



Quantitative assessment of regional land use and climate change impact on runoff across Gilgit watershed

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Received: 6 December 2020 / Accepted: 6 October 2021 / Published online: 31 October 2021
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Abstract

Regional climate change (CC) and land use changes (LUCs) can significantly influence the hydrological processes at watershed scale. Different studies have investigated the impact of climate change in the Indus Basin. However, there is a need to investigate the impact of environmental changes on the regional hydrology over a complex topographic region. This study quantitatively assesses the relative contributions of CC and LUC on runoff alterations across Gilgit watershed by using multivariable calibration approach using the Soil and Water Assessment Tool (SWAT). Mann–Kendall (MK) and Pettitt tests are applied to identify the trends and changes in runoff and climatic variables during 1985–2013. The supervised classification is performed to acquire land use maps and other quantitative details required for the analyses. Moreover, Indicators of Hydrologic Alterations (IHA) analyses were performed for the first time in the Gilgit watershed to investigate the impact of CC and LUCs during the pre- and post-impact periods. The results demonstrated that precipitation, temperature, and runoff of the Gilgit watershed presented significant increasing trends. The change point using Pettitt test is depicted in 1999, 1995, and 1998, respectively. The mean annual increasing rate of precipitation, temperature, and runoff is 4.92 mm/year, 0.04 °C/year, and 2.60 m³/year, respectively. SWAT model performed well and the relative attributed contribution of CC to runoff change is 97.22% and it is 2.78% for LUC. The IHA results showed that runoff has significantly increased in post-impact (1999–2013) as compared to pre-impact (1985–1998), which was further confirmed by analyzing the IHA results using percent bias (PBIAS). Significant overestimation of runoff (higher runoff in post-impact period) was observed in the wet (maximum runoff) season. This study demonstrated that the high contribution of CC to runoff change is mainly due to the change in climate variables and global warming trends.

Keywords Climate change · Land use changes · Water resources · IHA · Gilgit watershed

Introduction

Climate and land use changes are the two important factors responsible for the runoff changes (Chen et al. 2019; Jiang et al. 2017; Li et al. 2018; Su et al. 2006). Climate change (hereinafter, CC) can significantly alter the runoff by changing the spatial and temporal distribution of precipitation (Ay and Kisi 2015; Dahal et al. 2019; Shi et al. 2014). The land use changes (hereinafter, LUC) directly affect the flow and runoff generation processes. The anthropogenic activities (changes taking place due to human influence) are the main sources for LUC in a watershed (Langat et al. 2019; Latif et al. 2018; Li et al. 2019; Osei et al. 2019), which significantly affect the flow generation and impact the runoff in the middle or lower reaches of a stream network (Anand et al. 2018; Rahman et al. 2017; Zhang et al. 2019).

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Different studies have reported the impact of CC and LUC on runoff and other variables associated with runoff, e.g., Murphy et al. (2020) reported changes in sediment due to LUC. Similarly, Liu et al. (2021) and Pham-Duc et al. (2020) concluded that climate change has a significant impact on water resources. Therefore, to better understand and manage the runoff of a watershed, it is essential to assess the impact of regional CC and LUC (Seyam and Othman 2015; Shahid et al. 2018; Shang et al. 2019). There are different methods to understand the effect of LUCs and CCs on the generated runoff in a watershed. Such analyses are challenging for large-scale watersheds, and hydrological models are considered to be an important tool to perform runoff attribution in such a watershed (Bocchiola and Diolaiuti 2013; Guan et al. 2019; Jiang et al. 2017).

Runoffs mostly originate from mountainous regions, which is necessary for the sustainable management of ecosystem (Mohsin and Gough 2010; Oliveira et al. 2017; Viviroli et al. 2007). Due to its importance in water resources management, the assessment of hydrological processes in the mountains has achieved great attention (De Jong et al. 2005; Fathian et al. 2015; Seyam and Othman 2015). The accurate estimation of the hydrological processes is essential for water resources of Hindu Kush Himalayas (HKH) that provide water to one-tenth of the global population. The water from these mountains is necessary for the people residing in the downstream parts of the watershed. Due to its importance, the glacial regions of HKH are also referred to as the water towers of Asia (Ali et al. 2017; Scott et al. 2019). Previous studies concluded that during the past few decades, the temperature has increased in the HKH (Krishnan et al. 2019). The proper management of water resources of the HKH is a global challenge, as any change in this region will affect the largest population of the world (Immerzeel et al. 2010; Tiwari and Joshi 2012).

Hydrological models are essential tools and enhance our understanding about the hydrological processes of river watersheds. These models support the operational management of watersheds, which have spatial and temporal variability (Lutz et al. 2016; Rahman et al. 2017). Moreover, an accurate estimation of the hydrological process in the mountains can be performed by using the hydrological models. Hydrological modeling in the mountain is a challenging task due to a few reasons including steep elevations, complex topography, complex dynamics of hydrological variables, and insufficient measurements of variables (de Jong 2015; Nolin 2012). The hydrological process may vary from region to region, and CC plays an important role affecting the hydrological process even in similar climatic conditions (Oliveira et al. 2017; Pagliero et al. 2019). Several studies have applied different hydrological models including semi-distributed conceptual hydrological HBV models (HBV-Met and HBV-PRECIS), SWAT, and fully distributed SPHY

(Spatial Processes in Hydrology) model in HKH region (Akhtar et al. 2008; Garee et al. 2017; Lutz et al. 2016). These models are applied in the Upper Indus basin (UIB) and also across different sub-basins of the UIB. In a few studies, the future runoff is predicted using General Circulation Models (GCMs) (Iqbal et al. 2018; Yu et al. 2013). Only a few studies have used multivariable calibration approaches (Konz et al. 2007; Pellicciotti et al. 2012; Rao et al. 2018). Moreover, Akhtar et al. (2008), Immerzeel et al. (2010) and Lutz et al. (2016) used conceptual and fully distributed models instead of the physical hydrological model. The simple lumped and temperature-based models have been used, which do not represent the physical properties of the Indus basin.

The aforementioned studies have used hydrological models for runoff simulations only, while there are no studies thoroughly investigating the hydrological effects in changing environments. The hydrological processes are changing rapidly in some parts of the HKH, which needs proper attention and investigation for sustainable water management practices. Moreover, in the HKH region, fewer information is available about the application and the performance of the Soil and Water Assessment Tool (SWAT), which is a physically based hydrological model. Therefore, the objective of the current study is to evaluate the runoff regime in the Gilgit watershed using SWAT and to quantitatively analyze the contributions of CC and LUCs to runoff/runoff changes. Further, the Indicators of Hydrologic Alteration (IHA) analyses are performed for the first time across the Gilgit watershed to demonstrate the components of runoff, which are changing most significantly under the CC and LUC scenarios.

The current study is structured as follows: “Materials and methods” represents the study area, datasets and methodology, “Results” introduces comprehensive interpretation of the results and discussion, and “Discussion and Conclusions” lists the main findings of the current research.

Materials and methods

Study area

The Gilgit watershed, which is the originating source of Gilgit River (a main tributary of the Indus Basin) and a major watershed of Gilgit–Baltistan, is considered for the current study. The Gilgit River flows southeast of Gilgit District where the Hunza River joins it, and both rivers meet the Indus River at Bunji. The watershed has the highest peaks of Hindukush Mountains, and its slope varies from gentle to steep (31°–45°) (Ali et al. 2019). The study area lies between 35 and 37° N and 72 and 75° E with an area of 12,708 km². The elevation of the study area ranges from 1452 to 7060 m

a.m.s.l. (above mean sea level), while the majority of the Gilgit watershed lies between 4000 and 5500 m. The watershed area above 5000-m elevation is mainly covered with snow and glaciers. The Gilgit watershed has a maximum snow cover area in winter, and it decreases in summer. The glaciers and snowmelt during the summer season significantly contribute to the runoff of the Gilgit and Indus rivers. The melting process of glaciers start in July and continues until October. The study area lies in a cold desert climatic regime and has ten districts. The climate of the study area ranges from arid to semi-arid, where vegetation, bare land and forest are the dominant land use types. The vegetation types include grass, perennial herbs, herbs, forbs, trees and shrub. The population of the study area increased rapidly during the past few decades and is reported as 1.2 million. Agriculture is the main source of livelihood and the cropping pattern includes wheat, maize, barely, potato, vegetables and fruits (Ahmed and Joyia 2003; Anwar et al. 2019; Adnan et al. 2017a, b). The CC in the Gilgit watershed may affect its frozen water resources. Moreover, during the last few decades, the economic and development activities rapidly increased in the Gilgit watershed (Ali et al. 2019).

Methodological framework

The methodological framework for the current study comprise an overview of the available data and procedures related to hydrological modeling using SWAT model. The main steps of the methodological framework include trend analysis of the hydrological and meteorological variables, procedure to quantify the relative contribution of LUC and CC, and description and preparation of datasets for SWAT model. The trend analysis was performed to identify the change point and magnitude of variables. Moreover, DEM, soil data and land use maps were prepared for the SWAT model. Finally, calibration and validation of the SWAT model was performed and the Indicators of Hydrologic Alterations method was used to identify the indicators that significantly affected the runoff. A detailed description of this framework is presented in the following sections.

Overview and description of data

The Gilgit watershed is a poorly gauged watershed with few meteorological stations, which collect the weather and climate data of the watershed. The meteorological stations consist of Yasin, Gupis, Ushkore, and Gilgit stations, which either exist within or in the vicinity of the Gilgit watershed. The meteorological data of Gilgit and Gupis stations, obtained from Pakistan Meteorological Department (PMD) and Water and Power Development Authority (WAPDA), are available for the long time period, while the data of other stations are available for a shorter duration of time.

Therefore, the meteorological data of Gilgit and Gupis stations have been used in this study. The precipitation, temperature, relative humidity, wind speed, and solar radiation data of Gilgit and Gupis stations available from 1985 to 2013 were used for analyses in the current study. The runoff data of the Gilgit watershed, obtained from WAPDA, available during 1985–2013 was used for runoff simulation and IHA analyses in the current study. Figure 1 shows the location of weather/climate stations and runoff gauge in the study area.

The mean monthly maximum and minimum temperatures are estimated from collected data obtained from WAPDA/PMD. The mean maximum monthly and mean minimum monthly temperatures are ranging from 9.2 to 36.5 °C and – 2.2 to 18.5 °C, respectively. The mean annual observed precipitation (calculated) in the Gilgit watershed is 175.4 mm. The mean annual flow of the Gilgit watershed recorded at the Gilgit gauge is 275.3 m³/s. The collected weather data are directly used in SWAT, and no interpolation method has been utilized because the available stations are not sufficient to apply an interpolation method.

