



Identifying the Annual and Seasonal Trends of Hydrological and Climatic Variables in the Indus Basin Pakistan

Muhammad Shahid^{1,2} · Khalil Ur Rahman²

Received: 27 June 2019 / Revised: 26 December 2019 / Accepted: 17 March 2020 / Published online: 26 March 2020
© Korean Meteorological Society and Springer Nature B.V. 2020

Abstract

The uneven hydro-climatic changes and droughts have significantly affected the socioeconomic condition of people dependent on the Indus basin, Pakistan. This study aims to examine the annual and seasonal hydro-climatic trends for the Upper Indus Basin (UIB), Middle Indus Basin (MIB) and Lower Indus Basin (LIB). The mean monthly data from 44 meteorological and 30 hydrological stations have been analyzed. The Mann Kendall test, Spearman's rho test, linear trend estimation method and Van Belle and Hughes test have been used to perform analysis of hydro-climatic trends. The Standardized Precipitation Index (SPI), Sequential Mann Kendall test and rescaled range analysis have been introduced to detect the seasonal and annual drought. The results showed that significant warming has been observed throughout the Indus basin. The spring precipitation decreased significantly in the UIB with the maximum decrease of 5.3 mm/year. The streamflow of UIB has presented significant increasing trends on annual basis and spring season due to significant warming and glacier melt. The streamflow of MIB presented a significant increase in spring, and it decreased in summer, which can be related to significant warming. The annual precipitation of LIB presented significant increasing trends, and a similar trend has been observed in autumn. However, the LIB showed decreasing streamflow trends on an annual and seasonal basis which is possible due to significant warming trends and water regulation in upstream. The Hurst index value indicates that the Indus basin is expected to maintain current trends and the degree of drought is expected to increase in the future.

Keywords Precipitation · Temperature · Streamflow · Water resources · Trend analysis · Indus basin

1 Introduction

In the twenty-first century, climate change is the key challenge for agriculture and water resources management (Lu et al.

2015; Porter et al. 2014). The projected warming trends can disturb the global hydrological system. This disturbance can be in the form of changes in average water availability and extreme hydrological events. Such changes in the global hydrological system can cause water insecurity especially in developing countries (Khattak et al. 2011; Mahmood and Jia 2017; Shahid et al. 2016). The climate of a region can be accessed by the trend analysis of its historical climatic data. The climate data can provide information about the variation of climatic variables in a specific period. Several studies have been reported globally to understand the trends in temperature, rainfall and streamflow e.g. in USA (Karmeshu 2012; Ouyang et al. 2017), in Canada (Gan 1998; Jiang et al. 2017) in Europe (de Luis et al. 2014; Zelenáková et al. 2017), in Asia (Latif et al. 2018; Yang et al. 2012) and in Africa (Langat et al. 2017; Oyerinde et al. 2015). The specific impact of climate change may vary at regional and local scales (Melillo 2014). Thus, understanding of hydro-climatic trends at a regional and local scale is necessary for sustainable water resources management.

Responsible Editor: Tianjun Zhou.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s13143-020-00194-2>) contains supplementary material, which is available to authorized users.

✉ Muhammad Shahid
shahidbaloch@gmail.com

Khalil Ur Rahman
hlrfm17@mails.tsinghua.edu.cn

¹ NICE, SCEE, National University of Sciences & Technology, Islamabad, Pakistan

² State Key Laboratory of Hydrosience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

Global climate risk index shows that Pakistan is the 7th most vulnerable country in the context of climate change (Eckstein et al. 2017). The Hindukush Karakoram Mountains contain the largest glaciers outside the Polar Regions, and it is known as “The Third Pole” of the earth (Soncini et al. 2015). These mountains are considered as the water towers for the Indus River, which originates from these mountains (Bashir et al. 2017; Immerzeel et al. 2010; Ragettli et al. 2016). Several studies investigated the hydro-climatic trends in different parts of the Indus basin (Ahmad et al. 2014; Archer and Fowler 2004; Bashir et al. 2017; Bocchiola and Diolaiuti 2013; Fowler and Archer 2005; Fowler and Archer 2006; Hasson et al. 2017; Khattak et al. 2011; Mukhopadhyay et al. 2015; Sheikh et al. 2009). Most of the studies mentioned above have focused on the UIB and only considered the trends of temperature and precipitation. Ahmad et al. (2014) performed the trend analysis of precipitation and temperature data of the MIB and LIB over the period of 1971–2010. The impact of climate change on the Indus basin has been briefly discussed in literature and some of the recent studies (Azmat et al. 2019; Forsythe et al. 2019; Khan 2015; Khan et al. 2015a; Khan et al. 2015b; Latif et al. 2018; Mahmood et al. 2016; Nepal and Shrestha 2015; Shrestha et al. 2019) have significant conclusions in this regard. Moreover, the impact of climate change has been reported in the Ganga river basin (Khan et al. 2016a; Khan et al. 2016b) which exist near the Indus basin.

