Modeling the Impact of Climate Change on the Flow Regimes of River Sindh of Kashmir Valley

Mehlath Shah[1] · M. A. Lone[1]

Abstract Climate change and its uncertainties may have profound impact on the hydrological regimes. In the study, the authors have modeled the impact of changing climate on the hydrological regime of the river Sindh of Kashmir valley. The Hydrological Engineering Centre-Hydrological Modeling System (HEC-HMS) model was used to project future changes in the study area based on the Representative Concentration Pathways (RCP 4.5 and RCP 8.5) of Canadian earth system model (CanESM2) General Circulation Model (GCM) outputs. Statistical Downscaling Model version 4.2.9 (SDSM 4.2.9), which is based on linear regression, was used to downscale the maximum (T_{max}) and minimum (T_{min}) temperature, and daily precipitation (Pr) in the study area. The downscaled climate data indicated increase in the mean maximum temperature and the mean minimum temperature between the range of 0.4–2 °C and from 0.4 to 2.0 °C, respectively, under different RCPs. Also, under different RCPs, an increasing trend of 24 % has been detected in precipitation of the study area. Hydrologic Modeling System (HEC-HMS) was set up, calibrated (2001–2017), and validated (1992–2000) for the River Sindh, and then, discharge was projected for three future periods, i.e., 2030s, 2060s and 2090s. The simulated discharge of each period was correlated with the simulated discharge of the baseline period to find the variations in mean, median, high and low flow. Modeling results indicated these climatic changes will have a significant impact on the hydrological regime of River Sindh. It is thus impossible to plan proper management and utilization of water resource in the study area without considering the changes in the climate indicators especially temperature and precipitation.

Introduction

The socioeconomic development of the country depends potentially on future predictions of hydrologic processes which provide valuable data for the management of water resources and improved practices of agricultural under various climatic changes. To evaluate the effect of changing climate on hydrological cycle, physically based hydrologic and statistical models are widely used [1–3]. Under the estimated future climate changes, hydrologic cycle is projected to change, affecting the water balance components which may lead to changes in discharge and availability of water [4, 5].

The future changes in the hydrological regimes are dependent on the variations in features of the flood and droughts [4, 6]. Therefore, evaluation of future variations in streamflow is important as it will provide great support in the planning of improved management practices of water resources [7, 8]. Various studies have publicized that variations in various factors of climate can have drastic impact on the hydrological systems, though these impacts on hydrologic systems may vary from region to region [9–12]. The physical features of the basin, climatic conditions, and human activities together affect the hydrologic cycle of a basin [6]. The climate factors like evaporation, rainfall, and temperature are the prime focus of the scientists [13, 14] as they are found to be the main climatic parameters affecting the unpredictability of a river.

✉ Mehlath Shah
  mehlath.shah02@gmail.com

[1] Department of Civil Engineering, National Institute of Technology, Srinagar, J&K 190006, India

1166

J. Inst. Eng. India Ser. A (December 2022) 103(4):1165–1181

Assessment of the probable impact of climate variation in hydrology and water resources is done by using impact approach in most of the hydrological research works. The impact approach usually comprises of four steps, i.e., selecting appropriate hydrological model based on calibration and validation of the hydrological model; generating climate change scenarios using different downscaling approaches; using observed and future climatic data for simulation run of the model; and evaluating the impacts by comparing the outcomes with the baseline simulation. Different hydrological models are observed to generate a relation between changes in climate variables and water resources through simulation of numerous hydrologic processes [15].

Tarekegn et al. [16] used the SWAT (Soil and Water Assessment Tool) model to assess the impact of climate change on the hydrology of Andasa watershed. He concluded that changing climate might cause considerable impact on the hydrology of the watershed due to increase in potential evapotranspiration (PET) and decrease in discharge and soil water, respectively. Malik et al. [17] studied the use of Soil and Water Assessment Tool (SWAT) 2012 model for simulating the streamflow at Lidder catchment of the Kashmir valley for the period of 8 years (2007–2015). They stated that in order to develop a best fit model for the study area, absolute knowledge regarding the hydrological processes of the river basin and information about significant parameters affecting the streamflow is important.

Khelifa and Mosbhai [18] aimed to estimate peak discharges of flood using HEC-HMS model in a small urban ungauged watershed located in Northeast of Tunisia. Rational formula was used for rough evaluation of maximum flood discharge at different return periods. Meresa Hadush [19] attempted to derive flood frequency curve in ungauged Keseke river catchment, South Nation Nationality and People (SNNP)-Ethiopia by adopting empirical and deterministic modeling approach. It was concluded that Soil Conservation Services-Curve Number (SCS-CN) and Artificial Neural Network (ANN) approaches are suitable to forecast river-runoff with realistic accuracy in the study area, and satisfactory correlation was obtained between predicted and observed satellite rainfall.

Agriculture is the prime factor affecting the Indian economy which in turn is mainly at the mercy of the water resource of the Indus basin. It is a great test for water resource managers to resolve water issues as numerous studies have discovered that country's water resources are extremely vulnerable to climate change threats. Today, India is counted in the list of most water-stressed countries as availability of water in the country has reduced because of a rapid increase in population, which is an alarming situation. Although tension has already been created among the provinces due to the shortage and improper distribution of water, the potential changes in water can accelerate some serious problems. Therefore, for the better planning and management of hydrological components in any watershed of the country, a clear assessment of impact of changing climatic conditions on water resources is important.

Sindh River is one of the major tributaries of River Jhelum and is an important source of water for irrigation and domestic purposes. Also, it is the only river in Jammu and Kashmir, on which three hydroelectric power projects are active. The characteristic of hydrological variables, especially rainfall, is strongly influenced by local and global climatic conditions. It is therefore important to determine the extent to which global climate change will affect the variable nature of Sindh River's hydrological and flow regimes. This information is valuable in determining the appropriate course of action for the future development and management of Sindh River. Changes in flow rates affect the availability of water for agricultural, domestic, industrial, and recreational uses. For the present study area, understanding the potential impacts of climate change on river flows is necessary to ensure adequate supply in the future.

HEC HMS was chosen due to easy approach and simplicity of the model. Also, it is freely available software with great efficiency and includes a variety of model choices for each segment of the hydrologic cycle [20]. HEC HMS model supports lumped and distributed parameter-based modeling. It offers a wide range of hydrological modeling options with main focus on discharge hydrographs. It also offers various components for calculating rainfall losses, routing and direct runoff. Many researchers in the past have tested the efficiency of this model for different study areas. For instance, Darji et al. (2021) used HEC HMS for estimating runoff in Machhu river basin of Gujarat, India, and found a good correlation value of 0.85. Similarly, Salil Sahu et al. [21] determined the efficiency of HEC HMS for simulating runoff in Shipra river basin in Madhya Pradesh. They found that the model was highly efficient with coefficient of determination equal to 0.85. HEC HMS model was successfully used to simulate discharge by Radmanesh et al. [22], Saeedrashid [23], Tassew et al. [24], Mehmood and Jia [14], and Meenu et al. [20] at various river basins.

A lot of research has been done on river Jhelum with respect to climate change effects on the hydrological parameters, however, no such research has been done on river Sindh of India. For instance, the researchers like Mahmood and Jia 2016 used HEC-HMS to assess climate change impact on river Jhelum. In view of research and practical gap, this study was conducted with two chief objectives, i.e., (1) to apply HEC HMS software in the river Sindh of Northwest Himalayas, which is primarily affected by monsoon rains and (2) to study the impact of climate change on the flow regimes of river Sindh. Furthermore, the calibrated parameters of this model can be used for future hydrological studies in this and adjacent catchments

J. Inst. Eng. India Ser. A (December 2022) 103(4):1165–1181

1167

Materials and Methods

Overview of the Study Area

River Sindh is one of the major tributaries of river Jhelum (Fig. 1a). It flows through the Ganderbal district of Union territory of Jammu and Kashmir and has a length of 108 km. Total area under river Sindh is 1560.32 Sq. Km. River Sindh forms the Sindh Valley and is located between latitudes of 34° 10′ to 34° 28′ N and longitudes of 74° 40′ to 75° 25′ E (Fig. 1). It is one of the most significant tributaries of river Jhelum having three hydroelectric power plants which are functional. These hydroelectric power plants are Upper Sindh hydroelectric power project 1st at Sumbal, Upper Sindh hydroelectric power project 2nd at Kangan, and Lower Sindh hydroelectric power project at Ganderbal. The water of this tributary is used by locals for irrigation purposes and for domestic use after going through water treatment plant. The drainage system of the area forms a dendrite pattern (Fig. 1). River source is a glacier called Machoi glacier near Sonmarg (elevation of 4800 Km), and mouth is at Shadipora (elevation of 1600 Km) where it sinks into the main river of Kashmir valley, i.e., river Jhelum. Figure 1b shows the dendrite pattern of drainage network and different guage stations selected in the study area.

Hydro-Meteorological Data

The daily discharge data were obtained from Irrigation and Flood control (IFC) department of J&K, India, for 25 years, i.e., 1992–2017. The discharge data were collected for the three gauge stations of the Sindh valley watershed, i.e., Dudarhama, Narayanbagh and Preng. The data were collected for the period of 25 years (1992–2017) at two gauge stations, i.e., Dudarhama and Narayanbagh. For Preng station, discharge data were available for the period of 22 years, i.e., 1992–2001 and 2005–2017. The basic information about the three gauge stations are shown in Fig. 2 and Table 1. Based on data available, one meteorological station, i.e., Shalimar station was selected for the present study. Daily precipitation, maximum and minimum temperature for the period of 34 years (1985–2019) were collected from the Agro-Met department of Sher-e-Kashmir University of Agriculture Science and Technology-Kashmir, Shalimar, Jammu and Kashmir (SKUAST-K), India.

