamflow under two climate scenarios: SSP 2-4.5 and SSP 5-85. The resulting projected streamflow data from SWAT analysis provided insights into how different climate change pathways might affect water availability, peak flows, and flood risks in the basin. SWAT Calibration and Uncertainty Procedures (SWAT-CUP) is used for calibration and validation to ensure the accuracy and reliability of the hydrological model (Roy et al., 2021; Gebrechorkos et al., 2020). A total of 26 parameters were used for calibration, which indicates significant components affecting the hydrological dynamics of the basin (Table 1). To get the most effective match between simulated and observed data, these parameters helped. The parameters are redefined throughout the calibration to ensure the effectiveness and correctness of the model.

The Gumbel distribution method was employed to conduct flood frequency analysis for the Panjkora river basin. This statistical method is widely used for extreme value analysis, particularly for modelling the distribution of maximum or minimum values such as annual flood peaks (Bhagat, 2017). The Gumbel distribution was applied to both historical and future scenarios to estimate the magnitude of flood events for different return periods. The expected flood magnitudes were calculated for a range of return periods to understand the potential risks associated with different levels of flooding. The return periods considered in the analysis were 5, 10, 25, 50, 100, 200, 500, and 1000 years. This comprehensive analysis provided valuable insights into the flood risks under current and future climatic conditions. HEC-RAS was used for hydraulic modelling of the Panjkora River. The projection file and DEM (Digital Elevation Model) were used as primary data input for setting up the model.

The geometric definition of the river was performed by delineating the river centerline and banks within the HEC-RAS environment. Cross-sections are critical for capturing the variations in the river channel's shape and size, which affect the flow characteristics. Flow paths were also defined to represent the flow directions and extents within the river system.

Steady flow data were integrated into the model using expected flow values corresponding to different return periods. These flow values were derived from both historical data and future scenarios (SSP 2-4.5 and SSP 5-8.5). The return periods considered included 5, 10, 25, 50, 100, 200, 500, and 1000 years, providing a comprehensive range of flood inundations in the study area.

4. Results and Discussion

In the results section, important findings from the model simulations, paying particular attention to the frequency and magnitude of floods that are affected by the alternative climate scenarios, will be discussed.

4.1. Calibration and Validation of the Hydrological Model

To ensure the effectiveness and correctness of the model, the model was calibrated and validated (Wei et al., 2002). Parameters in Table 1 were used to calibrate the model. For the data set 1992-2002 R^2 value is 0.73, and the Nash-Sutcliffe efficiency (NS) value is 0.72. These values show that there is good reliability between observed and simulated data, as shown in Figure 7.

Figure 8 shows that the validation results give $R^2 = 0.72$ and NS value = 0.71 for the dataset spanning from 2001 to 2010. The satisfactory values of the above statistics prove that the model can successfully simulate the hydrological modelling of the Panjkora Basin.

To check the correctness of the model, some parameters presented in Table 1 are used, which makes the model reliable for the simulation of the hydrologic reaction of the Panjkora basin.

4.2. Projection of future stream flow

After the calibration and validation process, the model was then used to extract future stream flows for different climate scenarios, by further using ensembled data of five GCMs, viz.: MPI-ESM1-2-HR, ACCESS ESM1-5, GFDL-ESM4, NorESM-2-LM, and IPSL-CM6A-LR from Australia, USA, France, Germany, and Norway. The resolution of the models is 1.3°x1.90°, 1.3°x1.00°, 1.3°x2.5°, 0.90°x0.90° and 1.90°x2.50°. These models are of different environmental conditions, which are wet cold, dry cold, dry hot, wet, cold, and average. It is observed that flows under the climate scenario 5-8.5 were higher than climate scenario 2-8.5 which as shown in Figure 9 (a,b).

Table 1: Parameters used for the calibration and validation process (Neitsch et al., 2011; Gassman et al., 2007).

ID	PARAMETER	Range
1	Baseflow Alpha Factor (V__ALPHA_BF.gw)	0.011 - 0.51
2	Curve Number for Moisture Condition IIv (R__CN2.mgt)	35.01 – 98.01
3	Groundwater Delay Time (days) (V__GW_DELAY.gw)	30.01 - 451
4	Threshold Depth of Water in Shallow Aquifer for Flow (mm) (V__GWQMN.gw)	0 - 2501
5	R__SFTMP.bsn)	-10.1
6	Snow Melt Base Temperature (°C) (R__SMTMP.bsn)	-10.1
7	Snow Pack Temperature Lag Factor (R__TIMP.bsn)	0.011 – 1.01
8	Melt Factor for Snow on June 21 (mm/°C-day) (R__SMFMX.bsn)	02-Oct
9	Groundwater "revap" Coefficient (R__GW_REVAP.gw)	0.021 - 0.21
10	Melt Factor for Snow on December 21 (mm/°C-day) (R__SMFMN.bsn)	0.11 - 6
11	Minimum Snow Water Content for 100% Cover (mm) (R__SNOCOVMX.bsn)	0 - 501
12	Minimum Snow Water Content for 50% Cover (mm) (R__SNO50COV.bsn)	0 - 201
13	Threshold Depth of Water in the Shallow Aquifer for Return Flow (mm) (V__GWHT.gw)	0 - 1001
14	Deep Aquifer Percolation Fraction (R__RCHRG_DP.gw)	0 – 1.01
15	Soil Evaporation Compensation Factor (R__ESCO.hru)	0.011 – 1.01
16	Manning's "n" Value for Main Channel (R__CH_N2.rte)	0.011 - 0.31
17	Effective Hydraulic Conductivity in Main Channel (mm/hr) (R__CH_K2.rte)	0 - 151
18	Baseflow Alpha Factor for Bank Storage (R__ALPHA_BNK.rte)	0.011 - 0.51
19	Bulk Density (g/cm³) (R__SOL_BD(..).sol)	1.12 - 1.81
20	Available Water Capacity of the Soil Layer (mm H2O/mm soil) (R__SOL_AWC(..).sol)	0.11 - 0.42
21	Saturated Hydraulic Conductivity (mm/hr) (R__SOL_K(..).sol)	0.011- 101
22	Precipitation Lapse Rate (mm/km) (R__PLAPS.sub)	-201
23	Temperature Lapse Rate (°C/km) (R__TLAPS.sub)	-21
24	Threshold Depth of Water in Shallow Aquifer for "Revap" (mm) (R__REVAPMN.gw)	0 - 1001
25	Surface Runoff Lag Time (days) (V__SURLAG.bsn)	Jan-25
26	Plant Uptake Compensation Factor (R__EPCO.hru)	0.011 – 1.01