The elevation information of the Gilgit watershed obtained from the digital elevation model (DEM). DEM of the study area was retrieved from ASTERDEM, its resolution is 30 m, and it is a global product, which is freely available on the website (<http://reverb.echo.nasa.gov/reverb/>). The soil data were obtained from the FAO digital soil maps in the scale of 1: 5,000,000; the land use maps for the years 1996 and 2012 were sourced from the Landsat images. The supervised classification method was performed to develop land use maps of the Gilgit watershed from Landsat images. The detailed description of the supervised classification method is available at Butt et al. (2015), Khare et al. (2017) and Pande et al. (2018). The stratified random method was used to evaluate the accuracy of the classified images. It is performed by visual interpretation and using 50 points ground truth data. The classified data are statistically compared with reference data and an error matrix is developed. The statistical significance of the classification matrix was evaluated through the kappa coefficient (Congalton, 1991; Gwet, 2002; Shahid et al., 2018).

Trend analysis and runoff attribution

The Mann–Kendall (MK) test is used to identify the long-term trends in the hydroclimatic variables including precipitation, temperature, and runoff data. The MK test does not require statistical distribution for the datasets and cannot be affected by the outliers. This test is suitable to evaluate the hydrological and meteorological data (Shen et al., 2017; Shahid et al., 2020). Moreover, the Pettitt test (of change point) is also used to identify the abrupt change in the runoff series (Cong et al. 2017). The readers are referred to Shahid et al. (2018), Su et al. (2006), Subash and Sikka (2014) and

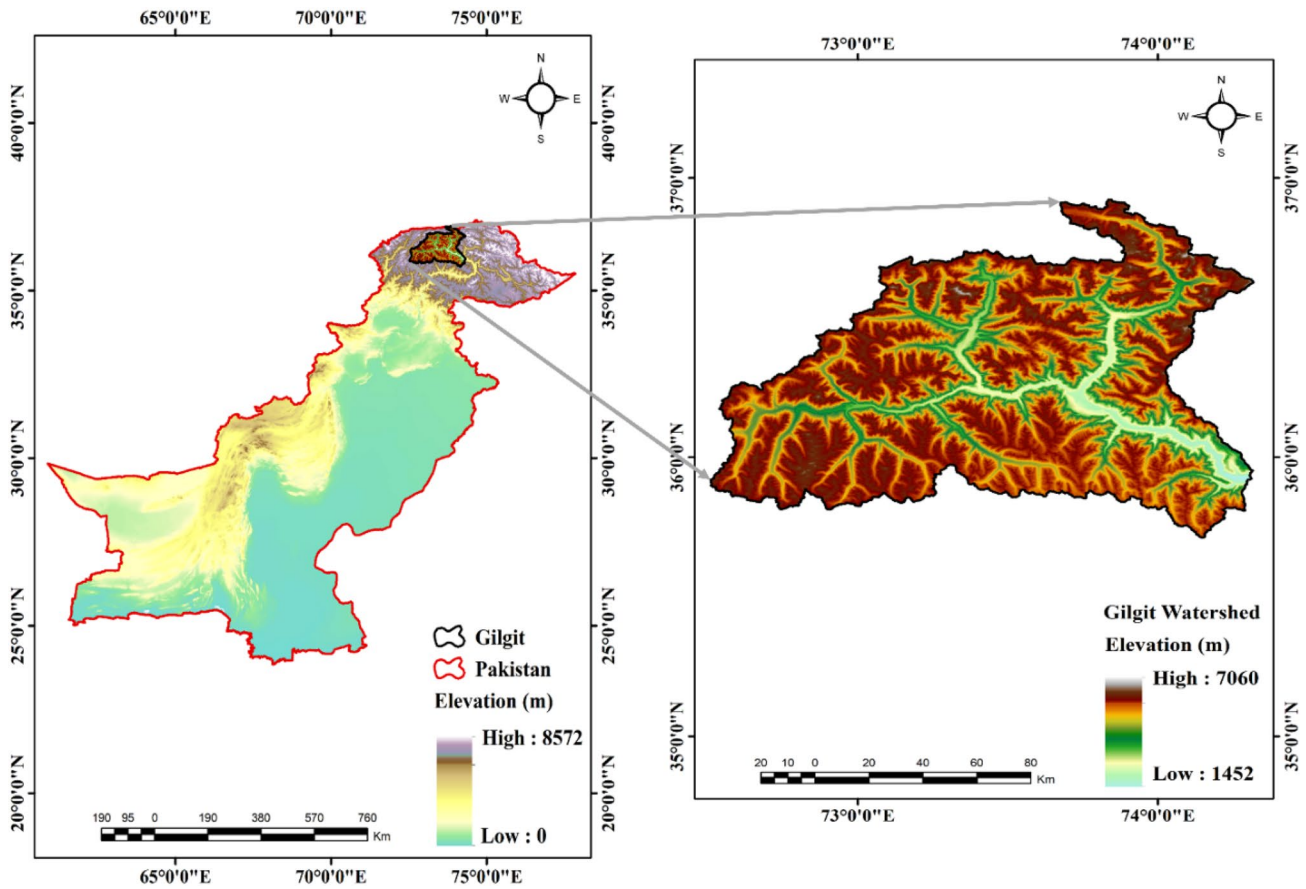


Fig. 1 Study area map with its location in Pakistan and distribution of weather and runoff stations

Tehrani et al. (2019) for detailed description of the MK test and the Pettitt test. Based on the Pettitt test results, runoff time series is divided into pre- and post-change periods. The terms Q_1^{obs} and Q_2^{obs} represent the mean annual runoff during pre- and post-change periods, respectively. The final mean annual runoff change (ΔQ) during pre- and post-change periods due to the combined effects of LUC and CC is calculated using the Eq. (1).

$$\Delta Q = \overline{Q_2^{obs}} - \overline{Q_1^{obs}} \tag{1}$$

ΔQ is due to climate variability and the difference in watershed characteristics during the two periods and can be represented as:

$$\Delta Q = \Delta Q_c + \Delta Q_l \tag{2}$$

where ΔQ is the change in the total mean annual runoff, ΔQ_c indicates the runoff change attributed to climate variability, and ΔQ_l represents the land use attributed changes to runoff.

The ΔQ_c and ΔQ_l are further analyzed to investigate the changes in runoff associated with the impact of CC and LUCs. The land use conditions in the pre- and the post-change periods are represented as LU_1 and LU_2 , respectively.

Further, SWAT model calibration and validation are performed during the pre- and post-change periods, respectively, to understand and quantify the LUC and CC impacts on annual runoff. Moreover, the LUCs are assumed to be stable during the calibration and validation periods. The calibrated parameters of SWAT and land use conditions during pre-change period (hereinafter, period-1), and climate condition of post-change period (hereinafter, period-2) are used to simulate the runoff during period-2 Q_2^{sim} . The difference between the observed (Q_2^{obs}) and simulated (Q_2^{sim}) runoff during period 2 is considered as the change in runoff ΔQ_l attributed to LUCs. On the other hand, the difference between Q_1^{obs} (observed runoff during period-1) and Q_2^{sim} is considered to be the runoff change attributed to CC. The relative contribution of CC (η_c) and LUC (η_l) is estimated as:

$$\eta_c = \frac{\Delta Q_c}{\Delta Q} \times 100\% \tag{3}$$

$$\eta_l = \frac{\Delta Q_l}{\Delta Q} \times 100\% \tag{4}$$

SWAT model setup

SWAT is a semi-distributed and process-based hydrological model developed by the Agricultural Research Service of the United States, Department of Agriculture-Agricultural Research Service (Arnold et al. 1998). Hydrological response units (HRUs) are the smallest units of SWAT model and divide HRUs into a number of HRUs. HRUs are generated with the combination of different datasets, i.e., land use, soil data and slope. The hydrological cycle is estimated using the water balance technique, which is dependent on the climate variables, i.e., precipitation and temperature. There are two stages for the simulation of the hydrological process, i.e., land base stage and routing stage. During the land base stage, the hydrological cycle is simulated using the soil water balance. In the SWAT model, the water circulation follows the water balance law, and its equation can be expressed as:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{Surf} - E_a - W_{Seep} - Q_{gw}). \quad (5)$$

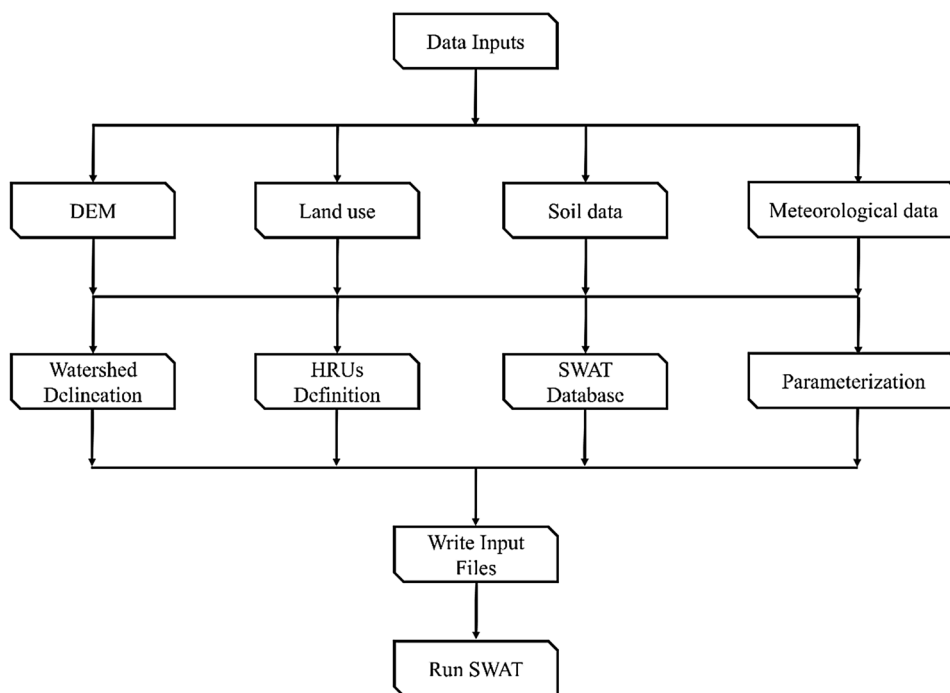
The terms SW_0 and SW_t represent the initial and final soil moisture conditions, respectively, while “ t ” represent time, R_{day} is the rainfall in a particular day, Q_{Surf} is a surface runoff for a particular day, E_a is daily evapotranspiration, W_{Seep} is seepage to the soil, and Q_{gw} is return flow. Note that all these variables are in “mm”. The surface runoff in the SWAT model is estimated using either the SCS curve number method or amp-green infiltration method. The SCS curve

number method requires daily precipitation data, while the Ampt infiltration method requires the sub-daily precipitation data. The routing stage handles the movement of nutrition and sediment loads from the channel to the outlet of the river basin. In the current study, the SCS curve method has been used to simulate runoff. The runoff simulation in SWAT is based on the water balance equation (Shang et al. 2019). Manning’s equation is used to define the rate and velocity of channel runoff. The water flowing through the channel is routed by using the Muskingum method or variable storage method. The elevation band method is used to model the snow and glacier melting process, because the SWAT model uses the temperature index method. The SWAT model can divide the sub-basins into ten different elevations and simulates the snow and glacier melt separately for each elevation band. Moreover, the SWAT model offers different methods to calculate the evapotranspiration. These methods include Priestley–Taylor, Food, and Agriculture Organization Penman–Monteith (FAO-PM) and Hargreaves methods. The process flowchart of the SWAT model is presented in Fig. 2, and detailed information of the SWAT model can be downloaded from https://www.card.iastate.edu/swat_articles/.