Table 1 shows mean flow calculated for three gauge stations, i.e., Dudarhama, Narayanbagh and Preng of the study area. Figure 2 shows the monthly discharge at different gauge sites for the study period, i.e., 1992–2017. May to August are witnessed to be the peak flow months, and months from October to February are observed to be low flow months in the Sindh Valley watershed. In the study area (Fig. 1), as shown in Fig. 2a, discharge at three different gauge stations starts rising in March and April owing to snow melting in the area and reaches the extreme values in the months of May, June and July due to the added influence of the monsoon showers. The peak flow at Dudarhama station is attained in June, while the peak discharge at Narayanbagh and Preng station occurs in the month of May and June, respectively. Similarly, Fig. 2b shows the mean monthly temperature and precipitation recorded at the study station from 1985 to 2019. It can be clearly seen in Fig. 2b that months between Januarys to April are observed to be high precipitation months, whereas maximum temperature and minimum temperature reach its peak values in the months of July and August.

### Digital Elevation Data (DEM), Land use Land Cover (LULC) and Soil Data

A DEM (Digital Elevation Model) is a digital representation of elevation data that is used globally to extract topographical characteristics of terrain [6]. A 30 m resolution Shuttle Radar Topography Mission-DEM (SRTM-DEM) was obtained from the website of Earth explorer, i.e., http://earthexplore.usgs.gov and was used to define the topography of the Sindh valley watershed. The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) was used in the present study to extract different basin parameters (flow length, flow direction, longest flow path, basin area, etc.) from the DEM. Only the slope, LULC, Soil texture and elevation map are revealed in Fig 3.

To assess the changes in land use land cover of the study area, satellite image of land use land cover obtained from the website of earth explorer (http://earthexplore.usgs.gov.) was brought to Universal Transverse Mercator (UTM) projection in zone 43N and the quality of image was enhanced using histogram equalization as shown in Fig. 3c.

Figure 3d shows the main classes of soil found in the Sindh valley watershed. The elevation and slope map of the study area are also shown in Fig. 3a and b. Soil and land use land cover data are important to extract initial estimations of hydrological properties of basin (e.g., maximum moisture deficit, etc.). Table 2 shows the detail and source of satellite imagery used to study for study. Various types of vegetation (agriculture, aquatic vegetation, bare land, built up, moderately dense forests, very dense forests, pastures, plantations, open scrubs and rock out crops) found in the area are shown in Fig. 3c. The major classes of land cover dominating the area are moderately dense forests, very dense forests and rock out crops, which cover the areas of 29.13%, 18.07% and 11.59% of the watershed, respectively. The main soil groups of the area are also shown in Fig. 3d. The two major groups of soil found in the area are sandy clay loam and sandy loam soils, covering 425.85 Sq. Km and 368.35 Sq. Km of the total study area.
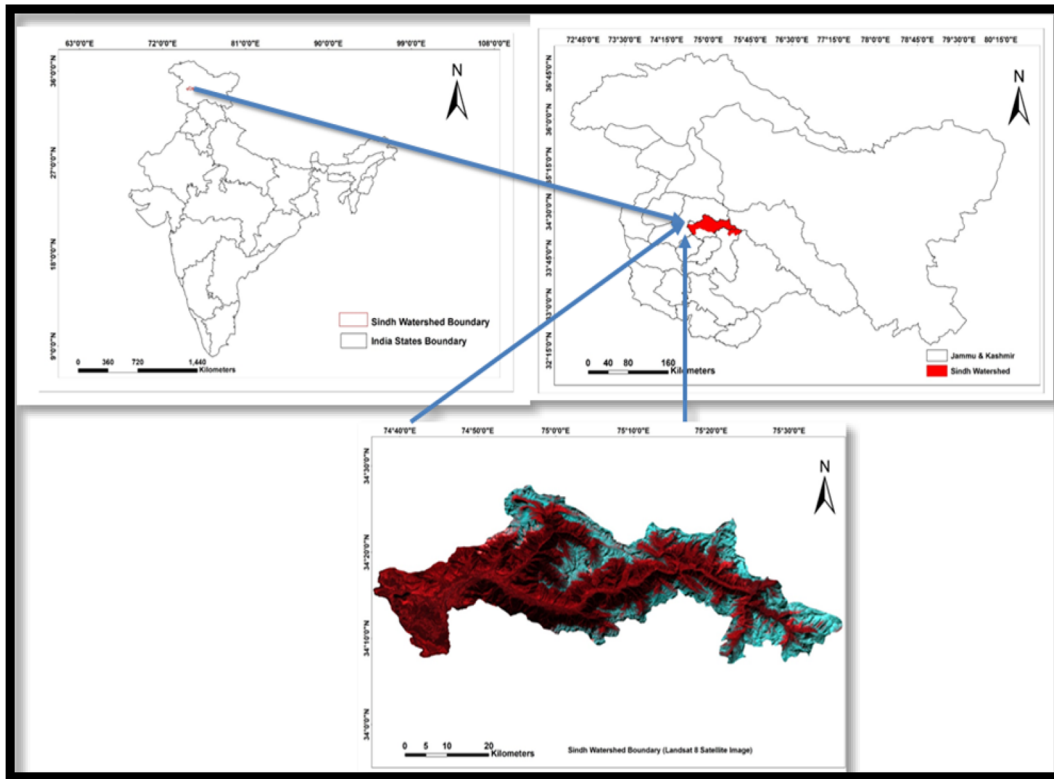
(a) Location of Study Area (River Sindh)
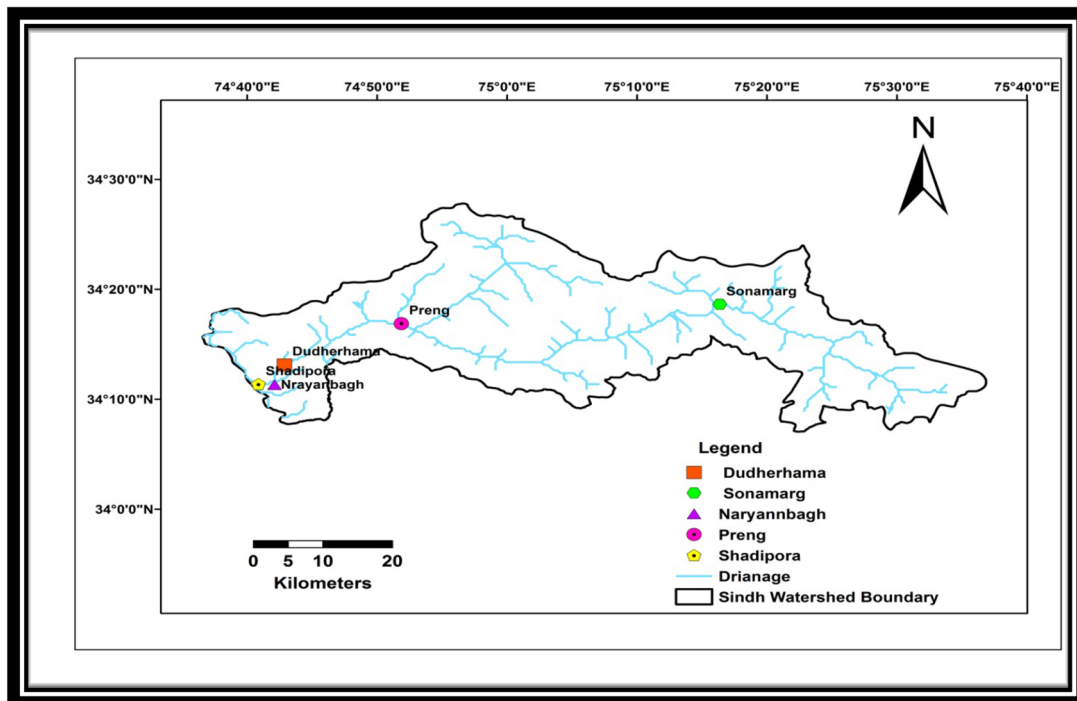
(b) Drainage pattern of River Sindh

Fig. 1 **a** Location of Study Area (River Sindh), **b** Drainage pattern of River Sindh

Fig. 2 a Mean monthly discharge at different sites of the study area for the period 1992–2017 at Dudarhama and Narayanbagh and for 1992–2001 and 2005–2017 at Preng station and **b** Mean monthly variations in climate parameters of study area (1985–2019)
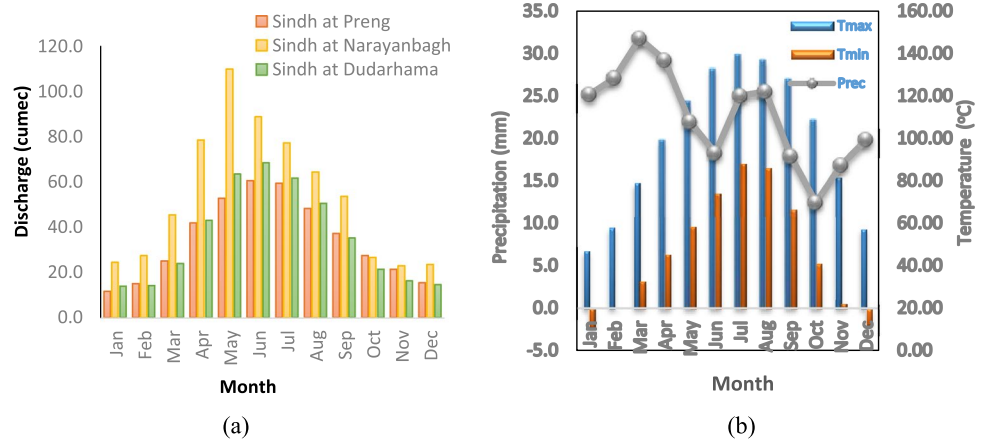

(a)

(b)

Table 1 Data about the gauging stations in the Sindh Valley watershed

River	Station	Latitude	Longitude	Period (Year)	Mean discharge m³/s
Sindh	Dudarhama	34° 12′ N	74° 45′ E	1992–2017	37.5
Sindh	Narayanbagh	34° 17′ N	74° 69′ E	1992–2017	53.9
Sindh	Preng	34° 27′ N	74° 86′ E	1992–2000, 2005–2017	31.3

Statistical Downscaling Model (SDSM 4.2.9)

The linear regression-based SDSM 4.2.9 model was used to downscale the temperature and precipitation in the study area. First, quality control check was performed for observed maximum, minimum temperatures and precipitation in SDSM model, to look for missing data prior to model calibration. Temperature (maximum and minimum) are modeled as unconditional process, whereas precipitation is modeled as conditional process [20]. Based on previous researches regarding GCM selection in the Kashmir Valley, CanESM2 was selected for the study. For instance, Ahsan et al. [25] and [26] used CanESM2 successfully for the entire Kashmir region of India. Also, at present, CanESM2 is the only model included in fifth Coupled Model Inter Comparison Project (CMIP5) available for which ready to use SDSM predictors are available [25]. After performing the auto-regression, correlation values are obtained between observed and predictands variable. Based on the correlation coefficients, predictor variables are selected which best fits the observed data. Various predictor variables used in the study for predicting Tmax, Tmin and Pr are shown in Table 3.