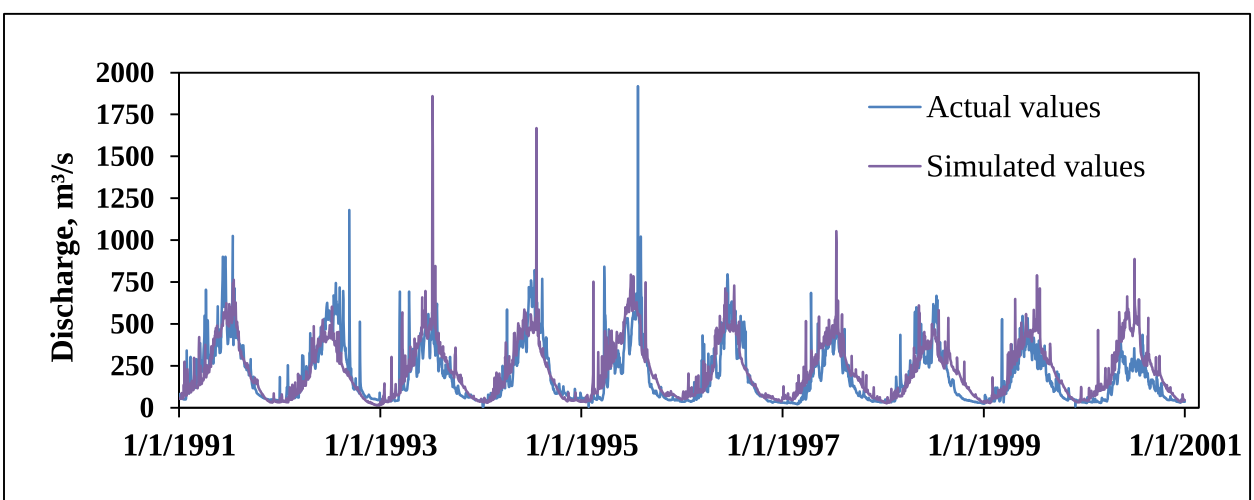


Fig. 7. Discharge value comparison in actual and simulated values for the Panjkora River.

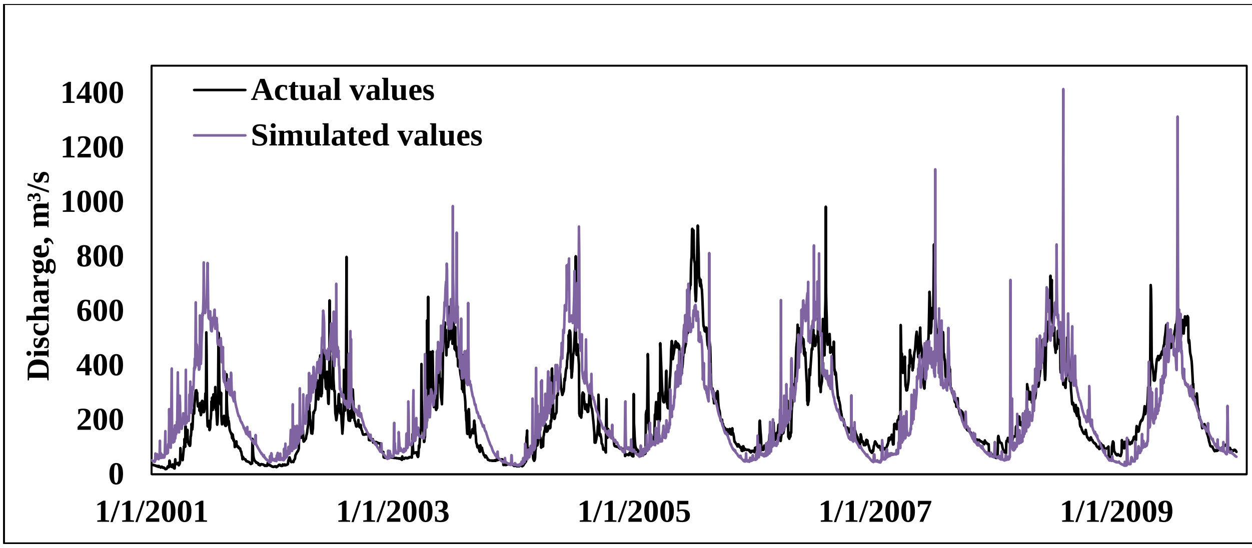


Fig. 8: Validation graph of Flow data, Panjkora River (2001-2010).

