Adaptive Water Governance in the Upper Indus Basin: Navigating Climate Change Challenges for Water Resource Management

File Number : PDF/2023/001948

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[SERB Qualified Unique Identification Document: SQUID-1993-SH-5883]

Submission Date : 09-Aug-2023

PROPOSAL DETAILS

(PDF/2023/001948)

Principal Investigator	Mentor & Host Institution
Dr. Shafkat Ahsan shafkatwani52@gmail.com Professor(Civil Engineering) **Contact No** : +919596474648 **Date of Birth** : 06-Oct-1993 **Name of Father/Spouse :** Mohammad Ahsan Wani	**Abdul Qayoom Dar** aqayoom2001@yahoo.com Professor and HoD(Civil Engineering) **National Institute of Technology, Srinagar** National institute of technology, hazartbal, Srinagar, Jammu and kashmir-190006 **Contact No.** : +919419001914 **Registrar Email** : registrar@nitsri.ac.in **No. of PHD Scholars** : 5 **No. Post-Doctoral Fellow** : 0

Details of Post Doctorate

Ph.D. (Geography)[Degree Awarded on : 27-Feb-2023]

Impact of climate change on the surface hydrology of Kashmir, Jammu and Kashmir, India.

Research Supervisor/Guide & Institution :

Prof. M. Sultan Bhat

University of Kashmir

Brief details of Thesis work :

Sustainable water resource management would be a pressing concern in the future owing to the ever-increasing human populace, agricultural expansion, and increasing affluence in human lifestyle coupled with stresses like enhancing pollution levels, urbanization, land-use changes, and climate change. In this context, the hotspot or headwater regions attain significance for sustaining the perennial water supply in both upstream and downstream basins. My Ph.D. work focused on assessing the surface water availability and also the irrigation water demand under climate change scenarios in the Jhelum catchment of the upper Indus basin. Using robust statistical techniques, I have investigated the hydroclimatic variability in the Jhelum basin from observed data. There are strong signals of climate change in the basin highlighted by rising temperatures (0.024 ˚C/ year from 1980-2016) and declining precipitation (5.7 mm/year from 1980-2016). I have also attempted to analyze the behavior of climatic extremes and there has been a steady increase in the warm temperature-based extremes and a decrease in cold extremes. Similarly, the hydrological extremes viz., droughts and floods have registered an increase in frequency and severity. Moreover, I have carried out statistical downscaling and bias correction using multiple techniques for developing the climate change projections for the basin. In addition, I have used Bayesian Model Averaging (BMA) to produce the multi-model ensemble that addresses the uncertainty associated with climatic projections. The annual mean maximum temperature in the basin is projected to rise by 0.41–2.31 °C and 0.63–4.82 °C, and the mean minimum temperature will increase by 1.39–2.37 °C and 2.14–4.34 °C under RCP4.5 and RCP8.5 respectively, over the 21st century. While precipitation is expected to decrease by 7.2–4.57 % and 4.75–2.47% under RCP4.5 and RCP8.5 correspondingly. To evaluate the implications of climate change on the hydrological regime of river Jhelum, I have used SWAT hydrological model coupled with climate change projections. The analysis revealed robust fallout on the streamflow, decreasing by magnitudes of 23-37% under RCP4.5 and 19-46 % under RCP8.5. Using the SWAT model, I also evaluated the consequences on the catchment water balance. Since the basin is primarily inhabited by the agrarian population, I also evaluated the irrigation water requirements for the Rice crop (dominant and highest water-intensive crop) using the CROPWAT model and found surface water resources would not be sufficient to sustain the current area under rice cultivation in Jhelum catchment under climate change scenarios.

Technical Details :

Research Area : Earth & Atmospheric Sciences (Earth & Atmospheric Sciences)

Project Summary :

The Upper Indus Basin (UIB) forms a critical region from the climate change perspective, especially the sensitive water resource base of the region (Orr et al., 2022). Hosting the largest freshwater resources outside the polar areas, the region holds immense significance in supplying water to about 235 million human population spanning four countries - India, China, Pakistan, and Afghanistan (Wester et al., 2019; Immerzeel et al., 2019). The buffers of water security in the form of glacial ice and snow reserves are directly witnessing the heat of climate change, resulting in enhanced ablation and earlier melting (D. Li et al., 2022). The imprints of the altered snow/Ice melt dynamics are already ominous over the hydrological regimes of the river systems originating there with considerable shifts in the volume and timing of runoff (Barnett et al., 2005; Jeelani et al., 2012). Under climate change projections, alarming reductions in the water volumes and timings of the runoff have been reported in earlier studies (Akhtar et al., 2008; Viviroli et al., 2020). Thus, the water security of the upstream and downstream areas remains uncertain (Yao et al., 2022). The water-dependent sectors, viz., Domestic, Agricultural, industrial, and hydropower generation, are bound to witness long-term deficits and induce stress within and between nations. The enhanced ablation of the Himalayan glaciers has garnered considerable attention at the global level, with future water security as a principal concern (Bolch, 2017). The water flow between the various riparian nations is being regulated under water treaties (e.g., Indus Water Treaty), and the alterations of flow regimes would surely attempt to re-negotiations of water allocation to offset the political conflicts that can emanate thereof (Qamar et al., 2019). To this end, analyzing the future state of water availability and demand in the HKH region becomes quintessential under various climate change projections. This requires a reliable estimation of the water resources and their spatiotemporal distribution and availability. The adaptive and mitigative mechanism would largely rest upon the magnitude of climatic changes, the hydrological responses, and a projection of the sectoral water demands. Climate change is expected to amplify the demand for all water use sectors, particularly for agriculture, which forms the dominant water use in the basin (QUA et al., 2023). The projections of future sectoral demand become thus important. The supply-demand gap will worsen under changing climate and socioeconomic conditions (Smolenaars et al., 2021). Moreover, under the decreased surface water resources, the groundwater resources in the basin need to be assessed, which can be used to minimize the deficits (Biemans et al., 2013). Assessing the glacial/ snow reserves which form a basis in maintaining the perennial water supply requires a detailed assessment of their behavior under changing climatic regimes.

Objectives :

- To assess the magnitude of future climatic changes in UIB using CMIP6 simulations.
- To evaluate the response of water resources and their availability under changing climatic regimes.
- To project the sectoral water demand and development of optimum water allocation strategies.

Keywords :

climate change Hydrology

Expected Output and Outcome of the proposal :

Being a transboundary river implies a high potential for water-induced conflicts between the riparian nations. The estimation of the climate change on water security becomes thus important for fostering peace in regional and global Contexts. The project will attempt to evaluate the behaviour of water resources using the methodological amalgam of hydrological and climate modelling. Since climate change will also impact water demand, an evaluation of the demands from various sectors is also required for optimum water allocation. The project will attempt to model the agricultural water demand for different crops. Agriculture forms a dominant water use in the basin, using about 90% of the total water withdrawals. CROPWAT model substantiated by the in-situ measurements will be evaluated. The water allocation to different sectors will be evaluated using the WEAP model. In addition to this, the hydropower potential would be measured using the integrated WEAP-LEAP models. The deliverables of the project would be key in developing the adaptive framework for sustainable management of water resources. It will aid in understanding the choice of crops, irrigation timings, infrastructure requirements, management of sectoral water demand, and policy implications. The current project would form a baseline for developing the best management practices for sustainable water use in the basin.

Reference Details :

S.No	Reference Details
1	**Prof. Ghulam Jeelani** **Department of Earth Sciences,** **University of Kashmir-190006.[+7006316171]** geojeelani@uok.edu.in
2	**Prof. M Sultan Bhat** **Department of geography and disaster management, University of Kashmir-190006.[+9906577391]** msbhatgeog@yahoo.com

Methodology

GCM outputs from the latest CMIP6 models will be downscaled/ bias corrected for the climate change projections under different Shared Socioeconomic Pathways (SSPs). The uncertainty would be addressed by developing the multi-model ensemble using the Bayesian algorithm (Huang, 2014). Moreover, MODIS data and climatic variables will assess snow cover behavior over the 21st century(Singh et al., 2022). The surface water availability under climate change scenarios would be modeled using the HBV coupled with glacial retreat models (H. Li et al., 2015). The water demand for agriculture, domestic, and industrial sectors will be assessed using the WEAP model (Mourad & Alshihabi, 2015). For hydropower water generation potential, integrated WEAP-LEAP modeling would be employed (Handayani et al., 2020). The balance between the supply and demand of water resources under climate change scenarios would be used to develop sustainable water management practices and optimum water allocation for the selected sub-basins of different climatic regimes.

Research Plan and Timeline

The first quarter will involve interacting with the mentor and other experts, preliminary training, exposure to the various models, and a literature review. The second quarter would involve the setup of the models and preparation of the input layers for ice melt dynamics. The field observations and model calibration/validation will be executed in the third quarter. The fourth quarter will include the assessment of sectoral water demand. The last two quarters will be utilized in drafting the results and preparing the manuscript for submission to scientific journals.

Quarter	Work to be Done
1-4 months	Preliminary Training & climate change projections
4-8 months	Training and Model setup of glacial melt dynamics
8-12 months	Field measurements & calibration/ validation
12-16 months	Sectoral water demand assessment/WEAP-LEAP
16-20 months	Drafting and publication of results
20-24 months	Drafting and publication of results

BIO-DATA

1. Name and full correspondence address:

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2. Email(s) and contact number(s)

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3. Institution

Department of Geography and Disaster Management, University of Kashmir, Hazratbal, Srinagar-190006

4. Date of Birth
06/10/1993

5. Gender (M/F/T)
Male

6. Category Gen/SC/ST/OBC
GEN

7. Whether differently abled (Yes/No)
No

8. Academic Qualification (Undergraduate Onwards)

	Degree	Year	Subject	University/Institution	% of marks
1.	Graduation	2013	Geography	University of Kashmir	73.5
2.	Post-Graduation	2016	Geography	University of Kashmir	76.6
3.	PhD	2023	Geography	University of Kashmir	-
4.	Post Graduate Diploma in Disaster Management	2020 (Distance Mode)	Disaster Management	Indra Gandhi National Open University, India	70

9. Ph.D. thesis title, Guide's Name, Institute/Organization/University, Year of Award.
Title: ***Impact of climate change on the surface hydrology of Kashmir, Jammu and Kashmir, India (2023)***

Institute: **Department of Geography and Disaster Management, University of Kashmir, Hazratbal, Srinagar- 190006.**
Supervisor: Professor, M. Sultan Bhat, Department of Geography and Disaster Management
Email:msbhatgeog@yahoo.com

11. Professional Recognition/ Award/ Prize/ Certificate, Fellowship received by the applicant.

S.No	Name of Award	Awarding Agency	Year
1.	**UGC-NET**	**University Grants Commission, India**	**2015**
2.	**UGC-JRF**	**University Grants Commission, India**	**2017**

12. Publications *(List of papers published in SCI Journals, in year-wise descending order)*.

S.No.	Author(s)	Title	Name of Journal	Volume	Page	Year
1.	Hilal Ahmad Sheikh, M. Sultan Bhat, Akhtar Alam, **Shafkat Ahsan©** & Bilquis Shah	*Evaluating the drivers of groundwater spring discharge in Sindh basin of Kashmir Himalaya*	Environment, Development and Sustainability, Springer, **IF:4.9**			2023
2.	Hilal Ahmad Sheikh, M. Sultan Bhat, Akhtar Alam, **Shafkat Ahsan©** & Bilquis Shah	*Modeling runoff responses to 1.5 °C and 2 °C rise in temperature in snow-fed basin of western Himalayas*	Sustainable Water Resources Management, Springer; **IF:2.1**			2023
3	Bilquis Shah, Akhtar Alam, M. Sultan Bhat, **Shafkat Ahsan**, Noureen Ali & Hilal Ahmad Sheikh	*Extreme precipitation events and landslide activity in the Kashmir Himalaya*	Bulletin of Engineering Geology and the Environment, Springer; **IF:4.7**			2023
4	**Shafkat Ahsan**, M. Sultan Bhat, Akhtar Alam, Hilal Ahmed Sheikh & Hakim Farooq	*Hydrological extremes and climatic controls on streamflow in Jhelum basin, NW Himalaya*	Theoretical and Applied Climatology Springer; **IF:3.4**	**151**	1729–1752	2023
5	**Shafkat Ahsan,** Mohammad Sultan Bhat, Akhtar Alam, Hakim Farooq & Hilal Ahmad Shiekh.	*Complementary use of multi-model climate ensemble and Bayesian model averaging for projecting river hydrology in the Himalaya*	Environmental Science and Pollution Research, Springer; **IF:5.9**	**30**	38898–38920	2022
6	**Shafkat Ahsan**, M. Sultan Bhat, Akhtar Alam, Hakim Farooq & Hilal Ahmad Shiekh	*Evaluating the impact of climate change on extreme temperature and precipitation events over the Kashmir Himalaya*	Climate Dynamics Springer; **IF:4.6**	58	1651–1669	2022
7	Hilal Ahmad Sheikh, M. Sultan Bhat, Akhtar Alam, **Shafkat Ahsan©** & Bilquis Shah	*Assessing the groundwater spring potential of Sindh basin in the Kashmir Himalaya*	Arabian Journal of Geosciences Springer	15	1710	2022
8	**Shafkat Ahsan,** M. Sultan Bhat, Akhtar Alam, Naveed Ahmed, Hakim Farooq & Bashir Ahmad	*Assessment of trends in climatic extremes from observational data in the Kashmir basin, NW Himalaya*	Environmental Monitoring and Assessment Springer; **IF:3**	193	649	2021

15. Any other Information (maximum 500 words)

Trainings & Workshops

1. Training Course on “Hydrological Modelling Using SWAT”, 11-22 June 2018 at the National Institute of Hydrology, Roorkee, India.
2. Science and Training Workshop on Climate Change over the High Mountains of Asia, 8-12 Oct 2018, IITM Pune, India
3. 12-week Geospatial Technologies & Applications, (12 Nov 2018 to 1 Feb 2019), National Remote Sensing Centre, Hyderabad, India,
4. 1-week Training course on "Geospatial Technologies for Climate Technologies" 8-14 April 2019 National Remote Sensing Centre, Hyderabad, India,
5. Workshop on Flood Management with Focus on Jhelum Basin 8-12 July 2019, Water Resources Management Centre National Institute of Technology Srinagar Hazratbal-190006, J&K
6. National workshop on Climate Crisis; Vulnerabilities and Adaptation Strategies Science and Policy Interface 14-15 March 2018, University of Jammu in collaboration with J&K State Climate Change Centre, Department of Ecology, Environment & Remote Sensing, Government of J&K.

Endorsement Certificate from the Mentor & Host Institute

This is to certify that:

I. The applicant, Dr. Shafaat Ahsan, will assume full responsibility for implementing the project.
II. The fellowship will start from the date on which the fellow joins University/Institute where he/she implements the fellowship. The mentor will send the joining report to the SERB. SERB will release the funds on receipt of the joining report.
III. The applicant, if selected as SERB-N PDF, will be governed by the rules and regulations of the University/ Institute and will be under administrative control of the University/ Institute for the duration of the Fellowship.
IV. The grant-in-aid by the Science & Engineering Research Board (SERB) will be used to meet the expenditure on the project and for the period for which the project has been sanctioned as indicated in the sanction letter/ order.
V. No administrative or other liability will be attached to the Science & Engineering Research Board (SERB) at the end of the Fellowship.
VI. The University/ Institute will provide basic infrastructure and other required facilities to the fellow for undertaking the research objectives.
VII. The University/ Institute will take into its books all assets received under this sanction and its disposal would be at the discretion of Science & Engineering Research Board (SERB).
VIII. University/ Institute assume to undertake the financial and other management responsibilities of the project.
IX. The University/ Institute shall settle the financial accounts to the SERB as per the prescribed guidelines within three months from the date of termination of the Fellowship.

Dated: 21/7/23

Signature of the Mentor:

Name & Designation:

विभागाध्यक्ष जनपद अभियांत्रिकी
राष्ट्रीय प्रौद्योगिकी संस्थान श्रीनगर
हजरतबल-१९०००६, जम्मू और कश्मीर, भारत
HOD Civil Engineering
National Institute of Technology Srinagar
Hazratbal-190006, J&K, India

Dated: 21/7/23

Signature of the Registrar of University/Head of Institute

Seal of the Institution

कुलसचिव
राष्ट्रीय प्रौद्योगिकी संस्थान श्रीनगर
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REGISTRAR
National Institute of Technology Srinagar
Hazratbal-190006, J&K, India

The Jammu & Kashmir State Board of School Education

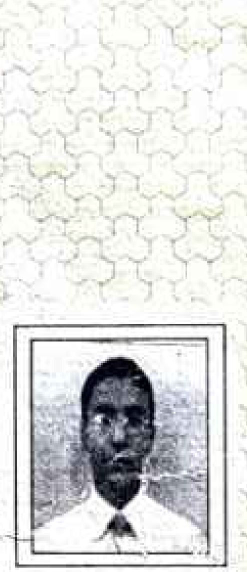
Secondary School Examination

ANNUAL (REGULAR-2008)

Serial No. 08ARKAM-5012739

Roll No. 505227

Registration No. 07NKM502975



This is to certify that SHAFKAT AHSAN

Son/daughter of MOHAMMAD AHSAN WANI & PARVEENA BEGUM

Date of birth 06/10/1993
(Sixth October Nineteen Hundred Ninety Three)

Passed the above examination of this Board, with DISTINCTION

From : NEW MILLENNIUM PUBLIC SCHOOL HANDWARA

Kashmir : May 20, 2010

JAK STATE BOARD OF SCHOOL EDUCATION

JOINT SECRETARY SECRETARY CHAIRMAN

THE JAMMU & KASHMIR STATE BOARD OF SCHOOL EDUCATION THE JAMMU & KASHMIR STATE BOARD OF SCHOOL EDUCATION THE JAMMU & KASHMI

Sr. No. - KU/SGR/DC/23/001312

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10077-HD- 2011

University of Kashmir

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NAAC Accredited Grade 'A+'

on the recommendation of the Academic Council

Shafkat Ahsan

is admitted to the

Degree of Doctor of Philosophy

(Ph.D)

on the topic "Impact of Climate Change on the Surface Hydrology of Kashmir, Jammu and Kashmir, India"

in the Subject of **Geography**, School of Earth & Environmental Sciences

on Twenty Seventh of February in the Year Two Thousand Twenty-Three.

Controller of Examinations

[redacted]

Vice Chancellor

Hazratbal, Srinagar, Jammu & Kashmir, India - 190006

Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-022-24913-6

RESEARCH ARTICLE

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Complementary use of multi-model climate ensemble and Bayesian model averaging for projecting river hydrology in the Himalaya

Shafkat Ahsan[1] · Mohammad Sultan Bhat[1] · Akhtar Alam[1] · Hakim Farooq[1] · Hilal Ahmad Shiekh[1]

Received: 8 September 2022 / Accepted: 18 December 2022

Abstract

Considering the sensitivity and importance of water resources in the Himalayan uplands, this study intended to assess the hydrological responses to climate change in the Jhelum basin. Representative concentration pathway (RCP)–based projections from six dynamically downscaled global circulation models (GCMs) were bias-corrected for developing the climatic projections over the twenty-first century. The uncertainty associated with GCM outputs was addressed by using multi-model ensemble projections developed through Bayesian model averaging (BMA) technique. The assessment reveals that compared to the baseline (1980–2010) values, the annual mean maximum temperature in the basin will rise by 0.41–2.31 °C and 0.63–4.82 °C, and the mean minimum temperature will increase by 1.39–2.37 °C and 2.14–4.34 °C under RCP4.5 and RCP8.5, respectively. While precipitation is expected to decrease by 7.2–4.57% and 4.75–2.47% under RCP4.5 and RCP8.5, correspondingly. BMA ensemble projections were coupled with the Soil and Water Assessment Tool (SWAT) to simulate the future hydrological scenarios of the drainage basin. With the changing climate, the discharge of rivers in the Jhelum basin is expected to witness reductions by about 23–37% for RCP4.5 and 19–46% for RCP8.5. Moreover, the water yield of the basin may also exhibit decreases of 17–25% for RCP4.5 and 18–42% for RCP8.5. The projected scenarios are likely to cause water stress, affect the availability of water for diverse uses, and trigger transboundary water-sharing-related conflicts. The impact of climate change on discharge demands early attention for the formulation of mitigation and adaptive measures at the regional level and beyond.

Keywords Climate change · Jhelum basin · RCP · Water balance · SWAT model · Multi-model ensemble · BMA

Introduction

Changing climatic regimes and their impact on water resources have attracted considerable attention in the contemporary world because of their tremendous environmental and socioeconomic implications (Jasper et al. 2004; Luo et al. 2019; Reshmidevi et al. 2018). Mounting evidence exists about the impact of the increase in global mean temperatures on the regional water budget (Huntington 2006). Moreover, changing precipitation patterns and evapotranspiration rates projected under the climate change scenarios will further alter the hydrological systems (Kundzewicz et al. 2008; Raneesh & Santosh 2011). Therefore, while devising effective water management policies and adaptation strategies to offset climate change-induced stresses, it becomes quintessential to evaluate the hydrological responses and sensitivity of the riverine systems to the changing climate (Bhatta et al. 2019; Reshmidevi et al. 2018; Rodrigues et al. 2020).

Multiple studies have assessed the hydrological imprints of changing climate across the different river basins of the world, e.g., Liu et al. (2011) in the Yellow River basin, Tan et al. (2017) in the Kelantan River basin, Vetter et al. (2017) in 12 major sub-basins of the world, and Yu et al. (2018) in Yangtze River basin. Global circulation models (GCMs) are the popular tools in use for projecting climate change under different emission scenarios. However, GCMs provide information on a coarse scale with large grid sizes and insufficiently capture the regional heterogeneity that impacts the hydrological processes on the basin scale (Hakala et al. 2019). Regional climate models (RCMs) with a finer grid

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Published online: 31 December 2022

size have been developed to improve the outputs of GCMs. Although RCMs perform better in simulating the local climate, they inherit significant error/bias from GCMs (Chen et al. 2013). As a result, using the RCM outputs directly into the hydrological models can yield significant deviations in the model outputs with respect to the observed data (de Oliveira et al. 2017). As a result, prior to any hydrological simulations, bias adjustment of the raw RCM results is critical (Luo et al. 2019). "Coupled Model Intercomparison Project Phase 5(CMIP5)" GCMs provide the outputs based upon the representative concentration pathways (RCPs) that describe the net radiative forcing levels until 2100 ranging from a mitigating pathway (RCP2.6), medium stabilizing pathways (RCP4.5/RCP6), and extreme climatic pathway (RCP8.5) (Meinshausen et al. 2011; Taylor et al. 2012).

GCM output carries a substantial amount of uncertainty with it and must be taken into cognizance while carrying out any impact assessment studies. The cascade of uncertainty is nestled in the range of socioeconomic or developmental pathways that the world may take in the future; incomplete knowledge or representation of the climatic system and its interactions; and the structural or parametric differences in the GCMs. As such, the single model's results must be interpreted cautiously (Reshmidevi et al. 2018). To this end, ensemble projections have been proposed on account of their reliability and uncertainty assessment (Khan et al. 2021). In comparison to the outputs from separate models, the multi-model ensemble has been demonstrated to be more effective in the representation and simulation of climatic variables (Gleckler et al. 2008; Knutti et al. 2010; Zhang & Huang 2013). The ensemble techniques can vary from the simple arithmetic ensemble mean wherein each model is weighted equally irrespective of its performance, to the weighted ensemble mean. Additionally, ensemble projections have been generated through the adoption of the median values from the projections of multiple climate models (Cloke et al. 2013; Yang et al. 2022). These techniques improve the simulation results; however, uncertainty in the estimates is not addressed. BMA is a weighted ensemble method in which the relative competence of models is determined and model weights are optimized so that BMA ensemble projections closely match the observed data (Massoud et al. 2020). In this way, higher weights are applied to more skillful models as compared to low-skillful models. Additionally, the use of BMA is justified by the fact that uncertainty is included in the estimate in a substantially more efficient manner than when using a simple mean or a median ensemble. BMA has been previously used for developing ensemble projections in studies like Huang, (2014), Khan et al., (2021), and Massoud et al., (2020).

Generally, hydrological models forced with climatic scenarios have been employed to simulate the possible implications on stream flows, catchment storage, and other water balance components. Different hydrological models that can replicate the hydrological properties and processes operating within a basin have already been developed (Krysanova & Hattermann 2017). Soil and Water Assessment Tool (SWAT) is being widely used for evaluating the likely implications of changing climatic regimes on hydrological processes (Bajracharya et al. 2018; Bhatta et al. 2019; Rodrigues et al. 2020; Narsimlu et al. 2013; Touseef et al. 2021). Numerous studies have also employed the SWAT model for simulating the combined impact of changing land-use patterns and climatic scenarios with reasonable precision (Ahmed et al. 2022; Yonaba et al. 2021a). Furthermore, the SWAT model contains a snowmelt module relevant for modeling the basins where snowmelt is a significant contributor to the streamflow. In addition to this, the SWAT model has been successfully used for simulating the streamflow in and around the Jhelum basin, e.g., Saddique et al. (2019), Shah et al. (2020), and Ougahi et al. (2022). Hence, the applicability of the SWAT model was extended to the present study.

The potential implications of climate change are more noticeable in the mountainous regions like the Himalayas, particularly on water resources, where snowmelt and glacial ice melt are the major determinants of streamflow (Viviroli et al. 2007; Lutz et al. 2014; Immerzeel et al. 2013). Significant increases in the temperature along with declining precipitation patterns have been reported for the Jhelum basin (Ahsan et al. 2021, 2022). Having established climate change signals, it becomes obvious that the water resources will be most affected in this region. The imprints of the observed climatic variability are already visible over the hydrological regime of the Jhelum basin. For example, climate change is putting a lot of strain on the aquatic systems in the region (Alam et al. 2020). Lone et al. (2022) reported significant decreasing trends in the streamflow, driven by observed climate variability. Hence, climatic changes are likely to further impact the water security of the region and challenge the existing management strategies. The hydrological consequences of the climatic changes can transmit to the overall prosperity of the region due to dependence of other sectors, viz., irrigation, domestic, industrial, tourism, and hydropower generation on the water resource base. Limited studies have been attempted so far in the Jhelum basin that project the hydrological responses to changing climate, e.g., Singh Jasrotia et al. (2021). However, the key limitations of this study are that it uses outputs of a single RCM and lacks any detailed assessment of water balance components. Hence, it is imperative to have a rigorous quantification of the hydrological responses to the projected changes in climatic regimes. For this purpose, the current study utilizes outputs from 6 GCMs under a medium stabilizing pathway (RCP4.5) and an extreme pathway (RCP8.5). The study primarily aims to develop robust climatic projections for the twenty-first century, using the multi-model ensemble based on the Bayesian model averaging framework. The study subsequently employs the hydrological model SWAT coupled with the climatic scenarios to project the changes in the streamflow and different components of water balance over the twenty-first century. No such comprehensive study has been attempted yet for the Jhelum basin; the present one can thus serve as a benchmark study while planning for the mitigation of hydrological implications ascribed to climate change and pave the way for the formulation of adaptive policy for sustainable water management.