The calibrate model in SDSM 4.2.9 model was used to compute parameters of multiple regression equations by using an optimization algorithm [20]. From 34 years of observed data, 16 years, i.e., 1985–2001 were selected for calibration and 12 years, i.e., 2007–2019 were used for validation of the model. After calibrating and validating the model successfully, Scenario generator in SDSM

was used produce downscaled weather series supplied by the CanESM2 (RCP 4.5 and RCP 8.5), corresponding to selected predictors for both observed and future climate variables. The CanESM2 data were obtained from Second Generation Earth System Model, Canada at a grid resolution of 2.7906° × 2.8125°. The output from SDSM is processed and used as an input in the hydrological model, HEC-HMS.

HEC-HMS Model Setup

In the present study, a rainfall-runoff simulation model, HEC-HMS, framed at the Hydrologic Engineering Centre by the U.S Army Corps of Engineers, was used to study the impact of climate change on the Sindh valley watershed. A complete description of the model formulation and its various processes is available in the User's Manual and Technical Reference Manual of HEC-HMS [27, 28]. The general methodology followed during the modeling is shown in Fig. 4. Six loss methods (i.e., SCS (Soil Conservation Service) curve number method, initial and constant method, etc.) are present in the model for estimation of excess precipitation. Direct runoff is calculated from the excess rainfall by using the five base flow estimation methods and six channel routing methods (e.g., Muskingum Method) present in the HEC-HMS model. HEC-HMS setup comprises of four basic components: (1) Basin Model (2) Meteorological Model (3) Control Specification Model and (4) Input Time Series. These components are required to be accurately linked with one another for the proper working of the model. Basin
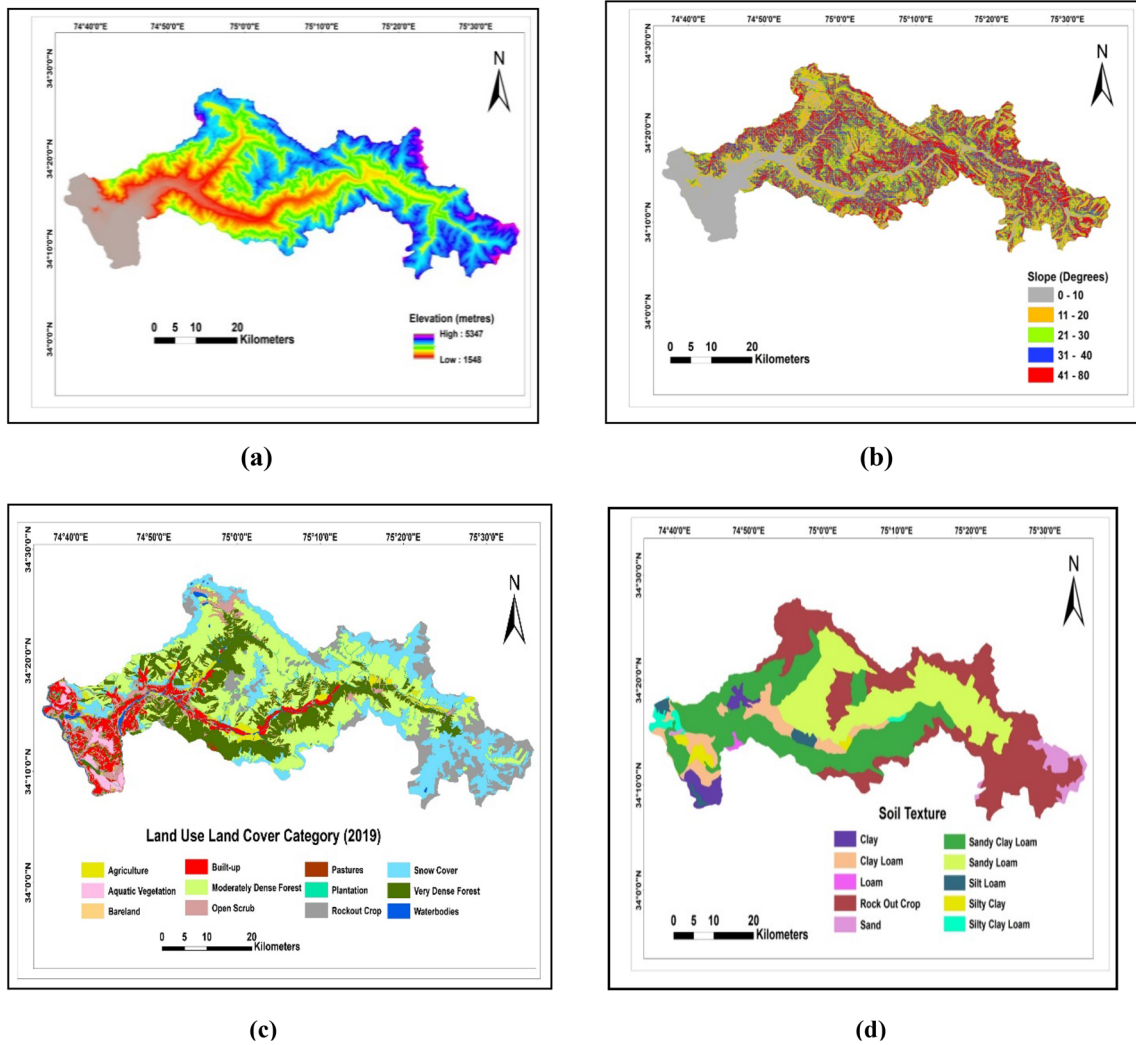
(a)

(b)

(c)

(d)

Fig. 3 **a–d** Elevation, Slope, LULC, Soil Texture, of the Sindh Valley Watershed [6]

Table 2 Detail of Satellite imagery used in the study

Image	Resolution/Scale	Date of acquisition	Source
SRTM DEM	30 m	September 2019	http://earthexplore.usgs.gov
Soil Map	1 Km	October 2019	https://fao.org/Soilportal
Landsat8	30 m	October 2019	http://earthexplore.usgs.gov

Table 3 Selected predictors and their partial correlation coefficient during screening of Variables

Predictands	Predictor variable	Depiction	Partial R
Maximum temperature	Nceptempgl	Mean temperature at 2 m	0.76
	Ncepp5_zgl	500 hPa Velocity	0.52
Minimum temperature	Ncepp500gl	500 hPa geopotential height	0.71
	Nceps5_zgl	500 hPa Velocity	0.48
Precipitation	Ncepmslpgl	Mean sea Level Pressure	0.45
	Ncepp8_zgl	850 hPa Velocity	0.32

Fig. 4 General Methodology
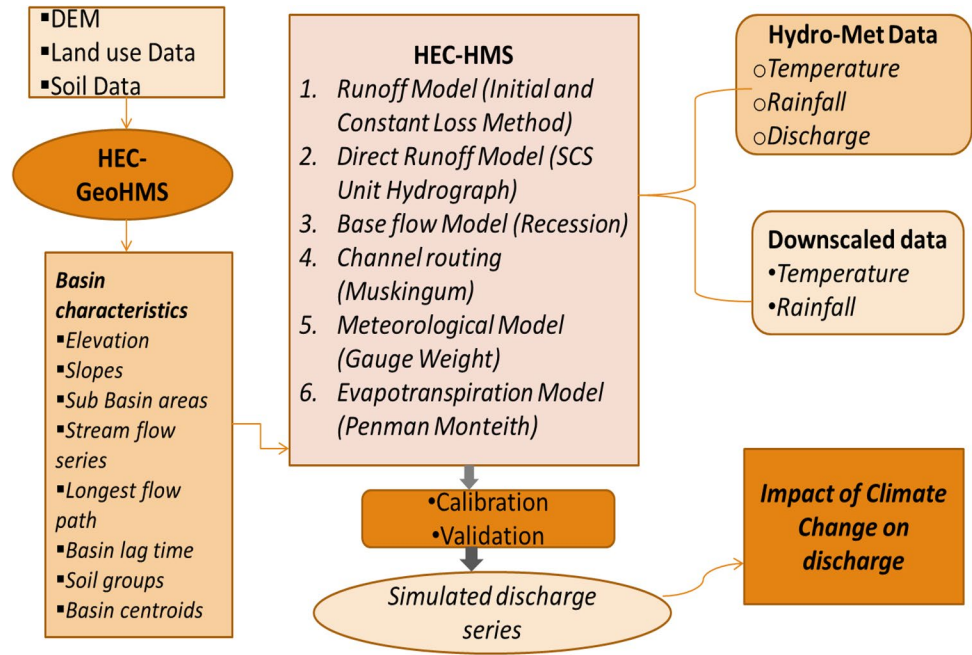
model shows the basin slope, laps rate, length of the stream and area of basin of the watershed. A base flow method, loss method, transforming method and channel routing method are used to calculate the physical features of the watershed. Control specification method of the model contributes in controlling the period of simulation. Components of input time series are needed to control meteorological data (maximum temperature, minimum temperature and rainfall) and flow.

In the present study, for estimating the excess-precipitation, direct-runoff transformation, channel routing, and baseflow, the basin model included the deficit and constant loss (DCL) method, the SCS unit hydrograph method, Muskingum method, and the recession method, respectively. In some earlier studies, parallel approaches have been implemented. Shrestha et al. 2014 used HEC-HMS to study climate change impact on river flow and hydro power production in Kulekhani hydro power project in Nepal, and Meenu et al. [20] successfully applied the HEC-HMS deficit and loss method to assess the future effects of climate change in the Tunga-Bhadra watershed.