In UIB, the observations have been analyzed from manually operated stations existing at a lower elevation. Whereas the streamflow of UIB mostly originates from elevation 2500–5500 m.a.s.l (Faruqui 1997). The serial correlation and seasonality of the data are not considered which can affect the results (Caloiero et al. 2011; Cong et al. 2017; Yue et al. 2002). Moreover, these studies used the data of limited meteorological stations, e.g., Ahmad et al. (2014) used the data of seven and five meteorological stations for the Middle and Lower Indus basins respectively. It has been observed that the historical climatic trends of the UIB are not consistent with the global trends, e.g., seasonal temperature (Fowler and Archer 2006) and seasonal precipitation (Archer and Fowler 2004). Similarly, Sheikh et al. (2009) concluded that the climatic trends of Pakistan show significant departure from global trends. However, limited attention has been paid to the river flow trends, which can reflect the impact of the climatic variables over the catchment. Moreover, many hydropower projects have been proposed at different sections of the Indus basin (Ullah et al., 2018), and trend analysis of hydro-climatic variables could be used as a reference. A detailed assessment of sub-regional hydro-climatic trend assessment is still lacking and hence this study aims to contribute in this knowledge gap. The present work covers

the hydro-climatic stations from the entire Indus basin lying in Pakistan. Apart from temperature and precipitation, streamflow trends are also investigated in this study.

Accordingly, this study presents a comprehensive trend analysis of hydro-climatic variables in the Indus basin Pakistan. The streamflow data of 30 hydrological stations and climatic data of 14 manual and 30 automatic weather stations have been used in this study. In this study, the climatic data represents precipitation and temperature (maximum and minimum) data. The Manan Kendall test, Spearman’s rho test, linear trend estimation method and Van Belle and Hughes tests have been used to perform analysis of hydro-climatic trends. The Standardized Precipitation Index (SPI), Sequential Mann Kendall test and rescaled range analysis has been used to detect the seasonal and annual drought. The objectives of this study are as follows: (1) to identify the characteristics of the Hydro-climatic variables in the Indus basin during the past two and a half decades. (2) to analyze the trends of Hydro-climatic variables at different time scales based on sequential autocorrelation. (3) to investigate the meteorological drought based on SPI index.

2 Data and Methodology

2.1 Indus River Basin

The Indus basin covers an area of 1,120,000 km², with 56% distributed in Pakistan, 6.7% in Afghanistan, 10.7% in China and 26.6% in India (Wolf et al. 1999). More than 40% of the Indus basin is located at an elevation higher than 2000 m above sea level. The Indus River is the main river within the Indus basin which originates from the Tibetan Plateau and flows through Kashmir and Pakistan before draining into the Arabian Sea (Negi 1991). The other rivers that flow through the Indus basin are the Jhelum, Chenab, Ravi, Beas, Sutlej, and Kabul. All these rivers are tributaries of the Indus River. The irrigated area of the Indus basin is 228,694 km² which is 21% of total area, about 60.9% of the irrigated area is located in Pakistan, 37.2% in India and 1.9% in Afghanistan. The Indus Basin Irrigation System (IBIS) is considered one of the largest irrigation systems in the world (Laghari et al. 2012). The hydrology of the Indus basin is complex the streamflow in the upper part of the basin mainly receives snow/glacier melting water (Hewitt 2011). However, the middle and lower parts receive monsoon rainfall as the main source of water (Ali et al. 2009). The streamflow of the Indus River and its tributaries varies between seasons. It is low in the winter and increases in summer when snow in the mountain regions starts to melt. Mostly rivers of the basin receive discharge during July to September, which is