Study area

The present study is attempted for the Jhelum basin (Fig. 1) located in the lap of the Himalayas with an area of about 15,000 km^2. The trunk stream, Jhelum constitutes an important tributary of the Indus River system forming an elongated bowl-shaped basin that originated from the collision between the Indian and Eurasian plates (Alam et al. 2015, 2017). Based on stratigraphy and elevation, the basin can be divided into 3 major physiographic divisions, viz., mountainous uplands, extensive plateaus of lacustrine deposits (Karewas), and valley floor with the numerous streams draining into Jhelum (Bhat et al. 2018). The slope and elevation of the basin lie between 0 to 65° and 1450 to 5500 mamsl, causing significant microclimatic variations. The region's climatic regime is controlled by two distinct weather patterns, viz., Western disturbance in winter months and southwest monsoons in the summer half. The impact of the latter is somewhat limited, and the major proportion of the precipitation is received in the winter months, mainly in the form of snowfall. The winter precipitation feeds the glaciers and acts as a buffer in maintaining the streamflow of the river Jhelum during the dry periods. Snowmelt currently

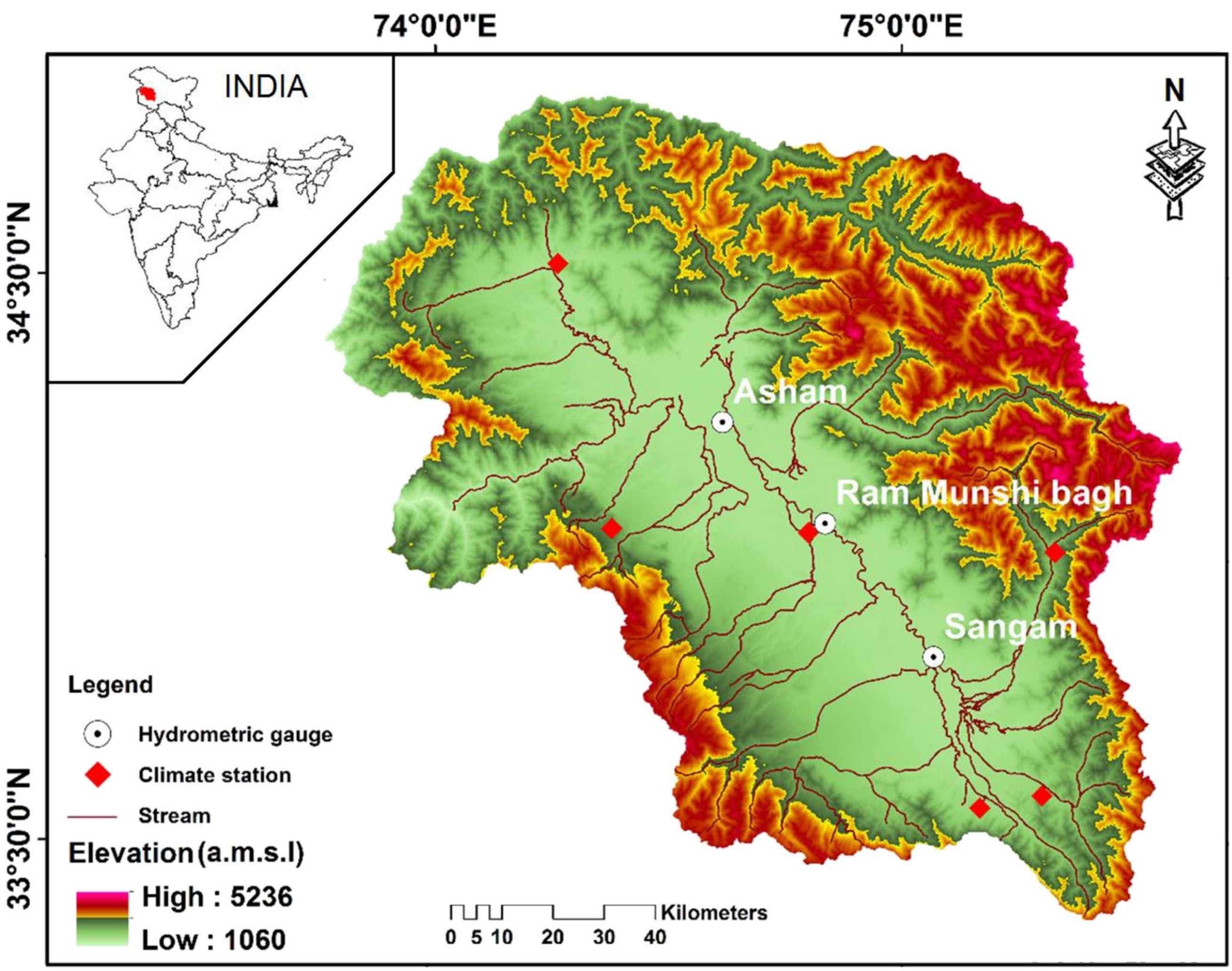

Fig. 1 Location of the Jhelum basin with the major streams, climatic stations, and the river gauges

contributes about 29% during the spring season, 58% during the summer season, and 38% during the autumn season to the streamflow of river Jhelum (Lone et al. 2022). The annual mean precipitation in the valley is around 100.5 cm with about 71.6% received during Oct–May and 28.4% during the Jun–Sep (Dad et al. 2021). The climate of the region is moderate having a sharp seasonality and has been categorized as a Sub-Mediterranean type (Bagnolus and Meher-Homji 1959). The valley records an annual mean maximum temperature of 17.6 ± 0.8 °C and a minimum temperature of 5.4 ± 0.4 °C (Dad et al. 2021). However, the annual temperature variations of the region range from sub-freezing during the winter and up to as high as 35 °C during the summer. The two major types of soil found in the basin are *eutric cambisols* on the valley floor and *lithosols* in the peripheral uplands (Romshoo et al. 2020). The region supports a population of ~ 7 million persons with heavy reliance on water resources for sustenance.

Materials and methods

Observed hydroclimatic data

Observed climate data (1980–2016) for temperature and precipitation variables at a daily scale was procured from the India Meteorological Department, Regional Office Srinagar, J&K, India. This data was utilized for the bias correction of the GCM data and also as input for the baseline run of the SWAT model. For the other SWAT input climatic variables, i.e., relative humidity, wind speed, and solar radiation, and "Climate Forecast System Reanalysis (CFSR)" data were used. CFSR data have been used and validated in the past for the Kashmir basin by Ahsan et al. (2021). The observed streamflow data for the 3 gauges on the trunk stream, viz., Sangam, Asham, and Ram Munshi Bagh, were used in calibrating and validating the SWAT model.

Climate scenario projections

The Coordinated Regional Climate Downscaling Experiment (CORDEX) was developed under the aegis of the World Climate Research Programme to stimulate climatic scenarios and improve regional impact assessment. CORDEX over the south Asian domain provides data for multiple GCM-RCM combinations at a grid size of 0.44° (~ 50 km). CORDEX-SA has previous successful applications in the Himalayan regions (e.g., Dimri et al. 2018; Krishnan et al. 2019). A total of 6 GCMs (Table 1) downscaled dynamically using the RegCM4 RCM (Giorgi et al. 2012) were used in the projection of the climatic scenarios under RCP4.5 and RCP8.5. The projected span (2006–2099) was split into 3 periods, viz., 2011–2040 (2020s), 2041–2070 (2050s), and 2071–2099 (2080s). The relative changes in mean climatology over the different spans of the twenty-first century were computed from the baseline (1980–2010) climatology.

Bias correction of GCM/RCM data

Prior to using the GCM/RCM data for the projection of climatic changes or their hydrologic implications, it is necessary to apply the bias correction techniques because the data obtained from the climate models inherit systematic biases (Luo et al. 2019). A wide range of bias correction techniques have been devised (Teutschbein and Seibert 2012); and in the present study, variance scaling (VS) was used for bias-correcting the temperature data, while a hybrid of power transformation (PT) and local intensity scaling (LOCI) techniques were employed for bias correcting the precipitation data. These bias correction methods use monthly correction factors to adjust the daily climate data.

Variance scaling is an effective technique and has the advantage of correcting both the mean and variance (Teutschbein and Seibert 2012). VS uses Eq. 1 to correct the bias in temperature. Power transformation of the precipitation data also corrects both mean and variance in the raw data. However, the limitation of the PT method is that it does not correct the wet day frequency. Hence, before its use, the

Table 1 List of CMIP5 GCMs used in the present study

Model	Grid Resolution		Contributing CMIP5 Modeling Center
	Latitude	Longitude	
CanESM2	2.79	2.81	Canadian Centre for Climate Modelling and Analysis (CCCma), Canada
GFDL-ESM2M	2.02	2.50	National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory (GFDL), USA
CNRM-CM5	1.40	1.41	Centre National de Recherches Me´te´orologiques (CNRM), France
MPI-ESM-MR	1.87	1.88	Max Planck Institute for Meteorology (MPI-M), Germany
IPSL-CM5A-LR	1.89	3.75	Institute Pierre-Simon Laplace (IPSL), France
CSIRO-Mk3.6.0	1.87	1.88	Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia

wet day frequency is adjusted using the local intensity scaling method. In LOCI (Eq. 2) initially, a threshold for wet day $P_{\mathrm{thresh,m}}$ is obtained from the raw data to match the wet day frequency in raw and bias-corrected precipitation. This is followed by the calculation of a scaling factor $S_m = \frac{\mu(P_{\mathrm{obs,m,d}}|P_{\mathrm{obs,m,d}}>0)}{\mu(P_{\mathrm{raw\ ,m,d}}|P_{\mathrm{raw\ ,m,d}}>P_{\mathrm{thres\ ,m}})}$ to match the mean of raw and bias-corrected precipitation.

$$T_{\mathrm{bc\ ,m,d}} = \left[T_{\mathrm{raw\ ,m,d}} - \mu\left(T_{\mathrm{raw\ ,m}}\right)\right] \times \frac{\sigma(T_{\mathrm{obs,m}})}{\sigma(T_{\mathrm{raw\ ,m}})} + \mu\left(T_{\mathrm{obs,m}}\right) \quad (1)$$

$$P_{bc,m,d} = \begin{cases} 0\ if P_{raw,m,d} > P_{thresh,m} \\ P_{raw,m,d} * S_m otherwise \end{cases} \quad (2)$$

After adjusting the wet day frequency using the LOCI method, in the PT method, b_{m} is initially estimated to minimize $f\left(b_{\mathrm{m}}\right) = \frac{\sigma(P_{\mathrm{obs,m}})}{\mu(P_{\mathrm{obs,m}})} - \frac{\sigma\left(P_{\mathrm{LOCI,m}}^{b_{\mathrm{m}}}\right)}{\mu\left(P_{\mathrm{LOCI,m}}^{b_{\mathrm{m}}}\right)}$. After optimizing the b_m, a scaling factor $S_m = \frac{\mu(P_{obs,m})}{\mu(P_{LOCI,m}^{b_m})}$ is computed to match the mean of LOCI corrected and observed precipitation. In the final step, Eq. 3 is used to correct the bias.

$$P_{bc,m,d} = S_m * P_{\mathrm{LOCI,m}}^{b_{\mathrm{m}}} \quad (3)$$

where T is the temperature, P is precipitation, μ is the mean, σ is the standard deviation, e.g., $T_{\mathrm{bc\ ,m,d}}$ is the bias-corrected temperature for the *dth* day of *mth* month; $\sigma\left(P_{\mathrm{obs,m}}\right)$ is the standard deviation of the observed precipitation series for *mth* month (Fang et al. 2015).

To check the skill and efficiency of the RCM simulations, RCM data (raw and bias-corrected) were compared with observational data on a monthly timescale using the efficiency indicators like coefficient of determination (R^2), percentage bias (PBIAS), Nash Sutcliffe efficiency (NSE), and Kling-Gupta efficiency (KGE). Moreover, Taylor diagrams (Taylor 2001) were employed to assess the competence of RCMs for both raw and bias-corrected data. R^2 given by Eq. 4 is a measure of goodness-of-fit among the observed and model data ranging between 0 and 1. $R.^2$ values nearing 1 imply a higher agreement among observed and model values. PBIAS (Eq. 5) measures the model data's mean tendency to be greater or lesser than actual observations. PBIAS has an optimum value of 0 with positive values depicting underestimation and negative values depicting overestimation in model simulations. NSE is a standardized statistic (Eq. 6) that measures deviations between the modeled and observed data normalized by the observational data variance (Takele et al. 2021). It values between -∞ to 1 and NSE = 1 depicts modeled data are equal to that of the observed data (Nash and Sutcliffe 1970). KGE (Eq. 7) is an integrated efficiency criterion evaluating correlation, bias, and variability of model output in comparison to the observed data (Kling et al. 2012). Varying between -∞ and 1, the model performance can be deemed as poor ($0 \leq \mathrm{KGE} \leq 0.5$), acceptable ($0.50 \leq \mathrm{KGE} \leq 0.75$), good ($0.75 \leq \mathrm{KGE} \leq 0.9$), or excellent ($\mathrm{KGE} \geq 0.9$) (Yonaba et al. 2021a)

$$R^2 = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(M_i - \overline{M}\right)}{\sqrt{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2 \sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}} \quad (4)$$

$$PBIAS = \frac{\sum_{i=1}^{n}\left(O_i - M_i\right) \cdot 100}{\sum_{i=1}^{n}\left(O_i\right)} \quad (5)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(O_i - M_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad (6)$$

where O_i are the observational data values and M_i are the model simulated values.

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \quad (7)$$

where r is the correlation coefficient between observed and simulated values, β is the ratio of simulated and observed means, and γ is the ratio of simulated and observed coefficients of variation.

Bayesian model averaging (BMA) for multi-model ensemble

On account of parametric and structural differences, GCMs/RCMs produce different outputs (Wallach et al. 2016). Hence, a single climate model's output may still be subject to uncertainty (Uusitalo et al. 2015). The bias-corrected RCM output with different GCM forcing was utilized to develop multi-model ensemble projections employing the Bayesian model averaging (BMA) technique. BMA is an advanced statistical technique for deriving the multi-model ensemble and combines the individual models using optimized weights; weights being proportional to the relative skills of models in reproducing observed data over a historical baseline. The regression model in BMA takes into account all conceivable combinations of variables (in this case, GCMs) before calculating a weighted average. The posterior model probability (PMP) used as a weight is a measure of the model's skill during training (Raftery et al. 2005). Let k be the number of available models; the maximum count of regression models is $s = 2^k$. Here in the study using 6 models, the number of regression models is $s = 2^6 = 64$. PMP of n-th model $\left(M_n \mid D\right)$, in 2^k candidate regression models is computed using Bayes theorem as given in Eq. 8

$$P(M_n \mid D) = \frac{p(D \mid M_n) \cdot p(M_n)}{p(D)} \tag{8}$$

where $p(D \mid M_n)$ is the observed data likelihood given n-th model, $p(M_n)$ is the n-th regression model's prior probability, and $p(D)$ is a constant used for normalizing as given in Eq. 9:

$$p(D) = \sum_{n=1}^{s} p(D \mid M_n) \cdot p(M_n) \tag{9}$$

Different forms of priors are available in the literature; for this investigation, we selected a uniform prior distribution based on Khan et al., (2021), which gives equal weight to all possible regression models. For the likelihood function $p(D \mid M_n)$, Gaussian likelihood (Vogel et al. 2008) was used following Khan et al. (2021). Equatin 10 gives the variable's conditional prediction PDF based on training data.

$$p(y|D) = \sum_{n=1}^{S} p(y|M_n, D) \cdot p(M_n|D) \tag{10}$$

where $p(y \mid M_n)$ is the prediction probability density function (PDF) based on *the* n-th regression model and $p(M_n|D)$ is the associated posterior probability and is being used as weight (Khan et al. 2021). The BMA analysis and visualization were carried out with R software using the various packages viz., *BMA*, *BMS*, *BAS,* and *ensembleBMA*.

SWAT model setup

Hydrological modeling is a key aspect in evaluating the hydrological implications of climatic changes (Praskievicz and Chang 2009). The basin was modeled by employing the SWAT hydrological model to project the changes in streamflow and water budget components for the twenty-first century. The water balance in the model is governed by Eq. 11:

$$SW_t = SW_0 + \sum_{i=1}^{n} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \tag{11}$$

where SW_t denotes the water content of soil at t timestep, SW_0 denotes the initial water content of the soil, R_{day} is daily precipitation, Q_{surf} denotes the surface runoff, E_a denotes the actual evapotranspiration, w_{seep} denotes the percolation, and Q_{gw} denotes the groundwater flow (Bajracharya et al. 2018). The units of all components are in millimeters (mm).

Snowmelt was incorporated in the runoff calculations and is governed by Eq. 12:

$$SNOWmlt = bmlt * snowcov\left(\left(\frac{Tsnow + Tmax}{2}\right) - Tmlt\right) \tag{12}$$

where *SNOWmlt* denotes the amount of daily snowmelt (mm), *bmlt* denotes the factor of daily melt (mm/day °C), *snowcov* denotes the fraction of snow-cover in the hydrological response unit (HRU) area, *Tmax* is the day's maximum temperature, *Tsnow* is the temperature of the snowpack (°C), and *Tmlt* denotes the snowmelt threshold temperature (°C) (Bhatta et al. 2019).

SWAT uses various inputs, viz., climate data, soil map/attributes, land use map/attributes, digital elevation model (DEM), and the observed streamflow. The climatic input variables used are given in "Observed hydroclimatic data". For the current study, the ALOS PALSAR Digital Elevation Model having a grid size of 12.5 m was used (https://search.asf.alaska.edu/#/). The land use/land cover data for the region was produced by the supervised classification of Landsat 8 OLI imagery acquired on 2013/06/03, using a maximum likelihood classification algorithm in ArcGIS 10.2. A total of 11 classes, viz., agriculture, built-up, barren, marshes, pasture, sparse forest, horticulture, water, scrub, dense forest, and glacier/ice were identified. The accuracy of the resultant map was assessed using the Kappa coefficient and had a value of 0.87. Values greater than 0.80 indicate robustness to the perfect amount of agreement (Yonaba et al. 2021b). For soil data, a 30-arc-second raster dataset from the Harmonized World Soil Database (HWSD) of the Food and Agriculture Organization (FAO) was employed.

DEM was employed as an input in the *QSWAT* interface in *the QGIS* environment to divide the catchment into subbasins. A threshold of 10,000 ha was used in the delineation of the drainage network and the analysis identified 41 sub-basins in the Jhelum basin. The smallest model unit is the hydrological response unit (HRU), which is defined by a unique fusion of soil type, slope class, and land use (Romagnoli et al. 2017). Since the seasonal snowmelt determines the basin's hydrology, elevation bands were created to represent the snowmelt as well as the orographic controls of precipitation and temperature. SWAT model provides a maximum of 10 elevation bands for a particular sub-basin and in the present analysis 5 elevation bands were set for the sub-basins having a significant attitudinal range whereas for sub-basins with less orographic differences only one elevation band was used, e.g., Bajracharya et al. (2018).

SWAT model calibration and validation

Multi-site calibration and validation were carried out for the 3 gauges on the trunk stream, viz., Sangam, Asham, and Ram Munshi Bagh. It has been demonstrated that multisite calibration considerably enhances the spatial patterns as depicted by the SWAT model (Gbohoui et al. 2021). Observed monthly streamflow data for 10 years (2002–2011) were used in calibration while as 5 years (2012–2016) were used in the validation of the model. Before the calibration of the model, sensitivity analysis was carried out to filter the most influential parameters determining the streamflow variations. The parameters were ranked as per their sensitivity towards the streamflow using the global sensitivity analysis embedded in the SUFI-2. It employs the p-stat and t-stat to determine the most sensitive parameters, having lower *p* values and higher *t* values (Bhatta et al. 2019). The SWAT-CUP considers the parameter uncertainty, model uncertainty, input error, and yields uncertainty measures like 95% prediction uncertainty (95PPU), r-factor, and p-factor. The r-factor (Eq. 13), which runs from 0 to ∞, is the mean width of the 95PPU divided by the standard deviation of the observational datasets. Similarly, the p-factor refers to the percentage of the observed data series that is encompassed by the 95PPU and ranges between 0 and 1. Satisfactory model performance is indicated by p-factors greater than 0.7 and r-factors less than 1.5 (Abbaspour et al. 2015).

$$r\_\text{factor} = \frac{\frac{1}{n}\sum_{t_i=1}^{n}\left(x_s^{t_i,97.5\%} - x_s^{t_i,2.5\%}\right)}{\sigma_0} \quad (13)$$

where $x_s^{t_i,97.5\%}$ is the upper limit of the 95PPU band and $x_s^{t_i,2.5\%}$ is the lower limit of the 95PPU band at *t* timestep in the *ith* simulation. σ_0 is the observed standard deviation and *n* is the number of data points.

Statistical indicators such as R^2, PBIAS, and NSE were also utilized to assess model performance. NSE was also used as an objective function for parameter optimization during the calibration of the model. Moriasi et al. (2007) and Almeida et al. (2018) have defined the thresholds of satisfactory and acceptable model performance for $0.50 < R2 \leq 0.60$, $\pm 15 < \text{PBIAS} \leq \pm 25$, and $0.36 < \text{NSE} \leq 0.60$.

Multi-model ensemble climatic projections were coupled with the calibrated model parameters to simulate the hydrological implications of changing climatic patterns in the Jhelum basin. After ascertaining the robustness of BMA projections, these were utilized as an input to project the streamflow at Ram Munshi Bagh, Asham, and Sangam gauges under RCP4.5 and RCP8.5. Moreover, the impact of climatic changes was assessed separately on the different components of catchment water balance, viz., evapotranspiration, snowmelt, surface runoff, and water yield. For estimating evapotranspiration (ET), the Hargreaves method (Eq. 14) was used (Hargreaves and Samani 1985). Due to the paucity of observed data, the SWAT simulated output for these components during the baseline run (2001–2010) was used as a reference to estimate the relative changes over the twenty-first century (Bajracharya et al. 2018).

$$ET = 0.0023 \cdot (Tm + 17.8) \cdot (Tx - Tn)^{0.5} \cdot R_a \quad (14)$$

where *T*m, *T*x, and *T*n are the mean, maximum, and minimum air temperatures in °C, respectively. R_a is the water equivalent of solar radiation in mm/day.

Results

Bias correction of the GCM/RCM output

The competence of the bias correction techniques was evaluated by the comparison of RCM data (raw and BC) with the observational data on a monthly scale, using efficiency metrics, viz., R^2, PBIAS, and NSE (Table 2). For *T*max and *T*min, R^2 values were high before bias correction but PBIAS and NSE got significantly improved. The raw *T*max (*T*min) displayed substantial biases, and bias correction minimized the PBIAS from − 60.6 to − 37.40 (− 135 to − 47.2) to 1.9–3.9 (2.3–6.5). Likewise, the NSE values for *T*max (*T*min) in raw RCM were of the order − 0.84 to

Table 2 Performance metrics of the bias corrected (raw) GCM output and multi-model ensemble for the training period (1980–2005)

Variable	Metric	CanESM2	CNRM-CM5	CSIRO-Mk3	IPSL-CM5A-LR	MPI-ESM-MR	GFDL-ESM2M	BMA ensemble
Tmax	R^2	0.90 (0.90)	0.92 (0.88)	0.91 (0.90)	0.90 (0.90)	0.92 (0.88)	0.90 (0.86)	0.94
	PBIAS	3.7 (− 42.5)	2.20 (− 55.40)	1.90 (− 37.40)	4.70 (− 41.4)	3.90 (− 50.3)	2.60 (− 60.6)	0
	NSE	0.89 (0.06)	0.91 (− 0.54)	0.90 (0.25)	0.89 (0.11)	0.91 (− 0.25)	0.89 (− 0.84)	0.94
	KGE	0.94 (0.25)	0.95 (− 0.25)	0.95 (0.39)	0.93 (0.29)	0.94 (− 0.02)	0.94 (− 0.52)	0.94
Tmin	R^2	0.93 (0.97)	0.95 (0.91)	0.94 (0.90)	0.92 (0.87)	0.95 (0.88)	0.92 (0.89)	0.97
	PBIAS	4.4 (− 47.2)	4.7 (− 123.2)	2.3 (− 67.2)	6.5 (− 64.2)	6.4 (− 100)	4.1 (− 135.4)	0
	NSE	0.92 (0.11)	0.95 (− 0.05)	0.93 (0.63)	0.92 (0.55)	0.95 (0.22)	0.92 (− 0.29)	0.97
	KGE	0.94 (− 1.25)	0.95 (− 4.31)	0.96 (− 1.04)	0.93 (− 0.79)	0.93 (− 4.7)	0.94 (− 2.4)	0.95
Prcp	R^2	0.11 (0.04)	0.16 (0.02)	0.20 (0.04)	0.18 (0.03)	0.13 (0.01)	0.13 (0.05)	0.41
	PBIAS	0.8 (130.6)	− 4.30 (150.8)	− 2.10 (57.50)	− 2.30 (116.2)	0.10 (194.2)	4.4 (194.0)	0
	NSE	− 0.40 (− 1.43)	− 0.24 (− 1.49)	− 0.34 (− 1.01)	− 0.40 (− 1.43)	− 0.28 (− 0.36)	− 0.14 (− 1.21)	0.35
	KGE	0.31(-0.39)	0.37 (-0.27)	0.38 (0.04)	0.28 (− 0.36)	0.36 (− 0.35)	0.35 (− 0.40)	0.4

0.06 (− 0.29 to 0.55) and bias correction improved the values to 0.89–0.91 (0.92–0.95). Bias correction procedures worked very precisely for temperature as indicated by the increase in KGE values. In contrast to this, GCMs tend to resolve the precipitation poorly as indicated by lower values of efficiency metrics. However, the bias correction could improve the match between the simulated and the observational data (Table 2). Furthermore, Taylor diagrams (Taylor 2001) are used to display the RCM's performance (raw and BC) (Fig. 2).

Considering the uncertainty in the single RCM output, multi-model ensemble projections were derived using BMA and were also compared with the baseline data. The BMA ensemble data matched more closely with the observed data than any of the individual RCMs, supported by the increased values of the efficiency indicators (Table 2). The PBIAS in the BMA estimates of climatic variables reduced to 0 along with further improvements in R^2, NSE, and KGE. Figure 3 depicts the performance of the BMA technique during the training period.

Climate change projections for the twenty-first century

The projections from the individual models and the BMA ensemble for the Jhelum basin are presented in Table 3. The results infer substantial warming in the annual mean maximum (*T*max) and minimum (*T*min) temperatures with varying rates of warming among the different GCMs. Multi-model ensemble projections show that under RCP4.5, the *T*max (*T*min) of the region will increase by 0.41 (1.39) °C during 2020s, 1.80 (2.12) °C during 2050s, and 2.31 (2.37) °C during 2080s. The rate of the warming for *T*max (*T*min) enhances under the RCP8.5 forcing levels by increments of 0.63 (2.14) °C during 2020s, 2.56 (3.12) °C during 2050s, and 4.82 (4.35) °C during 2080s. While comparing the magnitude of change simulated by the different models, it varied substantially; e.g., for *T*max, it varied from 0.81 °C (CNRM-CM5) to 1.42 °C (MPI-ESM-MR) for the 2020s, 1.59 °C (CNRM-CM5) to 3.01 °C (CSIRO-Mk3) for 2050s, and 2.17 °C (CNRM-CM5) to 3.66 °C (CSIRO-Mk3) for 2080s under RCP4.5 forcing levels. CNRM-CM5 showed consistently the least amount of change for *T*max and *T*min during the different spans of the twenty-first century under both RCPs. The station-scale BMA projections (Table 4) reveal higher warming rates in *T*max and *T*min for the Gulmarg, while the lowest warming rates were found for Srinagar (*T*max) and Pahalgam (*T*min). Moreover, ensemble estimates project enhanced night-time warming in the region over the twenty-first century pinpointed by the higher warming rates of *T*min as compared to the *T*max. The asymmetrical warming patterns of *T*max and *T*min exist even between models and also among the different spans of the twenty-first century, e.g., the CSIRO-Mk3 model projects higher rates of warming in *T*min than *T*max for the 2020s and vice versa during the 2050s and 2080s. The BMA projections for the *T*max and *T*min in the Jhelum basin are shown graphically in Fig. 4a and Fig. 4b, respectively.

Precipitation projections for the Jhelum basin show reductions over the twenty-first century vis-a-vis the baseline (1980–2010). The BMA estimates project decreases by 7.2–4.57% (RCP4.5) and 4.75–2.47% (RCP8.5) during the different periods of the twenty-first century. Even though precipitation tends to increase from the 2020s to the 2080s (Fig. 4c), there is a net decrease when compared to baseline values. The diminishing patterns of precipitation rhyme across all the individual models although with higher magnitudes than BMA estimates (Table 3), except IPSL-CM5A-LR which projects an increase of 9.6% in the precipitation of the Jhelum basin during the 2080s under RCP8.5. The station-scale BMA estimates (Table 4) show enhanced decreases for Kokernag (RCP4.5 and 8.5), Kupwara (RCP4.5 and 8.5), and Gulmarg (RCP8.5). In contrast to this, stations like Gulmarg (RCP4.5) and Qazigund (RCP 8.5) witness increases in the precipitation, while Srinagar shows almost no change (< 1%) over the twenty-first century when compared with the baseline precipitation.