DCL method comprising of four key valuation constraints, i.e., initial deficit; constant rate; maximum deficit; and impervious percentage was used to estimate soil moisture changes in the study area. Soil and land use land cover data used as input in the model are approved only during calibration. These data are then used for estimating the above mentioned parameters (e.g., Initial deficit, etc.). The SCS unit hydrograph method converts the excess rainfall calculated by DCL method into direct surface runoff. In SCS method, basin lag is the only parameter required

for estimation. For estimating the initial value of basin lag, the time of concentration of a basin is multiplied by 0.6. Three parameters (recession constant, initial discharge, and threshold) of recession method are needed to be optimized to calculate the base flow of study area. The Muskingum method of the model needs two parameters, i.e., Muskingum coefficient (X) and travel time (K), to be finalized during the calibration so as to transfer the total flow (surface and base flow) through the channels [14] as shown in Table 4. Further, model offers temperature index and gridded temperature index methods for incorporating the contribution of

Table 4 Model Parameters used in the model (HEC-HMS)

Model parameter	Optimized average values
SCS-CN scale factor	0.02
Curve number (CN for LULC)	42.10
Muskingum method	
Muskingum X value	0.18
Muskingum K value	10.12 h
Deficit and constant method	
Initial deficit (mm)	11
Constant rate (mm/hr)	0.34
Imperviousness (%)	20
Temperature index method	
P_x temperature (°C)	2.6
Base temperature(°C)	0
Lapse rate (°C/100m)	− 0.61

snowmelt. In the present study, temperature index method is used as gridded temperature index method which is more complicated. The details of optimized average values of various parameters used in model are given in Table 4.

Calibration and Validation of HEC-HMS Model

After preparing all the required input data files (DEM, Soil and land use land cover, climate, etc.) for the model, a new HEC-HMS project was built for Sindh valley watershed. The observed discharge data for the period of 25 years, i.e., 1992–2017 were divided into two phases, for calibrating and validating HEC-HMS model. On the basis of the data accessibility, the period of 16 years, i.e., 2001 to 2017 was selected for calibration and period of 9 years, i.e., 1992 to 2000 was chosen for validation of the model. However, due to inaccessibility of data between 2001 and 2005 at Preng station of Sindh valley watershed, model was calibrated for 12 years, i.e., 2005 to 2017. Throughout the simulation period, the features of soil and land use land cover were deliberated to be persistent.

Performance Indicators of HEC-HMS Model

In this study four popular indicators, i.e., Nash–Sutcliffe efficiency (NSE), coefficient of determination (R^2), percent bias (PBIAS), and RSR (RMSE observations standard deviation ratio) statistics were calculated for evaluating performance of model during calibration and validation of HEC-HMS. For improved understanding, the measured flow was also paralleled graphically with the simulated flow to investigate the changes in the low and high flows [14]. In this study, the model was calibrated and validated at different gauge sites accessible in the study area.

Different equations used to calculate the above-mentioned performance indicators (NSE, R^2, PBIAS, and RSR) are given below.

Coefficient of Determination (R^2)

It is used to calculate the trend similarity between observed and simulated values of discharge using the following equation [6];

$$R^2 = \frac{\sum (Q_{obs} - \overline{Q_{obs}}) - (Q_{sim} - \overline{Q_{sim}})}{\sqrt{\sum \left(Q_{obs} - \overline{Q_{obs}}\right)^2 \times \left(Q_{sim} - \overline{Q_{sim}}\right)^2}}$$

where Q_{obs} is observed values of discharge and Q_{sim} is simulated values of discharge. The value of R^2 should be close to 1 for good results between observed and simulated values.

Nash-Scuffle Efficiency (NSE)

It indicates how well the observed and simulated data plot fits 1:1 line [29]. The value of NSE ranges from 0 to 1. Positive values closer to 1 are indications of good results. However, negative values closer to 0 are not satisfactory. NSE is calculated using the following equation:

$$NSE = 1 - \frac{\sum (Q_{sim} - Q_{obs})^2}{\sum (Q_{obs} - \overline{Q_{obs}})^2}$$

The results are considered to be good if the values of NSE are greater than 0.75 and satisfactory if the value of NSE lies between 0.36 and 0.75 [30, 6].

Percent Bias (PBIAS)

It calculates the average tendency of the simulated data to be smaller or larger than the observed data [31]. PBIAS is calculated using the following equation:

$$PBIAS = \frac{\sum (Q_{obs} - Q_{Sim}) \times 100}{\sum Q_{obs}}$$

The optimal value of PBIAS is 0 and model performance is considered to be best if PBIAS values are within low range.

Root-Mean-Square Error (RMSE)-Observation Standard Deviation Ratio (RSR)

It is the ratio of RMSE and standard deviation of observed and simulated values and is calculated by using the following equation [29]:

$$RSR = \frac{\sqrt{\sum \left(Q_{obs} - Q_{sim}\right)^2}}{\sqrt{\sum \left(Q_{obs} - \overline{Q_{obs}}\right)^2}}$$

The optimal value of RSR is 0. Lower RSR value is due to lower RMSE value indication best model performance [31].

Future Variations in Discharge

After successfully calibrating and validating the model, the downscaled climatic parameters, i.e., temperature and precipitation for the years between 1992 and 2099 (CanESM2) were served as input into HEC-HMS to simulate daily flow (i.e., surface flow and base flow) at different gauge sites in the River Sindh. In the entire simulation period, physical characteristics change was kept constant. The simulated discharge was divided into three upcoming periods, i.e., 2030s (2018–2040), 2060s

(2041–2070), and 2090s (2071–2099)—and one baseline period (1992–2017). The flows of the upcoming years were related to the baseline flow to calculate the future variations in the basin, as shown by Mehmood and Jia in 2016. The total observed cyclical and yearly values were also calculated for the period 1992–2017. These values can be used to observe the absolute streamflow values in the future. Since the flow data at Preng start from 1992 to 2001 and 2005 to 2017, the discharge was simulated at this site for the same periods using the observed meteorological data feeding into HEC-HMS, after calibration and validation of the model. Similarly, at Preng, flow data were generated for the period 2001–2005 because of lack of data for this period at the site. The indicators mean flow, low flow, median flow and high flow were calculated to study the future changes with respect to the simulated baseline streamflow under CanESM2.

Results and Discussion

Calibration and Validation of the Model

Calibration of the HEC-HMS model was done by comparing the observed and simulated discharge for the years 2001–2017. The results (Table 5) revealed that observed discharge fitted well with simulated discharge data. Similarly, validation of model done by matching observed and simulated discharge for the period 1992 to 2000 showed good agreement between the two data sets. The values of R^2, NSE, RSR, PBIAS as shown in Table 5 depict that model performance could be rated as "very good" [32]. The R^2 values ranged between 0.85 and 0.89 for both calibration and validation periods of study indicating a very good model performance. Also, NSE values stretched between the acceptable values range, i.e., 0.81 to 0.86 for calibration period (2001–2017) and 0.79 to 0.85 for validation period (1992–2000) at Dudarhama, Narayanbagh and Preng stations of River Sindh. During the calibration and validation period, the values of RSR and PBIAS were calculated for to be less than 0.03 and 2.76, respectively, at different gauging stations of River Sindh. In general, the hydrographs (Fig. 5a–f) generated by HEC-HMS model for both calibration and validation periods at the three gauging stations of Sindh showed the trend reasonably well.

Similarly, performance of statistical downscaling model (SDSM 4.2.9) was checked by calculating coefficient of determination (R^2). SDSM 4.2.9 was calibrated for the years 1985–2006 and for the years 2007–2019 as shown in Table 6. The R^2 calculated for the calibration period, i.e., 1985–2006 (Table 6) was found to be 0.89, 0.81 and 0.58 for maximum temperature (T_{max}), minimum temperature (T_{min}) and precipitation (Pr), respectively. For the validation period, i.e., 2007–2019, R2 was found to be 0.84, 0.83 and 0.49 for maximum temperature, minimum temperature and precipitation, respectively. Figure 6 and Fig. 7 show the comparison between observed and predicted maximum temperature (T_{max}), and minimum temperature (T_{min}), for the calibration and validation periods. Also, Fig. 8 shows relation between observed and predicted precipitation values for calibration and validation periods of study.

Change Anomalies in Climate Parameters (Maximum Temperature, Minimum Temperature and Precipitation)

Analysis for temperature and precipitation was carried for different seasons in the area, i.e., summer (March–May), Spring (June to September), autumn (October–November), and winter (December–February) [30], by using statistical tests, i.e., Mann Kendall for trend analysis and Sen's Slope estimator for magnitude of that trend [33], for available meteorological station (Shalimar Station) from 1985 to 2019. Projected increase in seasonal maximum temperature data shows maximum increase in autumn, followed by summer. Under RCP 4.5 projected increase during 2090s is 2.15 °C for autumn and 1.98 °C for summer season. Similarly, under RCP 4.5 projected increase in maximum temperature during 2090s is 1.95 °C and 1.86 °C for autumn and summer seasons, respectively. In all three periods, under both RCP 4.5 and 8.5 scenarios, winter shows the lowest maximum temperature projection. Likewise, maximum values of minimum temperature are projected in autumn season, which is followed by summer season, under both scenarios. Under RCP 4.5 scenario, 2090s projected highest minimum temperature with increase in 1.96 °C and 1.62 °C in autumn and summer season, respectively. Also, RCP 8.5 projected minimum temperature to increase by 2.18 °C in autumn season and 1.05 °C in summer season, during 2090s. The changes in seasonal maximum and minimum temperatures for the three

Table 5 Statistics of model performance during Calibration and Validation periods

Station	Calibration (2001–2017)				Validation (1992–2000)			
	R^2	NSE	RSR	PBIAS	R^2	NSE	RSR	PBIAS
Dudarhama	0.85	0.81	0.01	2.18	0.88	0.85	0.01	2.71
Narayanbagh	0.88	0.86	0.02	2.71	0.86	0.79	0.02	2.76
Preng	0.86	0.83	0.02	2.35	0.89	0.84	0.02	2.68