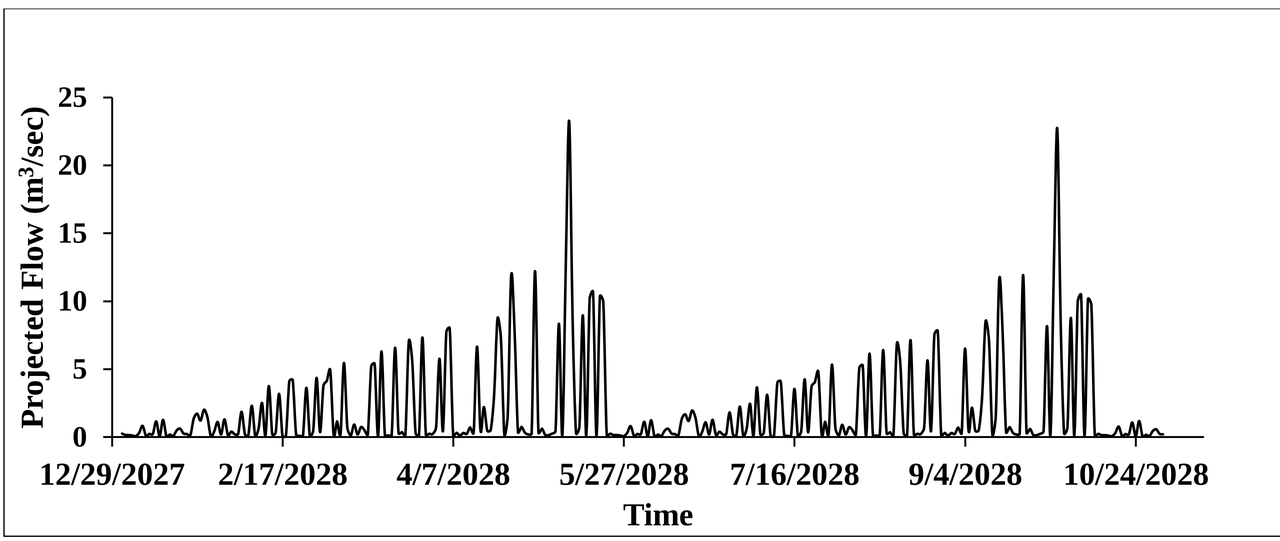


Fig. 9a. Projected flow data for SSP 2-4.5 climate scenario.

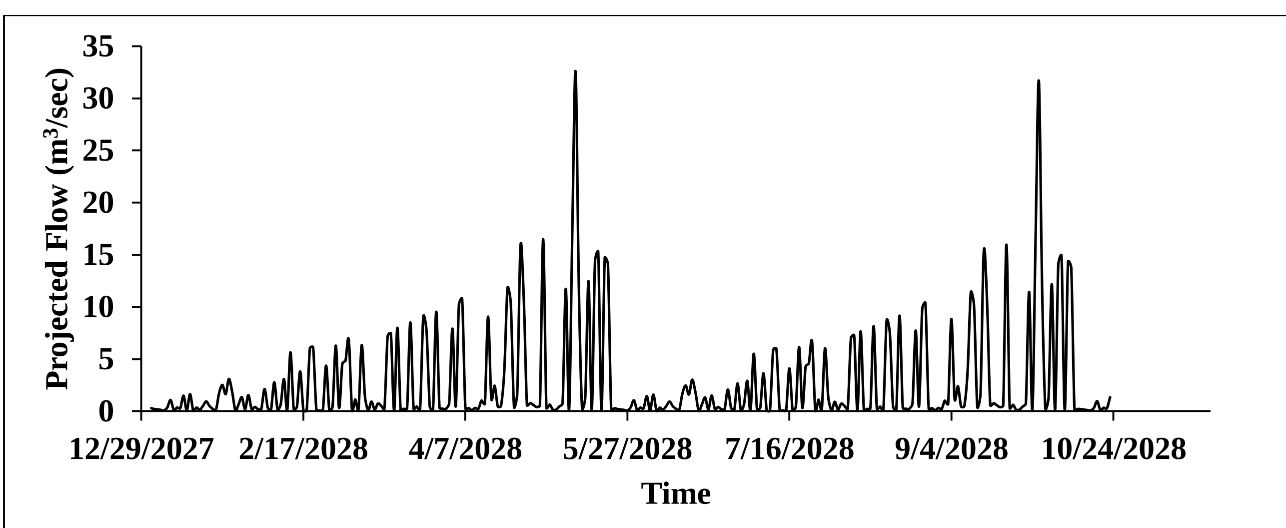


Fig. 9b. Projected flow data of SSP 5-8.5 climate scenario.

4.3. Flood Frequency Analysis

The Gumbel distribution was used for frequency analysis to investigate the floods of the Panjkora River Basin. The objective of this study was to forecast the intensity of flood events throughout the specified return periods (SSP 2-4.5 and SSP 5-8.5) under both historical and future climatic scenarios. The estimated flood magnitudes give the knowledge of the future flood risk under the different climate scenarios for return periods of 5, 10, 25, 50, 100, 200, 500, and 1000 years. Figure 10(a, b) presents the flood frequency analysis graphs, which show the link between return period and discharge for historical data (1982–2010) and future climate possibilities (bifurcated into near future 2026 - 2050, mid future 2051 – 2075 and far future 2076 - 2099) for climate change scenarios SSP 2-4.5 and SSP 5-8.5.