SWAT model calibration and validation

Any hydrological model must be adequately calibrated and validated before adopting its outputs for further analysis. The SUFI-2 algorithm, embedded within the SWAT-CUP, was employed to calibrate and validate SWAT. Multi-site calibration was done for Sangam, Asham, and Ram Munshi Bagh gauges, located on the trunk stream using the observed mean monthly streamflow values for 2000–2010. The model was validated using 5 years (2011–2016) of streamflow data. Prior to that, sensitivity analysis was executed to limit the count of parameters. Table 5 shows the 11 most sensitive parameters as well as their *p* value and t-stat, important in the estimation of streamflow variability. The model conformity during its calibrating and validating process was assessed using 3 statistical indicators, viz., R^2, PBIAS, and NSE. Furthermore, the uncertainty of the model outputs was evaluated using the r-factor and p-factor. The r-factor varied between 0.69 and 0.84 for the calibration period and 0.63 and 0.74 for the validation period. Similarly, the p-factor was found to be 0.39–0.47 and 0.43–0.54 for the calibration and validation phases. Overall, the uncertainty values reflect the satisfactory model performance; however, the r-factor in some instances was slightly less than the threshold value (0.7). Given the dearth of quality observed streamflow data for the region, such values can be taken as the acceptable limits of model performance. Table 6 shows the performance metrics of the SWAT model and the values reflect that model

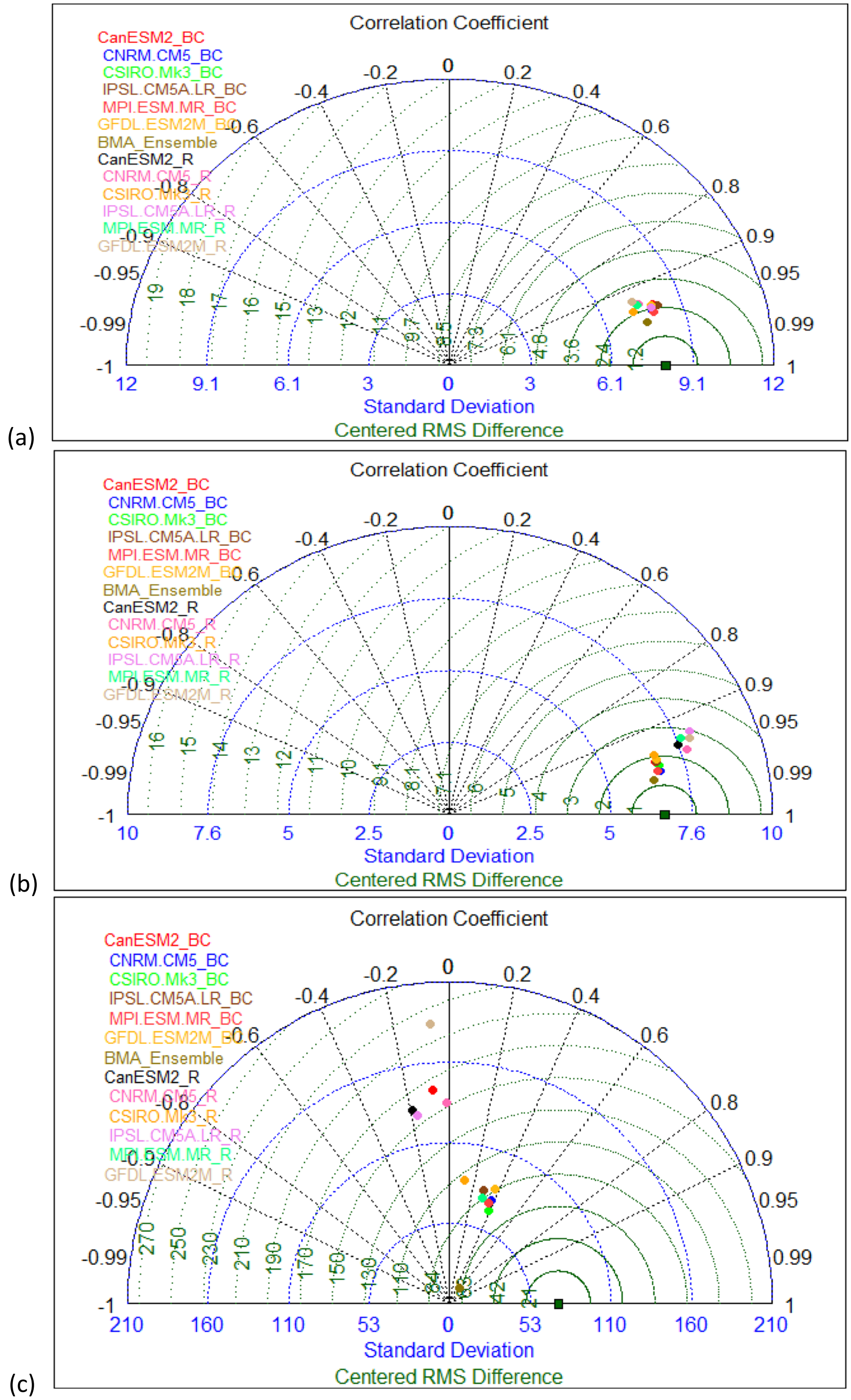

Fig. 2 Performance of GCMs and BMA ensemble during training period (1980–2005); **a** mean maximum temperature, **b** mean minimum temperature, and **c** precipitation. BC = bias-corrected GCM output, R = raw GCM output

performance was well within the acceptable limits. The close agreement between actual and modeled streamflow (Fig. 5)

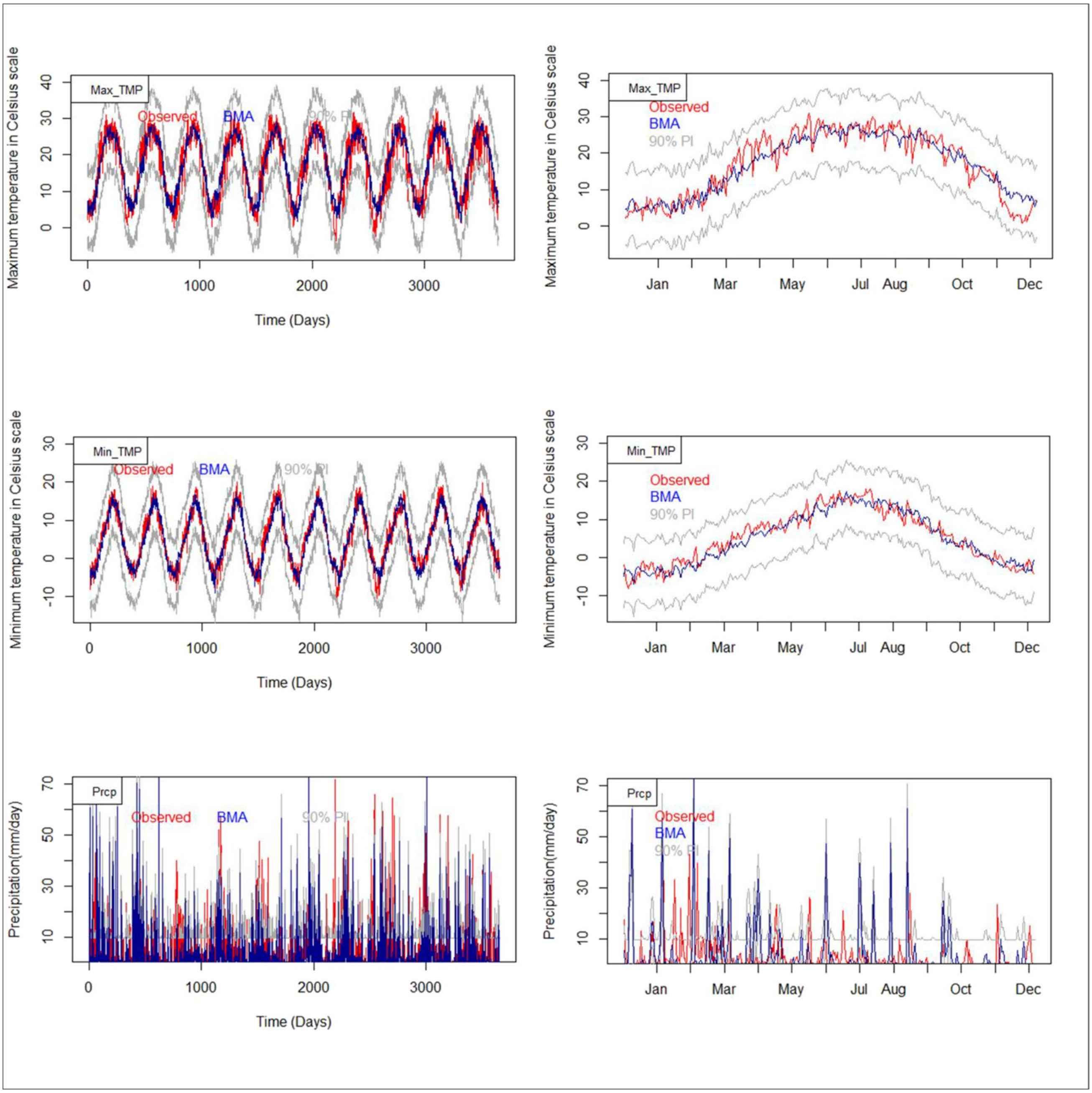

Fig. 3 Performance of the BMA during training period: left, daily data for 10yrs and right, data for only 1 year for detailed visualization. Max_TMP = mean maximum temperature, Min_TMP = mean minimum temperature, and Prcp = precipitation

reveals that the validated model could be employed with considerable confidence and accuracy to model hydrologic responses to climatic changes.

Projection of streamflow under climate change scenarios

After the calibration and validation, SWAT was employed to translate the climatic change signals into streamflow responses using the multi-model ensemble climatic projections obtained using BMA. The relative changes in the streamflow during the different spans of the twenty-first century were compared with the baseline (2001–2010) values for 3 gauges (Sangam, Asham, and Ram Munshi Bagh) located along the course of the trunk stream (Table 7). In the wake of rising temperatures and declining precipitation patterns, the Jhelum basin is going to witness substantial reductions in streamflow over the twenty-first century.

Table 3 Projected changes in mean maximum temperature (*T*max), mean minimum temperature (*T*min), and precipitation (Prcp) under RCP4.5 and RCP8.5 with respect to the baseline (1980–2010) for Jhelum basin

		RCP4.5			RCP8.5		
Variable	Model	2020s	2050s	2080s	2020s	2050s	2080s
Tmax (˚C)	CanESM2	1.13	3.00	3.57	1.27	3.63	6.02
	CNRM-CM5	0.81	1.59	2.17	0.83	2.17	3.44
	CSIRO-Mk3	1.12	3.01	3.66	1.03	3.24	5.64
	IPSL-CM5A-LR	1.26	2.98	3.54	1.05	3.61	6.30
	MPI-ESM-MR	1.42	2.55	2.95	1.66	3.35	5.71
	GFDL-ESM2M	1.09	2.05	2.46	1.30	2.86	4.67
	BMA Ensemble	0.41	1.80	2.31	0.63	2.56	4.82
Tmin (˚C)	CanESM2	2.19	3.10	3.31	2.90	4.05	5.32
	CNRM-CM5	1.20	1.67	2.00	1.47	2.15	2.95
	CSIRO-Mk3	1.77	2.76	3.07	2.13	3.23	4.69
	IPSL-CM5A-LR	2.29	3.02	3.26	2.74	4.03	5.36
	MPI-ESM-MR	1.64	2.36	2.57	2.21	3.30	4.71
	GFDL-ESM2M	1.55	2.06	2.30	2.30	3.14	4.23
	BMA Ensemble	1.39	2.12	2.37	2.14	3.12	4.35
Prcp (%)	CanESM2	− 19.88	− 26.84	− 12.05	− 17.86	− 17.36	− 7.82
	CNRM-CM5	− 25.90	− 13.51	− 18.65	− 28.57	− 20.33	− 11.36
	CSIRO-Mk3	− 17.98	− 13.83	− 9.35	− 10.80	− 5.52	− 8.64
	IPSL-CM5A-LR	− 30.59	− 19.61	− 8.64	− 25.61	− 14.46	9.66
	MPI-ESM-MR	− 34.03	− 30.26	− 28.05	− 27.52	− 31.94	− 30.84
	GFDL-ESM2M	− 25.02	− 17.88	− 15.60	− 12.34	− 13.71	− 7.37
	BMA Ensemble	− 7.20	− 5.88	− 4.57	− 4.75	− 4.51	− 2.47

Table 4 BMA estimates of the station scale changes in mean maximum temperature (*T*max), mean minimum temperature (*T*min), and precipitation (Prcp) under RCP4.5 and RCP8.5 with respect to the baseline (1980–2010) for Jhelum basin

		RCP4.5			RCP8.5		
Variable	Station	2020s	2050s	2080s	2020s	2050s	2080s
Tmax(˚C)	Gulmarg	0.87	2.14	2.66	1.03	2.96	5.21
	Kokernag	0.49	1.81	2.33	0.65	2.63	4.92
	Kupwara	0.45	1.79	2.32	0.54	2.62	5.03
	Pahalgam	0.71	1.88	2.34	0.84	2.63	4.72
	Qazigund	0.62	1.93	2.45	0.71	2.66	4.93
	Srinagar	0.48	1.68	2.19	0.60	2.48	4.69
Tmin(˚C)	Gulmarg	1.63	2.36	2.65	2.25	3.37	4.72
	Kokernag	1.38	2.11	2.38	2.08	3.17	4.53
	Kupwara	1.55	2.12	2.33	2.37	3.29	4.42
	Pahalgam	0.97	1.69	1.99	1.62	2.73	4.11
	Qazigund	1.61	2.26	2.50	2.31	3.31	4.57
	Srinagar	1.43	2.05	2.27	2.14	3.12	4.35
Prcp (%)	Gulmarg	0.40	5.28	7.25	− 5.26	− 5.48	− 4.39
	Kokernag	− 8.58	− 7.87	− 6.31	− 6.92	− 6.72	− 5.01
	Kupwara	− 5.90	− 5.44	− 4.34	− 3.87	− 4.39	− 2.72
	Pahalgam	− 4.60	− 2.75	− 1.74	− 2.48	− 1.69	0.46
	Qazigund	− 0.64	1.26	2.90	1.81	2.35	4.84
	Srinagar	− 0.51	0.08	0.15	0.29	0.39	0.74

Under RCP4.5 forcing levels, the decreases are of the order 23–27% during 2020s, 30–35% during 2050s, and 31–37% during 2080s. With intensifications in the radiative forcing level under RCP8.5, the reductions also get enhanced with magnitudes of 19–25% during 2020s, 31–37% during 2050s, and 40–46% during 2080s. In comparison to the baseline values, seasonal streamflow tended to decline over time. Summer (JJA) witnesses most of the decreases followed by

Fig. 4 BMA-based projected changes in annual mean maximum temperature (**a**), mean minimum temperature (**b**), and precipitation (**c**) under RCP4.5 and RCP8.5, with respect to the baseline (1980–2010) values for Jhelum basin

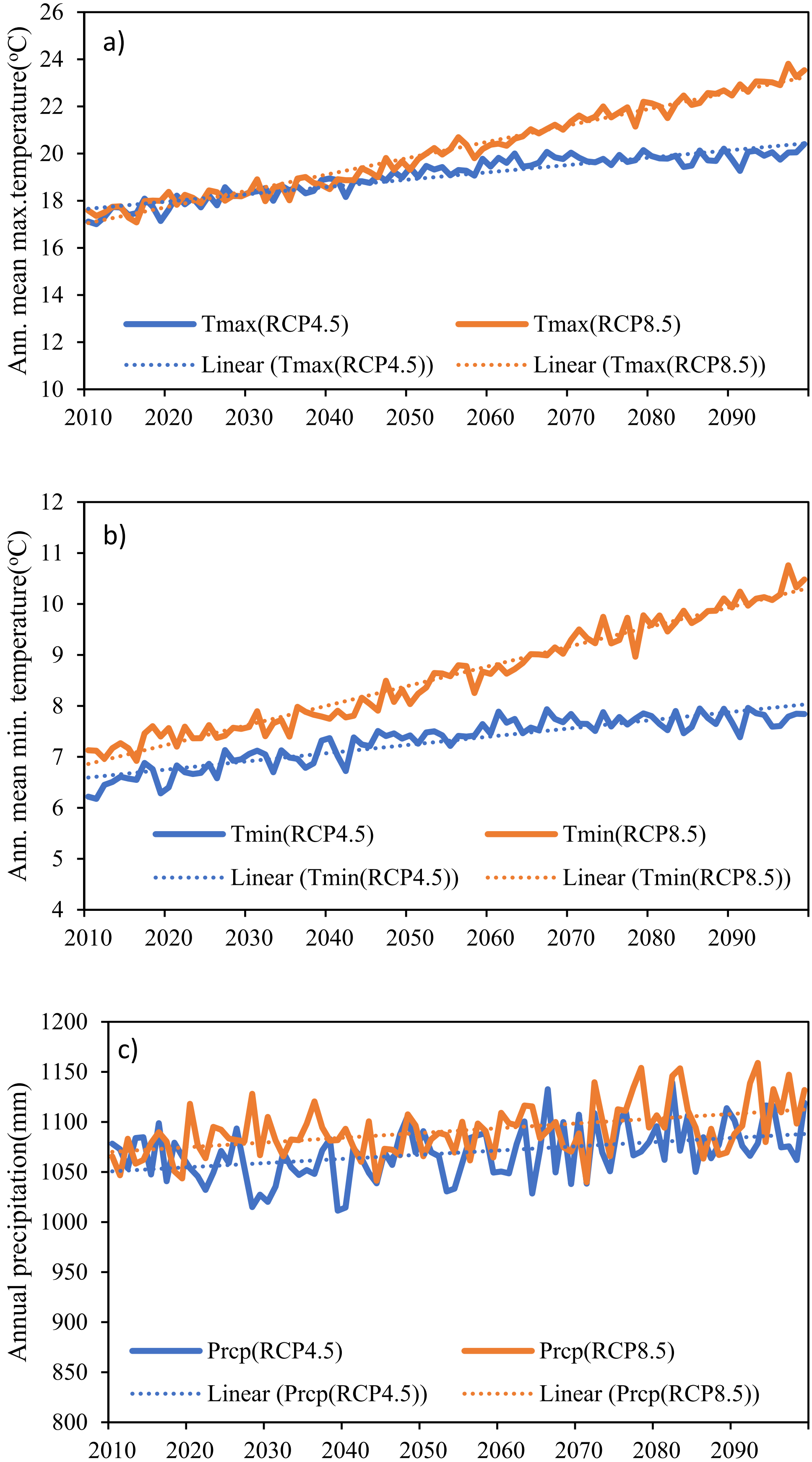

Table 5 List of the sensitive parameters used in calibration of SWAT

Rank	Parameter name	Definition	t-Stat	*p* value
1	v__TLAPS.sub	Temperature lapse rate (°C km^{-1})	− 31.89	0.00
2	r__CN2.mgt	SCS runoff curve number for moisture condition II	− 17.29	0.00
3	v__GW_DELAY.gw	Groundwater delay time (days)	− 12.37	0.00
4	v__RCHRG_DP.gw	Aquifer percolation coefficient	− 9.12	0.00
5	v__SOL_AWC(..).sol	Soil available water storage capacity (mm H2O/mm soil)	6.18	0.00
6	v__SFTMP.bsn	Snowfall temperature (°C)	3.81	0.00
7	v__ESCO.hru	Soil evaporation compensation factor	− 3.37	0.00
8	v__SURLAG.bsn	Saturated hydraulic conductivity (mm/h)	− 2.52	0.01
9	r__HRU_SLP.hru	Average slope steepness (fraction)	2.15	0.03
10	v__EPCO.hru	Plant uptake compensation factor	− 2.14	0.03
11	v__SMTMP.bsn	Snowmelt base temperature (°C)	1.65	0.10

v_ represents replacement of default parameter by given value, r_ represents the relative change in parameter

Table 6 Performance metrics of SWAT model during calibration (2002–2011) and validation (2012–2016) periods

Gauge	Period	R^2	PBIAS	NSE	KGE	p-factor	r-factor
Sangam	Calibration	0.72	− 14.6	0.67	0.76	0.69	0.47
	Validation	0.66	− 19.6	0.62	0.71	0.63	0.54
Ram Munshi Bagh	Calibration	0.81	− 7.4	0.72	0.79	0.84	0.39
	Validation	0.76	− 12.4	0.68	0.73	0.76	0.48
Asham	Calibration	0.75	− 8.1	0.7	0.77	0.75	0.43
	Validation	0.68	− 17.3	0.64	0.69	0.66	0.52

Winter (DJF) and Spring (MAM) under both RCPs. Summer shows a maximum reduction during the 2080s, by about 46–52% under RCP4.5 and 61–67% under RCP8.5. Moreover, Autumn (SON) is the least affected and shows only minimal changes in streamflow over the twenty-first century. For illustrative purposes, the projected variations in mean monthly, annual, and seasonal streamflow of river Jhelum at the Asham gauge under both RCPs are shown in Fig. 6.

Projection of water budget components under climate change scenarios

The variations in the streamflow are governed and linked with the different components of water balance like precipitation, evapotranspiration, surface runoff, snowmelt, etc. After having the precipitation projections for the twenty-first century, the current study also intended to assess the relative changes in other water balance components, viz., actual evapotranspiration (ET), potential evapotranspiration (PET), snowmelt, surface runoff (SurQ), and water yield (Wyield) under climate change scenarios (Table 8). These components were simulated using the SWAT model for the baseline period (2001–2010) from the observational climate data and BMA ensemble climatic projections were employed for future simulations. Due to a lack of observed data, the SWAT simulated output for these components during the baseline run (2001–2010) was used as reference data (Bajracharya et al. 2018). The percentage changes in the water budget components throughout various periods in the tnwety-first century, under both RCPs, were calculated by comparing them to baseline values. Figure 7 shows the projected changes in the Jhelum basin's average annual hydrological components over different periods in the future.

ET was estimated from the Hargreaves method (Hargreaves and Samani 1985), and it witnessed increases over the twenty-first century in the Jhelum basin. Actual ET shows increases of order 18% (20%) during 2020s, 28% (30%) during 2050s, and 31% (40%) during 2080s under RCP4.5 (RCP8.5). The changes in the ET for different sub-basins over the twenty-first century under both RCPs are shown in Fig. 8. ET projections show a progressive increase for the future, determined by levels of radiative forcing and time, viz., near, mid, or end century. This increase in the ET is consistent with the projected increase in the temperatures driven by the enhanced radiative forcing levels. Due to the continuously rising temperatures, the ET values show a consistent rise over the twenty-first century. ET constitutes a major abstraction in the water balance which reduces the net water availability for the runoff and is a measure of the irrigation water requirements.

Snowmelt contribution in the Jhelum basin witnessed significant decreases in the future under the changing

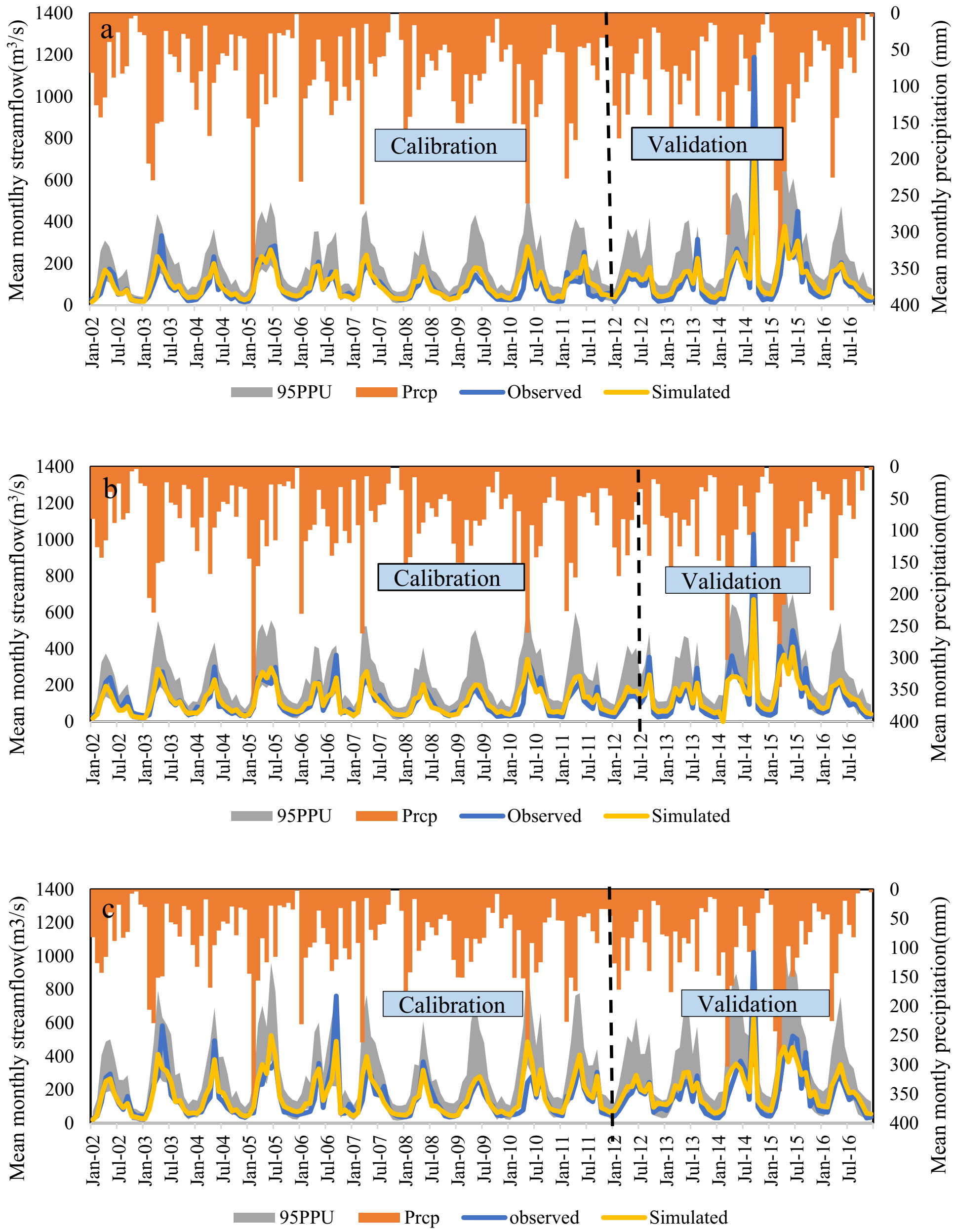

Fig. 5 Multi-site evaluation of the SWAT model during calibration (2002–2011) and validation (2012–2016) periods at Sangam gauge (**a**), Ram Munshi Bagh gauge (**b**), and Asham gauge (**c**)

climatic regimes. The snowmelt shows substantial reductions by about 53% (50%) during 2020s, 58% (62%) during 2050s, and 60% (72%) during 2080s under RCP4.5 (RCP8.5). Moreover, Fig. 9 reveals that most of the decreases will be observed in the sub-basins situated in the lower elevation. The decrease in snowmelt contribution may be attributed to the declining precipitation trends over the twenty-first century. Jhelum basin is projected to witness decreases in the overall precipitation, and this would mean a reduction in the winter season precipitation too that is in the form of snowfall. Significant decreasing trends are already ominous in the winter season precipitation of the Jhelum basin (Ahsan et al. 2021). Furthermore, the warming temperatures would also reduce the precipitation amount falling as snow and there will be more liquid precipitation.

Water yield is a measure of the cumulative water delivered to streamflow by sub-basins/HRUs and includes baseflow, lateral flow, and surface runoff (Andrade et al. 2021; Jain et al. 2017). The average water yield within the Jhelum basin witnessed a decline over the twenty-first century. For the RCP4.5 (RCP8.5), the water yield witnessed reductions by 17.7% (18.4%) during 2020s, 24% (32%) during 2050s, and 25% (42%) during 2080s. Figure 10 shows the spatial variations in the projected water yield of different sub-basins for different spans of the future. The projected decreases in the water yield can be attributed to the enhancement of the ET levels and decreases in the snowmelt contribution over

Table 7 Projected changes (%) in streamflow of Jhelum under multi-model ensemble climatic projections for the twenty-first century

Gauge	Season	RCP4.5			RCP8.5		
		2020s	2050s	2080s	2020s	2050s	2080s
Sangam	Winter	−28.54	−37.10	−39.34	−15.89	−34.04	−37.46
	Spring	−31.76	−32.33	−30.61	−28.97	−32.56	−37.22
	Summer	−23.96	−40.80	−45.83	−21.61	−44.20	−61.34
	Autumn	6.83	2.32	1.97	16.07	3.26	−4.82
	Annual	−23.76	−30.53	−31.52	−19.07	−31.15	−39.78
Ram Munshi Bagh	Winter	−31.89	−39.81	−41.84	−19.82	−35.78	−36.84
	Spring	−34.23	−35.21	−33.73	−31.80	−35.91	−40.84
	Summer	−27.46	−43.55	−48.38	−25.22	−46.80	−62.95
	Autumn	2.64	−2.34	−2.91	11.12	−2.01	−10.32
	Annual	−26.87	−33.51	−34.52	−22.52	−34.24	−42.38
Asham	Winter	−31.13	−41.38	−44.50	−19.53	−38.54	−41.56
	Spring	−35.06	−35.61	−34.59	−33.22	−37.27	−42.04
	Summer	−27.91	−45.98	−51.91	−27.55	−50.65	−67.94
	Autumn	1.92	−4.71	−5.75	9.80	−4.97	−12.93
	Annual	−27.68	−35.45	−37.28	−24.53	−37.41	−46.31

the twenty-first century. The progressive decline in the water yield during the twenty-first century infers that water availability will get reduced significantly and will aggravate the water scarcity and stresses in the basin.