Model calibration and evaluation

In the present study, SWAT model scenarios have been developed at a monthly temporal scale. The SWAT model calibration and validation is performed during period 1 and monthly runoff is simulated. The SWAT model is automatically calibrated using the SWAT-CUP (SWAT Calibration

Fig. 2 The process flowchart of the SWAT model



and Uncertainty Program) tool. The Sequential Uncertainty Fitting algorithm version 2 (SUFI-2) of SWAT-CUP is used to calibrate and validate SWAT model. Furthermore, one-at-a-time sensitivity analyses procedure is adopted to identify the sensitive parameters (Abbaspour et al. 2015). The parameters are selected based on previous studies conducted over similar region (Rahman et al., 2020; Tuo et al., 2016; Duan et al., 2019). Initially, the range of parameters values were considered wide and further narrowed down after each simulation. For the sake of parameters' sensitivity, we considered more than 30 parameters which are further reduced based on their sensitivity analyses. The streamflow simulated after each iteration is compared with observed flow and simulated flow (simulated using the previous iterations). A threshold of 0.01 (probability value, p value) is considered for the final selection of sensitive parameters. This procedure evaluates the sensitivity of the model by changing one parameter, and during this process, all other parameters remain constant; a total of three to four iterations are performed. The snow parameters are considered as sensitive parameters and can influence the simulation results. The initial set of parameters are found in acceptable range according to the previous studies (Garee et al. 2017) in similar regions and SWAT official guidelines. A total of 1200 simulations are performed for each iteration and ranges of parameters are constricted down after each simulation according to the new suggested parameters and protocol defined by Abbaspour et al. (2015). The Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970); Criss and Winston 2008) the percent bias (PBIAS, %) and the coefficient of determination R^2 statistical metrics are used to assess the model performance. NSE evaluates the degree of variation between the observed and simulated runoff and its value ranges from 0 to 1 (a perfect estimate). A negative NSE value depicts the incompetency of the model to simulate the runoff. PBIAS indicates the magnitude how much simulated values are higher or lower as compared to the measured/observed values. The ideal value of PBIAS is zero, and its positive and negative values indicate overestimation and underestimation, respectively. Similarly, the value of R^2 also ranges from 0 to 1, and it represents the similarity index between the observed and simulated runoff. In the present study, the model performance was evaluated as follows: unsatisfactory ($NSE \leq 0.50$ and $PBIAS \geq \pm 25\%$), satisfactory ($0.50 < NSE \leq 0.65$ and $\pm 15\% \leq PBIAS < \pm 25\%$), good ($0.65 < NSE \leq 0.75$; $\pm 10\% \leq PBIAS < \pm 15\%$) and very good ($NSE > 0.75$, $PBIAS < \pm 10\%$) (Moriassi et al. 2007; Zhang et al. 2009).

Indicators of hydrologic alterations (IHA)

Assessment of hydrologic alterations in a runoff is of significant importance in managing the water resources of a

watershed and for establishing sustainable ecological conditions for a biological health in a stream (Bunn and Arthington 2002; Lytle and Poff 2004; Poff and Zimmerman 2010). Several hydrological indicators are available to assess the impact of human-induced changes on the nature and magnitude of the runoff (Gao et al. 2009; Li et al. 2017; Magilligan and Nislow 2005; Olden and Poff 2003; Richter et al. 1997; Wang et al. 2016). One of the common indicators is IHA developed by Richter et al. (1997).

There are two types of analyses to assess the hydrologic alterations in runoff, i.e., RVA (range of variability approach) and 33 indicators of IHA (Richter et al. 1997). RVA is one the earliest approaches, which calculates the variation in runoff in terms of frequency, duration, magnitude, time and rate of change of flow events. These five indicators are later on included in 33 indicators of IHA (Richter et al. 1997). Readers interested in IHA analyses are referred to Richter et al. (1997), Gao et al. (2009), Mathews and Richter (2007) and Lee et al. (2014).

IHA analyses are included in the current study to amend our understanding about the CC and LUCs impact on runoff. RVA analyses are performed by dividing the flow into two periods, i.e., period 1 (1985–1998) and period 2 (1999–2013). Period 1 and period 2 in RVA analyses are referred to as pre-impact and post-impact periods, respectively. Moreover, the flow is divided into extreme low flow, low flow, high flow pulse, small flood and large flood events. The IHA analyses will help the water resource managers for sustainable management and planning of water resources in the Gilgit watershed as well as downstream watersheds of the Indus Basin.

Results

Trends in hydrological variables

The long-term precipitation, temperature, and runoff trends of the Gilgit watershed have been analyzed during 1985–2013 using the MK test. The temperature data are the arithmetic mean of maximum and minimum temperature of the Gilgit watershed. Figure 3 shows the average annual variability of precipitation, temperature and runoff during 1985–2013. The corresponding statistics of the MK test at a significant level of 0.05 is presented in Table 1. It can be observed that the precipitation, temperature, and runoff of the Gilgit watershed presented significant upward (increasing) trends. The increasing rate of precipitation is 4.92 mm/year, which is 2.80% of the mean annual precipitation (shown in Fig. 3 and Table 1). Similarly, the increasing rates of temperature and runoff are 0.04 °C and 2.60 m³/year representing 0.17% of the average annual temperature and average annual runoff, respectively. It is concluded that the

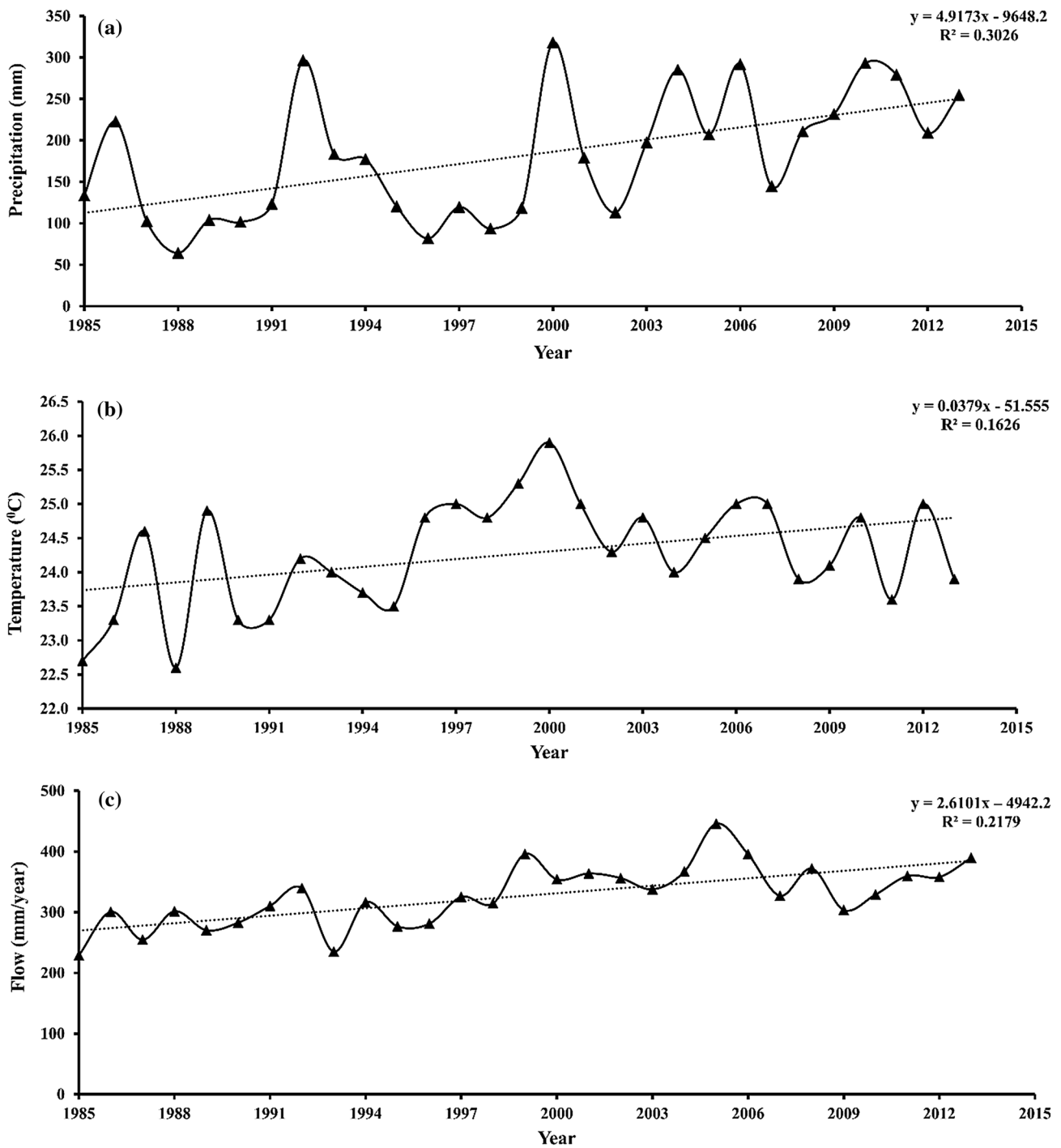


Fig. 3 Annual trend of the average annual **a** precipitation, **b** temperature and **c** runoff in the Gilgit Watershed during 1985–2013

Table 1 The changes in trends of precipitation, temperature and runoff data

Variable name	Mean annual	Significance ($p = 0.05$)	Trend	Change rate
Precipitation (mm/year)	175.40	Significant	Increased	4.92 (2.80%)
Temperature ($^{\circ}\text{C}/\text{year}$)	23.46	Significant	Increased	0.04 (0.17%)
Runoff (mm/year)	275.30	Significant	Increased	2.60 (0.96%)

climate of the Gilgit watershed is getting warmer and wetter every year. These findings are consistent with previous studies (Adnan et al. 2017a, b; Farhan et al., 2020; Yaseen et al. 2020 and Latif et al. 2021). Adnan et al. (2017a, b), Farhan et al. (2020) and Yaseen et al. (2020) evaluated the precipitation and temperature data of the Gilgit watershed stations during 1961–2010 and concluded that both of these

variables significantly changed during 1986–2010. Latif et al. (2021) performed trend analysis during 1961–2013 and reported significant warming and wetting in the study area.