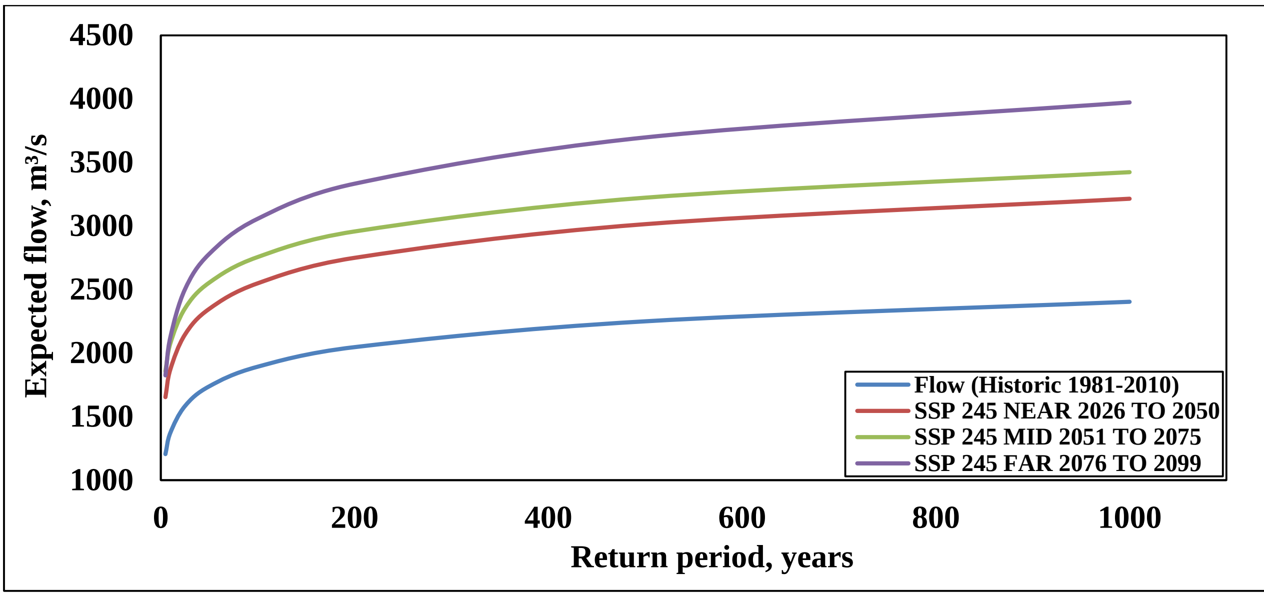


Fig. 10a. Flood frequency analysis graph for SSP 2-4.5.

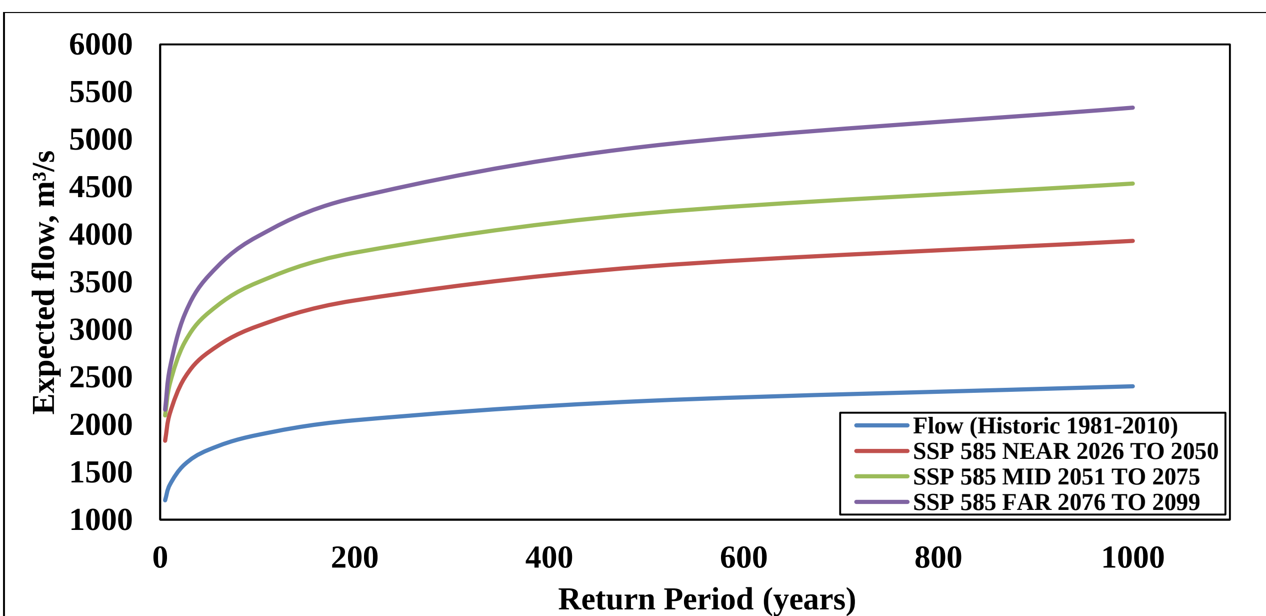


Fig. 10b. Flood frequency analysis graph for SSP 5-8.5.

Figure 11(a, b) show that the difference between historic data and the future climate scenarios is very high for all the time periods in the future climate scenarios. It is concluded from this analysis that there will be higher floods in the future in the study area. Considering the far future (2076 – 2099) for both climate scenarios, it can be noticed that there is a higher increase in flood flow, thereby requiring urgent attention towards flood control strategies to mitigate the floods. These results also emphasize the need for improved flood risk assessment and hazard zoning to protect the sensitive regions in the Panjkora River Basin.

4.4. Hydraulic Model Results

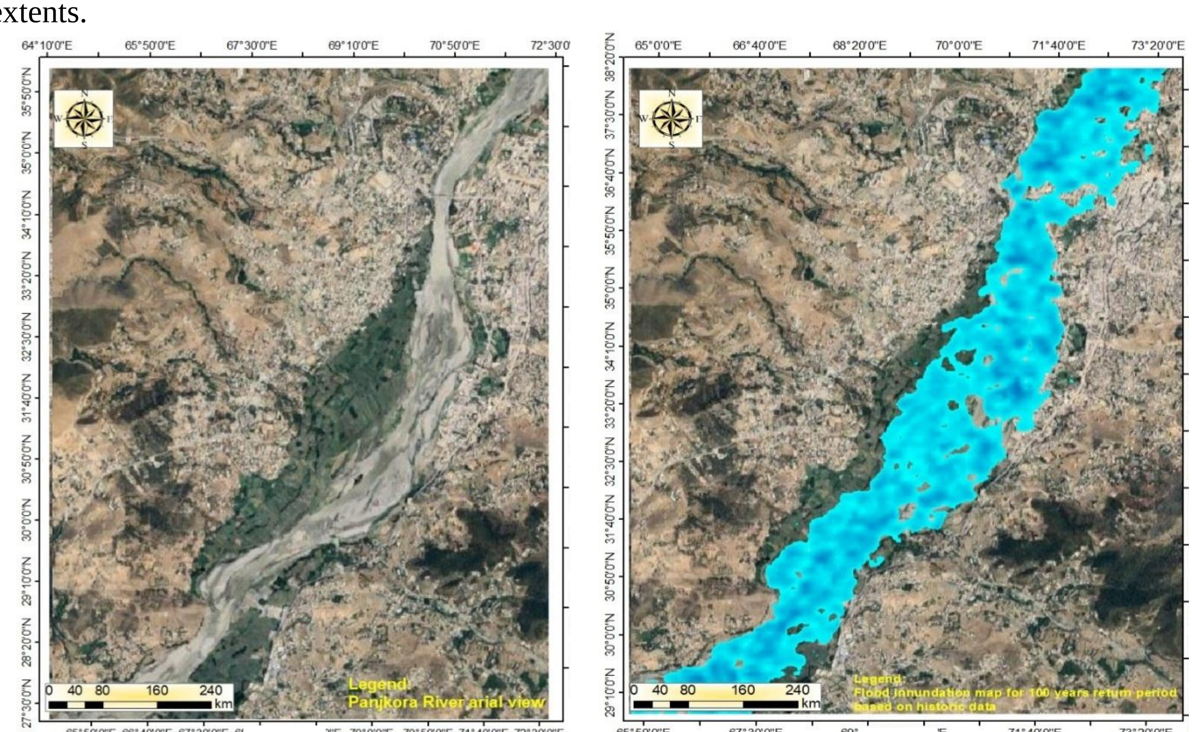
In Figure 12, the results of hydraulic modelling for the Panjkora River Basin are shown. The sensitivity of future floods for both climate scenarios is illustrated in the maps, along with the flood maps for the historical period. Based on the recorded data for the historic period ranging from 1982 to 2010, inundation maps were created, which provided a basic understanding of flood extents.