a monsoonal season (Hartmann and Buchanan 2014). The study area for the present study is confined to the major part of the Indus basin, which mostly lies in Pakistan. It lies between the latitude 24.02° and 37.07° N and the longitude 66.2° and 82.5° E, covering a total area of $855,045 \text{ km}^2$. Tarbela Dam is the first reservoir constructed on the Indus River in Pakistan, and the Warsak, Mangla and Marala dams are constructed on its tributaries. In the present study, the area above the Tarbela Dam is referred as the Upper Indus Basin (UIB), the area up to the Dhoke Pathan flow gauge is referred as the Middle Indus basin (MIB), and the rest area is regarded as the Lower Indus basin (LIB) as shown in Fig. 1.

2.2 Data Description

The catchment boundary and stream networks are delineated by using a digital elevation model (Farr et al. 2007). The Indus basin is poorly gauged basin, and the meteorological stations are sparsely distributed within Pakistan. The major meteorological networks are operated by Pakistan meteorological department (PMD) and the Snow and Ice Hydrology Project (SIHP) of the Water and Power Development Authority (WAPDA), Pakistan. The monthly maximum temperature (hereafter T_{\max}), minimum temperature (hereafter T_{\min}) and precipitation (hereafter P) data have been collected for 44 stations. Out of 44 stations, we obtained the meteorological data of 28 stations (14 automatic and 14 manual) from PMD, 12 automatic weather stations data from WAPDA, 2 automatic weather stations data from China Meteorological Administration, and 2 automatic weather stations data from Indian meteorological department (IMD). The data of IMD stations is downloaded from the website of the Global Historical Climatology Network (GHCN). Out of 44 meteorological stations, 22 stations are in UIB, 13 stations are in MIB and 9 stations are in LIB. The meteorological stations of UIB are represented as MUI to MU22, MIB are represented as MMI to MM13 and LIB are represented as MLI to ML9. The meteorological data of stations MU11-MU22 cover the period from 1995 to 2013, and the other station's data is available for 1986–2015. The flow data (hereafter Q) of Indus River and its tributaries are recorded by WAPDA. According to the geographic location and period of availability, the data of Q is collected for 30 hydrological stations. The hydrological data records of the stations start in 1985 and end in the year 2015. The stations with ID HU1 to HU12 are located in UIB, HM1 to HM15 are located in MIB and HL1 to HL3 are located in LIB. The location map of the hydro-meteorological stations is also presented in Fig. 1. The Indus basin has four seasons: Winter from December to February, spring from March to May, summer or

monsoon season from June to August and autumn from September to November. The spatial distribution of precipitation is highly variable in the Indus basin. The monsoon rainfall is the main source of water for the Indus basin. The climate of the Indus basin is diverse regarding climatic variables. The mean annual T_{\max} is between -1 and 35°C and the mean annual T_{\min} is between -10 and 22°C . The T_{\max} of 35°C is recorded at station ML2 and the T_{\min} of -10°C is recorded at station MU14. The mean annual P ranges from 80 mm to 1776 mm. The mean annual maximum P of 1776 mm is recorded at station MM4, and the mean annual minimum P of 80 mm is recorded at station MU8.

2.3 Preliminary Data Analysis

Statistical analysis is necessary to understand the characteristics of hydro-climatic time series. The homogeneity and autocorrelation test are performed for the hydro-climatic variables of the Indus basin. Homogeneity test is a fundamental test in hydrology (Kang and Yusof 2012; Qin et al. 2009). It is used to check the data variability, and it gives information about homogeneity or heterogeneity of data. If the data series shows shomogeneity then it is considered that data has been recorded with a similar instrument, techniques, and environment (Kang and Yusof 2012; Seyam and Othman 2015). Different tests are available in the literature to test the homogeneity such as Buishand's test, Pettitt's test and von Neumann test (Bartels 1984; Buishand 1982; Pettitt 1979). In literature, the Pettitt's test is mostly used to check the homogeneity (Cong et al. 2017; Shahid et al. 2017). In the present study, Pettitt's test is used to check the homogeneity of hydro-climatic variables. The presence of autocorrelation can distort the results; the two-tailed test is used to check the serial correlation of data series. The trend-free pre-whitening (TFPW) approach is applied to remove the serial correlation in data series.