The Pettitt test was applied to all variables to investigate the change point of the considered variables and results are shown in Fig. 4. The results show the precipitation, temperature and runoff presented a change point in the years

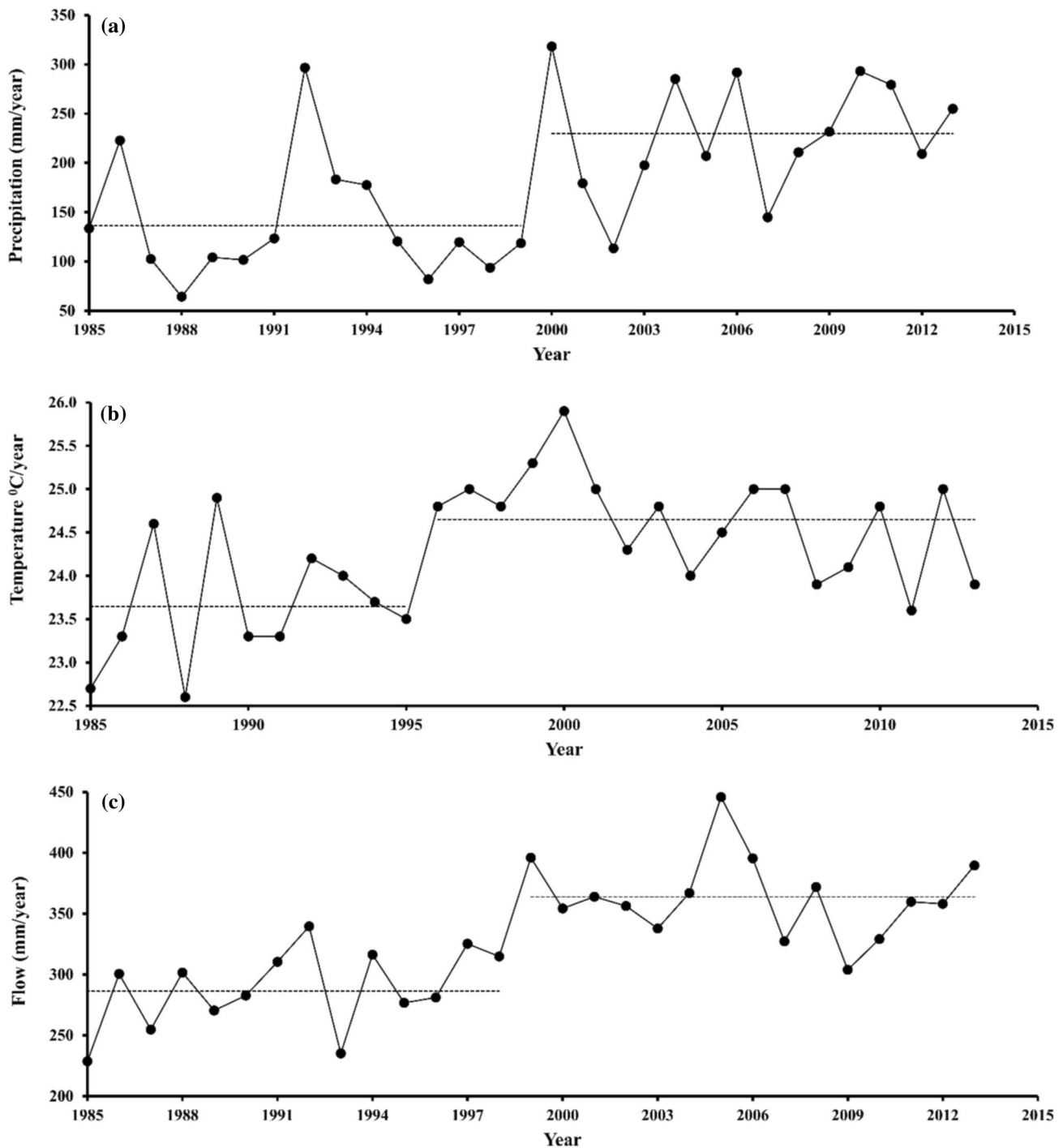


Fig. 4 Pettitt change point test results for a precipitation, b temperature and c runoff in the Gilgit Watershed during 1985–2013

1999, 1995, and 1998, respectively. According to the change point detection in runoff and other variables, it can be concluded that the Gilgit watershed has experienced significant alterations both in climate and land use. These findings are consistent with previous studies (Adnan et al. 2017a, b; Farhan et al., 2020; Yaseen et al. 2020; Latif et al. 2021). All these studies have evaluated the trends in precipitation and temperature for different periods and have consistently concluded similar changes in these variables. Similarly, Anwar et al. (2019) concluded that after the construction of Karakoram Highway, significant land use changes have been observed in Gilgit due to accessibility and improvements in marketing system where the local agriculture products become valuable. The change point in runoff is somehow consistent with the change point in temperature and precipitation. This could be due to global warming and climate change during the past few years, Pakistan is listed among those countries, which are vulnerable to climate change (Stocker et al. 2013). Moreover, Adnan et al. 2017a,b) used

the historical data of these three variables and reported a change point in 1985. Due to changes in temperature and precipitation data series, runoff response also changed which resulted in a consistent change point. To comprehensively understand the change in runoff, the runoff series is divided into two parts, i.e., the pre-changed period (1985–1998) and the post-change period (1999–2013) based on the change point detected in the year 1998.

SWAT model performance

A detailed depiction of the dominant land use types and their SWAT codes used for this study are presented in Table 2. In the current study, three iterations were performed for sensitivity analysis. During sensitivity analyses of different parameters associated with runoff were evaluated and 20 parameters were found to be sensitive, as presented in Table 3. The SWAT model was calibrated and validated during the pre-change period, i.e., 1985–1998, and simulations

Table 2 Land use types and their classification for the Gilgit watershed

Land use type	Land use classification	SWAT code
Forest	Evergreen forest, mixed forest, and deciduous forest	FRST
Vegetation	High, covered grassland, medium-covered grassland	HAY
Bare soil	Bare exposed rocks, bare ground, sand, clay	SWRN
Water	Water bodies, open water	WATR
Urban area	Urban area, residential land	URLD
Snow	Snow fields, ice	SNOW

Table 3 List of selected sensitive parameters with their description, physical range and fitted values. “r_”, “v_”, where “a” represents the relative change to the parameters’ initial values, replacement of default values by the specified value, and addition of specified value to the default value, respectively (Abbaspour et al. 2015)

Parameter name	Description	Physical range	Fitted value
r_CN2.mgt	SCS curve number	35–98	– 1.32
r_PLAPS.sub	Precipitation laps	– 1000–1000	– 0.56
r_SOL_AWC().sol	Available soil water capacity	0–1	0.5
r_SOL_K().sol	Saturated hydraulic conductivity	0–2000	6.5
v_ALPHA_BNK.rte	Base flow factor	0–1	0.07
v_CH_K1.sub	Hydraulic conductivity effect	0–300	0.9
v_CH_K2.rte	Channels hydraulic conductivity	– 0.01–500	– 0.03
v_CH_N1.sub	Manning (n) value for channels	0.01–30	0.16
v_CH_S1.sub	Slope of channel	0.001–10	312
v_DEEPST.gw	Initial aquifer depth	0–50,000	0.25
v_EPCO.hru	Plant evaporation factor	0–1	0.33
v_ESCO.hru	Soil evaporation factor	0–1	0.54
v_GW_REVAP.gw	Groundwater coefficient	0–500	0.25
v_RCHRG_DP.gw	Aquifer percolation	0–1	0.85
v_REVAPMN.gw	Threshold depth	0–5000	74.34
v_SHALLST.gw	Initial depth of Aquifer	0–5000	0.5
v_SLSOIL.hru	Slope length for subsurface flow	Variable	32.2
v_SUB_SMFMX().sno	Summer solstice	0–20	18.5
v_SUB_SMTMP().sno	Winter solstice	0–20	18.7
v_TLAPS.sub	Temperature laps	– 10–10	– 7.4

were carried out for the post-change period (1998–2013). The model was calibrated during 1985–1991, where the sensitive parameters were used to fit the daily-observed runoff data. The SWAT model was validated during the period 1992–1998. The comparison of the monthly simulated and observed runoff during the calibration and validation periods is presented in Fig. 5.

Influence of LUC and CC on runoff

To evaluate the impact of CC and LUC on runoff generation, the runoff in period 2 was simulated using the SWAT model. The runoff was simulated using the climate conditions of period 2 and land use conditions of period 1. Results of the

simulated runoff during period 2 are presented in Fig. 6. The relative contributions of LUC and CC were calculated by using Eqs. (1) to (4) and the results are shown in Table 4. It is observed that the runoff of the Gilgit watershed is mainly increased due to CC, and the LUC contributions are minimal. The results also show that the relative contribution of CC to runoff change is 97.22% and it is 2.78% for the LUC.

To investigate the impact of CC on runoff of the Gilgit watershed, the results of MK and Pettitt tests are considered for further analyses (Fig. 4). The results show that a significant change was observed for both variables when the temperature and precipitation data were analyzed. The temperature data of the Gilgit watershed presented 1995 as a change point, and after 1995 the temperature significantly increased.