4.4.1 SSP 2-4.5 Flood Inundation Maps

The climate scenario SSP 2-4.5 (2026-2050 near, 2051-2075 mid, 2076-2099 far) shows a high rise in flood extents more in the far future than mid and near, as shown in Figure 12, in comparison to the historical period. So, the results show that under different climate conditions, the flood damages notably rise.

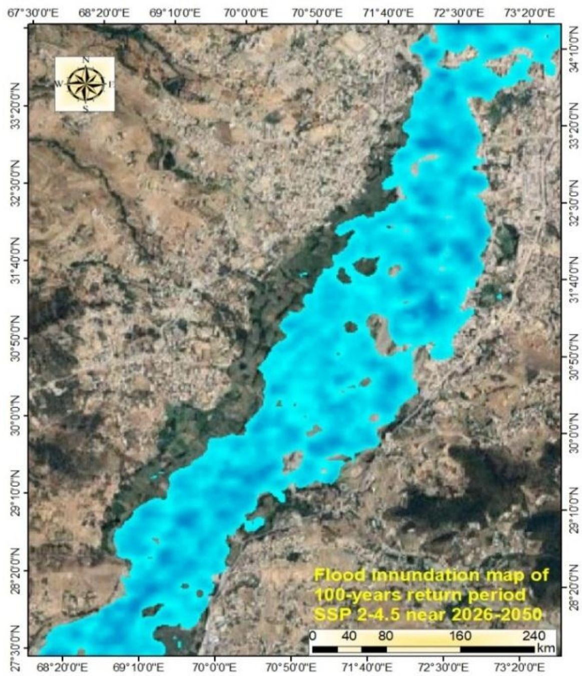
4.4.2 SSP 5-8.5 Flood Inundation Maps

The climate scenario SSP 5-8.5 (2026-2050, 2051-2075, 2076-2099) shows increased flood extents, especially in the far future 2076 to 2099 (Fig. 13c) in comparison to the historical period (Fig. 11) and climate scenario SSP 2-4.5 (Fig. 12). These results reiterate the fact that climate change will further worsen the magnitude and frequency of flooding with time.

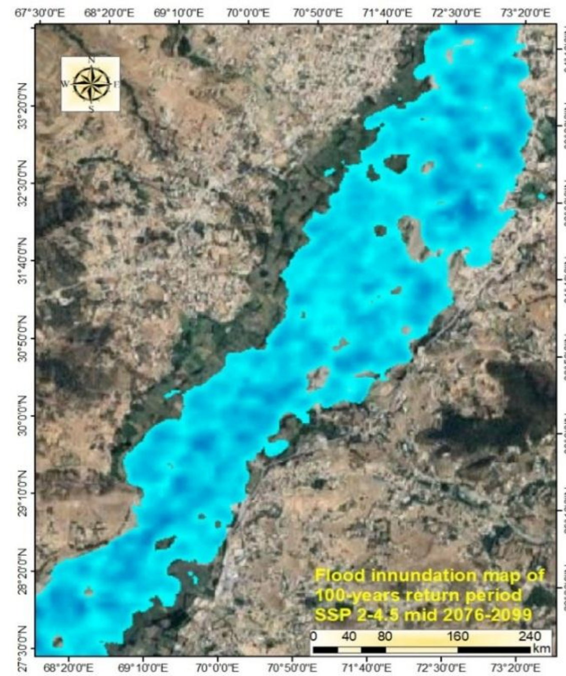


(a) (b)

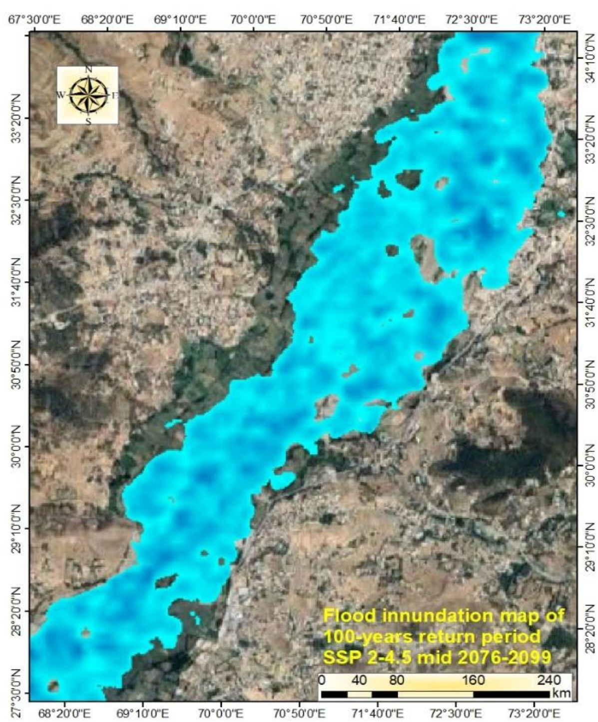
Fig. 11. Panjkora river flood inundation map based on historic data: a) Panjkora river aerial view, (b) flood inundation map of 100-year return period.