1174

J. Inst. Eng. India Ser. A (December 2022) 103(4):1165–1181

Fig. 5 a–f HEC-HMS model
Calibration (2001–2017) and
Validation (1992–2000) Hydro-
graph at different sites of River
Sindh

(a)

(b)

(c)

(d)

(e)

(f)
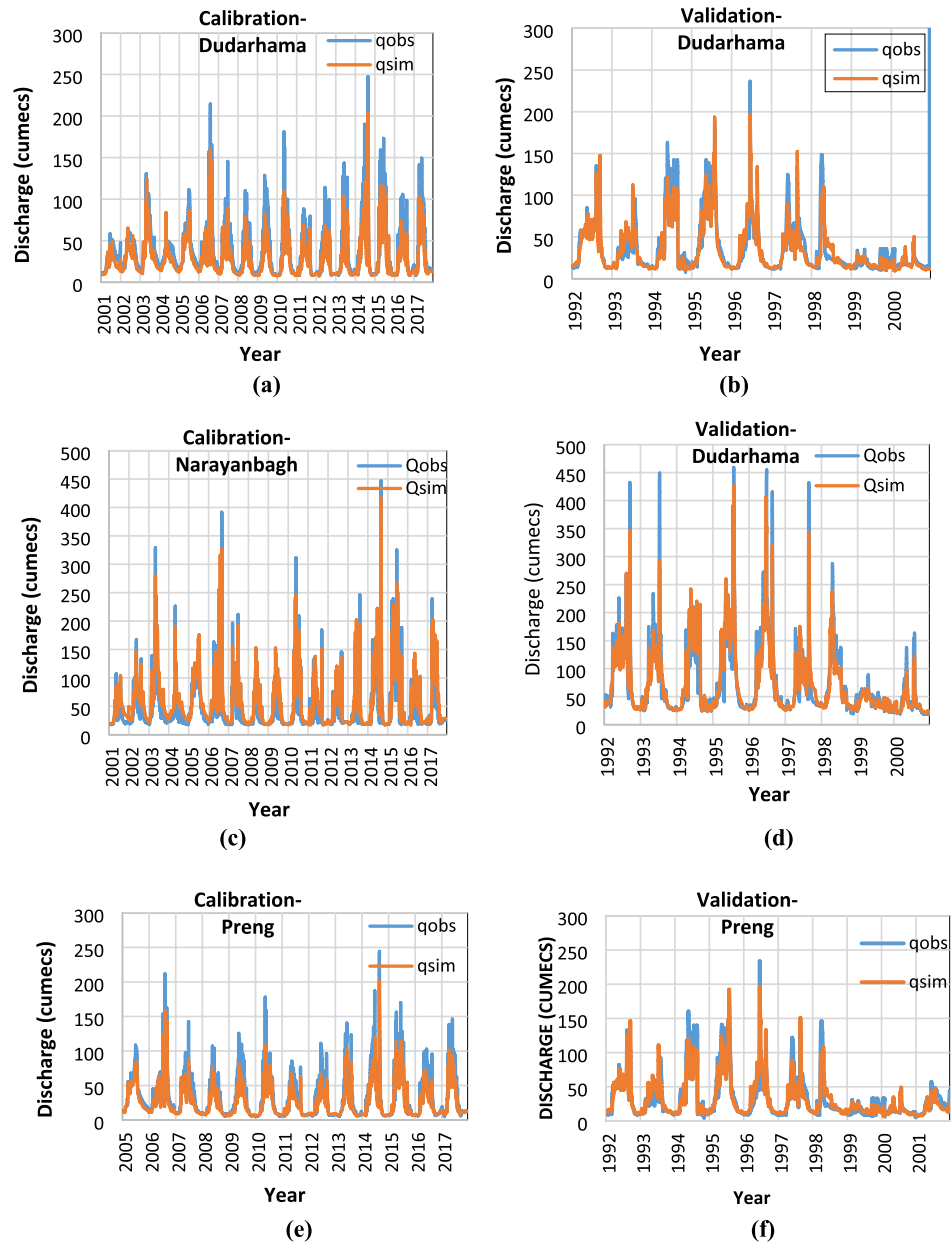
future periods, viz. 2030s (2022–2050), 2060s (2051–2075)
and 2090s (2076–2100) are shown in Figs. 9a and b, and 10a
and b, respectively.

Table 6 Statistical analysis of SDSM model for calibration and vali-
dation period

Climatic variables	Calibration (R^2) (1985–2006)	Validation (R^2) (2007–2019)
Maximum temperature	0.89	0.84
Minimum temperature	0.81	0.83
Precipitation	0.58	0.49

Similarly, precipitation was analyzed for the study sta-
tion and compared to the baseline period, i.e., 1985 to 2019.
Figure 11a and b shows the seasonal changes in precipitation
for the years 2022–2050 (2030s), 2051–2075 (2060s) and
2076–2100 (2090s). It was observed that the projected sea-
sonal rainfall was maximum in autumn followed by spring.
The change in precipitation under both RCP 4.5 and 8.5
scenarios varies between 2.2% and 13% in autumn season,
followed by variation between 2 and 5% in spring season.

Climate Change Impacts on Discharge

The predicted flow variations (percentage) in 2030s, 2060s,
and 2090s with respect to the modeled flow for the reference

Fig. 6 Evaluation of the observed and calibrated T_{max} for the **a** calibration period (1985–2006) and **b** validation period (2007–2019)
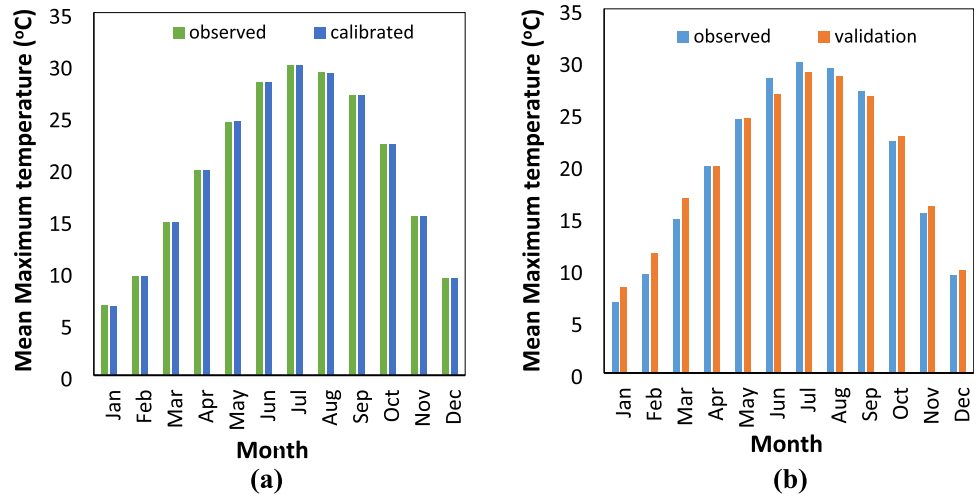

Fig. 7 Evaluation of the observed and calibrated T_{min} for the **a** calibration period (1985–2006) and **b** validation period (2007–2019)
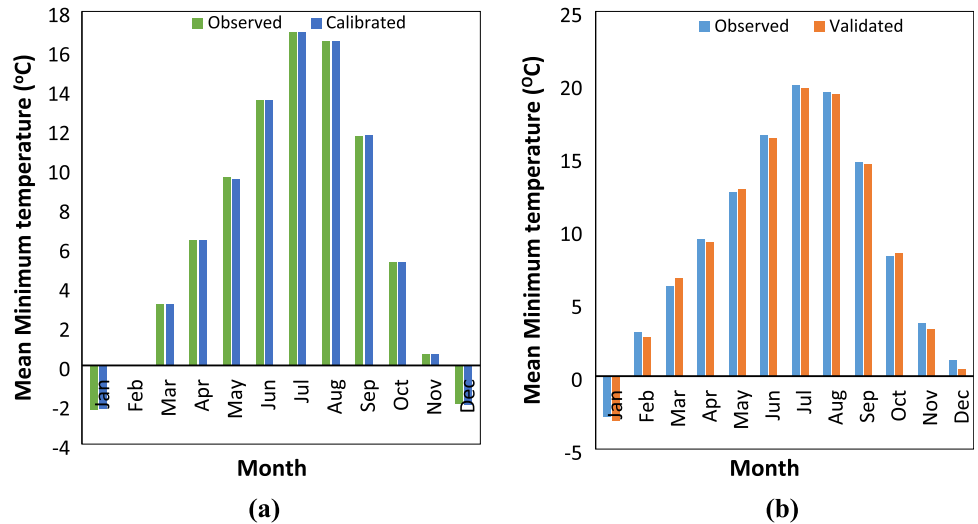