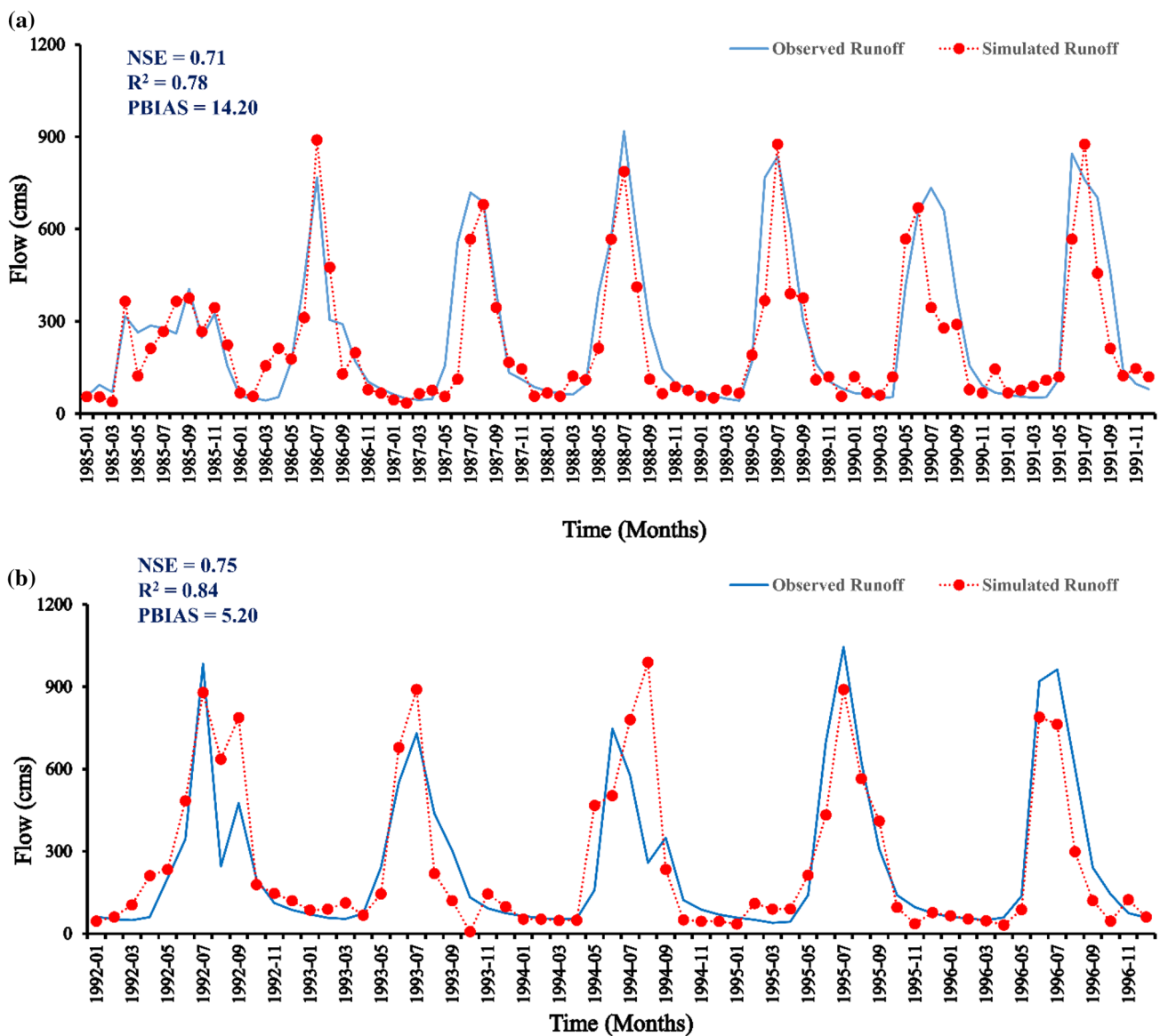


Fig. 5 Observed and simulated runoff using the SWAT model during (a) calibration and (b) validation periods

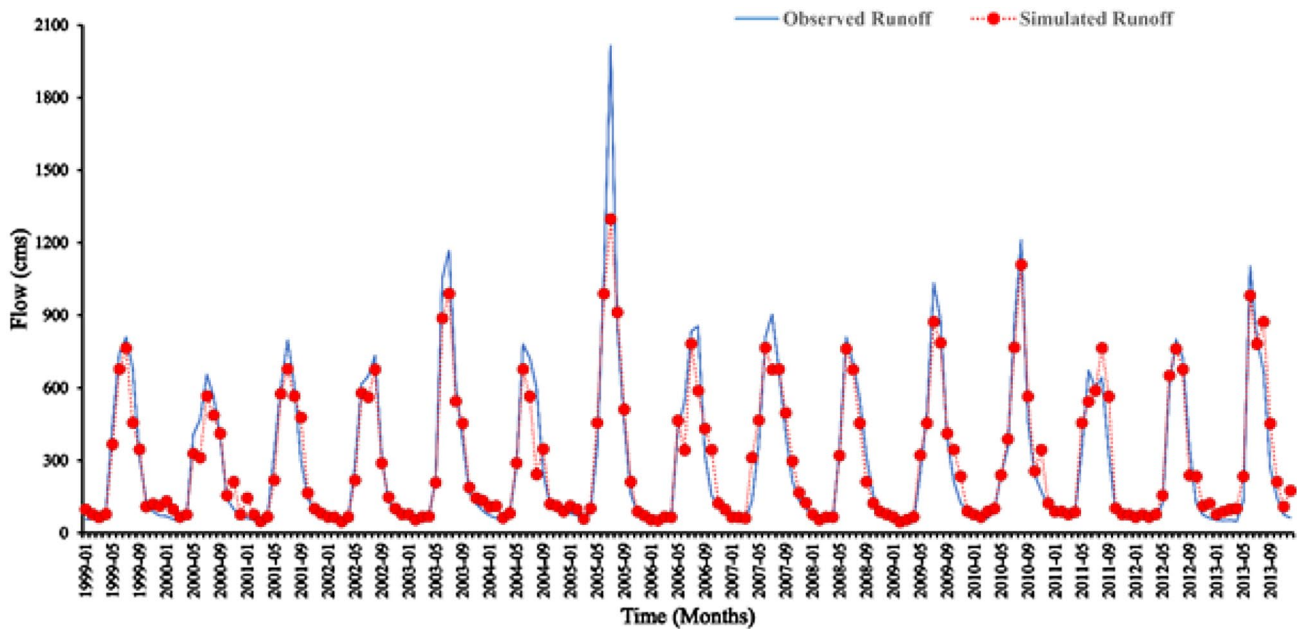


Fig. 6 Comparison of simulated and observed monthly runoff during the post-change period

Table 4 Annual runoff changes induced by CC and LUCs, and the relative contribution of these changes to runoff change

Study period	Runoff m ³ /s	Changes m ³ /s	Relative contribution
$Q_1^{obs}(1985-1998)$	257.5	$\Delta Q = 39.6$	
$Q_2^{obs}(1999-2013)$	297.0	$\Delta Q_c = 38.5$	$\Delta Q_c = 97.22\%$
$Q_2^{sim}(1999-2013)$	295.9	$\Delta Q_l = 1.1$	$\Delta Q_l = 2.78\%$

The results of the MK test also presented an increase of 0.04 °C/year in the mean annual temperature.

The increase in temperature shows that the watershed showed significant warming trends. Similarly, the precipitation data also presented a change point in 1997, and this indicates that after 1997, the basin showed wetting trends. These results show that the high relative contribution of CC to runoff change is mainly due to change in these two variables. The land use data of the Gilgit watershed was analyzed for 1996 and 2012, as presented in Fig. 7 and Table 5. The results of the overall classification and kappa values showed high accuracy for both classified images. The overall classification values and kappa coefficient ranged from 88 to 92% and 0.88 to 0.9, which are considered to be good (Lea et al. 2010).

The land use maps (Fig. 7) and land use statistics (Table 5) show that significant LUCs were observed during 1996–2012. The forest, vegetation and snow/ice areas in the Gilgit watershed are decreased by 12.38 km², 500 km², and 463 km², respectively. On the other hand, the bare

soil and urban areas are increased by 800 km², and 276 km². The observed changes can be considered as a reason for the increase in surface runoff, and the most significant is the decrease in snow/ice area. The decrease in snow/ice area during 1996–2012 shows that the snow/ice melted in this period, supporting the results of MK and Pettitt tests, which showed increasing temperature trends after the change point around 1995. Hussain et al. (2019) performed a study on the same watershed to understand the snow cover area from 2001 to 2013. They used moderate resolution imaging spectroradiometer (MODIS) data to understand the snow dynamics. They concluded that the snow cover area showed a decreasing trend during this period. Global warming and the increase in temperature are the main reasons for the decrease in snow cover. These findings support the results of the current study, which also shows that the snow cover area decreased and the decrease is due to an increase in the temperature of the study area.

Indicators of hydrologic alteration (IHA)

Figure 8 shows the comparison of runoff during two different seasons, i.e., dry season characterized by minimum runoff (January) and wet season characterized by maximum runoff (August). The results are obtained using the RVA analyses by dividing the runoff into two periods, i.e., pre-impact (period-1) and post-impact (period-2). The results depict that the runoff in the post-impact period is relatively higher than that in the pre-impact period, which confirms the results of the MK and Pettitt tests. The results

Fig. 7 Land use changes in the Gilgit watershed during **a** 1996 (pre-change) and **b** 2012 (post-change)

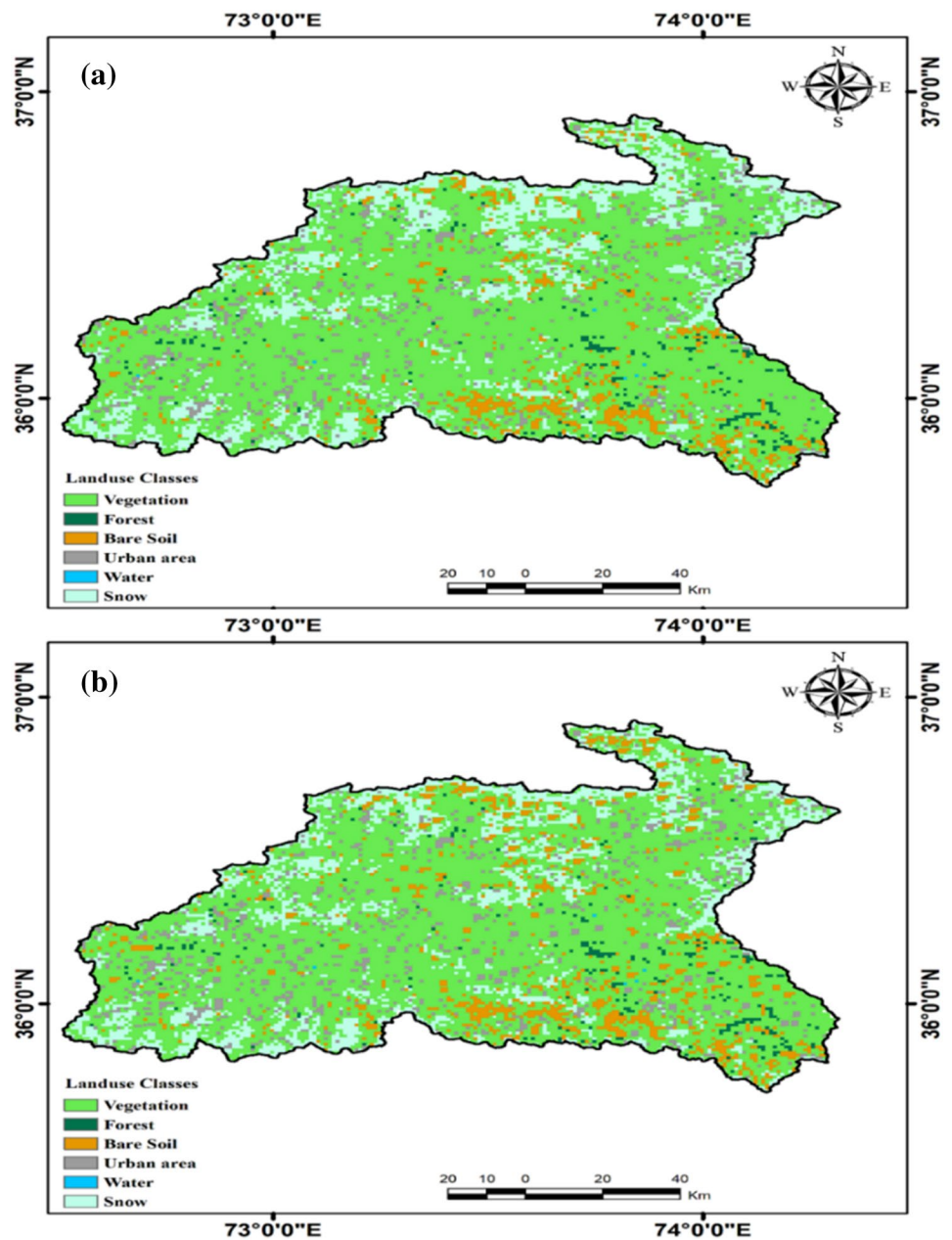


Table 5 The observed LUCs in the Gilgit watershed during 1996–2012

Land use type	1996	2012	Change
Forest	192.78	180.40	− 12.38
Vegetation	8368.47	7868.50	− 500.00
Bare soil	775.98	1576.00	+ 800
Water	130.00	130.00	0.00
Urban area	891.00	1167.00	276.00
Snow/ice	2349.81	1886.80	− 463.00

also show that there is significant change (increase) in the runoff magnitude during the wet seasons as compared to the dry season.