Discussion

The water resources of the mountainous basins are highly exposed to climatic changes wherein the regional hydrology is dependent on the glacial ice melt and seasonal snowmelt characteristics. The present study is attempted in the Jhelum basin—nestled in the complex folds of the North-Western Himalayas and forms important headwaters of the Indus River system. The imprints of global climate change are well established from the observational datasets in the Jhelum basin and its impacts are already being felt (Ahsan et al. 2021). Few studies (e.g., Ahsan et al. 2022) have also attempted to estimate the magnitude of climatic changes over the twenty-first century. However, these studies are limited in scope because the projections are based on a single GCM. It has been found that GCM outputs inherit considerable uncertainty in them and thus use of a single GCM can yield inaccurate results (Khan et al. 2021). For modeling the hydrological consequences of climatic changes, the development of rigorous and robust climate change projections is a primary requirement. To this end, 6 GCMs dynamically downscaled by the RegCM4 RCM from the CORDEX-SA experiments under a medium stabilizing forcing level (RCP4.5) and an extreme forcing level (RCP8.5) were collated for the present study. The use of RCM output is preferred for the basin-scale assessment than the GCM due to their higher resolution and the local sub-grid processes are parametrized better (Seager & Vecchi 2010). However, the raw RCM outputs may still contain significant biases, particularly over mountainous areas (Fowler et al. 2007). As a result, bias-correcting the RCM outputs is critical, and in this work, the temperature was bias-corrected using the VS approach, and precipitation was bias-corrected using a mix of LOCI and PT techniques. The bias correction significantly improved the performance indicators and yielded an overall better match between the observational data and the RCM simulation results during the baseline (1980–2010). Furthermore, to narrow the uncertainty, multi-model ensemble climate change projections were developed using the Bayesian model averaging (BMA) technique. There is consensus among the climate modeling community that by using the multi-model ensemble climatic projections, the uncertainty can significantly reduce, given the fact that individual models may simulate different aspects of the climate system well and the errors get canceled or reduced in the process (Brient 2019). Moreover, it has been reported that by using multiple simulations from a given RCM for different GCM forcings and emission scenarios, the accuracy of climatic projections can be further improved (Räisänen et al. 2004; van den Hurk et al. 2005; Salathé 2005).

The climate change projections from all the GCMs and BMA estimates show unequivocal warming for the Jhelum basin over the twenty-first century. The temperature increments are progressive over time and vary directly with levels of radiative forcing levels. BMA estimates project warming of *T*max by 0.41–2.37 (0.63–4.82) °C during the various spans of the future under RCP4.5 (RCP8.5). *T*min is getting warmer at a relatively higher rate vis-a-vis *T*max and increases are of the order 1.39–2.37 °C under RCP4.5 and 2.14–4.35 °C under RCP8.5. Precipitation in the Jhelum

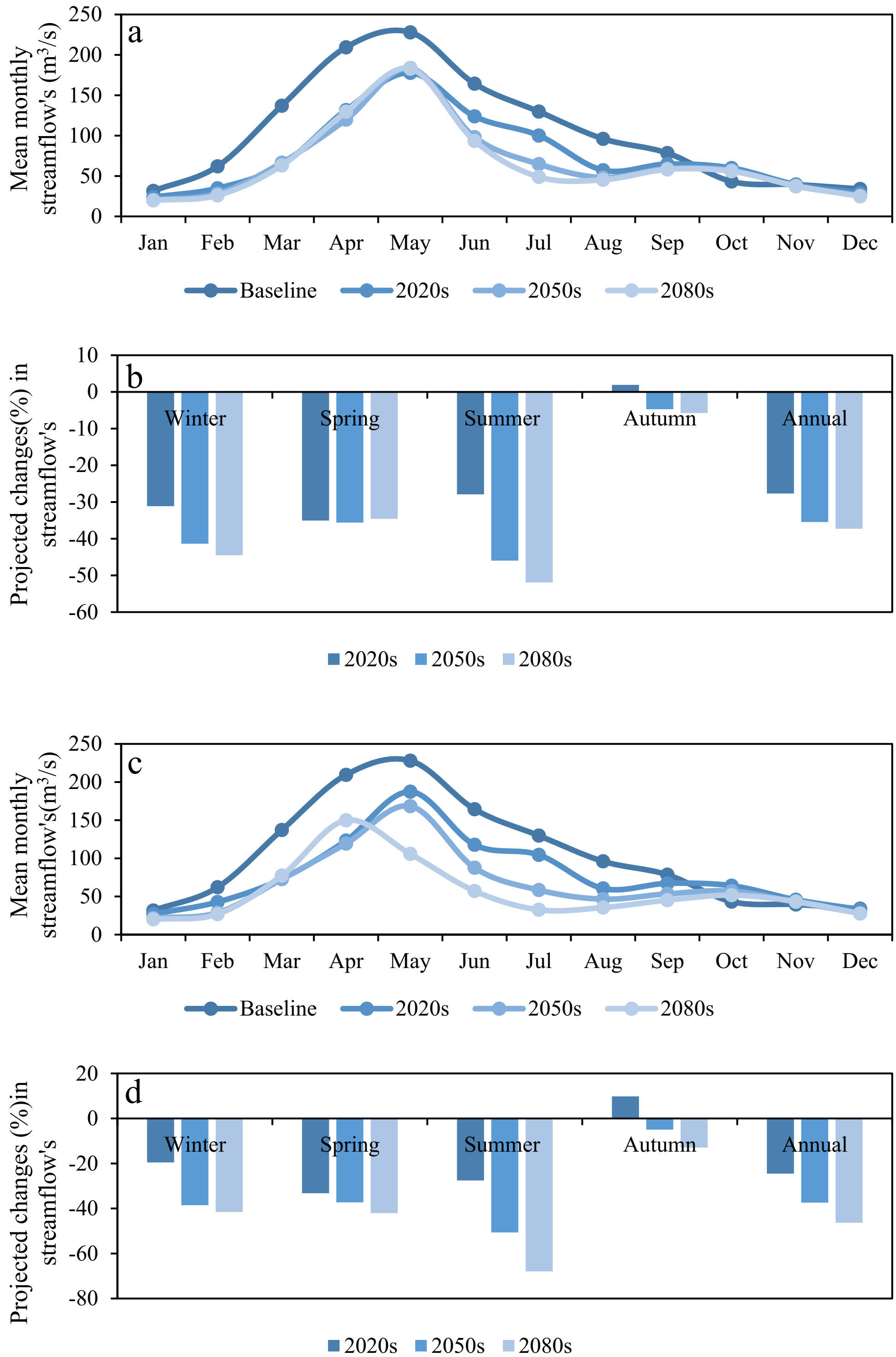

Fig. 6 Projected changes in mean monthly and seasonal streamflow of Jhelum at Sangam gauge under RCP4.5 (**a**, **b**) and RCP8.5 (**c**, **d**) over the twenty-first century

basin witnessed reductions by varying amounts across different GCMs. These changing climatic regimes are going to trigger several implications for key sectors, viz., water resources, agriculture, energy consumption, and human health (Ahsan et al. 2021). The possible implications on the streamflow and water budget of the basin were assessed by coupling the climate change scenarios into the SWAT model. SWAT model performed quite well in simulating the basin hydrology as inferred by high values of the model skill metrics. The streamflow of the river Jhelum is projected to witness substantial reductions over the twenty-first century under both RCPs. The decreases aggravate over time and forcing levels with the highest decrease of about 40–46% for the 2080s under RCP8.5. These reductions in streamflow

Table 8 Water budget components of Jhelum basin under climate change scenarios

		RCP4.5			RCP8.5		
	Baseline	2020s	2050s	2080s	2020s	2050s	2080s
Precipitation	1136.2	1054.39	1069.4	1084.27	1082.23	1084.95	1108.13
Snowmelt	196.02	92.09	82.33	78.41	96.56	75.43	54.45
ET	606.21	715.46	775.71	796.93	725.05	787.1	852.45
PET	1057.93	1021.9	1087.41	1118.15	1006.01	1105.02	1224.22
SurQ	112.6	86.01	80.64	76.16	82.66	78.4	73.92
Wyield	357.96	294.42	272.76	267.75	292.06	243.45	208.02

Units: millimeters (mm)

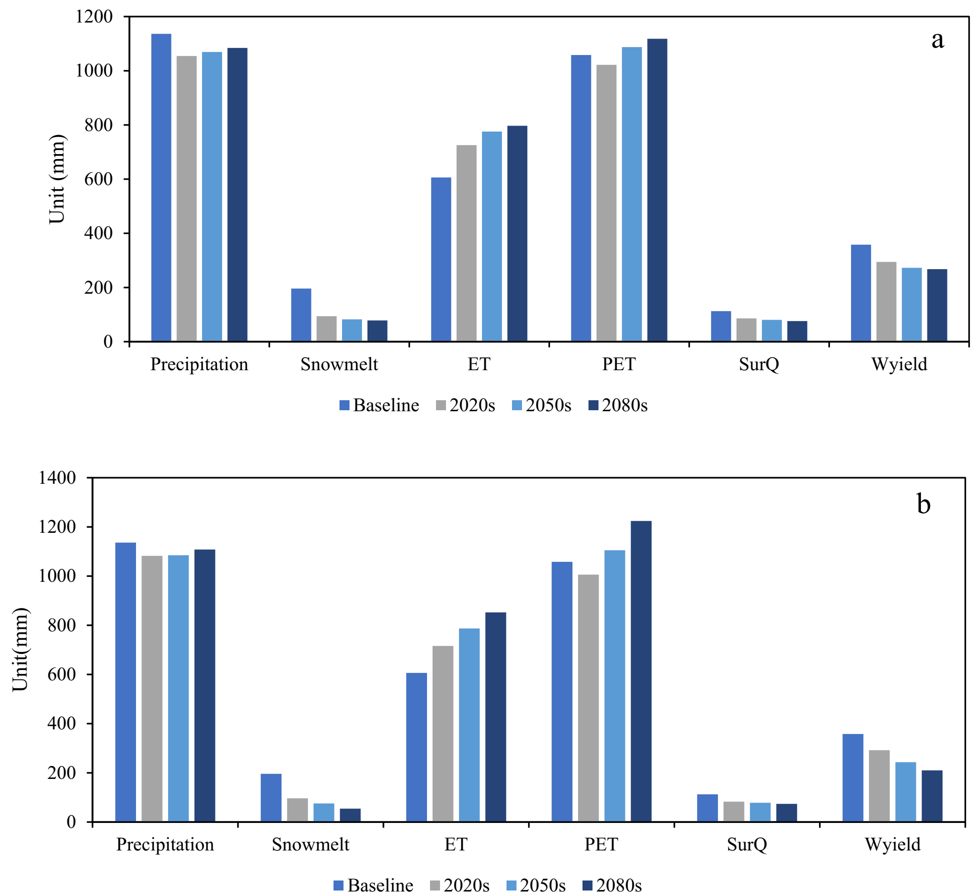

Fig. 7 Projected changes in the annual average water balance components of the Jhelum basin under RCP4.5 (**a**) and RCP8.5 (**b**) over the twenty-first century

are driven by influences of climatic changes on the different components of the water budget like evapotranspiration and snowmelt. Both potential and actual ET are showing a rise over the twenty-first century in response to the projected warming. Actual ET in the Jhelum basin witnessed a maximum increase of 31% under RCP4.5 and 40% under RCP8.5 during 2080s. Increases in the ET under climatic warming have been stated in other relevant studies like Andrade et al. (2021), Bajracharya et al. (2018), and Reshmidevi et al. (2018). Snowmelt is another important component of regional hydrology and sustains the streamflow in the Jhelum basin during the dry months (Jeelani et al. 2012). Under the changing climate, snowmelt witnessed a reduction of 50–70% over the twenty-first century. The decrease in the snowmelt may be attributed to the coupled impact of warming temperatures and diminishing precipitation. Higher temperatures particularly during the winter would cause more precipitation in the form of rain than snow and would ultimately decrease the snowmelt contributions. The decreasing snow and increasing rain proportion in the precipitation are already being observed in the basin as reported by Romshoo et al. (2018). This will also lead to the enhanced ablation of the glacial reserves in the basin. The glacial recession has amplified significantly in

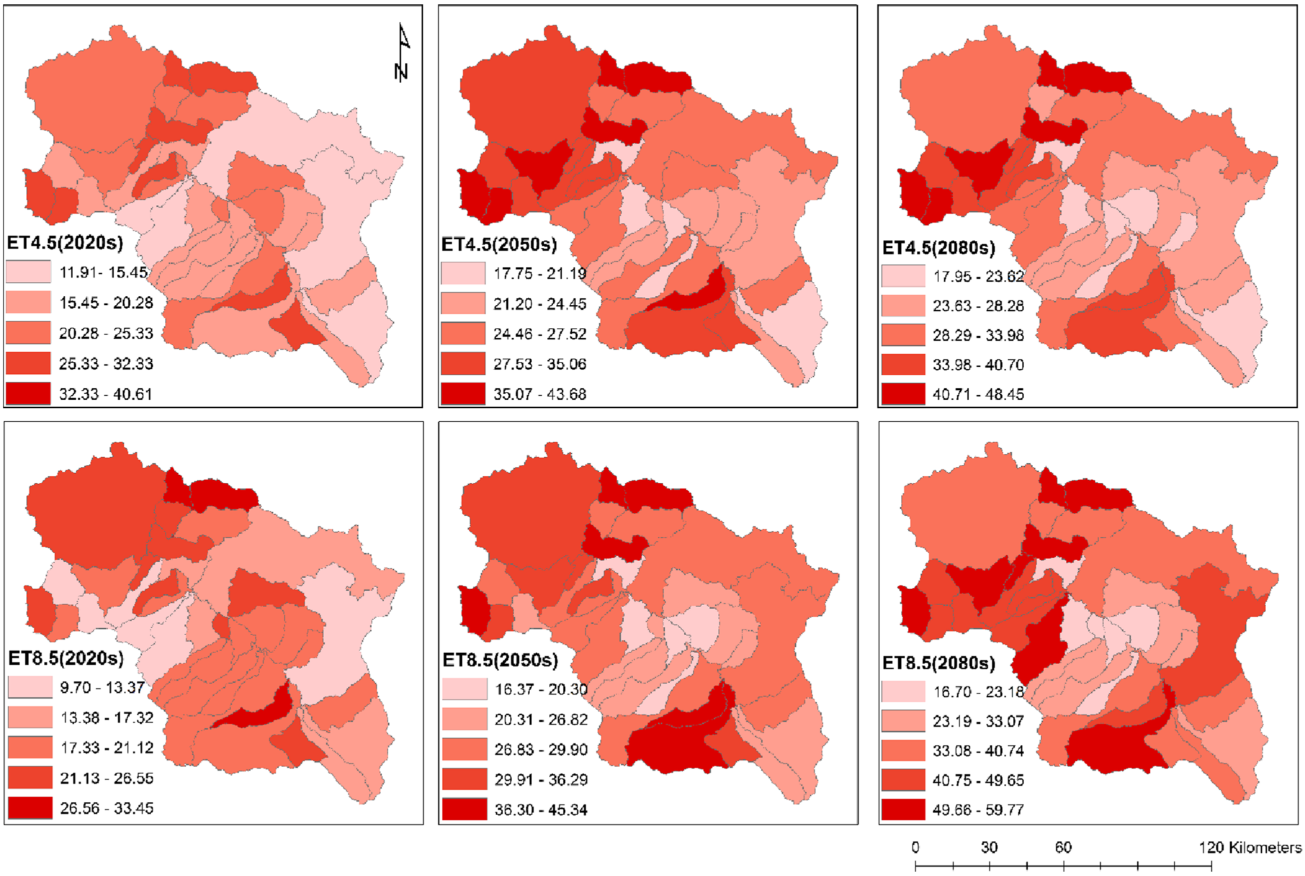

Fig. 8 Spatial distribution of the projected changes (%) in evapotranspiration of the Jhelum basin under RCP4.5 (top) and RCP8.5 (bottom)

the region during the last few decades (Murtaza & Romshoo 2016). Another important aspect of the snowmelt characteristic driven by the increasing temperatures is the earlier melting of the snowpacks. This impact is discernible during the 2080s under RCP8.5 where the peak streamflow month is showing a shift from May to March (Fig. 6c). This shifting of peak streamflow has been reported in numerous other snow-fed basins of the world and tends to create issues for water resource management due to the shifting of peak streamflow period away from peak demand season (Barnett et al. 2005). The combined impacts of the ET and snowmelt are yielding a decrease in the water yield of the basin and hence streamflow.

The current study evaluated the effects of climate change on the streamflow and water balance components using static land use. However, the regional water balance could potentially vary as a result of changes in land use in both the present and future states. Over the recent past, there have been rampant land use changes in the basin with a considerable reduction in water bodies and a progressive increase in the built-up area and horticultural area (Alam et al. 2020). The effects of climate change on streamflow may get exacerbated or get better as a result of these changes. The integration of dynamic land use in the SWAT model can further narrow the band of uncertainty and make the inferences more robust (Yonaba et al. 2021a). Hence, this still stands as the study's primary limitation, and future research should attempt to model the combined effects of land use and climate change scenarios. Also, under the scenario of diminishing surface water availability, groundwater would be a key resource in sustaining the future water demand (Sheikh et al. 2022). There is also a significant requirement for modeling groundwater availability vis-à-vis climate change for integrated water resource management.

Conclusions

The discharge from the rivers in the Jhelum basin is of tremendous importance from the perspective of ecology, environmental health, and water security. The river waters are generally tapped for irrigation, hydropower generation, domestic consumption, and recreation purposes. Hence, any changes in hydrological conditions induced by climatic changes will entail a profound influence on the environment and society. With the application of multiple downscaled

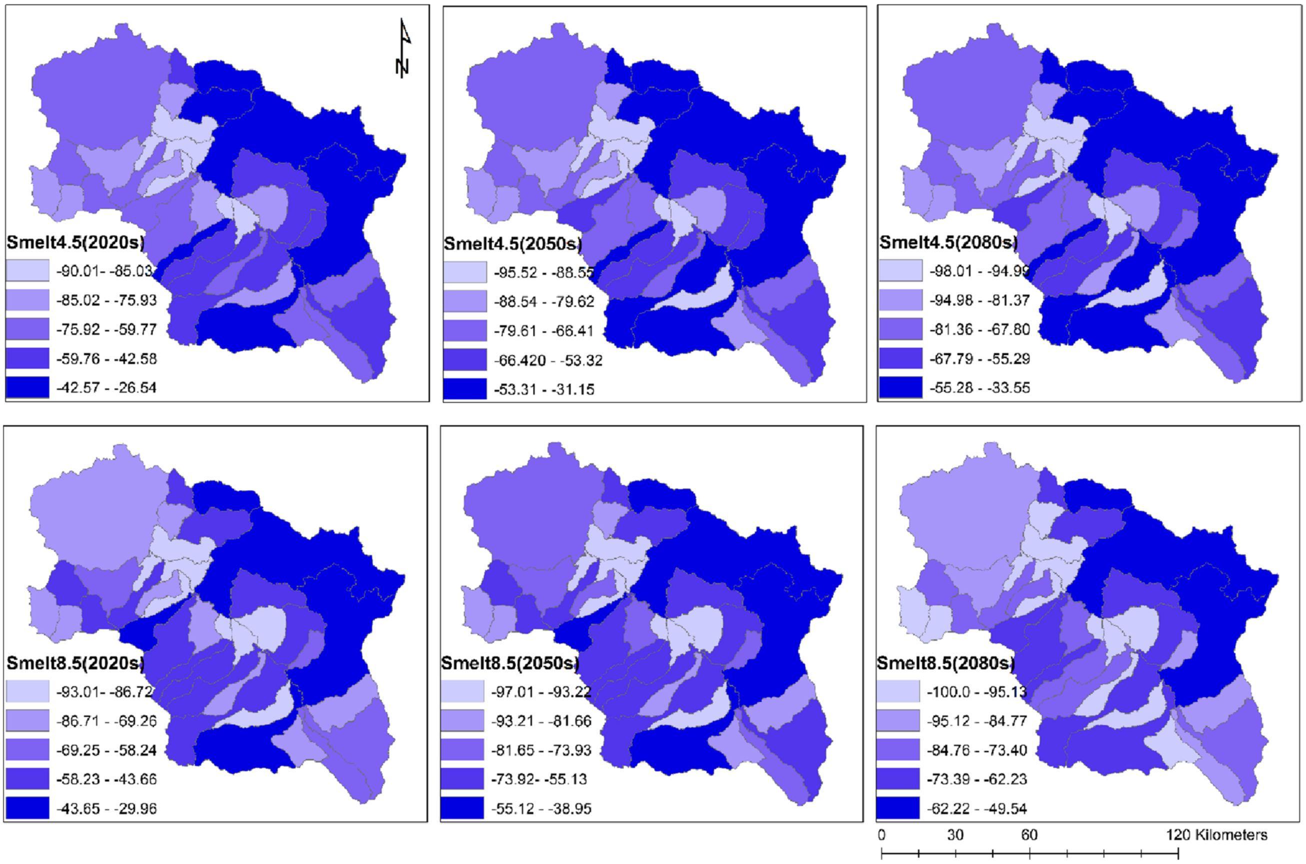

Fig. 9 Spatial distribution of the projected changes (%) in the snowmelt of the Jhelum basin under RCP4.5 (top) and RCP8.5 (bottom)

GCMs and BMA, the present study formulated robust climate change projections with due account of the inherited GCM uncertainties. The hydrological repercussions of climate change in the Jhelum basin for the twenty-first century were assessed with the SWAT model. The changes are projected for the annual mean maximum and minimum temperatures, precipitation percentages, and river discharge. Moreover, changes in the catchment water balance were simulated under changing climatic regimes. This analysis found that the maximum temperature may rise to 4.82 °C and the minimum temperature may go up by 4.35 °C coupled with a reduction in the precipitation to the maximum of 7.2% in the given period. Consequent to the changes in temperature and precipitation conditions, the discharge of the rivers is likely to fall by 17 to 42%. The significant drivers of diminishing streamflow are expected to be an increase in the evapotranspiration levels and a decrease in the snowmelt contributions. Temperature enhancements, the decline in precipitation, and the huge decrease in the seasonal flow of rivers may result in dwindling aquatic ecosystems, loss of biodiversity, reduced productivity, and conflicts in water-sharing agreements, e.g., Indus Water Treaty. The deliverables of the study may therefore serve as a guide for foreseeing future challenges and developing policies to mitigate and adapt to the changing climate and the flow regimes of the river basins in the Himalaya.

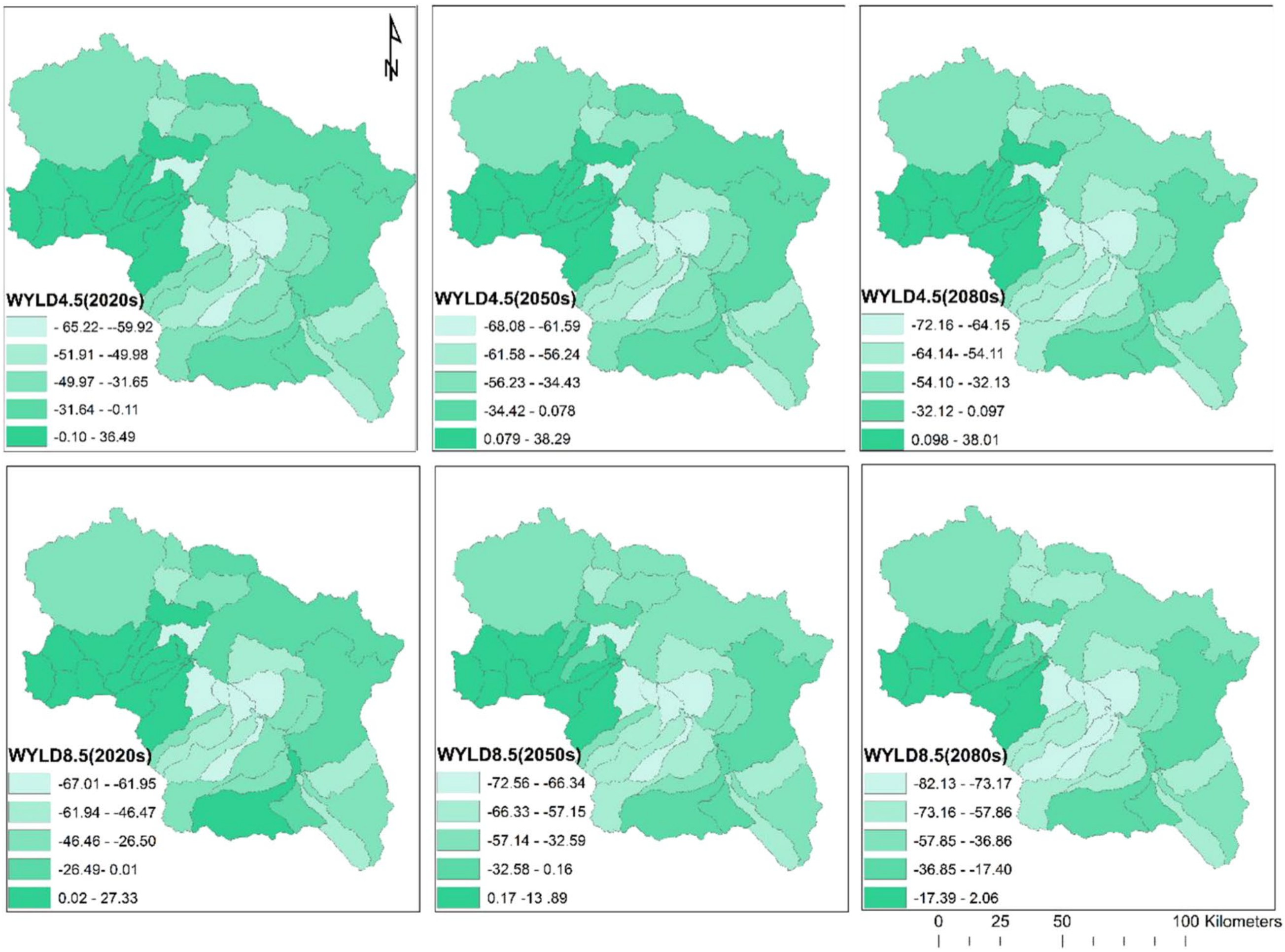

Fig. 10 Spatial distribution of the projected changes (%) in the water yield of the Jhelum basin under RCP4.5 (top) and RCP8.5 (bottom)

Acknowledgements The Working Group on Regional Climate of the World Climate Research Programme and the Working Group on Coupled Modelling, which served as CORDEX former coordinating body and was responsible for CMIP5, are respectfully recognized. The authors are grateful to the climate modeling groups for creating and making their model results public. CORDEX South Asia data was provided via the Earth System Grid Federation (ESGF) infrastructure and the Climate Data Portal at the Indian Institute of Tropical Meteorology (IITM) for Climate Change Research (CCCR). The authors would like to thank the developers of the CMIP5 climate models for keeping the data in the public domain. Acknowledgments are also due to the developers of the SWAT model and SWAT CUP software.

Author contribution The research was conceived and supervised by M. Sultan Bhat and Akhtar Alam. Shafkat Ahsan carried out the analysis and wrote the first draft. M. Sultan Bhat and Akhtar Alam edited the draft. Hilal Ahmed Sheikh and Hakim Farooq designed the artwork. All authors commented on the previous versions of the manuscript and approved the final manuscript.

Funding This research has been funded by University Grants Commission, New Delhi, under the CPEPA scheme being currently carried out at the University of Kashmir, Srinagar-190006.

Data availability The datasets in the study can be made available upon reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

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To

The Secretary
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Sir

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Theoretical and Applied Climatology (2023) 151:1729–1752
https://doi.org/10.1007/s00704-022-04346-4

RESEARCH

Hydrological extremes and climatic controls on streamflow in Jhelum basin, NW Himalaya

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Received: 6 May 2022 / Accepted: 23 December 2022 / Published online: 6 January 2023

Abstract
The present study intends to assess the climatic controls on the streamflow and its impacts on the changing form of hydrological extremes in the Jhelum basin. The study entails robust statistical analysis of the observed hydroclimatic data (1980–2016) using the standard procedures of trend and abrupt change point detection, flood frequency analysis (FFA), and streamflow drought index (SDI). The coupled impact of rising temperatures (0.024 °C/year) and diminishing precipitation (− 5.71 mm/year) is yielding substantial decreases in the streamflow of the Jhelum basin. The other manifestations of changing climatic regimes are the increasing trends in the spring season (March-May) streamflow and the concurrence of abrupt change points in the streamflow data with climatic variables. The climate change signals are well evident over the hydrological extremes, reflected in an enhanced occurrence of droughts through the latter half of the examined period. Moreover, the flood frequency estimates show that the magnitude of the peak discharges about different return periods has increased significantly during 1986–2016 compared to 1956–1985 estimates. The magnitude of 100-year recurrence interval flood has increased by 10.54–79.58% during 1986–2016. The current study calls for the inclusive restructuring of water management practices to offset the impacts of changing hydrological extremes in the basin.