Fig. 8 Evaluation of the observed and calibrated Pr (mm) for the **a** calibration period (1985–2006) and **b** validation period (2007–2019)
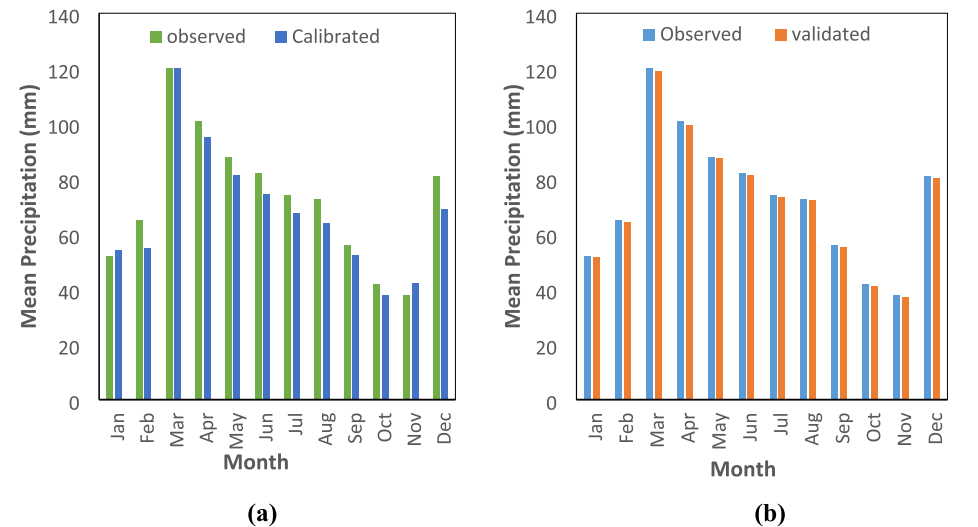
Fig. 9 Seasonal Deviation in
Maximum Temperature (°C)
for future periods (2030s, 2060s
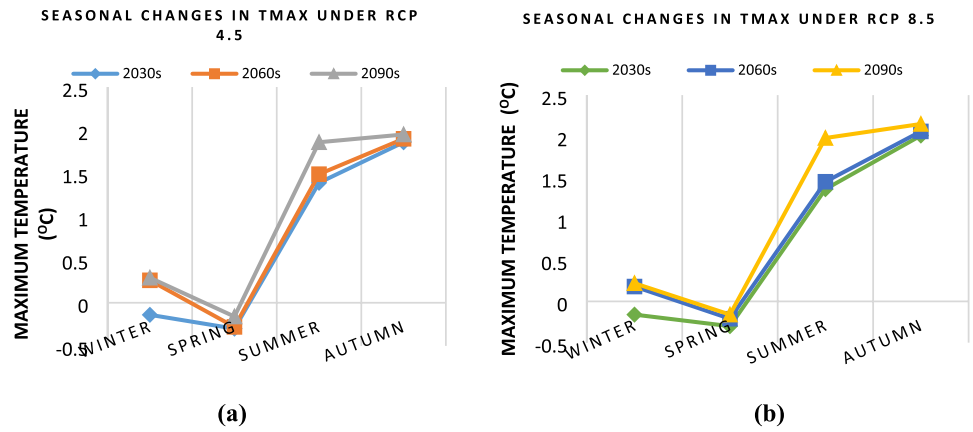and 2090s) under **a** RCP 4.5 and
b RCP 8.5

Fig. 10 Seasonal Deviation in
Minimum Temperature (°C) for
future periods (2030s, 2060s
and 2090s) under **a** RCP 4.5 and
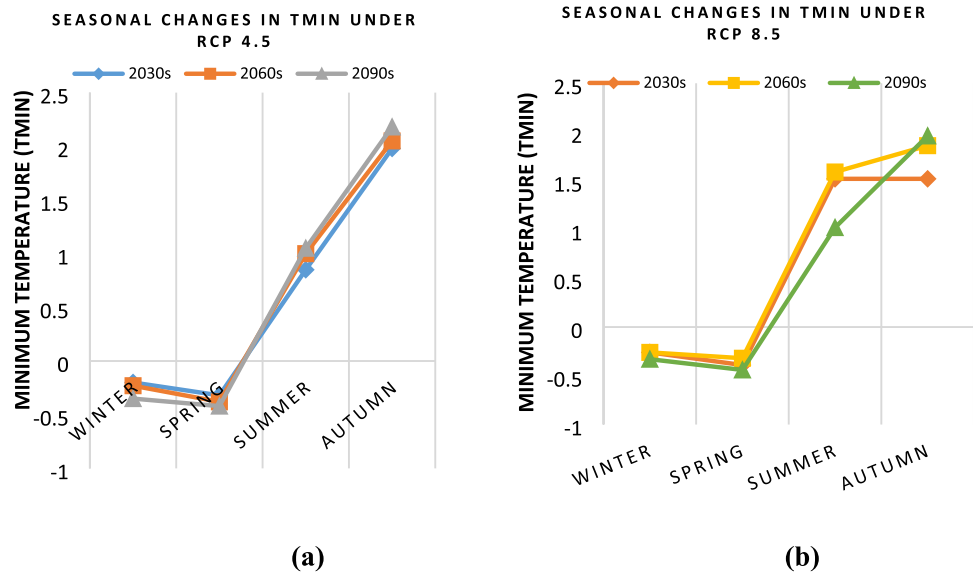**b** RCP 8.5

Fig. 11 Seasonal Deviation in
Precipitation (mm) for future
periods (2030s, 2060s and
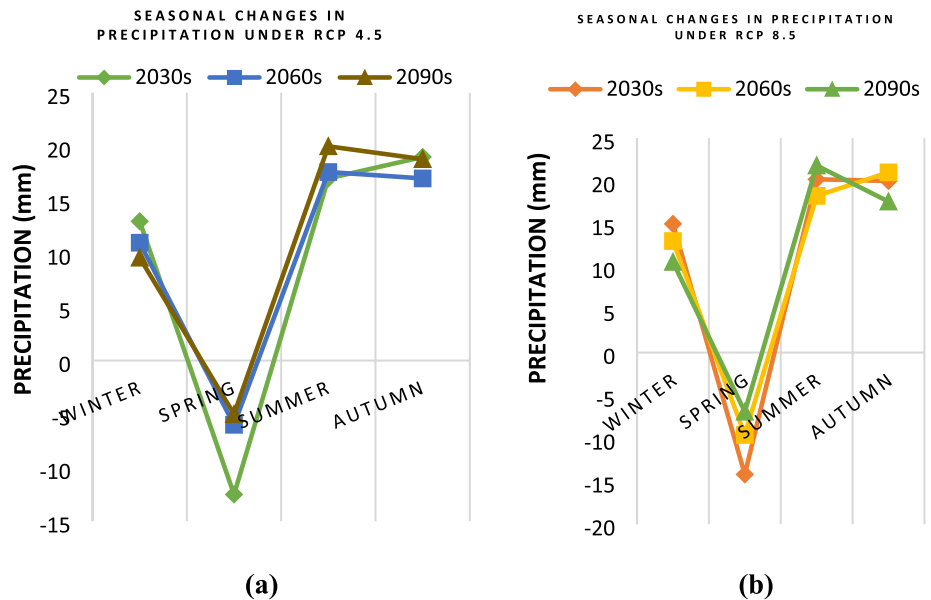2090s) under **a** RCP 4.5 and **b**
RCP 8.5

Table 7 Future variations (%) in discharge at different gauges relative to the baseline (1992–2017) in the Sindh Valley Watershed

| Seasons	Preng			Narayanbagh			Dudarhama		
	Observed	Simulated RCP 4.5	Simulated RCP 8.5	Observed	Simulated RCP 4.5	Simulated RCP 8.5	Observed	Simulated RCP 4.5	Simulated RCP 8.5
Stream flow (m³/s) for 1992 to 2017									
Winter	9	4	5	20	18	19	68	52	58
Spring	34	24	27	100	70	75	409	362	375
Summer	119	171	175	210	306	298	619	760	736
Autumn	20	38	41	49	115	108	152	299	285
Annual	43	59	58	100	131	132	348	418	415
Future changes (%) in 2030s									
Winter		10	−1.8		18	11.5		10.8	5.4
Spring		10.1	6.9		31.2	20.8		9.5	1.8
Summer		0.8	5.2		−8.4	−0.9		−9.7	−2.8
Autumn		7.7	−4.8		4.2	2.6		0.6	−0.8
Annual		7.1	2.8		10.8	7.2		2.8	0.2
Future changes (%) in 2060s									
Winter		8.6	−1.6		12.8	3.1		8.3	−4.8
Spring		25.8	24.5		9.9	3		7.1	4.2
Summer		−0.8	3.9		−2.2	1.5		−1.5	1.9
Autumn		6.8	−2.6		1.6	−1.1		−0.2	−3.6
Annual		10.9	6.8		5.8	0.9		2.6	−1.1
Future changes (%) in 2090s									
Winter		11.8	4.2		28.6	12.6		11.8	5.9
Spring		39.8	26.4		30.9	26.1		8.6	2.3
Summer		5.6	2.8		−0.1	2.6		−8.2	−4.1
Autumn		10.1	−0.2		9.9	11.6		2.5	7.5
Annual		18.3	9.8		16.5	14.2		5.1	4.7

period (1992–2017) are described in Table 7. Table 7 also presents the entire cyclical and yearly values of the observed flow and modeled flows for the baseline period. The average annual flow in the River Sindh at Preng, Narayanbagh and Dudarhama is 43 m³/s, 100 m³/s, and 348 m³/s, respectively, for the baseline period.

In all three periods, i.e., 2030s, 2060s and 2090s, the mean flows in winter (December–February), spring (March, April and May), and autumn (September–November) seasons projected toward increase at the three different gauges of the River Sindh. On the other hand, in the summer season (June–August) which is a season of highest flow, the flows are expected to decline at most of the sites in the coming years. In 2030s, maximum increase in spring season was calculated to be 31% and 10%, at Narayanbagh and Preng stations of River Sindh under RCP 4.5. On the other hand, in winter season, maximum increases of 18% and 11% at Narayanbagh and Dudarhama, respectively, were projected under RCP 4.5. On the contrary, summer

showed a maximum decrease of 10% at Dudarhama and 8% at Narayanbagh stations. The patterns of the projected changes in future were found to be the same for 2030s and 2060s, however, the magnitude of these variations was lesser in 2030s as compared to 2060s. In the 2090s, although the pattern of variations in periodic and yearly flow was found to be the same as in previous two periods, but the scales were higher. On the whole, it was observed that discharge will decrease during the 2060s relative to the 2030s, and then, it will increase again in the 2090s.

Figures 12 and 13 show a graph of the 29-year average daily runoff (1991–2017) compared to average daily runoff under RCP 4.5 and RCP 8.5 scenarios for the future period, namely the 2030s, 2060s and 2090s. In Dudarhama, there has been an increase in peak runoff in both scenarios for the next three periods. However, a slight decrease in peak discharge was observed at Narayanbagh and Preng stations of the Sindh River for all three future periods and under RCP scenarios 4.5 and 8.5.