The IHA analyses are further carried out to divide the runoff into five major environmental flow components (EFCs). The EFCs include extremely low flow, low flow, high flow pulse, small floods and large floods events (shown in Fig. 9). The figure shows a number of high flow pulses and small floods during 1985–2013. However, only four major flood events were observed across the Gilgit watershed. All the maximum runoff events were observed during the summer season (May–September), which are due to extensive snow/glacier melt in the region (reduction

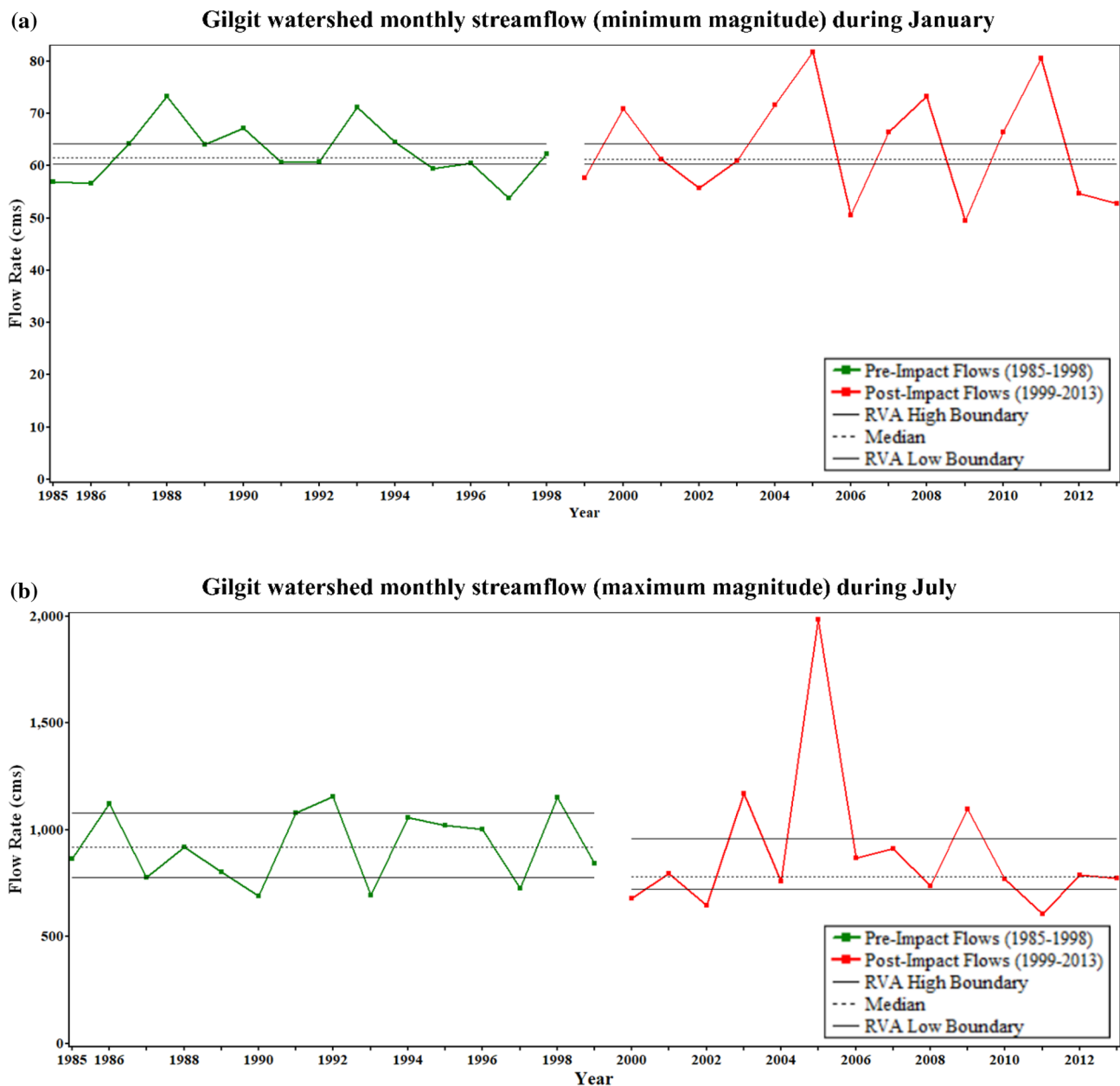


Fig. 8 Comparison of runoff during the dry **a** January and wet **b** July months using IHA (RVA) analyses

of 463 km² of snow observed during the land use impact analyses in the current study).

The analyses of IHA are further evaluated to demonstrate the alteration in runoff during period 1 and period 2 (Table 6). A statistical metric PBIAS is used to quantify the impact of CC and LUC on runoff during period 1 and period 2. The analyses show that the runoff in period 2 is always higher (overestimated) than the runoff in period 1. However, the runoff overestimation is proportional to the magnitude of runoff, i.e., higher overestimation in the wet season but lower estimation in dry seasons

Discussion and conclusions

CC and LUCs are two main factors responsible for the runoff changes in a watershed. Therefore, to better understand and manage the water resources of a watershed, it is important to evaluate the impact of LUC and CC. The accurate estimation of the hydrological processes is essential for the water resources of the Hindu Kush Himalayas (HKH) region that provides water to one-tenth of the global population. Therefore, the main objective of this

Gilgit watershed Environmental Flow Components (1985–2013)

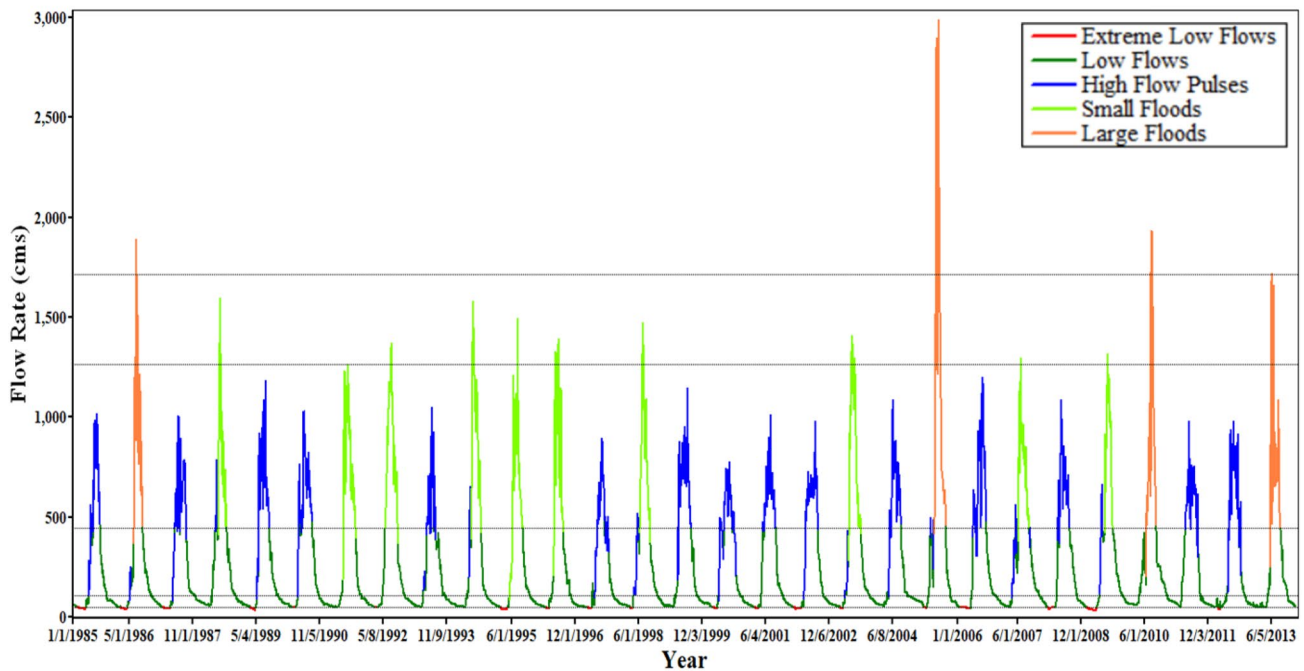


Fig. 9 Environmental flow components (EFCs) analyzed using IHA across the Gilgit watershed

Table 6 Average values of PBIAS calculated by comparing the pre-impact and post-impact values of RVA analyses

Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
-13.37	-16.09	-14.64	-35.63	-51.35	-53.07	-64.00	-32.88	-24.47	-25.60	-23.23	-17.63

Note that all values are presented in percentage (%) and negative values show overestimation of runoff during the post-impact period

study was to evaluate the runoff regime in the Gilgit watershed and to quantitatively assess the contribution of CC and LUC to runoff changes during 1985–2013. The MK and Pettitt test are used to evaluate the trends and change points in the hydroclimatic variables.

The SWAT model is used to analyze the relationship of LUC and CC on runoff across the Gilgit watershed. Researchers used hydrological modeling approach to evaluate the impacts of CC in different regions of the Upper Indus Basin (Akhtar et al. 2008; Immerzeel et al. 2010; Tahir et al. 2011; Lutz et al. 2016; Garee et al. 2017; Adnan et al. 2017a, b). It has been reported that the overall runoff presented declining trend at Tarbela dam station; however, rising trends are being observed in the Gilgit River flows since 1986. There are no consistent conclusions regarding the contribution of snowmelt and precipitation in overall flow of the Indus Basin. For instance, Piracha and Majeed (2011) concluded that 75% summer flow is due to snowmelt and Siddique and Hashmi (2012) concluded that contribution of snowmelt to runoff is 90%. Similarly, Adnan et al. (2017a, b) studied the runoff across Gilgit River watershed

and concluded that snowmelt is the main contributor (81%) in runoff and precipitation just contribute 19%.