1 Introduction

The impacts of climate change are extensive, largely affecting different natural and biophysical systems (Ahsan et al. 2022a). Water resources are one of the key sectors, having a high degree of vulnerability from a climate change perspective owing to their direct exposure and dependence on the climatic variables (Kundzewicz et al. 2007). Estimation of streamflow variability is a fundamental aspect of effective water resource management (Sen and Niedzielski 2010; Ilnicki et al. 2014) and has immense significance for society (Croitoru and Minea 2015). Streamflow represents the cumulative effect of various climatic and non-climatic factors in a watershed (Croitoru and Minea 2015). The analysis of streamflow variability on the regional scales is thus important and is largely determined by the regional or local climatic conditions (Klavins et al. 2002). Streamflow is very sensitive to climatic variables and the effect of precipitation is more imminent. In mountain ecosystems like the Himalayas where hydrological characteristics are dependent on the glacier and snowmelt behavior, changes in temperature and precipitation are anticipated to alter the melt processes significantly (Barnett et al. 2005; Immerzeel et al. 2010). Changes in the precipitation amounts are reflected in the volume of runoff, while temperature changes explicitly direct the timing of runoff and result in a seasonal shift in the distribution of runoff (Barnett et al. 2005). The study of historical discharge data and its trends forms the preliminary step in investigating the changing river hydrology before carrying out the modeling setup of the defined hydrological system (Dannenberg 2012). Therefore, it is quintessential to analyze the streamflow data and discern the river flow trends and variability in light of the current climate change. On the global and regional scales, there have been multiple studies describing the trends in streamflow and influences of changing climatic patterns on the river flows (Labat et al. 2004; Kundzewicz et al. 2005; Ma et al. 2008; Milliman et al. 2008; Dai et al. 2009; Döll and Schmied 2012; Danneberg 2012; Ilnicki et al. 2014; Croitoru and Minea 2015; Kundzewicz et al. 2015). In the regional context, significant correlations have been reported between the seasonal climate and the runoff in the upper Indus basin (UIB) (Archer 2003; Fowler and

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Archer 2005; Archer and Fowler 2008; Ahmad et al. 2012; Romshoo et al. 2018; Lone et al. 2022; Mattoo et al. 2021). The signatures of climate variability are apparent in the discharge regimes of the rivers of the northwestern Himalayas, and, subsequently, there has been a general decreasing trend in the dynamics of streamflow patterns (Bhutiyani et al. 2008). Furthermore, the seasonal water availability is also witnessing changes with considerable reductions in the summer (Singh and Bengtsson 2004). The future climatic projections devised for the UIB region demonstrate the impending threats to the biophysical and ecological spheres in consonance with robust fallout on the water resource availability (Akhtar et al. 2008; Orr et al. 2022). However, several studies conducted in the transboundary Jhelum basin or its sub-basins have found that future streamflow will increase in response to climate change scenarios, primarily because of the projected increase in precipitation and temperature over time (Mahmood and Jia 2016; Azmat et al. 2018; Saddique et al. 2019; Munawar et al. 2021; Kumar et al. 2022).

Climate change is leading to significant modifications in hydrological dynamics, with an overall inclination toward the amplification of hydrological extremes (Parry and Cox 2007; Fischer and Knutti 2016; Schleussner et al. 2017). The hydrologic extremes include floods and droughts which affect human lives, economic activities, and environmental functioning. The Jhelum basin has always been prone to floods on account of its unique physiographic setup, and the recent flood of 2014 is a dreadful example (Bhatt et al. 2017; Bhat et al. 2019; Alam et al. 2018). The hydrological droughts severely impact freshwater availability, ecological feedback, and agricultural systems (Van Loon and Laaha 2015) The droughts are primarily induced by meteorological anomalies and anthropogenic stresses (Manfreda et al. 2018). The incidence of hydrological drought is ominous in the reduced water levels in streams, reservoirs, and groundwater levels among which the streamflow is the most important and easily monitored indicator of the quantity of water (Nalbantis 2008). Hence, streamflow is the key component for characterizing the surface water, and hydrological drought can be linked to streamflow deficits compared to normal conditions (Tabari et al. 2013). Characterizing hydrological droughts is a complex phenomenon, and as a result, various indices have been devised (Dracup et al. 1980). However, most of the indices are computationally intensive and are data demanding. Streamflow drought index (SDI) is popular in use and has the distinctness of having features of simplicity and effectiveness (Nalbantis 2008; Tabari et al. 2013; Ozkaya and Zerberg 2019).

The Jhelum basin beholds the erratic behavior in the streamflow in light of the current climatic variability. This is significantly evident from the paradoxical behavior of streamflow patterns as the frequency of flood events has increased while the abnormally low flow regimes are also being observed, posing substantial challenges to water resource management in the Jhelum basin. The implications transcend beyond the water resource sector as most of the impacts on other sectors are mediated via water (Rogers 2008; Zhu and Ringler 2012). The streamflow of Jhelum extensively caters to the water requirements for agriculture, hydropower generation, domestic consumption, and tourism services in the region. Numerous researchers have attempted to evaluate the hydroclimatic variability in the Jhelum basin, e.g., Romshoo et al. (2018), Mattoo et al. (2021), and Lone et al. (2022). The current study adds to the body of research on the significance of water resource availability by examining the recent variability in the hydroclimatic conditions of the Jhelum basin, detecting the abrupt change points in the flow regimes, and identifying the climatic controls of the streamflow at the watershed scale. Furthermore, the study evaluates the response of the hydrological extremes, viz., floods, and droughts to the observed climate variability in the Jhelum basin. Although some studies investigating the flood dynamics in the Jhelum basin have been carried out, e.g., Bhat et al. (2019) and Umar et al. (2021), the temporal changes in the flood intensities in response to climate variability have not been attempted yet. Furthermore, there have been scant studies on the drought phenomenon in the region. The inferences from the study will provide useful insights into the vulnerability of the region to flood and drought events and will act as the benchmark study in the development of sustainable water use policy.

2 Study site description

The Jhelum is a transboundary river whose basin is shared between India and Pakistan. In India, the Jhelum basin epitomizes an elongated Graben-type basin having NW–SE orientation that evolved in the late Miocene or pulled apart sedimentary trough (Alam et al. 2017; Bhat et al. 2019). From the south to the southwest, the Jhelum basin is surrounded by the Pir-Panjal range, and from the north to the northeast, it is surrounded by the Great Himalayan range. The trunk stream Jhelum originates from a spring "Verinag" in the Pir-Panjal range and is joined by numerous tributaries from the right and left banks along its course (Fig. 1).

The region has a moderate climate overall although with distinct and sharp seasonality. The presence of strong altitudinal gradients and orographic controls shape the moderate nature of the climate in the region as compared to the rest of the Indian landmass. The valley records average annual precipitation of about 100.5 cm with annual mean maximum and minimum temperatures of 17.6 ± 0.8 °C and 5.4 ± 0.4 °C respectively (Dad et al. 2021). The major part of the precipitation is

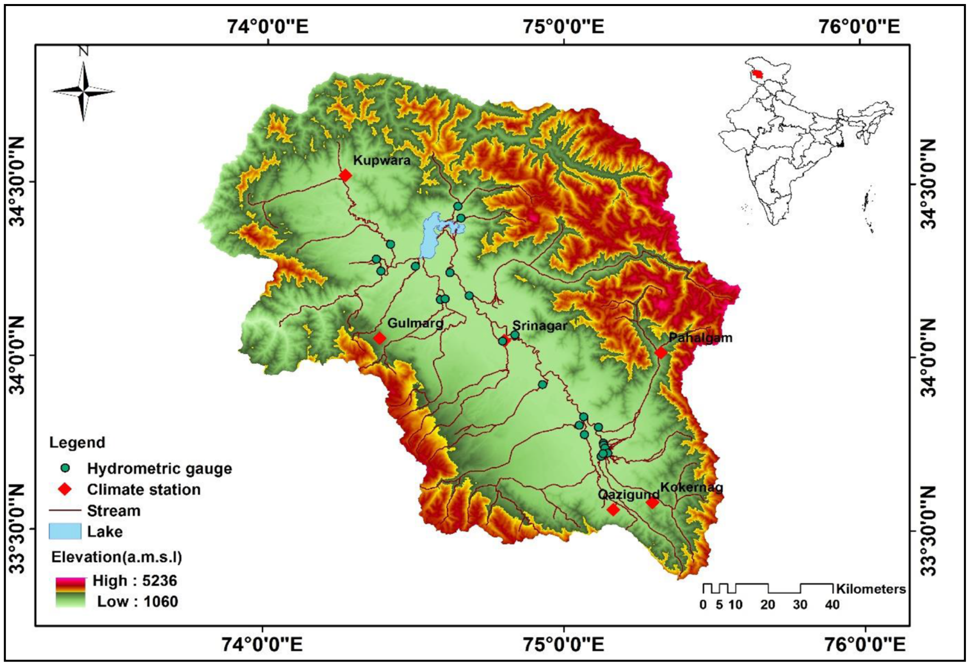


Fig. 1 Location of the climate stations and hydrometric gauges used in the present study

received during the winter months in the form of snowfall due to the western disturbances (Jeelani et al. 2013). The snow accumulates and acts as a buffer for sustaining the flow of the Jhelum and its tributaries during the dry periods. The region hosts about 7 million population with agriculture being the mainstay (Ahsan et al. 2022b). The river Jhelum garners significant regional importance as it provides the water for irrigation, drinking, recreation, and hydropower generation thus generally referred to as the lifeline of the region.

3 Materials and methods

3.1 Observed hydroclimatic data

The present investigation examined time series climate data from 6 weather stations and streamflow data from 24 gauges throughout the basin. Figure 1 depicts the locations of the meteorological stations and hydrometric gauges utilized in the investigation. Tables 1 and 2 show the station information for climatic stations and hydrometric gauges, respectively.

3.2 Trend analysis

The hydroclimatic variables are subjected to trend analysis for deciphering the gradual temporal changes. The most widely used method for detecting trends in meteorological and hydrological variables is Mann–Kendall's test (Mann 1945; Kendall 1975). The test is independent of the normality assumption and is best suited for non-parametric distributions like precipitation and streamflow data (Lins and Slack 1999; Zhang et al. 2001, 2015; Novotny and Stefan 2007; Kundzewicz et al. 2015; Croitoru and Minea 2015). The MK test statistic (S) is calculated as

Table 1 Details of the meteorological stations used in the study

Weather station	Lat	Lon	Elevation (a.m.s.l)	Physiography	Data span	Change point Temperature	Change point Precipitation
Srinagar	34.05	74.80	1588	Flood plain	1980–2016	1997 S ($p = 0.05$)	1996 S ($p = 0.1$)
Gulmarg	34.06	74.39	2705	Mountainous	1980–2016	1997 S ($p = 0.05$)	1998 S ($p = 0.05$)
Pahalgam	34.02	75.33	2310	Mountainous	1980–2016	1997 S ($p = 0.05$)	1997 N.S
Kokernag	33.59	75.30	1910	Karewas	1980–2016	1997 S ($p = 0.05$)	1997 S ($p = 0.1$)
Kupwara	34.53	74.27	1609	Karewas	1980–2016	1997 S ($p = 0.05$)	1996 S ($p = 0.05$)
Qazigund	33.57	75.17	1690	Foot hills	1980–2016	1997 N.S	1997 S ($p = 0.05$)

Table 2 Details of hydrometric gauges used in the study

Hydrometric gauge	Stream	Lat	Lon	Elevation (a.m.s.l)	Data span	Change point	Significance
Gur	Lidder	75.13	33.76	1597.46	1980–2016	1997	S ($p=0.05$)
Odur	Lidder	75.13	33.75	1596.85	1980–2016	1997	N.S
Kirkadal	Lidder	75.12	33.80	1597.76	1980–2016	1997	S ($p=0.05$)
Khanbal	Lidder	75.14	33.74	1600.50	1980–2016	1997	N.S
Mir Danter	Aripath	75.15	33.73	1601.42	1980–2016	1998	N.S
Kadelbal	Aripath	75.15	33.73	1596.54	1980–2016	1998	N.S
Danter	Bringi	75.13	33.73	1601.11	1980–2016	1998	N.S
Ladura	Dakil Nallah	74.39	34.25	1583.44	1980–2016	1998	S ($p=0.1$)
Barzulla	Doodhganga	74.79	34.05	1587.09	1980–2016	2011	N.S
Papchan	Erin	74.65	34.41	1617.88	1980–2016	1998	N.S
Trikulbal	Ferozpore Nallah	74.59	34.17	1583.44	1980–2016	1993	S ($p=0.05$)
Sonawari	Madhumati	74.64	34.44	1638.00	1980–2016	1995	N.S
Tarzoo	Ningal	74.50	34.27	1584.35	1980–2016	1998	N.S
Seloo	Pohru	74.42	34.33	1589.84	1980–2016	1997	S ($p=0.05$)
Nayani	Rambiara	75.05	33.81	1602.03	1980–2016	1990	S ($p=0.05$)
Pahoo	Romshi	74.93	33.93	1589.23	1980–2016	1998	N.S
Trikulbal	Sukhnag	74.60	34.17	1580.39	1980–2016	1998	S ($p=0.05$)
Narayan Bagh	Sindh	74.68	34.18	1583.74	1980–2016	1997	S($p=0.1$)
Minwar	Sandran	75.12	33.72	1598.68	1980–2016	1996	N.S
Chighama	Vij	74.37	34.29	1595.93	1980–2016	1998	S ($p=0.1$)
Arwani	Vishow	75.07	33.78	1600.20	1980–2016	1998	N.S
Asham	Jhelum	74.62	34.25	1582.83	1980–2016	1999	S ($p=0.05$)
Ram Munshi Bagh	Jhelum	74.84	34.07	1586.18	1980–2016	1998	S ($p=0.05$)
Sangam	Jhelum	75.07	33.83	1598.07	1980–2016	1998	S ($p=0.05$)

$$S = \sum_{x=1}^{n-1} \sum_{y=i+1}^{n} sgn(ax - ay)$$

where ax and ay represent the successive data values and n is the time series length.

The sign is computed by Eq. 1 as follows:

$$sgn(ax - ay) = \begin{cases} 1 & ax > ay \\ 0 & ax = ay \\ -1 & ax < ay \end{cases} \tag{1}$$

For $n \geq 8$, the test statistic is assumed to be normally distributed and the standardized test statistic (Z) is computed as follows,

$$Z = \begin{cases} \frac{(S-1)}{\sqrt{V(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & S < 0 \end{cases}$$

where

$$V(S) = \left[\frac{\left(n(n-1)(2n+5) - \sum_m t_m m(m-1)(2m+5)\right)}{18} \right]$$

t_m is the number of data points when $xj = xi$ and m is the number of tied groups.

The positive values of Z infer increasing trends and negative values infer decreasing trends. If the p-value < significance level, the null hypothesis of no trend is rejected and the alternate hypothesis of the presence of the trend in the series is accepted. For the present analysis, the significance levels were set at 0.05 and 0.1.

The slope of the trend (magnitude) was determined by using the Theil-Sen method. This method has the advantage of being insensitive to the effect of outliers on the slope. The Theil-Sen estimate (β) is the "median slope of all slopes determined by all pairs of sample points" (Theil 1950; Sen 1968) and is given by

$$\beta = Median\left[\frac{xj - xi}{j - i}\right]$$

3.3 Abrupt change point test

Detection of the abrupt change points in streamflow data series can aid in understanding the historic changes (Rouge et al. 2013) and thus provides more insights for effective water resource management (Zhang et al. 2015). The Pettitt test (Pettitt 1979) was used to identify the points of sudden changes in the hydroclimatic variables. Pettitt's test initially divides the time series into 2 sub-samples arbitrarily and then uses a rank-based comparison between them. The time series X (n) is divided into two sub-samples at the time step τ and the Pettitt statistics k (τ) is computed as follows:

$$k(\tau) = \sum_{i=1}^{\tau} \sum_{j=\tau+1}^{n} sgn(xj - xi)$$

where *sgn (xj-xi)* is defined as in Eq. (1). The most likely abrupt change point is designated at the time step τ, where $|k(\tau)|$ is maximum. Hence, the final Pettitt's statistics K and abrupt change point timestep T are introduced as given below:

$$T = arg \max_{1 \le \tau \le n} (|k(\tau)|)$$
$$K = \max_{1 \le \tau \le n} (|k(\tau)|)$$

The significance level and the probability associated with the test are approximated by:

$$p \approx 2\exp\left[\frac{-6k^2}{n^3 - n^2}\right]$$

If the p-value < 0.05 (significance level), the hen change point is deemed as significant and the data is divided at τ into two fragments (Ma et al. 2008).

3.4 Climatic controls of streamflow

The linkages between the climatic variables and the streamflow were explored using Pearson's correlation coefficient (r). It has been widely employed in relevant studies like Masih et al. (2011), Fathian et al. (2015), and Azmat et al. (2017). The precipitation and temperature variables having direct control over the streamflow patterns were correlated with streamflow data at different spatial and temporal scales. The correlation of streamflow with temperature was worked out by considering the mean maximum temperature since it has a more direct impact on the streamflow variability, determining the snow/ice melt characteristics and evapotranspiration regimes. On the spatial scale, r was worked out for all the important tributaries (sub-watersheds). For the present study, the hydrological year (Oct–Sep) was considered and was further divided into the winter half (Oct–Mar) and summer half (Apr–Sep). The strength of linkages was also explored for the core water use period (Jun–Sep) from the agricultural point of view. In the recent past, the streamflow of the Jhelum and tributaries has been very low during the peak demand season (Jun–Sep), affecting the water availability in the basin substantially.

3.5 Normality test of data series

Kolmogorov–Smirnov (K–S) test was employed to assess the normality in streamflow data at the significance level of 0.05 (Tabari et al. 2013; Ozkaya and Zerberg 2019). The raw data possessed skewness and was transformed into log-normal distribution. Figure 2 shows the number of data series possessing normal distribution for initial and log-transformed data. For the computations of the SDI, log-transformed data was utilized.

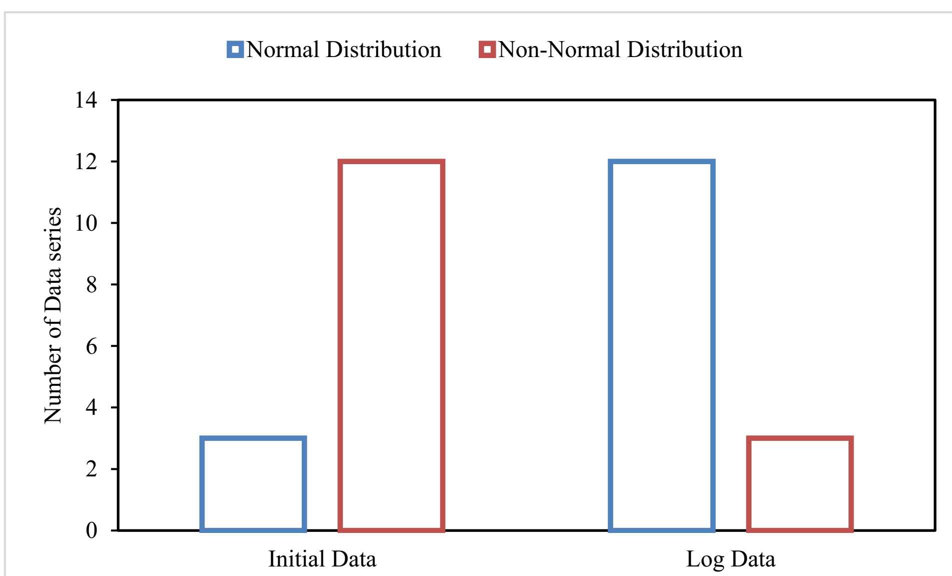


Fig. 2 Number of data series (accumulated streamflow for reference periods) that possessed normal distribution using the Kolmogorov–Smirnov test

3.6 Hydrologic drought assessment

The streamflow drought index (SDI) was used for characterizing the hydrologic droughts. SDI is based on the cumulative streamflow volumes for periods of 3 (Oct–Dec), 6 (Oct–Mar), 9 (Oct–Jun), and 12 months (Oct–Sep) within each hydrologic year (Oct–Sep). In this approach, the drought situation is evaluated every 3 months, and future drought severity estimates can be produced. These periods are termed reference periods in the analysis of SDI. In addition to reference periods, SDI was also calculated for the June–September period, since it is the period in which the water demand is highest.

The monthly streamflow volumes $Q_{i,j}$ (i = year; j = month within the hydrological year) is used to compute the cumulative streamflow volumes $V_{i,k}$ (k = reference period) for the above-mentioned reference periods as

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1,2,3\ldots; j = 1,2,\ldots 12; \; k = 1,2,3,4$$

where $k = 1$ for Oct–Dec, $k = 2$ for Oct–Mar, $k = 3$ for Oct–Jun, and $k = 4$ for Oct–Sep.

Using $V_{i,k}$, SDI is computed for each reference period (k) in the hydrological year (i) as follows

$$SDI_{i,k} = \frac{V_{i.k} - \overline{V_k}}{S_k}$$

where $\overline{V_k}$ and S_k are the long-term mean and standard deviation of the cumulative streamflow volumes for reference period k.

The streamflow data is often skewed, and to reduce the skewness of the data, it is transformed using log-normal distribution function. The final SDI is defined as

$$SDI_{i,k} = \frac{y_{i.k} - \overline{y_k}}{s_{y,k}} \quad i = 1,2,3\ldots \quad k = 1,2,3,4 \tag{2}$$

where $y_{i,k} = \ln(V_{i,k}) i = 1,2,3\ldots, k = 1,2,3,4$ and $\overline{y_k}$ and $s_{y,k}$ are the long-term mean and standard deviation of log-transformed data (Tabari et al. 2013).

Based on the values of SDI, droughts are classified according to severity. The positive values represent the wet periods and the negative values represent the drought conditions. The drought conditions are clustered into different classes based on the severity ranging from mild to extreme drought conditions (Table 3). The SDI analysis was restricted only to the main Jhelum channel. The trunk stream has 3 hydrometric gauge points located along with the profile of the river. The gauges can be taken as representative gauges since all the water from the upper (Sangam), middle (Ram Munshi Bagh), and lower reaches (Asham) drains through these gauges.

Table 3 Drought severity based on the SDI values (Nalbantis and Tsakiris 2009)

Description (drought severity)	Criterion
Non-drought	$0.0 \le \text{SDI}$
Mild drought	$-1.0 \ge \text{SDI} < 0.0$
Moderate drought	$-1.5 \ge \text{SDI} < -1.0$
Severe drought	$-2.0 \ge \text{SDI} < -1.5$
Extreme drought	$\text{SDI} < -2.0$

3.7 Flood frequency analysis (FFA)

Floods are the most prevalent form of "disaster" when it comes to the frequency and incidence of natural disasters in the Jhelum basin. Some studies have been attempted in the Jhelum basin highlighting the vulnerability of the region to flood hazards (Bhat et al. 2019; Umar et al. 2021). These studies have primarily assessed the magnitude of different recurrence intervals; however, no study has been attempted yet that assesses the impact of climate variability on flood frequency and intensity. Flood frequency analysis is a widely used statistical procedure that relates the magnitude of extreme events to their recurrence interval by using probability distribution functions derived from the historical peak discharge data (Stedinger and Cohn 1986). To assess the temporal changes in peak flood magnitudes of different recurrence intervals, 2 independent time spans, viz.,1956–1985 (baseline) and 1986–2016 (current), were subjected to frequency analysis. The peak discharges for 2, 5, 10, 25, 50,100, and 200 years return period floods were estimated using the 2 popular probability distribution models, viz., Gumbel (Gumbel 1941, 1958) and log-Pearson type III (Pearson 1916) for both baseline and current periods. The current period peak flood estimates were compared with the baseline estimates to evaluate the changes (%) in the intensity of different recurrence interval floods.

3.7.1 Gumbel's probability distribution

Gumbel's method is 2 parameter distribution and has wide applicability in predicting extreme events like floods (Zelenhasic 1970; Shaw 1983; Bhagat 2017). Gumbel's distribution and the equation used to predict the magnitude of the flood event (Q_T) of a given return period (T) is expressed as

$$Q_T = \overline{Q} + K.\sigma_Q$$

where $\overline{Q}$ is mean and σ_Q is the standard deviation of the data.

K is the frequency factor and is expressed as

$$K = \frac{Y_T - \overline{Y_n}}{\sigma_n}$$

In which Y_T is reduced variate, expressed as

$$Y_T = -\left[\ln.\ln.\left(\frac{T}{T-1}\right)\right]$$

$\overline{Y_n}$, σ_n are the expected mean and standard deviations of reduced extremes selected from Gumbel's extreme value distribution.

3.7.2 Log-Pearson type III (LP3)

LP3 is also called a 3-parameter Gamma distribution (Millington et al. 2011). It is the most widely used distribution model and has also been suggested by the US Water Resource Council on account of its flexibility (Singh 1998; Bhat et al. 2019). In the LP3 model, the discharge data (Q) is initially transformed into logarithmic series ($Z = Log_{10}Q$), and the equation used to predict the magnitude of the flood event Z_T of the given return period (T) is expressed as

$$Z_T = \overline{Z} + K.\sigma_Z$$

where $\overline{Z}$,σ_Z are the mean and standard deviation of the log-transformed series.

K is the frequency factor, which is the function of the skew coefficient (C_S) and recurrence interval (T).

Skew coefficient (C_S) for a sample size of n is given by

$$C_S = \frac{n\sum(Z-\overline{Z})^3}{(n-1)(n-2)\sigma_Z{}^3}$$

The final value Q_T is given by $Q_T = antilog\left(Z_T\right)$.

3.7.3 Goodness-of-fit test (GoF)

The suitability of probability distributions to a particular site is important in FFA to determine the best-fit distribution which can be discerned by employing the GoF tests (Millington et al. 2011). Kolmogorov–Smirnov (K–S) and Anderson–Darling (A–D) statistical tests were employed for the GoF analysis. It is important to mention here that the null hypothesis in these tests is curated from the sample data having a proposed distribution. Therefore, when the test statistic is less than the critical value at a given significance level ($\alpha = 0.05$), the null hypothesis is accepted. The critical values of A–D and K–S tests at $\alpha = 0.05$ are 2.5018 and 0.20517 respectively. Besides these tests, the cumulative distribution function (CDF) graphs and P-P plots were also used to identify the best-fit distribution.

4 Results and discussions

4.1 General climatic and hydrological characteristics of the region

The region's climate is largely categorized as a sub-Mediterranean type and has four distinct seasons based on the mean climatology (Bagnolus and Meher-Homji 1959). The long-term annual mean maximum (T_{max}) and minimum (T_{min}) temperatures of the basin over the 1980–2016 period are 17.56 °C and 5.37 °C respectively with a well-defined and distinct seasonality. The highest temperatures are recorded during the summer season (JJA), July being the peak month having T_{max} and T_{min} of 26.92 °C and 15.32 °C respectively. The temperature starts decreasing afterward, producing moderate temperatures during the autumn. The temperature dips to its lowest in winter (DJF) and January is the coldest month. The region receives annual precipitation of 1132 mm with much variability between the stations. Gulmarg station receives maximum precipitation (1484.4 mm) while Srinagar receives the minimum precipitation (717.28 mm). The region comes under the influence of the Western disturbances from October to May and yields copious precipitation with a peak centered over March month. About 28% of the annual precipitation is received during the winter (DJF) mainly in the form of snowfall. The snow is retained on the surface, until spring because of the sub-zero temperatures. The influence of WDs continues through the spring season and receives about 37% of the annual precipitation. On the other hand, summer and autumn receive 21% and 13% respectively. The impact of southwest monsoons is hindered due to the obstruction by the Pir-Panjal Mountain range. However, when the monsoon currents are strong enough to cross the barrier, this causes some precipitation in the region. The long-term annual and monthly variations in temperature (T_{max}, regional average) and precipitation (Prcp, regional average) are depicted graphically in Fig. 3.