2.4 Statistical Test for Trend Analysis

The trends of the hydro-climatic variables have been tested by using three methods. The nonparametric Mann Kendall (MK) test, the nonparametric Spearman's rho test (SR) and the parametric linear regression (LR) test. These methods do not require a normal distribution for data series. The equations of the MK test, SR test, and LR test are presented in supplementary material. The MK test requires serially independent data. The MK test can overestimate, the significance for positively correlated data and it underestimate the significance of the trend if data has a negative correlation. The serial correlation has been checked by using a two-tailed test, and TFPW method is applied to remove serial correlation as discussed in the preliminary data analysis section. Many studies have compared the

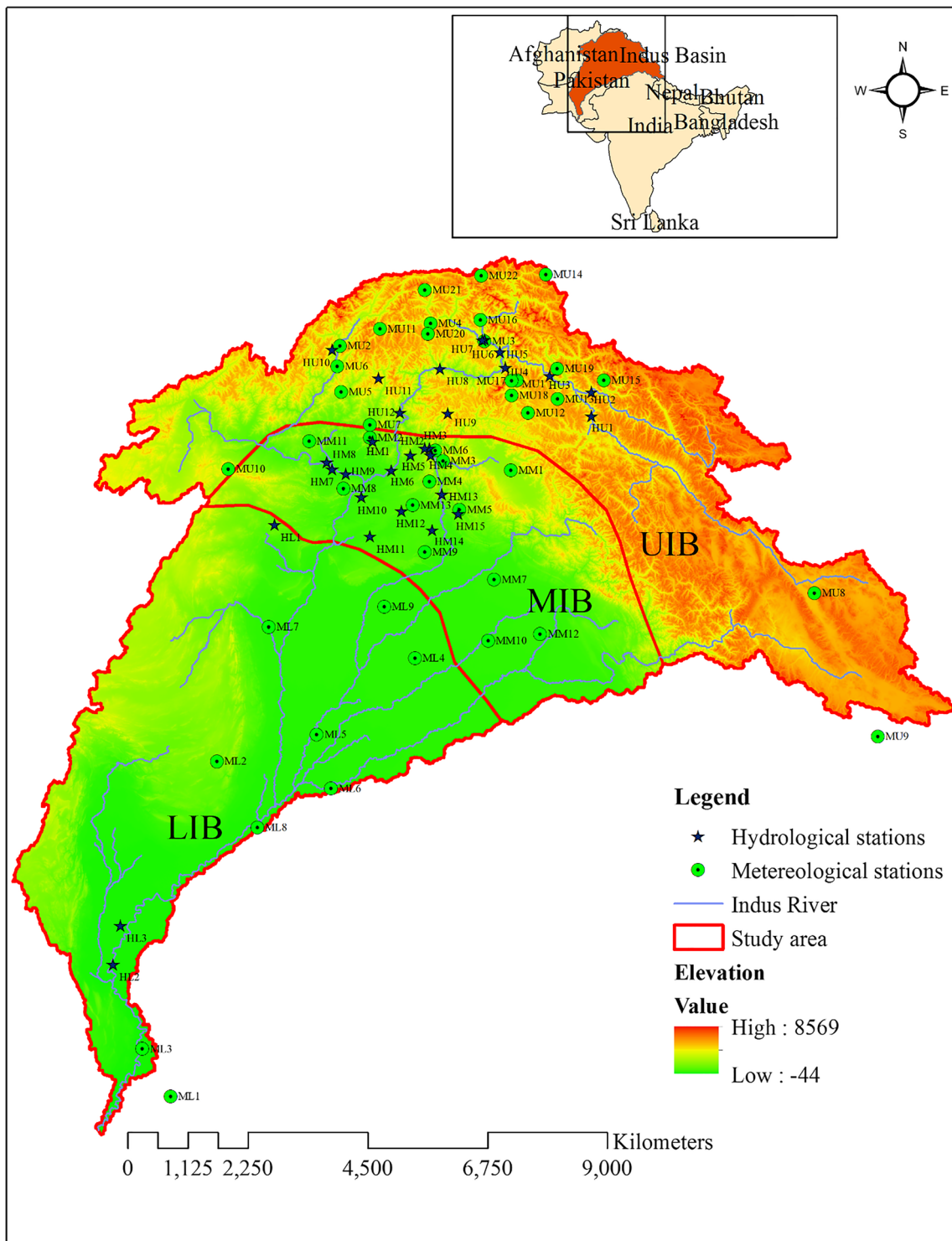


Fig. 1 Location map of the Indus basin and distribution of Hydro-meteorological stations

results of these three methods when performing trend analysis (Fathian et al. 2015; Tehrani et al. 2018; Zhao et al. 2017). All these methods have their strength and weakness, and their results can complement each other. The readers interested in a detailed explanation of these methods are referred to (Burn and Elnur 2002; Helsel and Hirsch 1992).