In the present study it has been concluded that temperature trends are increasing due to which the process of snowmelt has increased; therefore, runoff presented an increasing trend. It has been reported that an increase in temperature can be attributed to a decrease in snow cover area (Brown and Robinson, 2011; Peng et al. 2013). The sunshine hours and temperature are the primary factors that control snowmelt and increase in snow cover may reduce local temperature as snow reflects most of the solar radiation, which supports our conclusion. However, this conclusion may be uncertain due to some reasons. The availability of data and selection of study period can be one reason as it is reported that during 2001–2012, snow cover decreased in the Gilgit basin during winter and autumn seasons, but increased during summer (Tahir et al. 2011; Hasson et al. 2014). The snow cover increase in summer has been associated with winter warming and summer cooling effects (Fowler and Archer, 2006). Hasson et al. (2014) also concluded that the snow cover and snow

accumulation are directly linked, which can be attributed to increase in precipitation trends (Minora et al. 2013). Moreover, Latif et al. (2018) evaluated the hydroclimatic trends of the Gilgit basin during 1991–2013 and reported decreasing trends for the annual and seasonal temperature. The winter westerly disturbances enhanced by global warming can be a reason, as an increase in global temperature will increase moisture absorbing ability of atmosphere, which may increase the snow cover.

The distribution of gauges can be another reason; there are too much elevation differences in the study area, where the available meteorological stations cannot truly represent the regional climate. For example, using the climate data of Khunjerab station, it has been concluded that at such elevations temperature remains below $-6\text{ }^{\circ}\text{C}$ for almost 6 months in a year. This shows most of the precipitation falls as snow and at such monthly temperature, probability of snow is almost 100% (Bilal et al. 2019), which supports the increasing trends of precipitation as reported in the current study. For sustainable management of water resources of the study area, it is recommended to increase the number of meteorological stations. Due to parameters' sensitivity, there can be uncertainties in calculated relative contributions of LUC and CC. Further investigations should be carried out to understand the contribution of LUC in runoff of the Upper Indus Basin. Further, this study has not used recent data, which is one of the listed limitations and results may change with latest datasets. There are different sub-basins in the Upper Indus Basin and all these basins can be studied to evaluate the overall impact of CC and LUC on water resources of the Indus Basin.

The main findings of this research are listed below.

1. The Pettitt test was used to calculate the change point in hydro-climatic variables including precipitation, temperature and runoff data. The change point was observed in the years 1999, 1995 and 1998, respectively.
2. The increasing rate in climatic variable calculated through the MK test was 4.92 mm/year, 0.04 $^{\circ}\text{C}/\text{year}$, and 2.60 m^3/year mean annual increase in precipitation, temperature, and runoff, respectively.
3. The relative contribution of CC to runoff was estimated as 97.22% and it is 2.78% for LUC.
4. Runoff simulated using the SWAT model and evaluated using Nash–Sutcliffe efficiency (NSE), the percent bias (PBIAS, %), and the coefficient of determination (R^2) revealed very good performance in the Gilgit watershed.
5. The land use analyses are performed across two different periods, i.e., 1996 and 2012. The results show that the forest area decreased by 12.38 km^2 , vegetation area decreased by 500 km^2 and snow/ice decreased by 463 km^2 . The bare soil increased by 800 km^2 , and urban areas increased by 276 km^2 .
6. IHA (RVA) analyses confirmed that the flow is increased (overestimated) after the change point. High overestimation is observed during the wet season (May–September) when the flow increased.
7. IHA analyses also presented maximum number of high flow pulses, small floods and even large floods, which confirmed the snow melt contribution to runoff. The decrease in snow area supports the significant warming trends and significant contribution of CC to runoff change.

Acknowledgements The authors would like to thank the Pakistan Meteorological Department (PMD) and Water and Power Development Authority (WAPDA) for providing the ground data. The authors are grateful to the anonymous reviewers for their constructive comments and suggestions that significantly improved the manuscript quality.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

- Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Kløve B (2015) A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. *J Hydrol* 524:733–752
- Adnan M, Nabi G, Kang S, Zhang G, Adnan RM, Anjum MN, Iqbal M, Ali F (2017a) Snowmelt Runoff Modelling under Projected Climate Change Patterns in the Gilgit River Basin of Northern Pakistan. *Pol J Environ Stud*. <https://doi.org/10.15244/pjoes/66719>
- Adnan M, Nabi G, Poomee MS, Ashraf A (2017b) Snowmelt runoff prediction under changing climate in the Himalayan cryosphere: a case of Gilgit River Basin. *Geosci Front* 8(5):941–949
- Ahmed S, Joyia MF (2003) Northern areas strategy for sustainable development. International union for conservation of nature and natural resources, background paper: water—Pakistan, Northern Areas Programme 67
- Akhtar M, Ahmad N, Booij MJ (2008) The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios. *J Hydrology* 355:148–163
- Ali K, Bajracharya RM, Sitaula BK, Raut N, Koirala HL (2017) Morphometric analysis of Gilgit River Basin in mountainous region of Gilgit-Baltistan Province, Northern Pakistan. *J Geosci Environ Protect* 5:70
- Ali K et al (2019) Analyzing land cover change using remote sensing and GIS: a case study of Gilgit River Basin, North Pakistan. *Int J Econ Environ Geol* 10:100–105
- Anand J, Gosain A, Khosa R, Srinivasan R (2018) Regional scale hydrologic modeling for prediction of water balance, analysis of trends in runoff and variations in runoff: the case study of the Ganga River basin. *J Hydrol Reg Stud* 16:32–53
- Anwar S, Khan FA, Rahman A (2019) Impact of karakoram highway on land use and agricultural development of Gilgit-Baltistan, Pakistan. *Sarhad J Agric*. 35(2):417–431
- Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development 1 JAWRA. *J Am Water Resour Assoc* 34:73–89

- Ay M, Kisi O (2015) Investigation of trend analysis of monthly total precipitation by an innovative method. *Theor Appl Climatol* 120:617–629
- Bilal H, Chamhuri S, Mokhtar MB, Kanniah KD (2019) Recent snow cover variation in the Upper Indus Basin of Gilgit Baltistan, Hindukush Karakoram Himalaya. *J Mt Sci* 16(2):296–308
- Bocchiola D, Diolaiuti G (2013) Recent (1980–2009) evidence of climate change in the upper Karakoram, Pakistan. *Theor Appl Climatol* 113:611–641
- Brown RD, Robinson DA (2011) Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *Cryosphere* 5(1):219–229
- Bunn SE, Arthington AH (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ Manag* 30:492–507
- Butt A, Shabbir R, Ahmad SS, Aziz N (2015) Land use change mapping and analysis using Remote Sensing and GIS: a case study of Simly watershed, Islamabad, Pakistan. *Egypt J Rem Sens Space Sci* 18:251–259
- Chen Q, Chen H, Wang J, Zhao Y, Chen J, Xu C (2019) Impacts of climate change and land-use change on hydrological extremes in the Jinsha River Basin. *Water* 11:1398
- Cong Z, Shahid M, Zhang D, Lei H, Yang D (2017) Attribution of runoff change in the alpine basin: a case study of the Heihe Upstream Basin, China. *Hydrol Sci J* 62(6):1013–1028
- Congalton RG (1991) A review of assessing the accuracy of classifications of remotely sensed data. *Rem Sens Environ* 37:35–46
- Criss RE, Winston WE (2008) Do Nash values have value? Discussion and alternate proposals. *Hydrol Process Int J* 22:2723–2725
- Dahal N, Shrestha UB, Tuitui A, Ojha HR (2019) Temporal changes in precipitation and temperature and their implications on the runoff of Rosi River, Central Nepal. *Climate* 7:3
- De Jong C, Collins DN, Ranzi R (2005) *Climate and hydrology of mountain areas*. Wiley, Chichester
- de Jong C (2015) Challenges for mountain hydrology in the third millennium. *Front Environ Sci* 3:38
- Dile YT, Srinivasan R (2014) Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin. *J Am Water Resour Assoc* 50:1226–1241
- Duan Z, Tuo Y, Liu J, Gao H, Song X, Zhang Z, Yang L, Mekonnen DF (2019) Hydrological evaluation of open-access precipitation and air temperature datasets using SWAT in a poorly gauged basin in Ethiopia. *J Hydrol* 569:612–626
- Farhan SB, Zhang Y, Aziz A, Gao H, Ma Y, Kazmi J, Shahzad A, Hussain I, Mansha M, Umar M, Nasir J (2020) Assessing the impacts of climate change on the high altitude snow-and glacier-fed hydrological regimes of Astore and Hunza, the sub-catchments of Upper Indus Basin. *J Water Clim Change*. <https://doi.org/10.2166/wcc.2018.107>
- Fathian F, Morid S, Kahya E (2015) Identification of trends in hydrological and climatic variables in Urmia Lake basin, Iran. *Theor Appl Climatol* 119:443–464
- Fowler HJ, Archer DR (2006) Conflicting signals of climatic change in the Upper Indus Basin. *J Clim* 19(17):4276–4293
- Gao Y, Vogel RM, Kroll CN, Poff NL, Olden JD (2009) Development of representative indicators of hydrologic alteration. *J Hydrol* 374:136–147
- Garee K, Chen X, Bao A, Wang Y, Meng F (2017) Hydrological modeling of the upper indus basin: a case study from a high-altitude glacierized catchment Hunza. *Water* 9:17
- Guan X et al (2019) The capacity of the hydrological modeling for water resource assessment under the changing environment in semi-arid river basins in China. *Water* 11:1328
- Gwet K (2002) Kappa statistic is not satisfactory for assessing the extent of agreement between raters. *Stat Meth Inter Rat Reli Assess* 1(6):1–6
- Hasson S, Lucarini V, Khan MR, Petitta M, Bolch T, Gioli G (2014) Early 21st century snow cover state over the western river basins of the Indus River system. *Hydrol Earth Syst Sci* 18(10):4077–4100
- Hussain D et al (2019) Spaceborne satellite for snow cover and hydrological characteristic of the Gilgit River Basin, Hindukush-Karakoram Mountains, Pakistan. *Sensors* 19:531
- Immerzeel WW, Van Beek LP, Bierkens MF (2010) Climate change will affect the Asian water towers. *Science* 328:1382–1385
- Iqbal MS, Dahri ZH, Querner EP, Khan A, Hofstra N (2018) Impact of climate change on flood frequency and intensity in the Kabul river basin. *Geosciences* 8:114
- Jiang R, Gan TY, Xie J, Wang N, Kuo C-C (2017) Historical and potential changes of precipitation and temperature of Alberta subjected to climate change impact: 1900–2100. *Theor Appl Climatol* 127:725–739
- Khare D, Patra D, Mondal A, Kundu S (2017) Impact of landuse/land cover change on run-off in the catchment of a hydro power project. *Appl Water Sci* 7:787–800
- Konz M, Uhlenbrook S, Braun L, Shrestha A, Demuth S (2007) Implementation of a process-based catchment model in a poorly gauged, highly glacierized Himalayan headwater. *Hydrol Earth Syst Sci* 11(4):1323–1339
- Krishnan R et al (2019) Unravelling climate change in the Hindu Kush Himalaya: rapid warming in the mountains and increasing extremes. *The Hindu Kush Himalaya assessment*. Springer, Cham, pp 57–97
- Langat PK, Kumar L, Koech R (2019) Understanding water and land use within Tana and Athi River Basins in Kenya: opportunities for improvement Sustainable. *Water Resour Manag* 5:977–987
- Latif Y, Yaoming M, Yaseen M (2018) Spatial analysis of precipitation time series over the Upper Indus Basin. *Theor Appl Climatol* 131:761–775
- Latif Y, Ma Y, Ma W (2021) Climatic trends variability and concerning flow regime of Upper Indus Basin, Jehlum, and Kabul river basins Pakistan. *Theor Appl Climatol* 144(1):447–468
- Lea C, Curtis A (2010) Thematic accuracy assessment procedures: National Park Service Vegetation Inventory, version 2.0. Natural resource report NPS/2010/NRR—2010/204. National Park Service, Fort Collins, Colorado
- Lee A, Cho S, Kang DK, Kim S (2014) Analysis of the effect of climate change on the Nakdong River stream flow using indicators of hydrological alteration. *J Hydro-Environ Res* 8:234–247
- Li D, Long D, Zhao J, Lu H, Hong Y (2017) Observed changes in flow regimes in the Mekong River basin. *J Hydrol* 551:217–232
- Li R, Zheng H, Huang B, Xu H, Li Y (2018) Dynamic impacts of climate and land-use changes on surface runoff in the mountainous region of the Haihe river basin, China. *Adv Meteorol*. <https://doi.org/10.1155/2018/3287343>
- Li F, Zhang G, Li H, Lu W (2019) Land use change impacts on hydrology in the Nenjiang River Basin, Northeast China. *Forests* 10:476
- Liu Z, Herman JD, Huang G, Kadir T, Dahlke HE (2021) Identifying climate change impacts on surface water supply in the southern Central Valley, California. *Sci Total Environ* 759:143429
- Lutz AF, Immerzeel WW, Kraaijenbrink PD, Shrestha AB, Bierkens MF (2016) Climate change impacts on the upper Indus hydrology: sources, shifts and extremes. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0165630>
- Lytle DA, Poff NL (2004) Adaptation to natural flow regimes. *Trends Ecol Evol* 19:94–100
- Magilligan FJ, Nislow KH (2005) Changes in hydrologic regime by dams. *Geomorphology* 71:61–78