The mean annual discharge of Jhelum varies between 4207.3 cfs (Sangam), 4721.1 cfs (Ram Munshi Bagh), and 7246 cfs (Asham). The streamflow regime is characterized by the spring and summer maximum with about 132% and 148% of the mean annual discharge at the Asham gauge (tail gauge). Monthly, the highest streamflow is observed in May and the lowest flows are recorded in January for all three gauges. The precipitation received during the winter month is in the form of snowfall and gets accumulated due to the sub-zero temperatures. The spring marks the rise in the temperatures and snowmelt is initiated and continues up to summer. Among the tributaries, Sind, Lidder, and Vishaw are the largest in terms of mean annual discharge

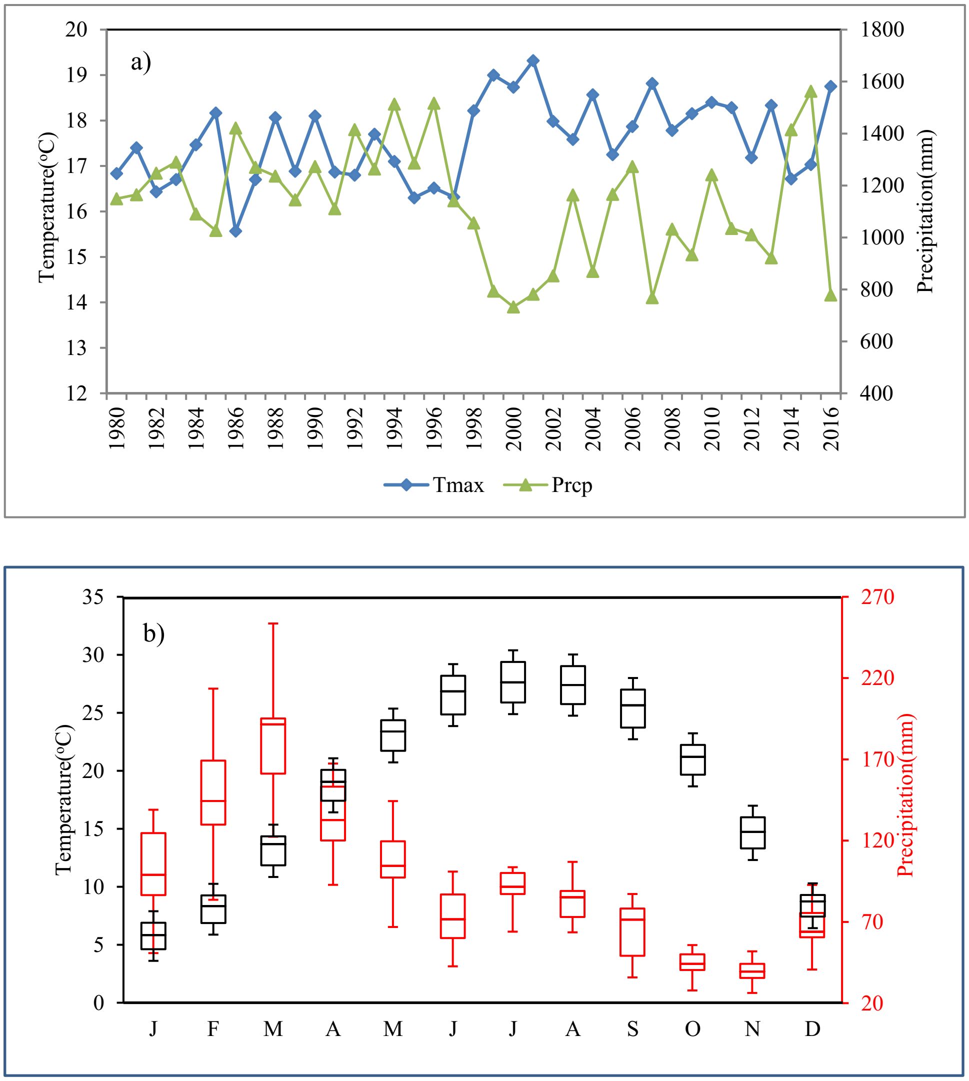


Fig. 3 Temporal variability in the temperature (T_{max}) and precipitation (Prcp) (regional average) at annual scale (**a**), and their intra-annual distribution (**b**)

contributing about 22.1%, 14.1%, and 12.23%, of the discharge respectively. The average annual and monthly variations in the streamflow of Jhelum are shown in Fig. 4.

4.2 Trend analysis of the climate data

The climatic data (1980–2016) was analyzed for the temporal trends using Mann–Kendall's tau test and Sen's slope estimator. The results reveal that the annual mean temperature (T_{mean}) of the region is showing an increasing trend of the magnitude of 0.24 °C/decade ($p=0.05$). The mean maximum (T_{max}) and minimum (T_{min}) temperatures show differential warming patterns as the mean maximum temperature increases at a greater rate (0.34 °C/decade) ($p=0.1$) than the mean minimum temperature (0.16 °C/decade) ($p=0.05$). Moreover, the station scale analysis (Table 4) reveals that the highest rate of warming for annual mean temperature is observed at Pahalgam station (0.42 °C/decade) ($p=0.05$) while the lowest rate is observed at Qazigund (0.13 °C/decade) ($p>0.1$). Seasonally, maximum warming is exhibited for winter with T_{mean} increasing by 0.46 °C/decade ($p=0.05$) followed by the spring (0.43 °C/decade) ($p=0.05$).

The annual precipitation (Prcp) data shows a gradual decrease over the region at the rate of 5.73 mm/year ($p>0.1$). Among the stations, Gulmarg shows the maximum decrease in precipitation (14.11 mm/year) ($p=0.1$). The seasonal distribution of the precipitation is also showing changes with major reductions in the spring season (4.2 mm/year) ($p=0.1$) and marginal reductions in summer, autumn, and winter of order 1.1, 0.3, and 0.7 mm/year ($p>0.1$) respectively. Numerous studies have examined regional temperature and precipitation trends, and their findings are in conformity with the increasing temperature trend and a declining precipitation trend (Zaz et al. 2018; Dad et al. 2021; Ahsan et al. 2021; Umar et al. 2022).

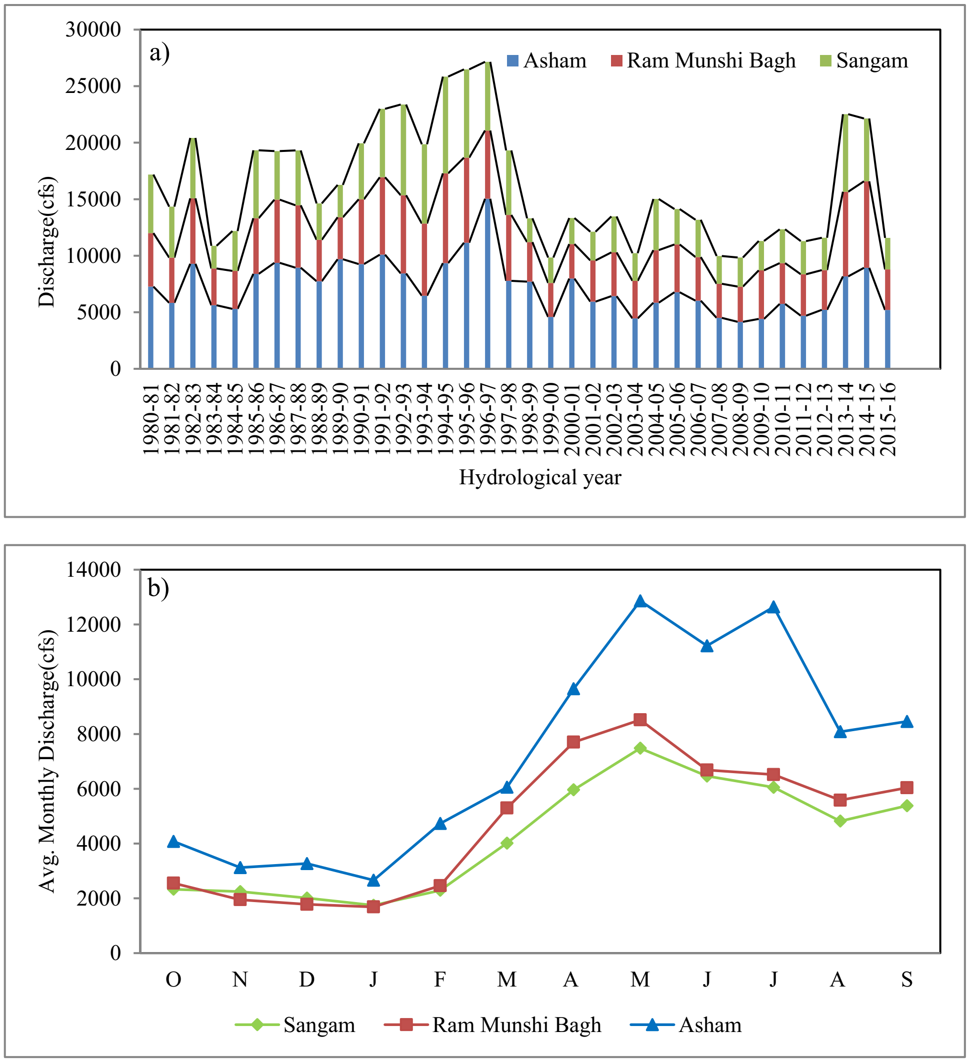


Fig. 4 Temporal variability in the streamflow of Jhelum at annual (**a**), and intra-annual scales (**b**)

4.3 Trend analysis of streamflow data

The streamflow data (1980–2016) were also subjected to trend analysis to look for long-term gradual changes. The trend analysis was carried out for the principal tributaries wherein the hydrometric gauges are installed and also for the gauges on the main channel. The hydrologic year (Oct–Sep) was taken as the annual unit of time. On the seasonal scale, the hydrologic year was divided into the winter half (Oct–Mar) and the summer half (Apr–Sep). Furthermore, the trends were also computed for the spring (Mar-May) and peak demand period (Jun–Sep). The results reveal decreasing trends of streamflow for most of the streams and the trends are usually statistically insignificant (Table 5). On the annual time scale, the Pohru tributary shows a maximum decrease of 11.43 cfs/year ($p=0.1$). There are some statistically insignificant increases on annual scale (Fig. 5a) for streams like Lidder (1.01 cfs/year), Madhumati (0.267 cfs/year), Doodhganga (0.098 cfs/year), Romishi (0.243 cfs/year), and Vij (1 cfs/year). Likewise, for the winter (Fig. 5b) and summer half (Fig. 5c), most of the streams show a decreasing trend. For the summer half, Lidder and Madhumati show statistically significant increases ($p=0.1$) of 5.19 and 4.42 cfs/year. Moreover, for the Jun-Sep period (Fig. 5d), Rambiara and Sukhnag show decreasing trends ($p=0.05$) whereas Madhumati shows an increasing trend ($p=0.1$). For the spring season (Mar-May), Doodhganga ($p=0.05$), Lidder ($p=0.1$), and Vij ($p=0.05$) streams show statistically significant increasing trends (Fig. 5e). Aripath, Romishi, and Vishow also show increasing trends although the trends are statistically insignificant. The trends were also assessed for the gauges on the trunk stream and revealed decreasing trends on all time scales. The tail gauge Asham recorded the highest decreases of magnitude 86.9 ($p=0.05$), 49.44 ($p=0.1$), 112.11 ($p=0.05$), 93.25 ($p=0.1$), and 127.5 ($p=0.1$) cfs/year for annual, winter half, summer half, Jun-Sep, and spring respectively. The present inferences are in line with the other studies which focused on the streamflow

Table 4 Results of Mann–Kendall's tau test and Sen's slope estimator for temperature and precipitation

Station	Variable	Spring	Summer	Autumn	Winter	Annual
Gulmarg	T_{max}	0.045	0.00	0.015	0.02	0.014
	T_{min}	0.039	0.006	0.029	0.033	0.033
	T_{mean}	0.035	0.005	0.011	0.025	*0.027***
	Prcp	− 7.746	− 2.012	− 1.235	− 2.901	*− 14.11***
Kokernag	T_{max}	0.05	0.007	*0.032***	*0.062**	0.039
	T_{min}	0.015	0.00	0.011	0.01	0.014
	T_{mean}	0.033	0.005	0.025	*0.038***	*0.026**
	Prcp	− 2.432	− 0.565	0.191	0.245	2.13
Kupwara	T_{max}	*0.084**	0.02	0.023	*0.071***	*0.047**
	T_{min}	*0.035**	*0.028**	*0.029**	0.007	*0.022**
	T_{mean}	*0.063**	*0.026***	*0.023**	*0.033**	*0.035**
	Prcp	*− 4.812***	− 2.28	− 0.564	0.511	*− 4.66**
Pahalgam	T_{max}	*0.058**	0	*0.026***	*0.076**	*0.041***
	T_{min}	*0.033**	*0.044**	*0.025**	*0.071**	*0.043**
	T_{mean}	*0.048**	*0.023**	*0.025**	*0.076**	*0.042**
	Prcp	*− 4.019***	0.158	1.145	0.352	− 1.71
Qazigund	T_{max}	*0.041**	− 0.007	− 0.024	0.033	0.015
	T_{min}	0.004	0.01	− 0.005	0.022	0.003
	T_{mean}	*0.025***	0.00	− 0.016	0.022	0.013
	Prcp	*− 4.586***	− 0.348	− 0.293	− 1.936	− 5.22
Srinagar	T_{max}	*0.056***	0.006	*0.028**	*0.074***	*0.044***
	T_{min}	*0.025**	*0.023***	*0.032**	0.015	*0.018**
	T_{mean}	*0.039***	0.016	*0.029**	*0.044**	*0.032**
	Prcp	− 1.78	− 0.805	0.024	0.205	− 2.00
Reg. Avg	T_{max}	0.057	0.007	0.02	*0.053**	*0.034***
	T_{min}	*0.026**	0.016	0.018	0.027	*0.016**
	T_{mean}	*0.043**	0.01	*0.016**	*0.046**	*0.024**
	Prcp	*− 4.237***	− 1.173	− 0.313	− 0.768	− 5.73

Numbers in italic represent the statistically significant trends, *significant at 0.05, **significant at 0.1

trends in the Jhelum basin, e.g., Romshoo et al. (2018), Marazi and Romshoo (2018), Mattoo et al. (2021), and Umar et al. (2022).

4.4 Abrupt change in streamflow

The abrupt change points in the streamflow for the various gauge points on the tributaries and the main channel were detected on annual streamflow data using Pettit's test. Significant change points were detected for 12 out of 24 hydrometric gauges at a 5% significance level (Table 2). The change points occurred between 1997 and 1998 for most of the tributaries. Furthermore, the change points in the streamflow are well synchronized with the climatic variations and most often coincide with the abrupt change points in the climatic variables (Table 1). Thus, the change points in the streamflow seem most likely to have been driven by climatic variability, notwithstanding the role of human activities like LU/LC changes that have occurred in the catchments.

4.5 Linkages between climate and streamflow

The climatic variables, viz., temperature and precipitation, were correlated with the streamflow data to explore the strength of the relationship between the climatic variables and streamflow. The streamflow data of the tributaries was initially correlated with all the nearest climate stations, and the station showing the best correlation coefficients was retained for the analysis. On the annual time scale, there exists a significant positive correlation between the streamflow and precipitation (Table 6). The Aripath, Vishow, Lidder, and Sukhnag streams show strong correlation coefficients ($r \geq 0.7$) between the precipitation and the streamflow. Bringi ($r = 0.6$), Romishi ($r = 0.63$), and Pohru (0.61) also show good correlation between the two. The correlation for the winter half is low as compared to the annual series because the precipitation received in the winter months is generally in the form of snowfall and does not produce immediate streamflow. In contrast to this, the correlation

Table 5 Results of the trend analysis for the streamflows of Jhelum and its tributaries

Stream	Annual	Winter half	Summer half	JJAS	MAM
Aripath	−1.9	−3.15	−0.93	−0.27	0.9
Bringi	−0.32	−0.7	−0.95	−0.88	−0.73
Dakil Nallah	−0.34	−0.55	−0.32	−0.54	−0.025
Doodh Ganga	0.098	−0.142	0.198	−0.913	_2.47*_
Erin	−0.297	0.048	−0.594	0.213	_−2.44**_
Ferozpora	−2.69	_−1.143*_	−4.144	−4.836	−1.469
Lidder	1.013	−1.742	_5.198**_	0.674	_6.385**_
Madhumati	0.267	−3.343	_4.426**_	_6.623**_	−5.11
Ningal	−0.109	0.375	−0.845	−0.5	−0.785
Pohru	_−11.432**_	−16.379	_−8.745**_	−0.453	−41.67
Rambiara	−7.128	−7.51	−7.83	_−7.2*_	−7.194
Romishi	0.243	0.468	−0.862	−1.212	1.2
Sandran	−2.138	−1.975	−2.779	−2.75	−4.569
Sindh	−7.948	−15.618	−3.762	4.4	−18.975
Sukhnag	−7.47	−5.14	−11.668	_−12.269*_	−6.195
Vij	1.01	_0.544**_	1.131	0.417	_2.515*_
Vishow	−1.07	−7.764	−1.573	−2.88	0.096
Jhelum (Sangam)	−37.41	_−41.84*_	−46.11	−57.85	−57.16
Jhelum (Ram Munshi Bagh)	−13.66	_−19.87**_	−26.57	−33.7	−41.24
Jhelum (Asham)	_−86.9*_	_−49.44**_	_−112.11*_	_−93.25**_	_−127.5**_

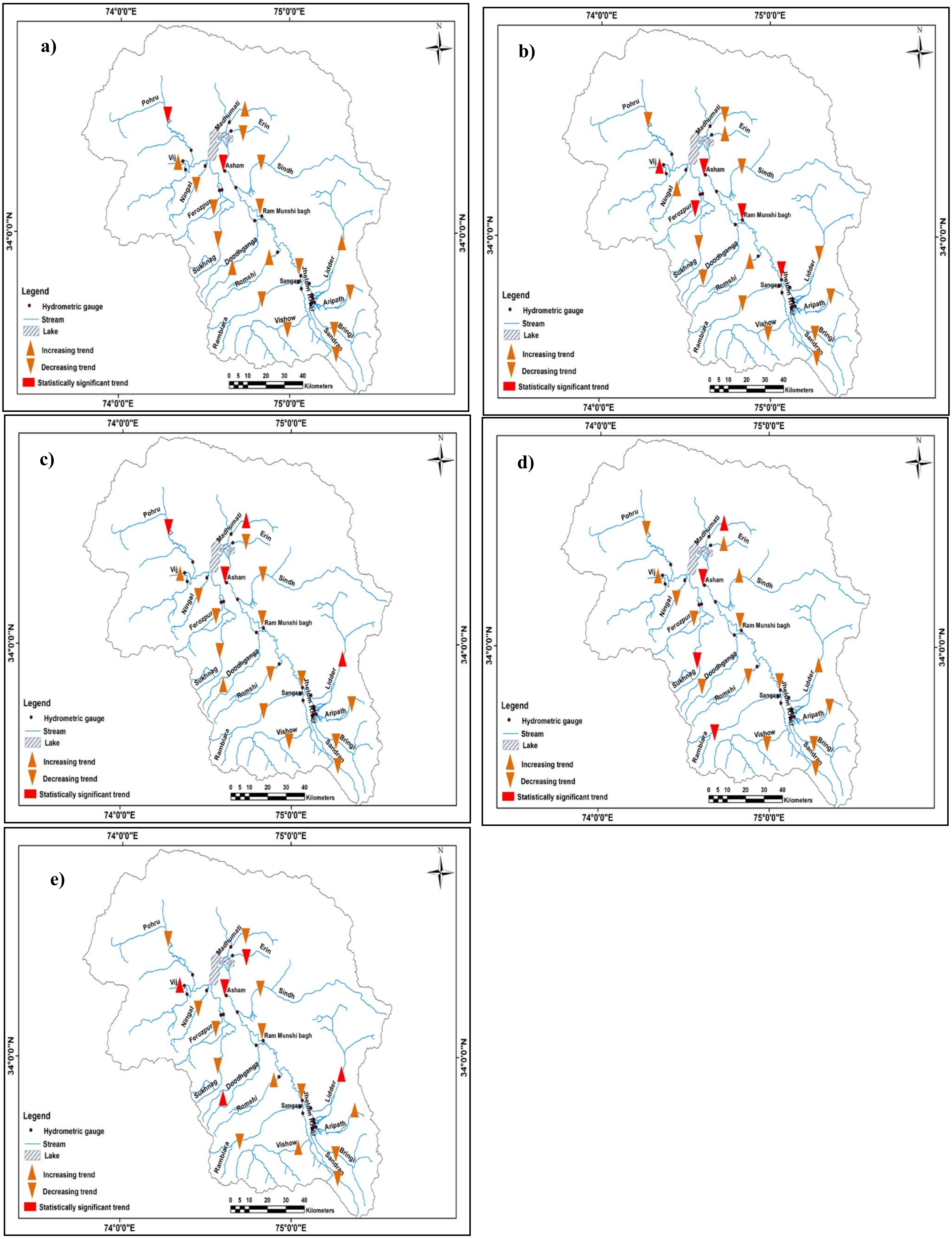
Numbers in italic represent the statistically significant trends, *significant at 0.05, **significant at 0.1

between the summer half precipitation and streamflow is relatively high as the precipitation is in the form of rain and produces immediate streamflow. Moreover, the summer streamflow (Apr–Sep) shows a good correlation with prior winter season (Oct–Mar) precipitation, which signifies the contribution of snowmelt runoff to the hydrology of the Jhelum basin. For the Jun–Sep period, there also exists a positive correlation of the streamflow with concurrent seasonal precipitation and prior winter precipitation. The reasons are well supported by the quantitative estimates drawn from the winter precipitation (snow) indicated by the dominant role of snowmelt in the annual streamflow of Lidder—a tributary of Jhelum (Jeelani et al. 2012, 2013). Furthermore, there exists a negative correlation between the summer temperature and the streamflow (Table 7). The inverse relationship holds on all the temporal scales and streams having glacial sources. Ideally, for the glaciated catchments, the higher temperatures during the summer half causing enhanced ice melt should manifest in the positive correlation between the temperature and streamflow. However, there exists a strong negative correlation ($r = -0.8$) between the temperature and precipitation in the region (Fig. 6d). The precipitation deficit during the summer half and in part the limited glacial reserves dwarf the effects of glacial meltwater increments on the streamflow. Hence, an overall inverse relationship is observed between the two. Keeping in view this relationship, it can be inferred that the glacial ice melt contribution to the streamflow of the Jhelum basin is limited. Jeelani et al. (2012) concur with the current inference of limited glacial melt contribution (2%) in the annual streamflow of the Lidder watershed, which has a pivotal role in the study area having prominent glacial signatures.

On the regional scale, the climatic controls of streamflow are more clearly visible (Fig. 6a). To quantify the strength of linkages, the streamflow at the tail gauge (Asham) was considered and correlated with the temperature and precipitation (averaged over the 5 meteorological stations located upstream of the Asham). The anomalies were computed by subtracting the mean and dividing by the standard deviation of the respective series. The precipitation anomaly bears a strong positive relationship with the streamflow anomaly at Asham (Fig. 6b) with a correlation coefficient of 0.87. In contrast to this, the temperature anomaly and the streamflow anomaly show an inverse relationship (Fig. 6c) with a correlation coefficient (r) amounting to -0.72.

4.6 Streamflow and hydrological droughts

For assessing the hydrological droughts in the region, the SDI proposed by Nalbantis and Taskariis (2009) was used. Generally, it is expected that the streamflow data may possess some degree of skewness (Tabari et al. 2013). To check the normality, the K–S test was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Sukhnag
Doodhganga
Romshi
Sangam
Jhelum River
Lidder
Aripath
Rambiara
Vishow
Bringi
Sandran
Legend
Hydrometric gauge
Stream
Lake
Increasing trend
Decreasing trend
Statistically significant trend
0 5 10 20 30 40
Kilometers

◂**Fig. 5** Spatio-temporal trends of streamflow in the Jhelum basin during 1980–2016 for annual scale (**a**), winter half (**b**), summer half (**c**), JJAS (**d**), and spring season (**e**)

used at a 0.05 significance level. For the raw streamflow data series, only SDI-12 (Asham) and SDI-4 (Ram Munshi Bagh, Sangam) followed a normal distribution with *p*-values greater than 0.05 while other data series did not follow the normal distribution (Table 8). For the present analysis, the data were transformed using the 2-parameter log-normal distribution. It is the simple and most widely used distribution for streamflow data in studies, e.g., Kroll and Vogel (2002), Yue and Wang (2004), Chen et al. (2006), Shukla and wood (2008), Nalbantis and Tsakiris (2009), and Tabari et al. (2013). The log-normal transformation also worked for the present analysis and 80% of the log-transformed data series followed a normal distribution. The final SDI values were computed for the log-transformed data using Eq. (2).

The SDI series for Oct–Dec (SDI-3) and Oct–Mar (SDI-6) reference periods are depicted in Fig. 7a and b respectively, based on 36 years' time series data of 3 principal gauges located on the main Jhelum stream. As shown in Fig. 7, for the Oct–Dec (a) and Oct–Mar (b) reference periods, mild to moderate droughts happened between 1999–2000 and 2014–2015 for all the 3 gauges. Relatively high streamflow was observed from 1992–1993 to 1997–1998 with positive SDI values ranging between 0.97–2.47 (SDI 3) and 0.87–2.40 (SDI 6). For the Oct–Mar reference period, the lowest SDI value of − 2.02 was recorded at Ram Munshi Bagh gauge during the hydrological year 2009–2010, while for the Oct–Dec period, the lowest SDI (− 1.45) was recorded at Sangam gauge during 2013–2014.

Similarly, for SDI-9 (Oct–Jun) and SDI-12 (Oct–Sep), the data series are shown in Fig. 7c and d. The SDI values for SDI-9 and SDI-12 follow a similar pattern as that of SDI-3 and SDI-6. Based on SDI-9 and SDI-12, severe droughts can be identified at the Asham gauge during 2008–2009 and 2009–2010. The annual SDI depicts that mild to moderate drought conditions existed in the basin consistently from 1998 to 1999.

For the present analysis, the SDI-4 was also computed for the Jun–Sep months to analyze the streamflow availability during these months, as the demand for surface water is highest during this period of the year. The SDI-4 data series depicted in Fig. 7e shows that up to the hydrological year 1996–1997, the streamflow was generally adequate except for the year 1983–1984 in which severe drought (SDI-4 = − 2.19 at Sangam gauge) happened in the Jhelum catchment and mild to moderate droughts existed in the middle and lower portions of the Jhelum basin. In contrast to this from the year 1998 to 1999, the streamflow has generally been deficient, reflected in the negative SDI values. The minimum SDI-4 is recorded at Asham Gauge (− 2.26) for the year 1998–1999. The successive years 2013–2014 and 2014–2015 recorded positive SDI values.

4.7 Results of flood frequency analysis

The annual peaks for 2 non-overlapping periods, viz., baseline (1956–1985) and current (1986–2016), were subjected to frequency analysis. FFA was carried out for 3 principal gauges; Ram Munshi Bagh, Sangam, and Asham located along the course of river Jhelum. The two widely used probability distributions, viz., the Gumbel and log-Pearson type III (LP3) methods, were utilized for estimating the flood magnitudes of different return periods (Tr) based on baseline period and current period. The GoF test results (Table 9) reveal that LP3 is the best-fit distribution for Sangam and Asham gauges while the Ram Munshi Bagh is best represented by Gumbel's method. These inferences can also be visualized by the CDF graphs (Fig. 8a–f) and the P-P plots (Fig. 9a–f).

As per the P-P plots, if the results of the distribution model are closer to the 1:1 line, a model is considered to be the best fit. The LP3 model results are closer to the 1:1 line for Sangam and Asham gauges. In contrast to this, Gumbel's model follows the 1:1 line at the Ram Munshi Bagh gauge. After having the best-fit distribution estimates for the gauges, the relative changes (%) in the flood intensities were computed. The peak flood estimates for 2-, 5-, 10-, 25-, 50-, 100-, and 200-year recurrence intervals based on 1956–1985 (Table 10) and 1986–2016 (Table 11) data are shown graphically in Fig. 10. The results reveal that the flood magnitudes of all recurrence intervals have witnessed significant amplification (Table 12). The magnitude of the 100-year recurrence interval flood has increased by about 64.62% at Sangam, and 79.58% at Asham gauge. For the Ram Munshi Bagh gauge, the increments are relatively lower ranging between 4 and 11% for all the returns periods. Figure 11a–c show the comparison of the flood magnitudes estimated from the baseline data and current data.