Fig. 12 Temporal shift in peak streamflow under RCP 4.5 at **a** Dudarhama **b** Narayanbagh and **c** Preng


(a)

(b)

(c)
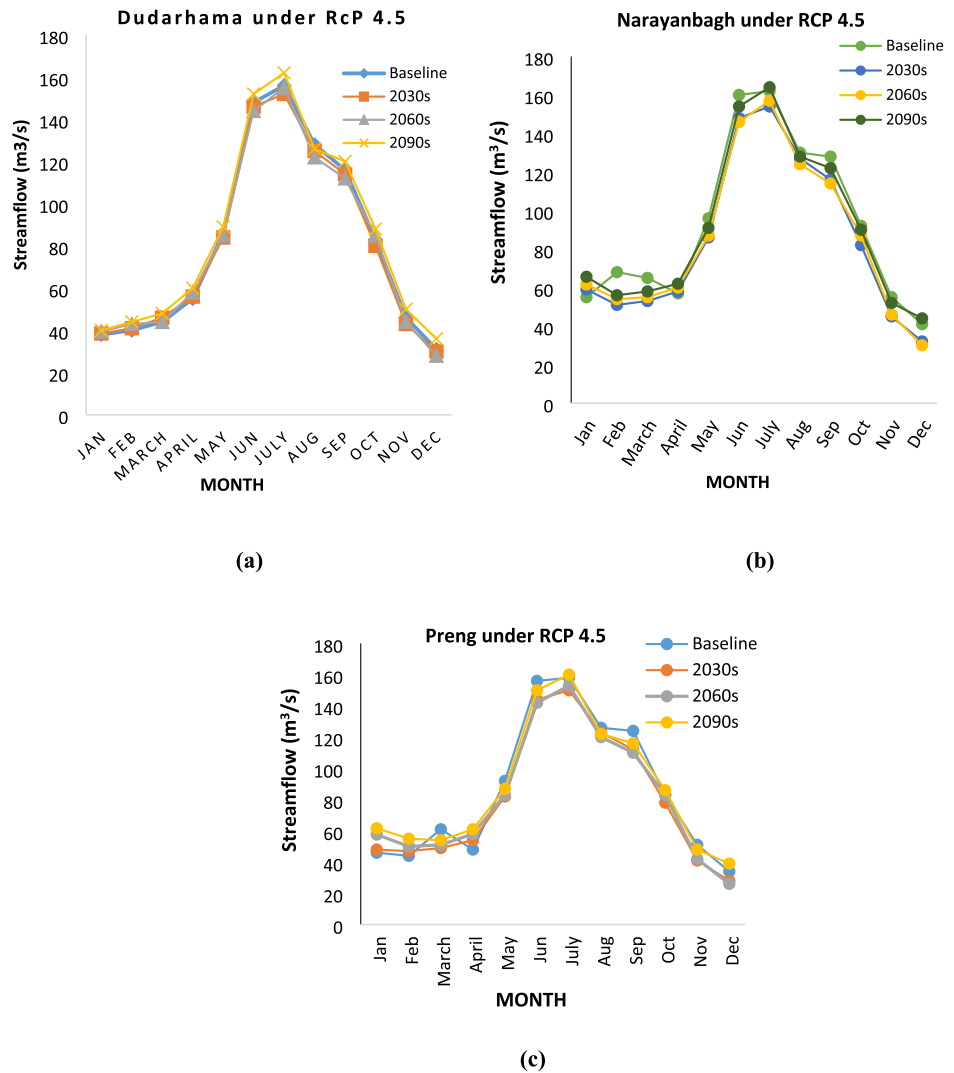
Projected Variations in Low, Median, and High Flows

Table 8 shows the predictable variations in high, median, and low flows at three different gauging stations for the future periods, i.e., 2030s, 2060s and 2090s with respect to the baseline period under RCP 4.5 and RCP 8.5. The observed flow and simulated flow data were used to calculate the total values of high (Q_5), median (Q_{50}), and low (Q_{95}) flows, for the baseline period (1992–2017) which is also described in Table 8. The high, median, and low flows in the basin are 1058 m³/s, 186 m³/s, and 50 m³/s at the Dudarhama. At the Dudarhama station, about 2–3% and 7–10% decrease in median and high flow were projected under both RCPs in the 2090s and increase in low flow by 5 to 7% were also projected for the same period. Similarly in Narayanbagh, low and median flow were projected to increase in 2090s by 24–28% and 19–24%, respectively.

In this study, HEC-HMS model was calibrated for the period of 16 years (2001–2017) and then validated for 8 years (1992–2000), at Dudarhama and Narayanbagh stations of the Sindh valley watershed. However, due to lack of data availability between the years 2001 and 2005 at Preng station, the model was calibrated for the period 1992–2000 and validated for the period 2005–2017. Three main performance indicators of the model used in the study are coefficient of determination (R^2), RSR, percent bias (PBIAS) and Nash-Sutcliffe (E). These indicators were considered for understanding the relationship between the observed and simulated flow. The values of R^2 and NSE fluctuated between 0.85–0.88 and 0.79–0.86 at three gauging stations of the Sindh River. The values of PBIAS and RSR were observed to be within the optimal range value indicating best model performance. The four performance indicators revealed that the simulated values of flow fitted close with the observed flow, indicating the model can be acceptably used to study the future discharge and evaluate the effect of climate variation on the River Sindh [6]. Also, SDSM 4.2.9 model was calibrated and validated for the periods

Fig. 13 Temporal shift in peak streamflow under RCP 8.5 at **a** Dudarhama **b** Narayanbagh and **c** Preng

(a)

(b)

(c)
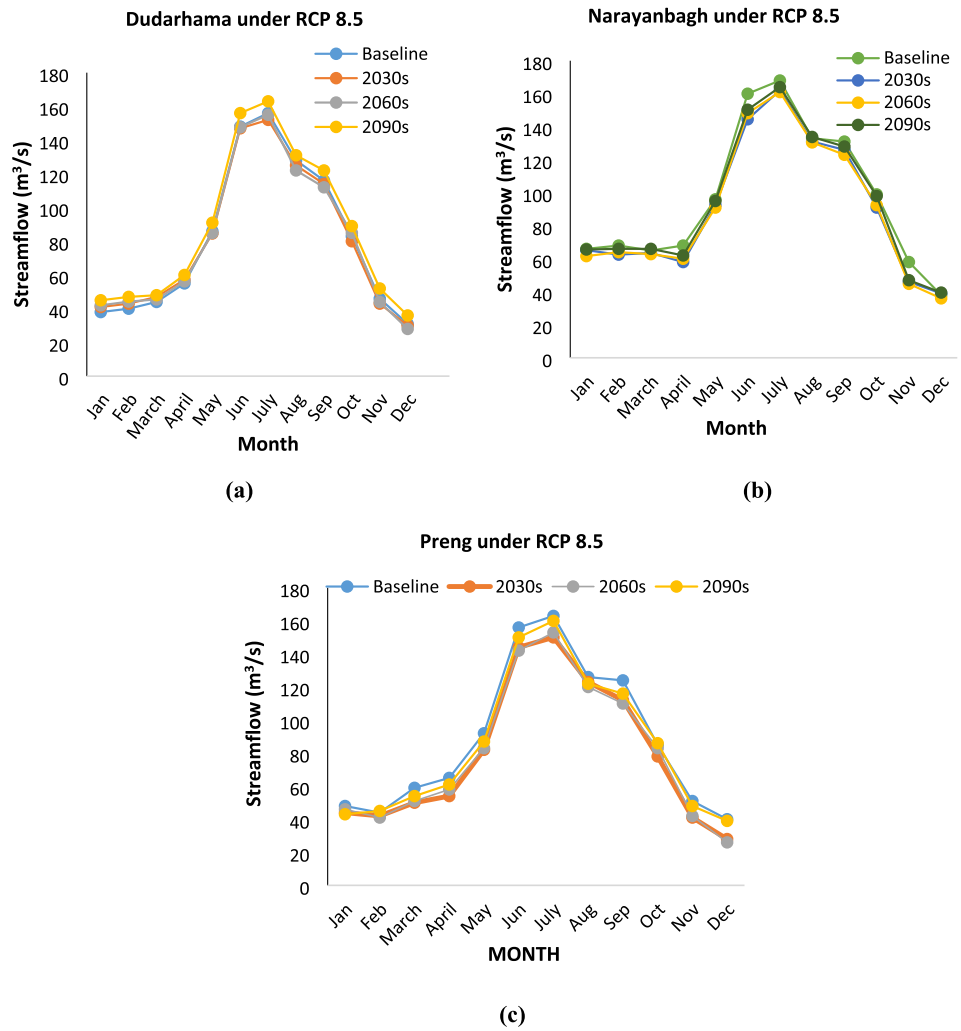
1985–2006 and 2007–2019, respectively. The R^2 values ranged between 0.58 to 0.89 and 0.49 to 0.84 for calibration and validation years, which shows that predictands fit well with observed data. Under RCP 4.5 and RCP 8.5, average annual flow was expected to increase in watershed, with a 3–12% increase in future. The flow in summer (monsoon season) was projected to decrease in the future, however, flows were likely to upsurge in future three seasons (i.e., winter, spring, and autumn) at all the three sites. The estimated escalation in yearly flow was extreme in the 2090s and lowest in the 2060s. This indicates that the yearly discharge in the future will escalate in 2030s, decrease in the 2060s comparative to the 2030s, and then rise once more in 2090s. Low and median flows are expected to increase at the end of this century, however, high flows are expected to decrease in future under both scenarios.

Overall, River Sindh of Kashmir valley is most likely to face increase in seasonal flow in the future excluding the summer season. The study area would also face added variations in the temporal and magnitudinal average discharge and highest discharge in the coming years. If strategy makers and water resource managers will not consider variations in climatic factors in the study area, it could cause many difficulties for them in future. For future studies, the main recommendation is to use the outputs of more than one GCM, so the worries unveiled by GCMs can be explored, and the probable effects of climate variability can be studied on other water resources in the area.