2.5 Test for Trend Homogeneity

The three methods used in this study implicitly assume the trend homogeneity between different seasons. (Belle and Hughes 1984) concluded that the overall statistics show no trends although there is a significant trend in data series.

Therefore, an overall trend test leads to an ambiguous conclusion when data have heterogeneous trends. This test uses Chi-square (χ^2) tests to determine the homogeneity of trends. The Chi-square statistics are calculated by the Van Belle and Hughes equations for homogeneity of the station, season and station season interaction as follows:

$$\chi^2_{total,qm} = \sum_{k=1}^q \sum_{j=1}^m Z^2_{kj} \quad (1)$$

$$\chi^2_{homogeneity,qm-1} = \sum_{k=1}^q \sum_{j=1}^m (Z_{kj} - \bar{Z})^2 \quad (2)$$

$$\chi^2_{season,q-1} = m \sum_{k=1}^q (Z_k - \bar{Z})^2 \quad (3)$$

$$\chi^2_{stations,m-1} = q \sum_{k=1}^m (Z_j - \bar{Z})^2 \quad (4)$$

$$\chi^2_{stat-season,(q-1)(m-1)} = \sum_{k=1}^q \sum_{j=1}^m (Z_{kj} - Z_k - Z_j + \bar{Z})^2 \quad (5)$$

$$\chi^2_{trend,1} = qm\bar{Z}^2 \quad (6)$$

In these equations Z is the normalized Kendall's statistic such that Z_k is the average Z value over m stations for k seasons, Z_j is the average Z value over q seasons for j stations, Z_{kj} is Z value for the season k at the station j and \bar{Z} is overall average Z value. The computed values of $\chi^2_{station}$, χ^2_{season} and $\chi^2_{station-season}$ are compared with critical values of Chi-square table with $(q-1)$, $(m-1)$ and $(q-1) * (m-1)$ DF (degree of freedom) respectively. If the computed χ^2 value of station, season and station-season interaction exceed from the critical value of Chi-square, then trends are considered as significant and heterogeneous. The Eq. (3), Eq. (4) and Eq. (5) can be used to determine homogeneity between seasons, stations and seasons stations interaction respectively. The overall global trend in a basin can be tested; in this regard, (Kahya and Kalaycı 2004), discussed four scenarios as follows:

1. When $\chi^2_{station}$, χ^2_{season} and $\chi^2_{station-season}$ are not significant then overall trend can be tested by comparing χ^2_{trend} with Chi-square value at DF = 1.
2. When χ^2_{season} is significant but $\chi^2_{station}$ is not significant then different trend direction in each season should be tested from qZ^2_k .
3. When $\chi^2_{station}$ is significant but χ^2_{season} is not significant then trend should be tested at each station by using mZ^2_j .
4. When both $\chi^2_{station}$ and χ^2_{season} are significant, then individual station season interaction, i.e., $Z_{kj}(k=1, 2, 3, 4)$, $J=(1, 2, 3, \dots, m)$ are tested for significance of trends. This can be done by refereeing each station's Z_{kj} statistics to the critical value of standard normal distribution at $\alpha = 0.05$. The null hypothesis of no trend is accepted if $-Z_{\alpha/2} < Z_{kj} < Z_{\alpha/2}$, where $\pm Z_{\alpha/2}$ is the standard normal deviate at

$\alpha = 0.05$. The overall trend significance can be tested by using Eq. (6). (Vousoughi et al. 2013).