5 Conclusion

Climate change has exacerbated the shifts in the river flow regimes drastically, the repercussions of which are markedly evident over the river Jhelum. The present study encompasses a detailed and comprehensive assessment of the hydroclimatic variability, inter-linkages between climatic variability and hydrological regimes, and hydrological extremes in the Jhelum basin. The trend analysis demonstrates that the annual mean temperature of the region has been showing an increase at the rate of 0.24 °C/decade

Table 6 Pearson's correlation coefficient (r) between the streamflows and the precipitation in the Jhelum basin

	Discharge for→	Annual	Winter half	Summer half		JJAS	
Stream	Based on precipitation→	Annual	Winter half	Summer half	Winter half	JJAS	Winter half
	Best-correlated climate station↓						
Aripath	Kokernag	0.71	0.68	0.64	0.41	0.68	0.4
Bringi	Kokernag	0.6	0.36	0.48	0.38	0.64	0.28
Sandran	Kokernag	0.5	0.2	0.46	0.42	0.6	0.43
Lidder	Pahalgam	0.7	0.39	0.58	0.4	0.41	0.41
Vishow	Qazigund	0.72	0.4	0.8	0.17	0.77	0.13
Rambiara	Qazigund	0.48	0.21	0.38	0.43	0.41	0.42
Romshi	Gulmarg	0.63	0.47	0.37	0.31	0.58	0.32
Doodhganga	Srinagar	0.55	0.33	0.49	0.39	0.57	0.33
Ferozpora	Srinagar	0.56	0.35	0.44	0.53	0.4	0.51
Sukhnag	Gulmarg	0.7	0.58	0.45	0.6	0.4	0.6
Ningal	Gulmarg	0.49	0.36	0.49	0.3	0.55	0.21
Dakil Nallah	Kupwara	0.38	0.19	0.42	0.13	0.45	0.13
Vij	Gulmarg	0.44	0.25	0.74	0.18	0.73	0.19
Sindh	Srinagar	0.47	0.36	0.42	0.36	0.2	0.3
Erin	Srinagar	0.5	0.35	0.54	0.29	0.14	0.15
Madhumati	Kupwara	0.42	0.16	0.54	0.01	0.58	0.02
Pohru	Kupwara	0.61	0.6	0.43	0.39	0.23	0.34

while the precipitation marks a decreasing trend. The streamflow on the other hand exhibits a general decreasing trend at all the hydrometric gauges. However, there are some increasing tendencies in streamflow for the spring season (Mar-May). The increasing trends in spring discharge may be considered the signature of changing climatic regimes, particularly the rising temperatures resulting in greater and earlier snowmelt during the spring season. The abrupt change points in the streamflow that emerged between 1997 and 1998 are well synchronized with the change points in the climatic variables. The study demonstrates that the flow conditions in the Jhelum basin are highly influenced by climatic variability indicating a high and significant positive correlation between the streamflow and precipitation on all temporal scales. The streamflow during the summer half shows a significant positive correlation with the prior winter half precipitation, highlighting the importance of snowmelt to the hydrology of the Jhelum basin. In contrast to this, streamflow and temperature exhibit an inverse relationship. This negative relationship rhymes the same for the summer half and Jun-Sep period too, thus indicating a limited contribution of glacial melt to the flows of river Jhelum.

Table 7 Pearson's correlation coefficient (r) between the streamflows and temperature (T_{max}) in the Jhelum basin

Stream	Best-correlated climate station	Annual	Winter half	Summer half	JJAS
Aripath	Kokernag	− 0.48	− 0.58	− 0.55	− 0.26
Bringi	Kokernag	− 0.38	− 0.36	− 0.36	− 0.26
Sandran	Kokernag	− 0.33	− 0.13	− 0.4	− 0.29
Lidder	Pahalgam	− 0.4	− 0.31	− 0.44	− 0.24
Vishow	Qazigund	− 0.61	− 0.4	− 0.62	− 0.37
Rambiara	Qazigund	− 0.57	− 0.5	− 0.44	− 0.29
Romishi	Gulmarg	− 0.56	− 0.25	− 0.43	− 0.38
Doodh-ganga	Srinagar	− 0.27	− 0.25	− 0.33	− 0.37
Ferozpora	Srinagar	− 0.51	− 0.3	− 0.46	− 0.42
Sukhnag	Gulmarg	− 0.44	− 0.25	− 0.39	− 0.08
Ningal	Gulmarg	− 0.39	− 0.18	− 0.44	− 0.31
Dakil Nal-lah	Kupwara	− 0.35	− 0.52	− 0.22	− 0.08
Vij	Gulmarg	− 0.28	− 0.03	− 0.47	− 0.32
Sindh	Srinagar	− 0.46	− 0.49	− 0.39	− 0.18
Erin	Srinagar	− 0.4	− 0.36	− 0.38	− 0.34
Madhumati	Kupwara	− 0.2	− 0.25	− 0.36	− 0.26
Pohru	Kupwara	− 0.41	− 0.44	− 0.47	− 0.38

Furthermore, the study discerns the marked imprints of climatic variability on the changing hydrological extremes. The study accentuates the vulnerabilities of the region owing to the erratic hydrological behavior of the Jhelum both in terms of flood and drought events. While the region tends to remain highly exposed to the vagaries of flood disasters, the flood intensity has increased significantly from 1986 to 2016. On the other hand, droughts are no longer an exception to the colloquial "water resource-rich region" of the Jhelum basin.

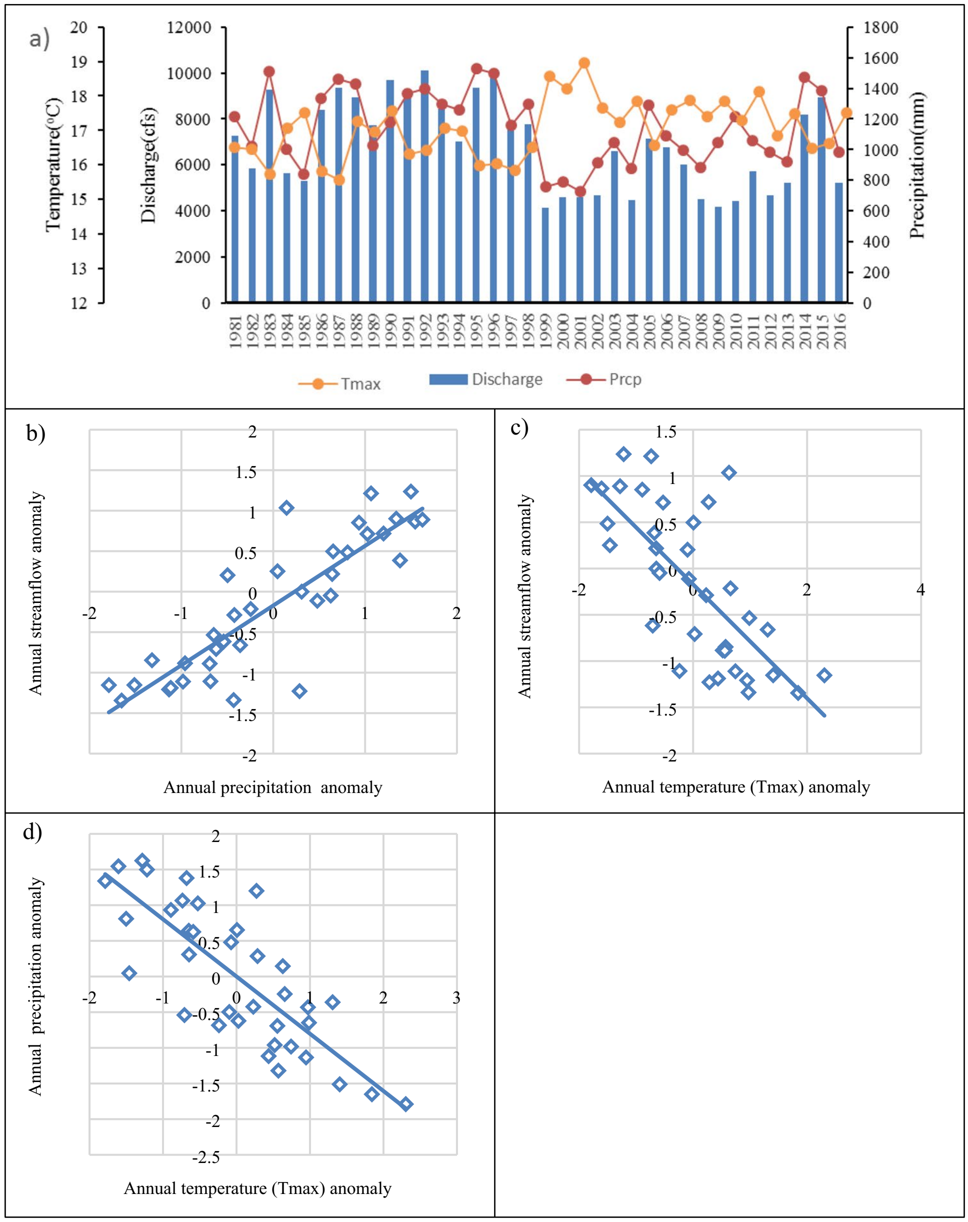

Fig. 6 Climatic controls of discharge at the regional scale; **a** co-variability of temperature, precipitation, and streamflow; **b** scatter plot between streamflow and precipitation anomalies; **c** scatter plot between streamflow and temperature anomalies; and **d** scatter plot between precipitation and temperature anomalies

Table 8 *p*-values based on the Kolmogorov–Smirnov test for the streamflow volume

		Sangam		Ram Munshi Bagh		Asham	
SDI	Ref. period	Initial data	Log data	Initial data	Log data	Initial data	Log data
SDI-3	Oct–Dec	0.000	0.014	0.001	0.183	0.001	0.152
SDI-6	Oct–Mar	0.000	0.004	0.010	0.200	0.029	0.169
SDI-9	Oct–Jun	0.009	0.085	0.019	0.2	0.009	0.067
SDI-12	Oct–Sep	0.002	0.096	0.004	0.027	0.102	0.200
SDI-4	Jun–Sep	0.130	0.200	0.065	0.200	0.022	0.200

Drought events are marking their presence and there has been an increase in the frequency and magnitude of hydrological droughts since 1998. There is a need for proactive and robust intervention in terms of drought mitigation measures. The study further calls for an inclusive restructuring of the water resource management practices and infrastructure that hitherto focuses only on flood disasters. The study validates and impresses upon the rolling out of the robust and

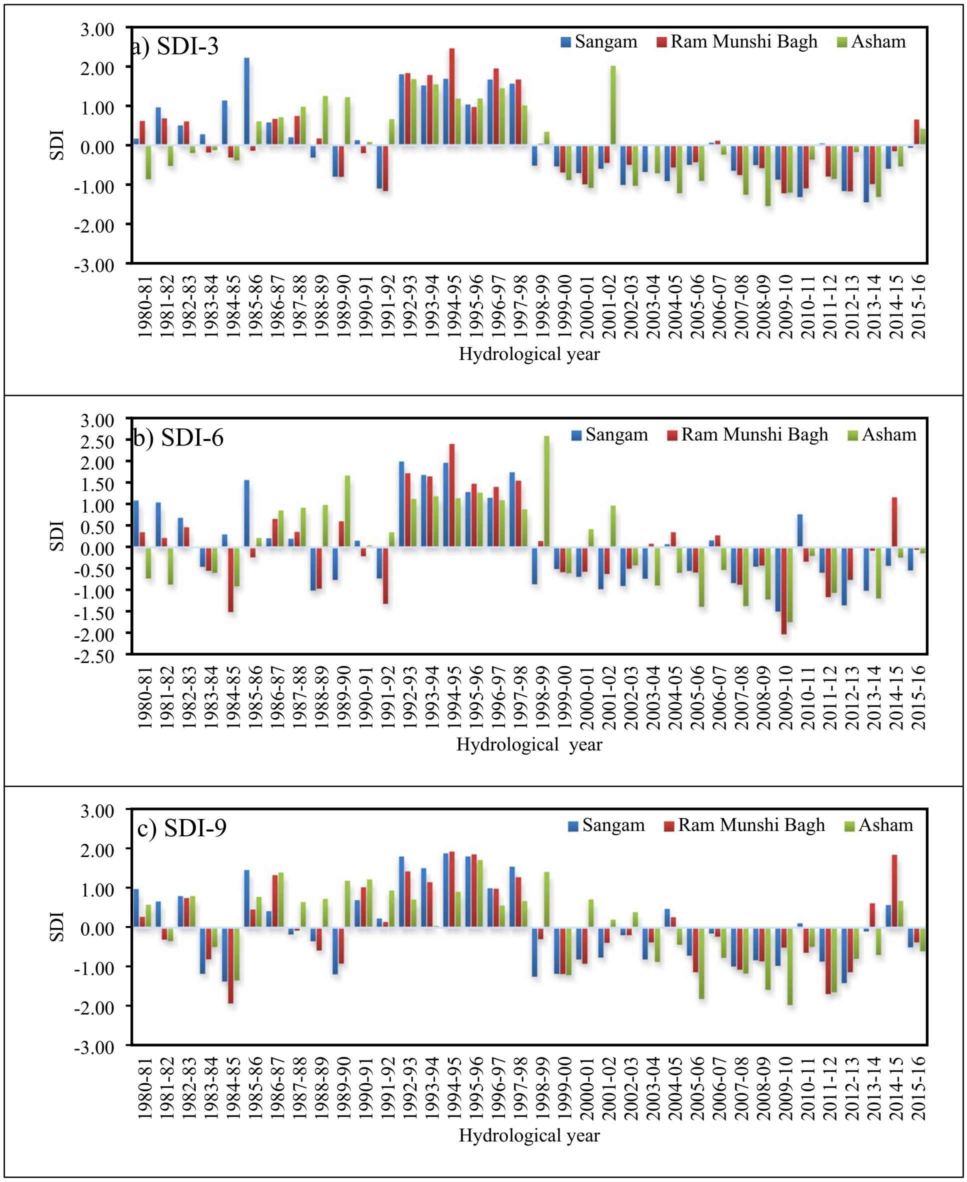

Fig. 7 **a–e** SDI values for different reference periods at Sangam, Ram Munshi Bagh, and Asham gauges

Fig. 7 (continued)

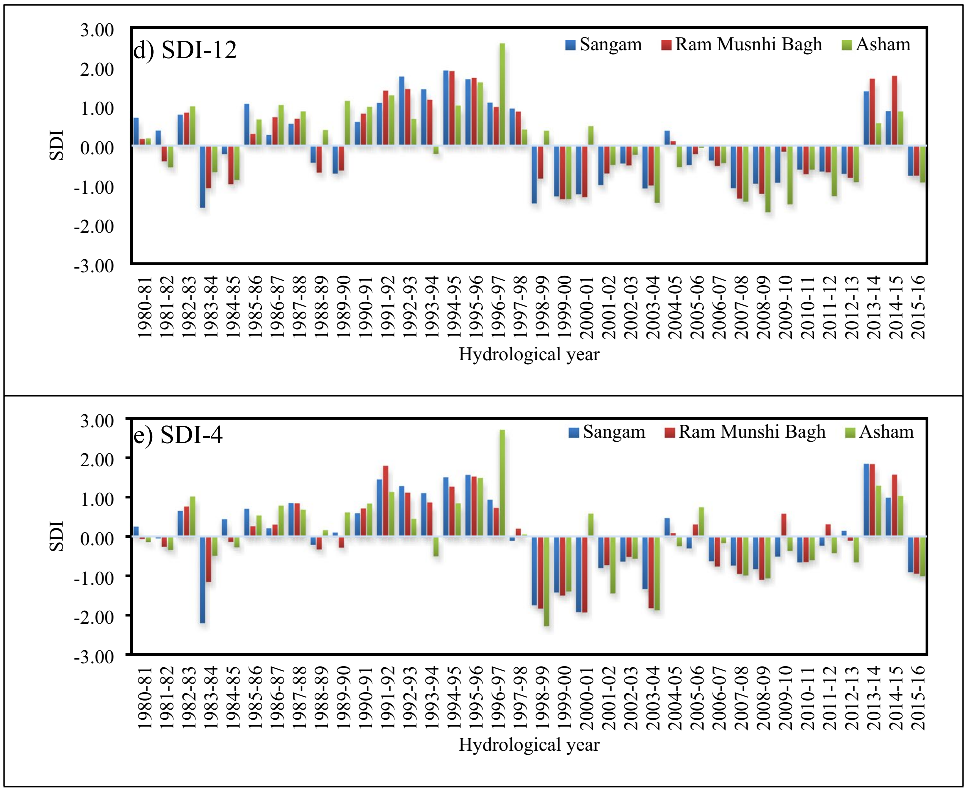

Table 9 Results of goodness of fit (GoF) tests, Komogorov–Smirnov and Anderson–Darling

Hydrometric gauge	Distribution	K–S test statistics		A–D test statistics	
		1956–1985	1986–2016	1956–1985	1986–2016
Sangam	LP3	0.08276	0.09799	0.25946	0.28309
	Gumbel	0.12276	0.13115	0.60001	0.73463
Ram Munshi Bagh	LP3	0.09073	0.08456	0.21667	0.1861
	Gumbel	0.08227	0.0726	0.24094	0.15724
Asham	LP3	0.09007	0.12608	0.32055	0.46423
	Gumbel	0.10903	0.16052	0.74333	0.76467

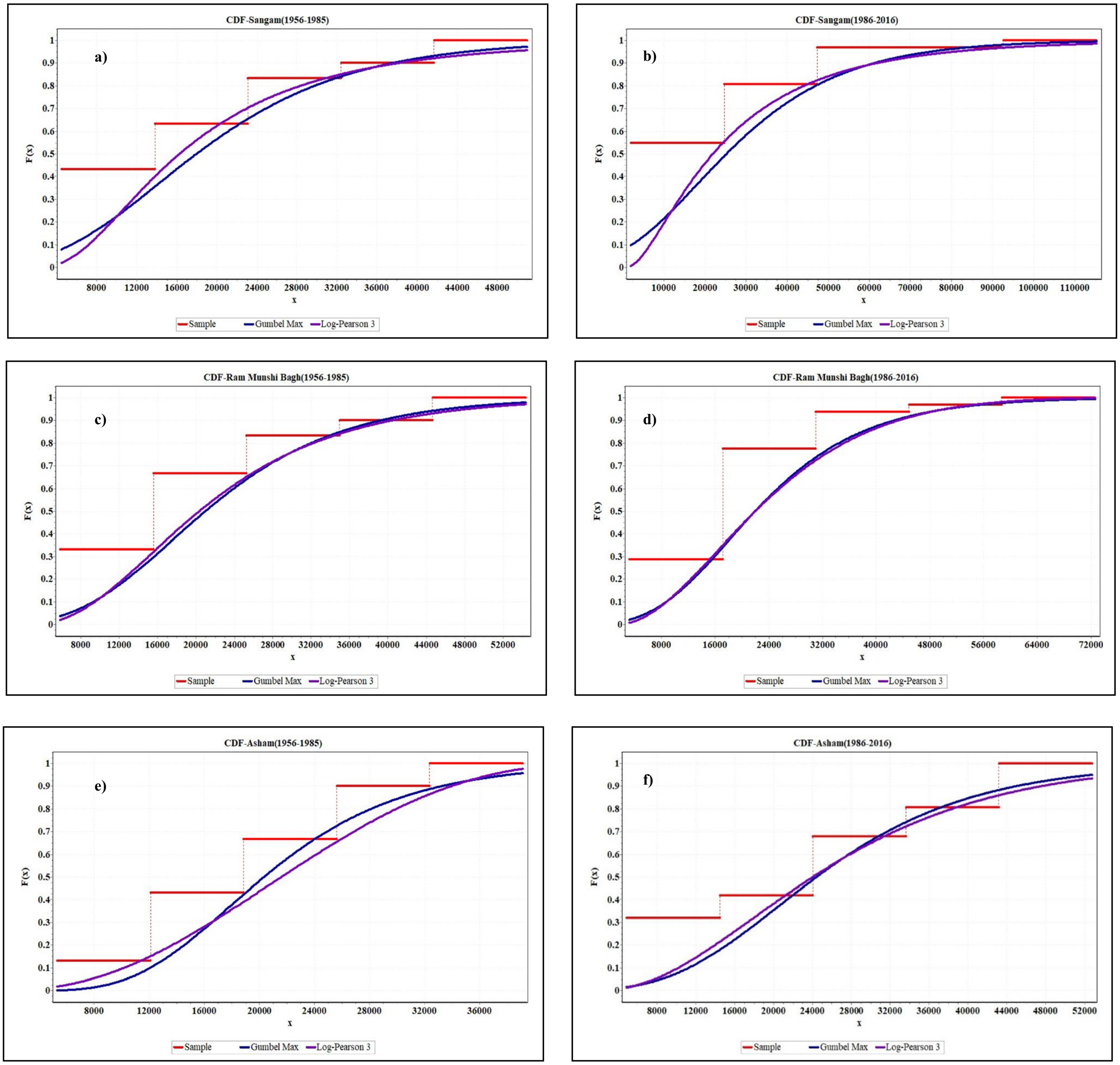

Fig. 8 CDF plots for annual peak discharge at Sangam (**a**, **b**), Ram Munshi Bagh (**c**, **d**), and Asham gauge (**e**, **f**)

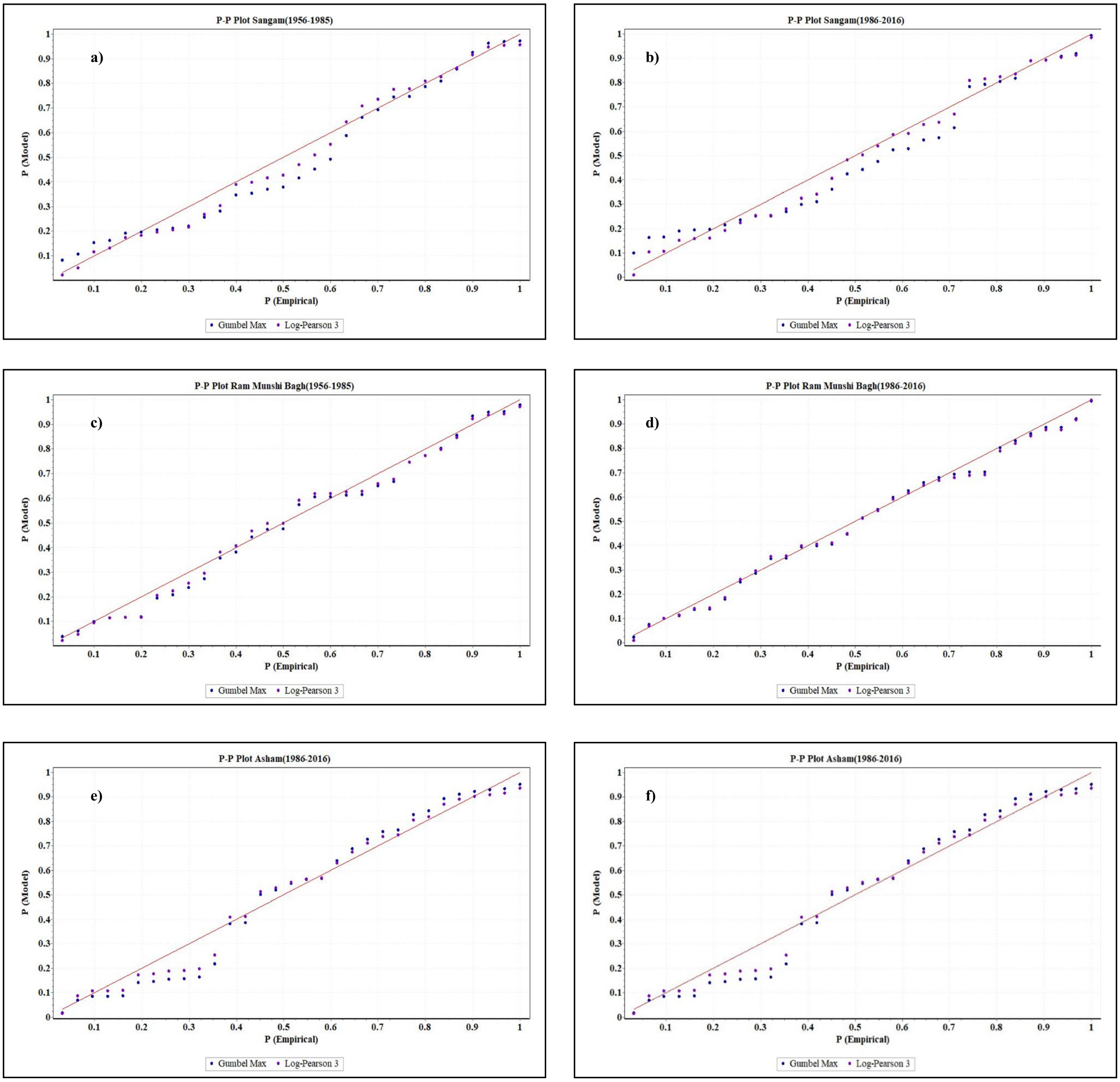

Fig. 9 P-P plots for annual peak discharge at Sangam (**a**, **b**), Ram Munshi Bagh (**c**, **d**), and Asham gauge (**e**, **f**)

Table 10 Magnitudes of the predicted flood events (cfs) using 1956–1985 time series

Hydrometric gauge	Distribution	Tr						
		2	5	10	25	50	100	200
Sangam	LP3	16,262.9	28,411.04	38,268.59	52,793.69	65,132.34	78,837.8	94,005.03
	Gumbel	18,109.83	31,755.15	40,789.53	52,204.5	60,672.77	69,078.52	77,453.59
Ram Munshi Bagh	LP3	20,333	32,246.22	40,491.44	51,133.4	59,152.8	67,174.91	75,270.63
	Gumbel	21,098.82	33,811	42,227.58	52,861.94	60,751.12	68,582.04	76,384.4
Asham	LP3	21,581.6	29,946.04	33,941.2	37,649.27	39,676.21	41,243.66	42,465.78
	Gumbel	23,481.59	33,821.03	40,666.63	49,316.07	55,732.72	62,102	68,448.03

Table 11 Magnitudes of the predicted flood events (cfs) using 1986–2016 time series

Hydrometric gauge	Distribution	Tr						
		2	5	10	25	50	100	200
Sangam	LP3	21,895	44,172.08	62,060.53	87,480.67	108,108.6	129,781.2	152,589.5
	Gumbel	25,458.65	50,479.82	67,046.01	87,977.43	103,505.6	118,919	134,276.2
Ram Munshi Bagh	LP3	21,962.24	35,226.63	43,364.34	52,670.56	58,885.55	64,504.28	69,630.35
	Gumbel	22,086.12	36,469.41	45,992.39	58,024.71	66,950.97	75,811.32	84,639.34
Asham	LP3	24,015.63	38,371.74	47,654.76	58,804.17	66,641.13	74,064.31	81,082.82
	Gumbel	28,639.9	44,786.7	55,477.29	68,984.88	79,005.58	88,952.29	98,862.7

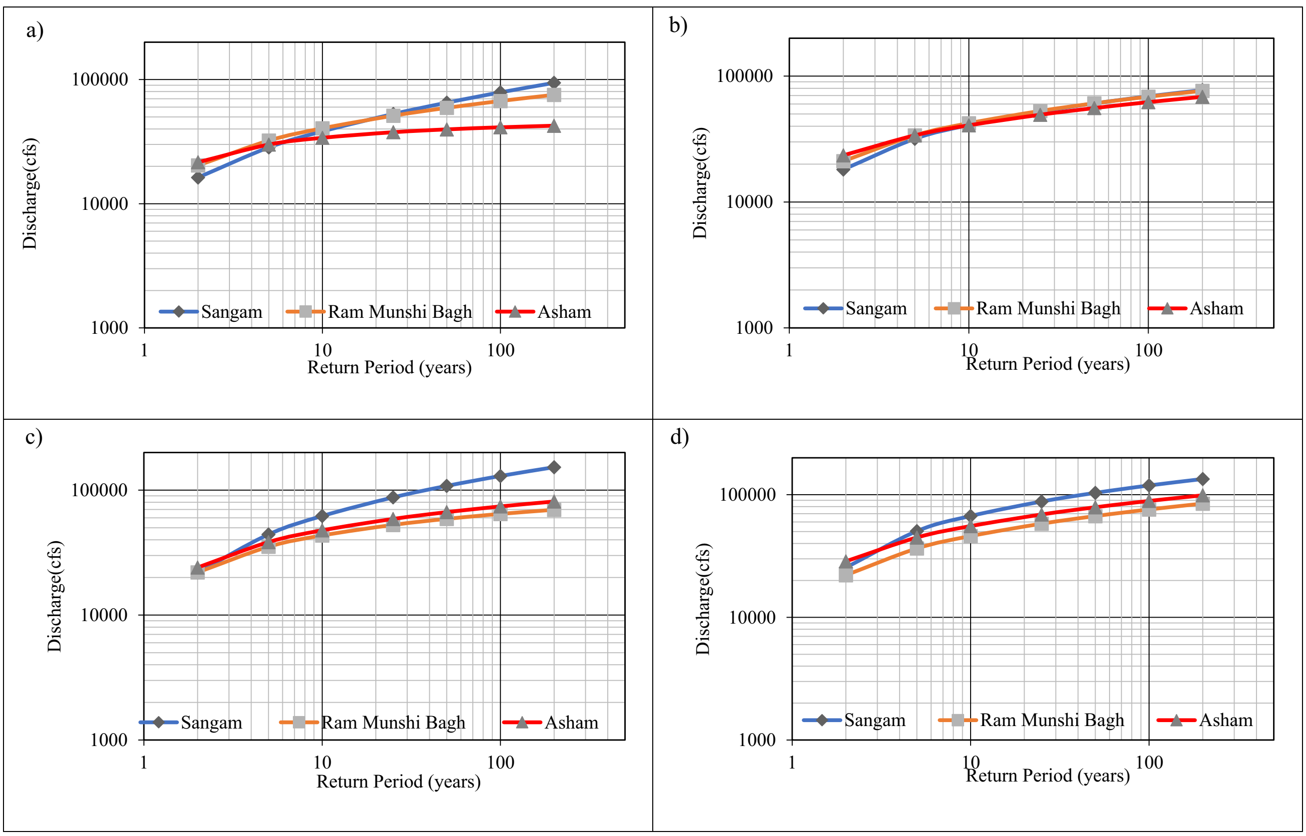

Fig. 10 Estimated flood magnitudes of different return periods based on the 1956–1985 time series (**a** LP3 model, **b** Gumbel's method) and 1986–2016 time series (**a** LP3 model, **b** Gumbel's method)