Table 8 Future variations (%) in low, median, and high flows with respect to the baseline (1992–2017) in the River Sindh

	Preng			Narayanbagh			Dudarhama		
	Observed	Simulated RCP 4.5	Simulated RCP 8.5	Observed	Simulated RCP 4.5	Simulated RCP 8.5	Observed	Simulated RCP 4.5	Simulated RCP 8.5
Stream Flow (m³/s)									
Q_5	160	255	250	307	385	382	1058	1115	1119
Q_{50}	21	22	28	58	82	80	186	313	307
Q_{95}	7	2	1	25	12	16	50	36	37
Changes (%) in 2030s									
Q_5		1.8	4.6		−6.8	−3.2		−6.8	−1.9
Q_{50}		11.8	−6.2		14.7	10.4		0.5	−5.8
Q_{95}		0.2	0.1		10.9	10.5		4.8	−0.6
Changes (%) in 2060s									
Q_5		0.2	6.5		−2.9	−2.3		−0.8	1.5
Q_{50}		11.6	2.1		6.8	1.2		−3.1	4.2
Q_{95}		0.0	0		16.6	10.2		6.4	−6.2
Changes (%) in 2090s									
Q_5		8.6	4.1		1.8	−0.1		−6.9	−9.8
Q_{50}		23.1	22.1		18.6	23.5		−2.4	3.9
Q_{95}		0.0	0		24.3	27.6		7.1	4.8

Declarations

References

1. Y.B. Dibike, P. Coulibaly, Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. J. Hydrol. **307**(1–4), 145–163 (2005). https://doi.org/10.1016/j.jhydrol.2004.10.012

2. J. Okkonen, B. Kløve, A conceptual and statistical approach for the analysis of climate impact on ground water table fluctuation patterns in cold conditions. J. Hydrol. **388**(1–2), 1–12 (2010). https://doi.org/10.1016/j.jhydrol.2010.02.015

3. J.A. Vano, T. Das, D.P. Lettenmaier, Hydrologic sensitivities of Colorado river runoff to changes in precipitation and temperature*. J. Hydrometeorol. **13**(3), 932–949 (2012). https://doi.org/10.1175/JHM-D-11-069.1

4. H. Middelkoop, K. Daamen, D. Gellens, W. Grabs, J.C. Kwadijk, H. Lang, B.W. Parmet, B. Schadler, M.V. Schulla, R. Shah, B. Thrasher, Soil moisture droughts under the retrospective and projected climate in India. J. Hydrometeorol. (2014). https://doi.org/10.1175/JHM-D81013-0177.1

5. C.H. Chang, G. Knight, M.P. Staneva, D. Kostov, Water resource impacts of climate change in southwestern Bulgaria. GeoJournal **57**(3), 159–168 (2002). https://doi.org/10.1023/B:GEJO.0000003611.11187.5c

6. M. Shah, M.A. Lone, Hydrological modeling to simulate stream flow in the Sindh Valley watershed, northwest Himalayas. Model. Earth Syst. Environ. (2021). https://doi.org/10.1007/s40808-021-01241-1

7. A. Jasrotia, D. Baru, R. Kour, S. Ahmad, K. Kour, Hydrological modeling to simulate stream flow under changing climate conditions in Jhelum catchment, western Himalaya. J. Hydrol. **593**, 125887 (2021). https://doi.org/10.1016/j.jhydrol.2020.125887

8. M.I. Brunner, D. Farinotti, H. Zekollari, M. Huss, M. Zappa, Future shifts in extreme flow regimes in Alpine regions. Hydrol. Earth Syst. Sci. **23**, 4471–4489 (2019). https://doi.org/10.5194/hess-23-4471-2019

9. J. Chu, J. Xia, C.Y. Xu, V. Singh, Statistical downscaling of daily mean temperature, pan evaporation and precipitation for climate change scenarios in Haihe River. China. Theor. Appl. Climatol. **99**, 149–161 (2010). https://doi.org/10.1007/s00704-009-0129-6

10. M.S. Khattak, M.S. Babel, M. Sharif, Hydro-meteorological trends in the Upper Indus River basin in Pakistan. Clim Res **46**, 103–119 (2011). https://doi.org/10.3354/cr00957

11. X.C. Zhang, W.Z. Liu, Z. Li, J. Chen, Trend and uncertainty analysis of simulated climate change impacts with multiple GCMS and emission scenarios. Agric For Meteorol **151**, 1297–1304 (2011). https://doi.org/10.1016/j.agrformet.2011.05.010

12. IPCC, Climate Change 2013, The physical science basis, In: Contribution of Working Group I to the Fifth Assessment Report of the Inter-government-Mental Panel on Climate Change, (Cambridge University Press, Cambridge, UK, New York, NY, USA, 2013), p. 1535

13. H. Wang, M. Zhang, H. Zhu, X. Dang, Z. Yang, L. Yin, Hydroclimatic trends in the last 50 years in the lower reach of the Shiyang River basin, NW China. CATENA **95**, 33–41 (2012). https://doi.org/10.1016/j.catena.2012.03.003

14. R. Mahmood, S. Jia, Assessment of impacts of climate change on the water resources of the transboundary Jhelum River Basin of

J. Inst. Eng. India Ser. A (December 2022) 103(4):1165–1181

1181

Pakistan and India. Water **8**(6), 2073–4441 (2016). https://doi.org/10.3390/w8060246

15. J. Andersen, J.C. Refsgaard, K.H. Jensen, Distributed hydrological modelling of the Senegal River Basin—model construction and validation. J. Hydrol. **247**(3–4), 200–214 (2001). https://doi.org/10.1016/S0022-1694(01)00384-5

16. N. Tarekegn, B. Abate, A. Muluneh, Modeling the impact of climate change on the hydrology of Andasa watershed. Model. Earth Syst. Environ. (2021). https://doi.org/10.1007/s40808-020-01063-7

17. M. Malik, A.Q. Dar, M.K. Jain, Modelling streamflow using the SWAT model and multi-site calibration utilizing SUFI-2 of SWAT-CUP model for high altitude catchments NW Himalaya's. Model. Earth Syst. Environ. (2021). https://doi.org/10.1007/s40808-021-01145-0

18. B.W. Khélifa, M. Mosbahi, Modeling of rainfall-runoff process using HEC-HMS model for an urban ungauged watershed in Tunisia. Model. Earth Syst. Environ. (2021). https://doi.org/10.1007/s40808-021-01177-6

19. H. Meresa, Modelling of river flow in ungauged catchment using remote sensing data: application of the empirical (SCS-CN), Artificial Neural Network (ANN) and Hydrological Model (HEC-HMS). Model. Earth Syst. Environ. **5**(1), 257–273 (2018). https://doi.org/10.1007/s40808-018-0532-z

20. R. Meenu, S. Rehana, P.P. Mujumdar, Assessment of hydrologic impacts of climate change in Tunga-Bhadra river basin, India with HEC-HMS and SDSM. Hydrol. Process. **27**, 1572–1589 (2013). https://doi.org/10.1002/hyp.9220

21. S. Sahu, S.K. Pyasi, R.V. Galkate, R.N. Shrivastava, Rainfall-Runoff Modeling using HEC-HMS Model for Shipra River Basin in Madhya Pradesh, India. Int. J. Curr. Microbiol. Appl. Sci. **9**(8), 3440- (2020). https://doi.org/10.20546/ijcmas.2020.908.398

22. F. Radmanesh, J.P. Hemat, A. Behnia, A. Khond, B.A. Mohamad, Calibration and assessment of HEC-HMS model in Roodzard watershed. In: Proceedings of the 17th International Conference of River Engineering, (University of Shahid Chamran, Ahva, Iran, 2020), pp. 26–28

23. Y.S. Saeedrashed, Hydrologic and hydraulic modelling of the greater zab river-basin for an effective management of water resources in the Kurdistan region of Iraq using DEM and raster images, in *Environmental Remote Sensing and GIS in Iraq*. ed. by A.M.F. Al-Quraishi, A.M. Negm (Springer, Cham, 2020)

24. B.G. Tassew, M.A. Belete, K. Miegel, Application of HEC-HMS model for flow simulation in the Lake Tana basin: the case of Gilgel Abay catchment, upper Blue Nile basin. Ethiopia. Hydrol. **6**(1), 21 (2019)

25. M.S. Ahsan, S. Bhat, A. Alam, H. Farooq, H.A. Shiekh, Evaluating the impact of climate change on extreme temperature and precipitation events over the Kashmir Himalaya. Clim. Dyn. **58**(5–6), 1651–1669 (2022). https://doi.org/10.1007/s00382-021-05984-6

26. M.U. Shafiq, S. Ramzan, P. Ahmed et al., Assessment of present and future climate change over Kashmir Himalayas India. Theor Appl Climatol (2019). https://doi.org/10.1007/s00704-019-02807-x

27. HEC-HMS, Hydrologic Modeling System HEC-HMS: User's Manual, (Institute for Water Resources: Davis, CA, USA, 2010) p. 318.32.

28. HEC-HMS. Hydrologic Modeling System HEC-HMS: Technical Reference Manual, (Institute for Water Resources: Davis, CA, USA, 2000) p. 157.

29. D.N. Moriasi, J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, T.L. Veith, Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE **50**(3), 885–900 (2007). https://doi.org/10.13031/2013.23153

30. S. Parvaze, J. Khan, R. Kumar, S. Allaie, Temporal flood forecasting for trans-boundary Jhelum River of Greater Himalayas. Theor. Appl. Clim. **144**(493), 1–14 (2021). https://doi.org/10.1007/s00704-021-03562-8

31. N.S. Abeysingha, A. Islam, M. Singh, Assessment of climate change impact on flow regimes over the Gomti River basin under IPCC AR5 climate change scenarios. J. Water Clim. Chang. **11**(1), 303–326 (2020). https://doi.org/10.2166/wcc.2018.039

32. K. Vandana, A. Islam, P. Parth Sarthi, A.K. Sikka, H. Kapil, Assessment of potential impact of climate change on streamflow: a case study of the Brahmani River Basin India. J. Water Clim. Change (2018). https://doi.org/10.2166/wcc.2018.129

33. F. Aditya, E. Gusmayanti, J. Sudrajat, Rainfall trend analysis using Mann–Kendall and Sen's slope estimator test in West Kalimantan. IOP Conf. Ser. Earth Environ. Sci. **893**(1), 012006 (2021). https://doi.org/10.1088/1755-1315/893/1/012006