2.6 Drought Analysis

The intensity of drought or wet events can be measured by standardized precipitation index (SPI). It is suitable for comparing the drought disorder at different time scales and regions having different climatic situations (Bonaccorso et al. 2003). It is recommended by the World Meteorological Organization (WMO) to monitor drought, and it has been used in different studies (Gocic and Trajkovic 2013; He et al. 2015). It depends on the equal probability transformation of accumulated monthly precipitation data into a standard normal variable. It works at 1, 3, 6, 12, 24 monthly scale precipitation data series. In this study, the SPI has been calculated at the seasonal scale (SPI-3) and annual scale (SPI-12). According to (McKee et al. 1993) for SPI value: 0 to 0.99 drought will be near normal, 1 to 1.49 drought will be moderate wet, 1.5 to 1.9 drought will be very wet, and for greater than 2 it will be extremely wet. Similarly, for SPI (-1 to -1.49), drought will be moderate, (-1.5 to -1.99) drought will be severe and for (< -2) it will be extreme drought. The positive value of SPI indicates that the precipitation is above average and negative SPI value indicates that precipitation is below average. The calculation procedure of SPI is available in WMO user guide (Svoboda et al. 2012). The Sequential Mann Kendall (SMK) test has been used to detect abrupt changes in SPI. The SMK test is suitable to detect the abrupt changes in data series. A detailed explanation of SMK test is presented in (Han et al. 2016). The long-term correlation of time series is evaluated by rescaled range analysis (Salomao et al. 2009) the detailed explanation of MK, SR, LR test and rescaled range analysis method is presented in the appendix.

3 Results and Discussion

3.1 Statistical Characteristics of Hydro- Climatic Variables

The hydro-climatic data is analyzed before processing homogeneity, and autocorrelation of the data series. It has been observed that the climatic data of some stations have shown non-homogeneous behavior. The non-homogeneous behavior has been observed for T_{max} , T_{min} , P , and mostly non-homogeneity is recorded between 1997 and 2005 as presented in Table 1. Similarly, the flow data is non-homogeneous for stations HU6, HU3, HU10, HM7, and HL2. Inhomogeneities have been reported regarding different stations in the Indus basin (Archer and Fowler 2004; del Rio et al. 2013; Forsythe et al. 2015; Fowler and Archer 2005), and such

Table 1 List of stations presenting non homogeneous behavior for Minimum Temperature (T_{min}), Maximum Temperature (T_{max}) and Precipitation (P)

Station ID for T_{min}	Year	Station ID for T_{max}	Year	Station ID for P	Year
MU3	2005	MU1	1996	MM4	1998
MU6	2005	MM2	1997	MU5	2001
MM7	1997	MU2	1996	MM6	1997
MU8	1997	MM3	1997	MU7	2000
MU9	1997	MU3	1996	ML4	2000
ML1	2005	MU4	1996		
ML2	2005	MM4	1997		
ML4	1997	MM6	1996		
MM10	1997	MM8	1999		
MM11	1997	MU8	1998		
ML5	1998	ML6	1997		
ML6	1997	MM12	1997		
ML8	2000	MM1	2002		
MM13	1997				
MM1	1997				

inhomogeneities are attributable to environmental changes (Bashir et al. 2017). Therefore, for careful interpretation of results, no correction method has been applied here. The autocorrelation is checked for hydro-climatic data series, and 20% (551 out of 2754) presented autocorrelation. It is observed that about 4%, 7%, 3% and 6% series of T_{max} , T_{min} , P and Q presented autocorrelation respectively which can influence the results of trends. The results for autocorrelation of data series are presented in Fig. 2 and it has been removed through TFPW method and then MK test, Spearman’s rho test and linear trend estimation methods are applied to these series.

3.2 Hydro-Climatic Trend Analysis

3.2.1 Results of Trend Tests

The MK test and SR test are used to perform trend analysis of hydro-climatic variables at a significance level of 5%, and

results are presented in Table 2. The Van Belle and Hughes’ test of trend homogeneity has been used to understand the overall trends of hydro-climatic variables closely. The homogeneity test results of all variables are presented in Table 3. The sub-basin wise annual significant trends and trends homogeneity for P , T_{max} , T_{min} and Q are discussed here. The trend slope of hydro-climatic variables are estimated by linear trend estimation method, and slope changes for all stations are presented in supplementary material Table S1-S3.