(a)



(b)

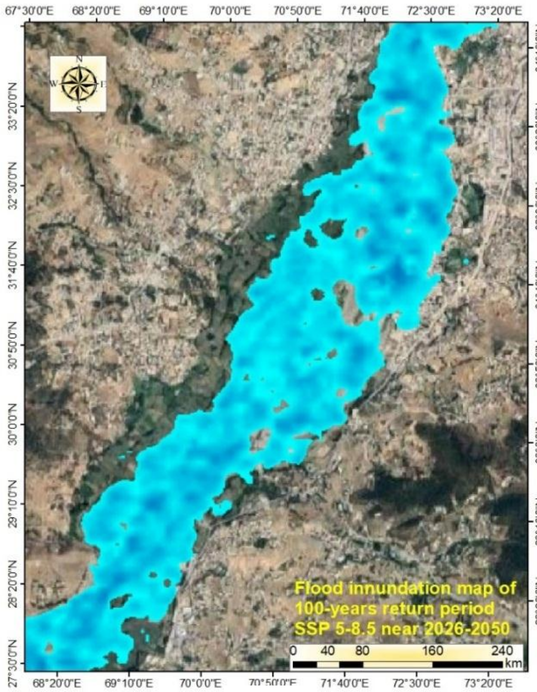


(c)

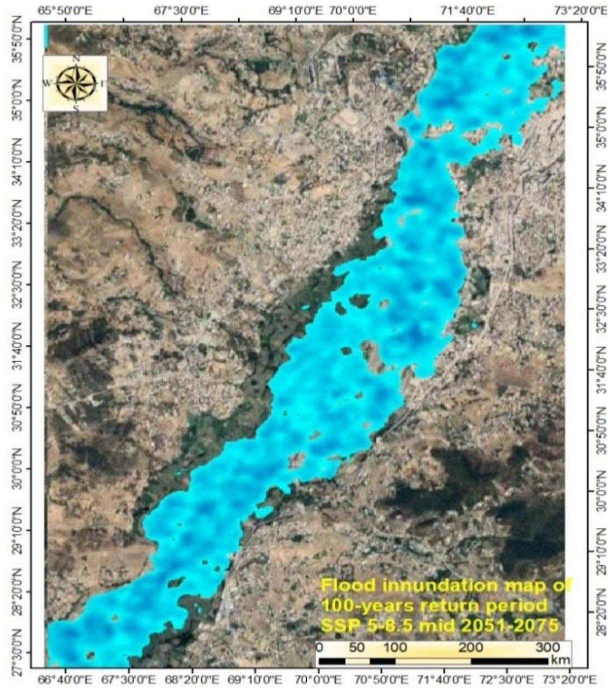
Fig 12. Flood inundation map of 100-year return period for SSP 2-4.5 (a) near 2026-2050, (b) mid future (2051-2075), and (c) far future 2076-2099).

Table 2: Comparison of flow depths under different climate conditions in various return periods.

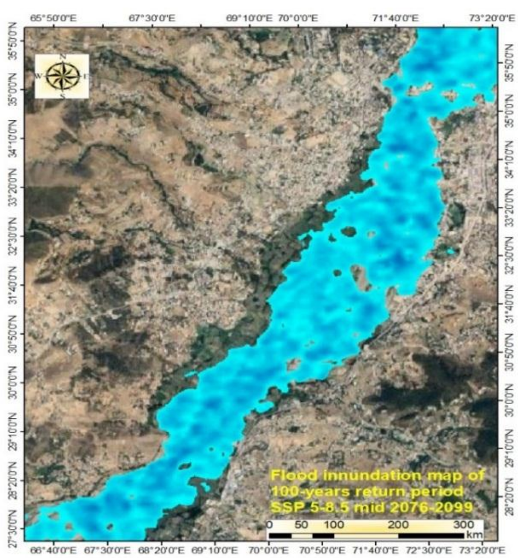
Return Period, Year	flow depth near future (m)		flow depth mid future (m)		flow depth far future (m)	
	SSP 2-4.5	SSP 5-8.5	SSP 2-4.5	SSP 5-8.5	SSP 2-4.5	SSP 5-8.5
5	30.869	31.579	31.169	31.649	31.669	31.849
50	31.489	32.269	31.809	32.409	32.359	32.629
100	31.789	32.449	32.039	32.601	32.539	32.801



(a)



(b)



(c)

Fig. 13. Flood inundation map of 100-year return period for SSP 5-8.5 **(a)** near 2026-2050, **(b)** mid future (2051-2075), and **(c)** far future (2076-2099).

Table 2 presents the values of the depth of flow for the near, mid, and far future for three different return periods of 5 years, 50 years, and 100 years under the average and extreme climate conditions. Considering the return period of 5 years, it is evident from Table 4 that the flow depth increases from 30.87 m to 31.17 m (a percentage increase of about 0.97) and 31.17 m to 31.67 m (a percentage increase of about 1.6) for the mid future scenario and far future scenario, respectively, under the SSP 2-4.5 climate condition. Similarly, the comparison of SSP 2-4.5 and SSP 5-8.5 for a return period of 100 years reveals that the flow depth increases from 31.79 m to 32.45 m (a percentage increase of about 2.08) and from 32.54 m to 32.81 m (a percentage increase of about 0.83) for the near-future scenario and far-future scenario, respectively. Thus, the analysis of the results in Table 4 confirms that the depth of the flow increases with the return period of the flood and severe climate change conditions.