- Mathews R, Richter BD (2007) Application of the Indicators of hydrologic alteration software in environmental flow setting 1. *JAWRA J Am Water Resour Assoc* 43:1400–1413
- Minora U, Bocchiola D, D'Agata C, Maragno D, Mayer C, Lambrecht A, Mosconi B, Vuillermoz E, Senese A, Compostella C, Smiraglia C (2013) 2001–2010 glacier changes in the Central Karakoram National Park: a contribution to evaluate the magnitude and rate of the “Karakoram anomaly.” *Cryosph Discus* 7(3):2891–2941
- Mohsin T, Gough WA (2010) Trend analysis of long-term temperature time series in the Greater Toronto Area (GTA). *Theor Appl Climatol* 101:311–327
- Moriassi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans ASABE* 50(3):885–900
- Murphy JC (2020) Changing suspended sediment in United States rivers and streams: linking sediment trends to changes in land use/cover, hydrology and climate. *Hydrol Earth Syst Sci* 24(2):991–1010
- Nolin AW (2012) Perspectives on climate change, mountain hydrology, and water resources in the Oregon Cascades, USA. *Mt Res Dev*. <https://doi.org/10.1659/MRD-JOURNAL-D-11-00038.S1>
- Olden JD, Poff N (2003) Redundancy and the choice of hydrologic indices for characterizing runoff regimes. *River Res Appl* 19:101–121
- Oliveira PT, e Silva CS, Lima K (2017) Climatology and trend analysis of extreme precipitation in subregions of Northeast Brazil. *Theor Appl Climatol* 130:77–90
- Osei MA, Amekudzi LK, Wemegah DD, Preko K, Gyawu ES, Obiri-Danso K (2019) The impact of climate and land-use changes on the hydrological processes of Owabi catchment from SWAT analysis. *J Hydrol Reg Stud* 25:100620
- Pagliero L, Bouraoui F, Diels J, Willems P, McIntyre N (2019) Investigating regionalization techniques for large-scale hydrological modelling. *J Hydrol* 570:220–235
- Pande CB, Moharir KN, Khadri S, Patil S (2018) Study of land use classification in an arid region using multispectral satellite images. *Appl Water Sci* 8:123
- Pellicciotti F, Buergi C, Immerzeel WW, Konz M, Shrestha AB (2012) Challenges and uncertainties in hydrological modeling of remote Hindu Kush–Karakoram–Himalayan (HKH) basins: suggestions for calibration strategies. *Mt Res Dev* 32(1):39–50
- Peng S, Piao S, Ciais P, Friedlingstein P, Zhou L, Wang T (2013) Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades. *Environ Res Lett* 8(1):014008
- Pham-Duc B, Sylvestre F, Papa F, Frappart F, Bouchez C, Crétaux JF (2020) The Lake Chad hydrology under current climate change. *Sci Rep* 10(1):1
- Piracha A, Majeed Z (2011) Water use in Pakistan's agricultural sector: water conservation under the changed climatic conditions. *Int J Water Resour Arid Environ* 1(3):170–179
- Poff NL, Zimmerman JK (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshw Biol* 55:194–205
- Rahman KU, Balkhair KS, Almazroui M, Masood A (2017) Sub-catchments flow losses computation using Muskingum-Cunge routing method and HEC-HMS GIS based techniques, case study of Wadi Al-Lith, Saudi Arabia. *Model Earth Syst Environ* 3:4
- Rahman KU, Shang S, Shahid M, Wen Y (2020) Hydrological evaluation of merged satellite precipitation datasets for runoff simulation using SWAT: a case study of Potohar Plateau, Pakistan. *J Hydrol* 587:125040
- Rao MP, Cook ER, Cook BI, Palmer JG, Uriarte M, Devineni N, Lall U, D'Arrigo RD, Woodhouse CA, Ahmed M, Zafar MU (2018) Six centuries of Upper Indus Basin runoff variability and its climatic drivers. *Water Resour Res* 54(8):5687–5701
- Richter B, Baumgartner J, Wigington R, Braun D (1997) How much water does a river need? *Freshw Biol* 37:231–249
- Scott CA, Zhang F, Mukherji A, Immerzeel W, Mustafa D, Bharati L (2019) Water in the Hindu Kush Himalaya. *The Hindu Kush Himalaya assessment*. Springer, Cham, pp 257–299
- Seyam M, Othman F (2015) Long-term variation analysis of a tropical river's annual runoff regime over a 50-year period. *Theor Appl Climatol* 121:71–85
- Shahid M, Cong Z, Zhang D (2018) Understanding the impacts of climate change and human activities on runoff: a case study of the Soan River basin, Pakistan. *Theor Appl Climatol* 134:205–219
- Shahid M, Rahman KU, Balkhair KS, Nabi A (2020) Impact assessment of land use and climate changes on the variation of runoff in Margalla Hills watersheds, Pakistan. *Arab J Geosci* 13(5):1–4
- Shang X, Jiang X, Jia R, Wei C (2019) Land use and climate change effects on surface runoff variations in the upper Heihe River basin. *Water* 11:344
- Shen Q, Cong Z, Lei H (2017) Evaluating the impact of climate and underlying surface change on runoff within the Budyko framework: A study across 224 catchments in China. *J Hydrol* 554:251–262
- Shi H, Li T, Wei J, Fu W (2014) Wang G (2016) Spatial and temporal characteristics of precipitation over the Three-River Headwaters region during 1961. *J Hydrol Reg Stud* 6:52–65
- Siddique M, Hashmi D (2012) Recent trends in high altitude temperatures and river flows in the Upper Indus Basin. *Centenary Celeb* 714:149–166
- Stocker TF, Qin D, Plattner GK, Alexander LV, Allen SK, Bindoff NL, Bréon FM, Church JA, Cubasch U, Emori S, Forster P. Technical summary. In: *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 2013* (pp. 33–115). Cambridge University Press.
- Su B, Jiang T, Jin W (2006) Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China. *Theor Appl Climatol* 83:139–151
- Subash N, Sikka A (2014) Trend analysis of rainfall and temperature and its relationship over India. *Theor Appl Climatol* 117:449–462
- Tahir AA, Chevallier P, Arnaud Y, Neppel L, Ahmad B (2011) Modeling snowmelt-runoff under climate scenarios in the Hunza River basin, Karakoram Range, Northern Pakistan. *J Hydrol* 409(1–2):104–117
- Tehrani EN, Sahour H, Booij M (2019) Trend analysis of hydro-climatic variables in the north of Iran. *Theor Appl Climatol* 136:85–97
- Tiwari PC, Joshi B (2012) Natural and socio-economic factors affecting food security in the Himalayas. *Food Secur* 4:195–207
- Tuo Y, Duan Z, Disse M, Chiogna G (2016) Evaluation of precipitation input for SWAT modeling in Alpine catchment: a case study in the Adige river basin (Italy). *Sci Total Environ* 573:66–82
- Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R (2007) Mountains of the world, water towers for humanity: typology, mapping, and global significance. *Water Resour Res*. <https://doi.org/10.1029/2006WR005653>
- Wang Y, Rhoads BL, Wang D (2016) Assessment of the flow regime alterations in the middle reach of the Yangtze River associated with dam construction: potential ecological implications. *Hydrol Process* 30:3949–3966
- Yaseen M, Ahmad I, Guo J, Azam MI, Latif Y (2020) Spatiotemporal variability in the hydrometeorological time-series over upper

- Indus River Basin of Pakistan. *Adv Meteorol.* <https://doi.org/10.1155/2020/5852760>
- Yu W, Yang Y-C, Savitsky A, Alford D, Brown C, Wescoat J, Debo-wicz D, Robinson S (2013) Future climate scenarios for the Indus Basin. *Ind Basin Pak* 77–93
- Zhang X, Srinivasan R, Bosch D (2009) Calibration and uncertainty analysis of the SWAT model using genetic algorithms and bayesian model averaging. *J Hydrol* 374:307–317
- Zhang X-F, Yan H-C, Yue Y, Xu Q-X (2019) Quantifying natural and anthropogenic impacts on runoff and sediment load: an investigation on the middle and lower reaches of the Jinsha River Basin. *J Hydrol Reg Stud* 25:100617
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