Table 12 Increase (%) in the magnitude of predicted flood events

Hydrometric gauge	Tr						
	2	5	10	25	50	100	200
Sangam (LP3)	34.63	55.48	62.17	65.70	65.98	64.62	62.32
Ram Munshi Bagh (Gumbel)	4.68	7.86	8.92	9.77	10.21	10.54	10.81
Asham (LP3)	11.28	28.14	40.40	56.19	67.96	79.58	90.94

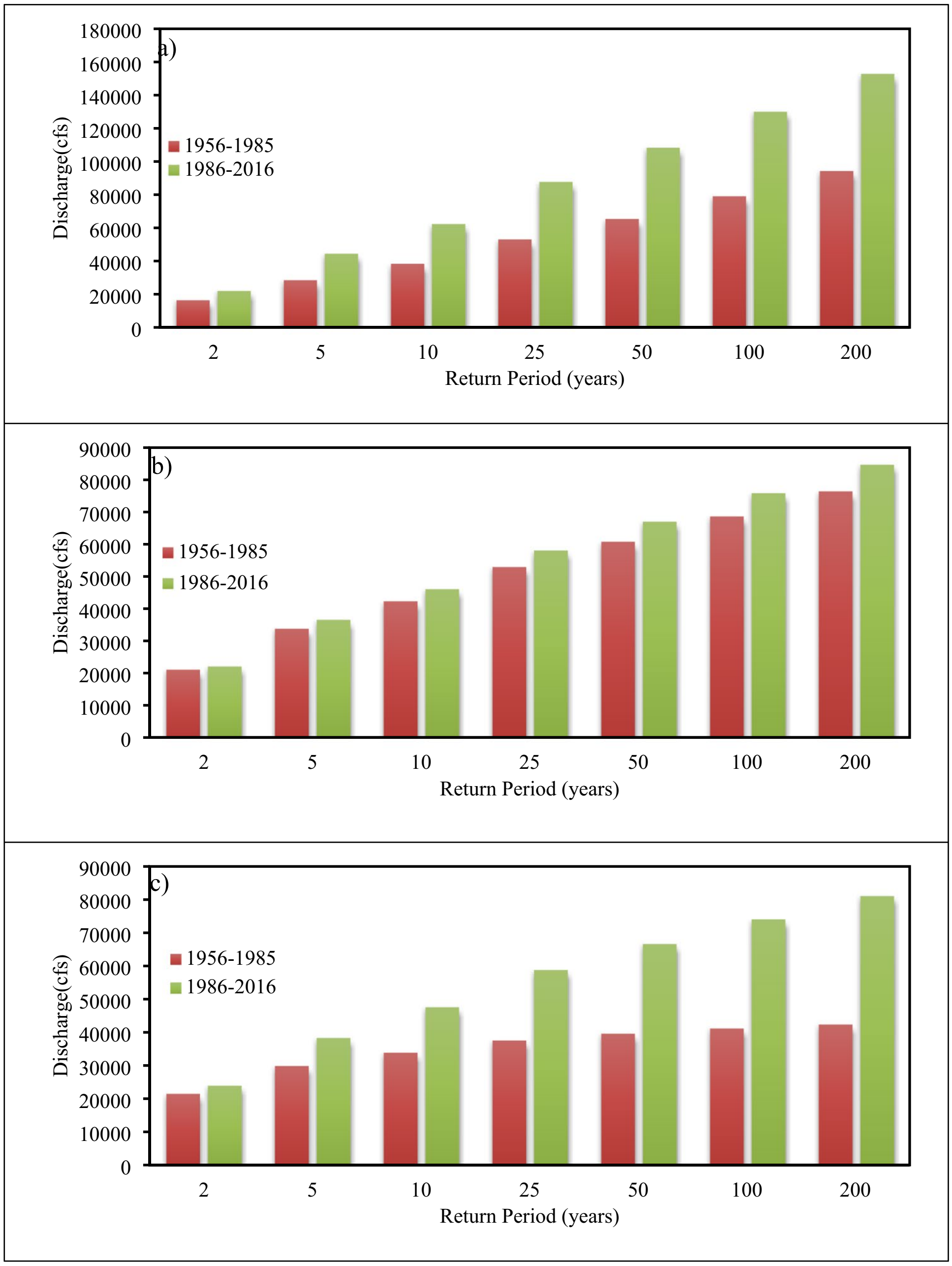

Fig. 11 Temporal changes in the magnitude of peak flood events (best-fit estimates) for different return periods: **a** Sangam using LP3 distribution, **b** Ram Munshi Bagh using Gumbel's distribution, and **c** Asham using LP3 distribution

action-oriented management of hydrological resources for the sustainable and reasoned use of water in the region.

Acknowledgements The authors would like to acknowledge the Indian Meteorological Department (IMD), Srinagar, and the National data center, Pune, for the climate data. The acknowledgments are due to the Irrigation and Flood control Department, Kashmir, for the necessary streamflow data. The authors would also like to thank the funding agency University Grants Commission, New Delhi, India.

Author contribution All authors contributed to the conception and design of the study. SA carried the analysis, interpretation, and wrote the first draft of the manuscript. MSB conceived, supervised, and edited the manuscript. AA edited and revised the manuscript. HAS helped in proofreading and graph work. HF prepared the final draft. All authors read and approved the final manuscript.

Funding The work was funded by the University Grants Commission, New Delhi, India, in the form of JRF fellowship to the first author.

Data availability All the datasets used in the study are in the public domain and can be obtained from the mentioned sources and departments.

Code availability The study used the open-source DrinC software for SDI computations.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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CURRICULAM VITAE

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Areas of Interest

Water Resources Engineering, Hydraulics Structures, Hydrological Modeling, Water Quality Modeling, Soft Computing in Water Resources Engineering.

Education Qualification

Examination Passed	Board/university /Institution	Division/ class/grade	Branch/ subject	Year	% Marks
Matriculation	J&K Board of School Education	2^{nd}.	General	1981	59.00
11^{th}.Class (PUC)	J&K Board of School Education	2^{nd}.	Faculty of Science	1982	57.83
Qualifying Exam.	J&K Board of School Education	Ist	Faculty of Science	1983	64.54
B.E.	University of Kashmir	Ist	Civil Engg.	1988	74.83
M.E.	University of Kashmir	Ist (Distinction)	Water Resources Engg.	1997	81.41
Ph.D	University of Kashmir	-	Civil Engg.	2007	-

Teaching Experience

S.No	Position	Length of service Years/Months	Period	
			From	To
1.	Lecture	06 Years	16-12-1989	15-12-1995
2.	Sr. Lecturer	05 Years	16-12-1995	15-12-2000
3.	S.G.Lecturer	05 Years /0.5 Months	16-12-2000	31-12-2005
4.	Associate Professor	7 Years / 8 months	01-01-2006	18-09-2013
5.	Professor	7 Years	18-09-2013	Till date

Subjects Taught

Course Name	**Level (UG/PG)**
Fluid Mechanics-I	UG
Fluid Mechanics-II	UG
Hydraulics and Hydraulic Machines	UG
Engineering Mechanics	UG
Environmental Engineering	UG
Applied Hydrology	UG
Hydrological Elements & Analysis	PG
Open Channel Flow	PG
Embankment Dams	PG
Fluid Mechanics	PG
GIS & Remote Sensing Application in Water Resources	PG
Hydraulic Structures	PG
Fluid Mechanics Lab-I	UG
Fluid Mechanics Lab.-II	UG
Fluid Mechanics Laboratory	AMIE (IE India)

Administrative Responsibilities

1. Head Civil Engineering Department (From 15-15-2021 till date)
2. Dean Planning and Development (From 01-08-2018 to 31-07-2020).
3. Chairman minor works committee/Contract committee, (From 10-09-2018 to 31-07-2020).
4. Chairman House/ Space allotment committee, (From 10-09-2018 to 31-07-2020)
5. Chairman Cafeteria / Canteen Committee, (From 10-09-2018 to 31-07-2020)
6. Member of the Central Research Facilities Centre (CRFC) of the Institute, (From 11-02-2016 to till date).
7. Chairman Purchase committee for Central Research Facilities Centre (CRFC) of the Institute, (From 11-02-2016 to till date).
8. Member for NIT Review Committee.
9. Advisory committee member for the Incubation Centre of the Institute.
10. Member of Annual Report preparation committee of the Institute, (From 2010 to 2011).
11. Member of Load Assessment Committee of the Institute, (From 2015 to 2018).
12. Member DPGC electronics and communication Engineering

Departmental Responsibilities

1. Officer In charge Water Resources Engineering Section.
2. Coordinator of M.Tech. Programme in Water Resources Engineering.
3. O/C Hydraulics and Environmental Section. (From 2016 to 2018).
4. Member of Departmental Board of studies Committee (From 2010 to 2016).
5. Coordinators of departmental time table (From 2006 to 2011).
6. Departmental O/C of examinations (From 2006 to 2010).
7. Coordinators of B.Tech. Projects and seminars (From 2007 to 2010).

Short Term Courses Organized

S. No	Details of Course	Organized at	Sponsored by/ Self Sponsored
1	Coordinator, 5 day Training Course on Disaster management (Earthquake Resistant Construction and Flood Management) from10-09-2012 to 10-09-2012	Department of Civil Engineering NIT Srinagar	Self Sponsored
2	Coordinator, 5 day Training workshop on Computer Applications in Civil Engineering from 29-06-2017 to 03-07 2017	Department of Civil Engineering NIT Srinagar	Self Sponsored
3	Coordinator, 5 day Short Term Training Course on Machine Learning and its Applications in Civil Engineering from 02-11-2020 to 06-11-2020	Department of Civil Engineering NIT Srinagar	TEQIP-III Sponsored
4	Coordinator, 5 day Short Term Training Course on Remote sensing Applications in Groundwater Extraction Measurements from 11-01-2021 15-01-2021	Department of Civil Engineering NIT Srinagar	TEQIP-III Sponsored

Research Projects Executed

S.No.	Title	Sponsoring Agency	Funds Sanctioned in Rs.	Duration Years
1.	Master Plan in Flood Control for Kashmir Valley	MHRD , New Delhi	Rs.5.00 Lakhs	2002-2005

Major Consultancy Projects Completed

S. No.	Details (Cumulative Amount more than 5 Lakhs)	Period	Organization	Amount (in Lakhs)
1	Performance Evaluation of Flood Split Channel Srinagar, Design of Sewerage Disposal System for NIT Srinagar & Testing of Precast concrete pipe testing.	2010	I&FC Kashmir, NIT Srinagar	6.45
2	Water testing of various Govt. and semi Govt. agencies	2005 to 2015	Various Government, Semi Government, and Private agencies.	6
3	Technical evaluation of DPR for relocation of House Boats in Dal Lake, Design of Settling Basin for Telbal Nallah, Design of cut and cover channel and Intake structures for Brari	2015	J & K Lakes and Waterways Development Authority	5.6

	Numbal Lagoon , River Jhelum			
4	Evaluation of designs for Solid Waste Management in various clusters of Kashmir Valley	2016-2017	Directorate of Urban Local Bodies Kashmir	21.02
5	Hydrological Analysis and Design of Weir at Manchar Nallah Lolab Kupwara	2017	Irrigation and Flood Control, Kashmir	11
6	Waste and water Characterization at of Garbage Dumping site Achan , Srinagar	2022	Srinagar Municipal Corporation	5.074

Research Publications

Journal

1. MohdAyoub Malik, AbdulQayoom Dar, Manoj K. Jain, Modelling the influence of changing climate on the hydrology of high elevation catchments in NW Himalaya's Journal of"Modeling Earth Systems and Environment"1 April 2022. https://doi.org/10.1007/s40808-022-014075-5.
2. Junaid Dar, Abdul Qayoom Dar Junaid Dar , Dominant Pattern of seasonal precipitation variability in association with hydrological extremes over the North–west Himalayas Journal of "Environmental Science and Pollution Research"Accepted: 12 May, 2022.https://doi.org/10.1007/s11356-022-20877-9.
3. SakibaNabi, Manzoor Ahmad Ahanger & Abdul Qayoom Dar, Employing sensitivity analysis to catchments having scanty data Journal of "Environmental Science and Pollution Research".Accepted: 25 April, 2022.,https://doi.org/10.1007/s11356-022-20514-5.
4. JasirMushtaq, Abdul Qayoom Dar and NavedAhsan, Characterization investigation on organic compost of municipal solid waste using physio-chemical, spectroscopic and thermal methods at different stages, "Int. J.Environmentl and Waste Management January 2022."
5. Sakiba Nabi, Abdul Qayoom Dar & Manzoor Ahmad Ahanger, The anatomy of extreme precipitation events over Srinagar, Kashmir, India, over the past 50 years, Arabian Journal of Geosciences (2021) 14:1412 https://doi.org/10.1007/s12517-021-07820-x.
6. Sakiba Nabi, Manzoor Ahmad Ahanger & Abdul Qayoom Dar, Investigating the potential of Morris algorithm for improving the computational constraints of global sensitivity analysis, Environmental Science and Pollution Research https://doi.org/10.1007/s11356-021-14994-0
7. Junaid dar & Abdul Qayoom dar, "Spatio-temporal variability of meteorological drought over India with footprints on agricultural production" Environmental Science and Pollution Research https://doi.org/10.1007/s11356-021-14866-7. (accepted June -2021).

8. Junaid Dar & Abdul Qayoom Dar, " The agro-metrological perspective of drought over northwest Himalayas: Kashmir valley from 1979 to 2014 Journal of Earth System Science. (accepted March -2021).
9. Ruhhee Tabbussum and Abdul Qayoom Dar, "Modelling Hybrid and Back Propogation Adaptive Neuro Fuzzy Inference Systems for flood forecasting", Natural Hazards, Springer, DOI: https://doi.org/10.1007/s11069-021-04694-w (accepted March -2021)
10. Tabasum Rasool, A. Q. Dar & M. A. Wani, Development of Predictive Equation for Modelling the Infiltration Process Using Gene Expression Programming, Water Resources Management https://doi.org/10.1007/S11269-021-02816-4 (accepted March -2021)
11. Syeedah Raazia and Abdul Qayoom Dar, Insights into the hydrogeological framework of the NW Himalayan Karewas (India), Environmental Challenges. (accepted)
12. Syeedah Raazia and Abdul Qayoom Dar, A numerical model of groundwater flow in karewa-Alluvium aquifers of NW Indian Himalayan Region, Earth Systems and Environment http://link.springer.com/article/10.1007/s40808-021-01126-3 (accepted Feb -2021)
13. Mohd Ayoub Malik, Abdul Qayoom Dar and Manoj K. Jain Modelling streamflow using the SWAT model and multi-site calibration utilizing SUFI-2 of SWAT-CUP model for high altitude catchments, NW Himalayas, Modelling Earth Systems and Environment https://doi.org/10.1007/S40808-021-01145-0 (accepted March -2021)
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63. Adil Mushtaq, A.Q.Dar and Shakeel Ahmad, Watershed management of Dal Lake Catchment (J & K) based on erosion intensity hazard using geospatial technique International conference on Geospatial Technologies and Applications"Geomatrix-12, February 26-29,2012 CSRE, IIT Bombay.
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65. Saqib Gulzar, A.R. Da, A.Q.Dar and Ovais Gulzar, Flood Resilient Construction in Jammu & Kashmir, National Inter-disciplinary Science Conference-2015 Sri Pratap College Srinagar, Jammu & Kashmir (Best Paper award).
66. Saqib Gulzar, A.R Dar and A.Q.Dar, Improving the flood performance of building infrastructure in Jammu & Kashmir, 11th J & K Science Congress 2015 University of Kashmir J& K India.
67. Faizan U.l Haq, Saqib Gulzar, A.Q.Dar, Irfan U.L Haq and Ovais Gulzar, Srinagar City: Expansion trends and need for vertical expansion, National

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69. Saqib Gulzar, Faizan U.l Haq and Dar A.Q, Applicability and Suitability of a Multiplicative Seasonal Model for Forecasting Water Quality Parameters for Dal Lake of Kashmir, 9th. J & K Science Congress & Regional Science Congress (ISCA)1-3 Oct.2013 University of Kashmir J& K India.
70. Adil Mushtaq and A.Q.Dar, Watershed prioritization of inaccessible Micro-watersheds of Dal Lake catchment (J&K) using geographical Information System, National seminar on Geospatial solutions for Resource Conservation and Management GEOS-12, 18-20 Jan 2012.Karnataka State Remote Application Centre Bangalore.
71. Adil Mushtaq, A.Q.Dar, Nasir A Rather and S AzharUd Din, Morphometric analysis of micro- watersheds of Dal lake catchment (J&K) using geospatial technique, National Conference on Hydraulics and Water Resources, Hydro- 2011, 29-30 Dec.2011 SVNIT,Surat.
72. Niyaz Ahmad Bhat, Sajid Mushtaq Pandit and A.Q.Dar, Solid waste generation of Srinagar city (J&K) -present and future perspectives, National Conference on Sustainable Development of Urban Infrastructure 18-19 June 2010.Visvsesvaraya National Institute of Technology Nagpur.
73. Niyaz Ahmad Bhat, Sajid Mushtaq Pandit and A.Q.Dar, Utilization of waste from construction Industry- recycling of concrete, National Conference on Sustainable Development of Urban Infrastructure 18-19 June 2010.Visvsesvaraya National Institute of Technology Nagpur.
74. A.Q.Dar, Mohmmad Ather ,Abid Ali and Niyaz Ahmad, Viability of vermicomptositing for solid waste management in Srinagar city (J& K), National Seminar on Cleaner Production Technologies 17-18 Nov.2009NITTTR, Chandigarh.
75. A.Q.Dar, and Arif Banday, Watershed Prioritization of Ramimbiara Catchments of Jhelum basin using Geoinformatics, National symposium on Climate change and water resources in India CCWRI,18-19Nov.2009, IIT Roorkee.
76. A.Q.Dar, and Arif Banday, Morphometric analysis of micro-watersheds of Jhelum basin using GIS Technique, National Seminar conference on sustainable water resources development and management SWADAM,13-14 June 2008 ,Govt College of Engineering Aurangabad

Book Chapters

1. Ruhhee Tabbussum and Abdul Qayoom Dar, “Analysis of Bayesian Regularization and Levenberg–Marquardt Training Algorithms of the Feedforward Neural Network Model for the Flow Prediction in an Alluvial Himalayan River”, Algorithms for Intelligent Systems in Cybernetics, Cognition and Machine Learning Applications, page 43-50, Springer, Singapore, April 2020.
2. Tabasum Rasool, Sajad Ahmad, Abdul Qayoom Dar, Mushtaq A. wani, Comparison of soil infiltration models under varying land cover condition

in a micro watershed of Western Himalayan Region, Hydrological Modelling Springer, (In Press)

Ph.D Supervision

1. Nasir Ahmed Rather, Protective filter design criteria based on the particle shape and gradation parameters, (Co-Supervisor) (Awarded, 2017).
2. Ms. Ruhhee Tabassum, Modeling Flood Prognosis Using Machine Learning Techniques, (Awarded, June 2021).
3. Ms. Tabasum Rasool, Modeling Vadose Zone Infiltration in the Himalayan Lake Catchment, (Awarded, June 2021).
4. Mr. Ishtiyaq Ahmad Rather, Water quality modeling of Dal Lake in North West Himalayan Region, (Awarded, July 2021).
5. Mr. Jasir Mushtaq Kaloo, Gis-based approach and characterization analysis of municipal solid waste in western Himalayan region (Awarded July, 2021).
6. Ms. Syeedah Raazia, Groundwater modeling of Karewa watersheds in a Western Himalayan basin (Completed, May, 2022).
7. Mr. Mohd Ayoub Malik ,Modeling impact of climate change on runoff and sediment yield of a high altitude catchment (In Progress).
8. Ms. Sakiba Nabi, Refining regional flood frequency analysis through flood profiling (In Progress).
9. Mr Junaid Ahmad, Spatial-temporal structure of precipitation extremes associated with tropical moisture export over India (In Progress).

P.G Dissertation Supervision

1. Seerat ul Mehraj, Flood Forecasting for Jhelum Basin using Unit Hydrograph Methodology (2005).
2. Nazia Nazir Zuhaid, Modeling of Water Quality Parameters of Dal Lake (J & K) (2006).
3. Rais Ahmad, Hydraulic Conductivity of Porous Material- Influence of Pore Channel and Nature of Gradation (2007)
4. Ishtiyaq Ahmad Rather, Forecasting Water Quality Parameters for Dal Lake of Kashmir, (2008)
5. Arif Ahmad Banday, Geomorphlogical Analysis of Upper Watersheds of Rambiara Catchment Using Geoinformatics (2009)
6. Adil Mushtaq , Watershed Management of Dal lake Catchment Using Geospatial Technique (2011).
7. Hakim Muzamil, Effect of Land Use/Land Cover on Runoff-A Case Study of Dal Lake Catchment (J&K), (2012).
8. Saima Showkat, Spatial and Temporal Assessment of Water quality of River Jhelum (J&K), (2013).
9. Ruhee Hamid, Flood Prediction in River Jhelum-J&K, India Using Artificial Neural Network and Multiple Linear Regression Techniques, (2004).
10. Daniyal Rasool, Soil Erosion Estimation using WEPP model in a Dal Micro watershed J & K –A case study, (2004).
11. Humaira Maqbool, Intensity -frequency-duration Studies of Kashmir Valley, (2015).
12. Lateef Ah.Dar, Rainfall -Runoff Modeling for River Jhelum (J& K) India, (2015).
13. Aqleem Shah, Flood plain mapping of River Jhelum using two dimensional Numerical model Telmac-2D, (2016).

14. Ishtiyaq Nabi, Assessment of water quality parameters of Dal Lake in Kashmir valley J & K India, (2016).
15. Sofi Aamir Majeed, Effect of Nature of Fluid on Hydraulic Conductivity of Soils, (2017).
16. Sajad Ahmed, Infiltration modeling in a micro water shed of Dal Lake catchment, (2018).
17. Mohd. Arbin Bilal, Modeling of stage discharge relationship for major gauging sites of Jhelum Basin, Jammu & Kashmir, India, (2019).
18. Danish Jeelani, Modeling of hydrologic response of Puhroo and Lidder River Catchment using ARCSAWAT, (2019).
19. Pebika Bania, Flood prediction in Pandu situated in Guwahati (Assam), India of the Brahmaputra River using Artificial Neural Networks, (2020).
20. Syed Mohammad Shariq Qadri, Multivariate Statistical Analysis of Physico-Chemical Water Quality Parameters of Wular Lake, (2020).
21. Aamir Mubarik, Rainfall runoff simulation and flood prediction using fuzzy logic based modeling, (2021).
22. Ajaz Ahmad Mir, Quantitative Analysis of Methane Gas Emissions from Municipal Solid Waste in Srinagar City, (2021).

AMIE Thesis Supervision

1. Evapotranspiration Studies of River Jhelum Basin (J & K) ST: 380527-7 (2010-2011).
2. Identification and remedies of the problems of Sugam canal Shopian J & K ST-468333-7. (2010-2011).

U.G Project Supervision +37

Awards

1. Best Paper award titled "Trend Analysis an Spatial Assessment of various Water Quality Parameters of river Jhelum, J & K for an Intensive Water Quality Monitoring Program" in International Conference on Modeling Tools for Sustainable Water Recourses Management, MTSWRM-2014 Anjuman college of Engineering and Technology, Nagpur (M.S).
2. Best oral Presentation Award "Rainfall intensity-duration-frequency relationships for different regions of Kashmir valley- J &K(India), 3rd International Conference on Science, Technology and Management (ICSTM-16) India International Centre, New Delhi 17 January 2016.
3. Best Paper award titled "Applicability and Suitability of a Multiplicative Seasonal Model for Forecasting Water Quality Parameters for Dal Lake of Kashmir Proc. of 9th. J & K Science Congress & Regional Science Congress (ISCA)1-3 Oct.2013 University of Kashmir J& K India.

Expert Lectures Delivered

1. Overview of Computer Application inWater Resources Engineering with Special Reference to ArcGIS, Participants of 5 day Training workshop on Computer Applications in Civil Engineering.
2. Design Flood Estimation Participants of for 5 day Training Course on Disaster management(Earthquake Resistant Construction and Flood Management

Membership

1. Fellow of Institution of Engineers India.
2. Life member of Indian Society of Technical Education.
3. Life member of Indian Society for Hydraulics.
4. Member of International Association of Hydraulic and Environmental Research.

Significant outreach Institute activities

1. Expert member of Inspection Team constituted by Hon'ble national Green Tribunal New Delhi for Solid Waste Management of Srinagar city (From Jan. 2017 to July 2017).
2. Member of Departmental Board of studies Committee for SSM College of Engineering and Technology. (From 2016 to 2018)
3. AICTE team member for the inspection of various institutions
4. Expert member of Inspection committee constituted by University of Kashmir
5. Evaluation of Ph.D and M.Tech thesis's of various Institutes.

Conferences/ Workshops/Seminars attended

S.No	Organization	Title	Period		
			From	To	Weeks/ Days
1.	Dept of Civil Engg NITTTR, Chandigarh	National Seminar on Cleaner Production Technologies	17-11-2009	18-11-2009	2 days
2.	Dept of Civil Engg. Govt. College of Engineering Aurangabad	National Conference on Sustainable Water Resources Development and Management SWRDAM-2008	13-06-2008	14-06-2008	2 days
3.	NEERI Nagpur	International conference on Sustainable Water Resources Management and Treatment	19-01-2011	21-11-2011	3 days
4.	SVNIT, Surat	National Conference on Hydraulics and Water Resources, Hydro-2011,	29-12-2011	30-12-2011	2 days
5.	CSRE,IIT Bombay	International conference on Geospatial Technologies & Applications "geomatrix-12	26-02-2012	29-02-2012	4 days
6.	IMT Nagpur	Workshop on "Statistical data	16-01-2013	18-01-2013	3 days

		analysis".			
7.	NI T Srinagar	Workshop on "National Mission on Education through Information Communication Technology	18-06-2013	18-06-2013	1 day
8	Esri India	ArcGISi: Introduction to GIS	17-07-2017	21-07-2017	5 day
9.	Esri India	ArcGIS3: Training Programme on Performing Analysis	17-07-2017	21-07-2017	5 day
10.	Jamia Millia Islamia New Delhi	GIAN Course on Managing Floods and droughts in a changing Climate	15-01-2018	20-01-2018	5 day

Summer/Winter/Short term courses attended

S.No	Organization	Title	Period		
			From	To	Weeks /Days
1.	Elect. & Comm. Dept. R.E.C.Srinagar	ISTE course on Programming and Programming Methodology	Nov.5,1991	Dec.28,1991	8weeks
2.	Dept. of Civil Engg., College of Engg. Goa.	ISTE course on Eco-Management of coastal areas	Feb.26,1996	Mar.10,1996	2weeks
3.	Dept of earthquake engineering University of Roorkee	AICTE course on Computational Modeling for Geo-Dynamic Problems	Feb.18,1997	Mar. 1, 1997	2 weeks
4.	CSRE, I.I.T.Bombay	NNRMS course on Remote Sensing Application to Water Resources	July,21,1997.	Aug. 14, 1997	4 weeks
5.	Civil Engg.Dept. VRCE,Nagpur	AICTE/ISTE course on Environmental Engg. Systems Optimization	June,11,2001	Jun, 22, 2001	2weeks
6.	WRDTC & NIH, IIT Roorkee	System Analysis Techniques and Computer applications in Water Resources Management	Jan.05,2004	Jan.20,2004	4weeks
7.	Dept. of Civil Engg. IIT Roorkee	Analytical Procedures for Water and Waste Water Quality	Dec.15,2006	Dec.19,2006	1week

8.	NIH Roorkee & CSMRS New Delhi	Water Quality and its Management	July16, 2007	July 20, 2007	1 week
9.	Dept.of Hydrology & Dept.of WRDM IIT Rooorkee	Advanced Techniques and Tools for Hydrological Analysis and Design	Oct.26, 2009	Oct. 31, 2009	1week