5. Conclusions

The current research study aimed to predict future flood events by incorporating the different variables of climate change for the Panjkora River, one of the major rivers in Khyber Pakhtunkhwa province of Pakistan, due to its large catchment area. For this purpose, modern hydraulic and hydrological modelling technologies, such as the Soil and Water Assessment Tool, were applied to evaluate flood hazards and their associated risks occurring in this basin under historical and future climatic scenarios using a comprehensive weather dataset of 30 years. The following are the main conclusions of this case study:

- The comparative analysis of projected streamflow extremes for return periods ranging from 5 to 1,000 years, relative to the historical record (1982–2010), was undertaken under the SSP2-4.5 and SSP5-8.5 emission scenarios. Findings reveal that the 500-year return period discharge, historically estimated at 2,248.99 m^3/s, is projected to increase to 3,694.39 m^3/s under SSP2-4.5 (2076–2099) and to 4,924.99 m^3/s under SSP5-8.5 (2026–2099). These results suggest a pronounced intensification of extreme hydrological events, underscoring the potential amplification of flood hazards in a changing climate.
- Flood inundation maps for historical periods and future scenarios (SSP 2-4.5 and SSP 5-8.5) show increasing flood extents with higher emissions scenarios. Future scenarios indicate a marked increase in flood risk due to climate change, necessitating adaptive measures. SSP 5-8.5 shows a consistently higher flood discharge compared to SSP 2-4.5, suggesting that higher emission pathways will exacerbate the flood risks.
- It is concluded from the inundation maps that the chances of flooding are higher in the end part of this century. This shows the importance of flood preventive measures and flood control strategies to lessen the chances of floods in the mentioned time periods. As the future frequency and intensity of floods are expected to be higher, it is needed to develop flood-resistant infrastructure, a good drainage system, and effective disaster mitigation customs. Furthermore, for the protection of vulnerable regions in the study area and the reduction of negative impact on society and the economy, it is important to adopt the management plans and sustainable land use planning projects.

6. Model Uncertainties and Future Improvements

In this study, the models used (SWAT and HEC-RAS) were set up carefully and were then calibrated and validated, but some uncertainties still exist in the models. During building models, some assumptions were made, for example, ARC-SWAT divides the watershed into units with average land and soil properties, which may not fully present the natural variations in the study area. Similarly, HEC-RAS uses flow conditions that may not capture real-time complexities of flood behavior. Then, on the climate side, the GCMs used were ensembled for good reliability; such data are produced on a global scale, which may not reflect the exact local climate patterns. So, the author suggests that the use of local climate data and real-time monitoring could help to reduce model uncertainties. Furthermore, the Reliability of the SWAT and HEC-RAS models depend upon the precision of hydrometeorological input data, the imagery sharpness of the Digital Elevation model, and the utilization of land management data. The authors recommend employing advanced techniques such as the incorporation of algorithms based on machine learning and assimilation methods for predicting future flood flows and the associated risk on the socio-economic situation of the general population surrounding the catchment area of the Panjkora River.

Acknowledgements

We would like to thank the anonymous reviewers for their vigilant evaluation of our initial manuscript and their insightful comments and useful suggestions.

Authors' Contribution

Hafsa Wadood proposed the main concept, *executed the research through software applications, carried out data collection and analysis, and prepared the manuscript. Mujahid Khan supervised the research work, provided technical guidance, and reviewed the manuscript. Salman Khan, co-supervised the research, contributed to model calibration and validation, and improved the technical quality of the study. Shehla Nawaz assisted in software understanding, supported data execution, and contributed to the interpretation of results.*

Funding: Not Applicable

Data availability

The datasets used and/or analyzed during the study are available on request from the corresponding author.

DECLARATIONS

Conflict of interest: The authors declare no competing interests.

Ethics approval and consent to participate.

The authors declare that they followed the ethics in scientific research.

Consent for publication.

Not applicable

Competing interests

The authors declare no competing interests.

Conflict of interests: The authors reported no potential conflict of interest.

References

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., van Griensven, A., Van Liew, M. W., Kannan, N., & Jha, M. K. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE, 55*(4), 1491–1508. https://doi.org/10.13031/2013.42256

Bahadar, I., Shafique, M., Khan, T., Tabassum, I., & Ali, M. Z. (2015). Flood hazard assessment using hydrodynamic model and GIS/RS tools: A case study of Babuzai-Kabal tehsil, Swat Basin, Pakistan. *Journal of Himalayan Earth Sciences, 48*(2), 129–138. Retrieved July 23, 2025, from http://ojs.uop.edu.pk/jhes/article/view/1953

Bates, P. D., Horritt, M. S., & Fewtrell, T. J. (2010). A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology, 387*(1–2), 33–45. https://doi.org/10.1016/j.jhydrol.2010.03.027

Bhagat, N. (2017). Flood frequency analysis using Gumbel's distribution method: A case study of Lower Mahi Basin, India. *Journal of Water Resources and Ocean Science,* *6*(4), 51. https://doi.org/10.11648/j.wros.20170604.11

Brunner, G. W. (2016). *River analysis system, 2D modeling user's manual (Version 5.0, CPD-68A, 171 pp.)*. U.S. Army Corps of Engineers. Retrieved from https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS

Budhathoki, A., Babel, M. S., Shrestha, S., Meon, G., & Kamalamma, A. G. (2021). Climate change impact on water balance and hydrological extremes in different physiographic regions of the West Seti River Basin, Nepal. *Ecohydrology & Hydrobiology, 21*(1), 79–95. https://doi.org/10.1016/j.ecohyd.2020.07.001

Callaghan, D. P., & Hughes, M. G. (2022). Assessing flood hazard changes using climate model forcing. *Natural Hazards and Earth System Sciences, 22*(8), 2459–2472. https://doi.org/10.5194/nhess-22-2459-2022

Cunderlik, J. M., & Burn, D. H. (2002). Local and regional trends in monthly maximum flows in Southern British Columbia. *Canadian Water Resources Journal, 27*(2), 191–212. https://doi.org/10.4296/cwrj2702191

Di Baldassarre, G., Schumann, G., Bates, P. D., Freer, J. E., & Beven, K. J. (2010). Flood-plain mapping: A critical discussion of deterministic and probabilistic approaches. *Hydrological Sciences Journal,* *55*(3), 364–376.

https://doi.org/10.1080/02626661003683389
Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., ... & Midgley, P. M. (Eds.). (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation*. Cambridge University Press.
Garee, K., Chen, X., Bao, A., Wang, Y., & Meng, F. (2017). Hydrological modeling of the Upper Indus Basin: A case study from a high-altitude glacierized catchment, Hunza. *Water, 9*(1), 17. https://doi.org/10.3390/w9010017
Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Transactions of the ASABE, 50*(4), 1211–1250. https://doi.org/10.13031/2013.23637
Gebrechorkos, S. H., Bernhofer, C., & Hülsmann, S. (2020). Climate change impact assessment on the hydrology of a large river basin in Ethiopia using a local-scale climate modelling approach. *Science of The Total Environment, 742,* 140504. https://doi.org/10.1016/j.scitotenv.2020.140504
HEC-US Army Corps of Engineers. (2016). *HEC-RAS river analysis system: User's manual (Version 5.0)*.
Hirabayashi, Y., Kanae, S., Emori, S., Oki, T., & Kimoto, M. (2008). Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal, 53*(4), 754–772. https://doi.org/10.1623/hysj.53.4.754
Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). *Global flood risk under climate change*. Nature Climate Change, 3(9), 816–821. https://doi.org/10.1038/nclimate1911
Horritt, M. S., & Bates, P. D. (2002). Evaluation of 1D and 2D numerical models for predicting river flood inundation. *Journal of Hydrology, 268*(1–4), 87–99. https://doi.org/10.1016/S0022-1694(02)00121-X
Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J. C. J. H., Mechler, R., Botzen, W. J. W., Bouwer, L. M., Pflug, G., Rojas, R., & Ward, P. J. (2014). *Increasing stress on disaster-risk finance due to large floods*. Nature Climate Change, 4(4), 264–268. https://doi.org/10.1038/nclimate2124
Khan, S. N., Khan, A. N., Ali, M., & Bangash, A. A. (2019). Flood probability analysis for different return periods in District Peshawar, Pakistan. *Journal of Himalayan Earth Sciences, 52*(2), 225–236. http://ojs.uop.edu.pk/jhes/article/view/1840
Khan, M., Uzair, A., Ali, U., & Khan, W. (2020). Flood modeling of Naray-Khwar using HEC-RAS. *Journal of Himalayan Earth Sciences, 53*(1), 1–11. http://ojs.uop.edu.pk/jhes/article/view/1808
Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K. & Sherstyukov, B. (2014). Flood risk and climate change: Global and regional perspectives. *Hydrological Sciences Journal, 59*(1), 1–28. https://doi.org/10.1080/02626667.2013.857411
Merz, B., Thieken, A. H., & Gocht, M. (2007). Flood risk mapping at the local scale: Concepts and challenges. *Advances in Natural and Technological Hazards Research, 25,* 231–251. https://doi.org/10.1007/978-1-4020-4200-3_13
Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). *Climate change: Stationarity is dead: Whither water management?* Science, 319(5863), 573–574. https://doi.org/10.1126/science.1151915
Moftakhari, H. R., Salvadori, G., AghaKouchak, A., Sanders, B. F., & Matthew, R. A. (2017). Compounding effects of sea level rise and fluvial flooding. *Proceedings of the National Academy of*

Sciences, *114*(37), 9785–9790. https://doi.org/10.1073/pnas.1620325114

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and Water Assessment Tool theoretical documentation*. Texas.

Ougahi, J. H., Cutler, M. E. J., & Cook, S. J. (2022). Modelling climate change impact on water resources of the Upper Indus Basin. *Journal of Water and Climate Change*, *13*(2), 482–504. https://doi.org/10.2166/wcc.2021.233

Papaioannou, G., Vasiliades, L., & Loukas, A. (2015). Multi-criteria analysis framework for potential flood-prone areas mapping. *Water Resources Management*, *29*(2), 399–418. https://doi.org/10.1007/s11269-014-0817-6

Roy, B., Khan, M. S. M., Islam, A. K. M. S., Mohammed, K., & Khan, M. J. U. (2021). Climate-induced flood inundation for the Arial Khan River of Bangladesh using open-source SWAT and HEC-RAS model for RCP8.5-SSP5 scenario. *SN Applied Sciences*, *3*(6), 1–12. https://doi.org/10.1007/s42452-021-04460-4

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F. W., Dutta, D., & Kim, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, *90*, 201–216. https://doi.org/10.1016/j.envsoft.2017.01.006

Ullah, K., & Zhang, J. (2020). GIS-based flood hazard mapping using relative frequency ratio method: A case study of Panjkora River Basin, eastern Hindu Kush, Pakistan. *PLoS ONE*, *15*(3), e0229153. https://doi.org/10.1371/journal.pone.0229153

Van Alphen, J., Martini, F., Loat, R., Slomp, R., & Passchier, R. (2009). Flood risk mapping in Europe: Experiences and best practices. *Journal of Flood Risk Management*, *2*(4), 285–292. https://doi.org/10.1111/j.1753-318x.2009.01045.x

Ward, P. J., De Moel, H., & Aerts, J. C. J. H. (2011). How are flood risk estimates affected by the choice of return periods? *Natural Hazards and Earth System Sciences*, *11*(12), 3181–3195. https://doi.org/10.5194/nhess-11-3181-2011

Wei, H., Gutowski, W. J., Vörösmarty, C. J., & Fekete, B. M. (2002). Calibration and validation of a regional climate model for Pan-Arctic hydrologic simulation. Retrieved May 25, 2025, from https://academicworks.cuny.edu/asrc_pubs/8