The trend analysis results in Table S2 show that the Pof UIB stations has not presented any significant trend on an annual basis. The MIB stations presented both positive and negative P trends on an annual basis, and 2 stations presented positive and negative trends respectively. The magnitude of decreasing annual trend (-14.6 mm/year) has been observed more significant as compared to the magnitude of the positive trend (10 mm/year). The LIB stations presented positive P trends on an annual basis, and only one station presented

Fig. 2 Number of stations showing significant autocorrelation

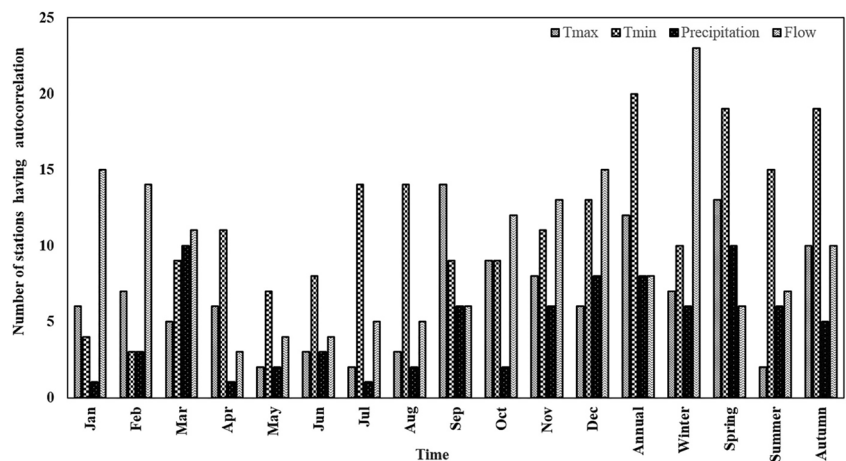


Table 2 Number of stations presenting significant Positive (P) and Negative (N) trends at annual and seasonal scale. UIB, MIB and LIB have 22, 13, 9 meteorological stations and 12, 15, 3 hydrological stations respectively

UIB Variables	Annual		Winter		Spring		Summer		Autumn	
	P	N	P	N	P	N	P	N	P	N
<i>P</i>	0	0	4	0	0	5	2	1	4	2
T_{\max}	3	1	2	1	7	0	2	0	1	1
T_{\min}	3	0	2	0	3	1	2	1	3	0
<i>Q</i>	4	0	1	0	4	0	2	1	2	0
MIB Variables										
<i>P</i>	2	2	0	0	0	1	0	0	1	0
T_{\max}	3	1	3	2	3	0	0	1	1	1
T_{\min}	2	0	0	1	3	0	2	0	1	0
<i>Q</i>	0	0	1	0	2	0	0	3	0	1
LIB Variables										
<i>P</i>	1	0	0	0	0	0	0	0	3	0
T_{\max}	1	0	2	1	1	0	1	1	2	0
T_{\min}	3	0	1	0	3	0	2	0	4	0
<i>Q</i>	0	1	0	0	0	1	0	0	0	1

this trend. The results for temperature trends are presented in Table S1 and these results show that UIB experienced warming trends on an annual basis, three stations presented positive trends and only one station presented a negative trend. The magnitude of annual T_{\max} trend varied between -0.01 °C/year and 0.05 °C/year. The T_{\min} also presented similar trends for UIB stations and positive trends are more significant. On an annual basis, three stations presented positive trends, and the highest trend magnitude is observed as 0.03 °C/year. The T_{\max} of MIB stations presented significant trends at annual scale, three stations presented a positive trend, and the negative trend has been observed in one station. The magnitude of annual trend varied between -0.01 °C/year and 0.05 °C/year. The T_{\min} of the MIB presented positive trend at an annual basis. Two stations presented a positive trend on an annual basis and highest trend magnitude of 0.02 °C/year has been observed. Similarly, the T_{\max} of LIB presented significant trends on the annual scale, and only one station presented a positive trend with the magnitude of 0.04 °C/year. The T_{\min} of LIB also presented significant positive trends on an annual basis. Three stations presented positive trends on an annual basis and the highest trend magnitude of 0.03 °C/year has been observed. The result of streamflow trends are presented in Table S3 and these results show that *Q* of UIB has experienced a positive trend on an annual basis. The positive trends have been observed for four stations, and trend magnitude ranged from 1.2 mm/year to 12.5 mm/year. The *Q* of MIB stations have not presented any significant trend on an annual basis. The *Q* of LIB stations presented a negative trend on an

annual basis, and this trend has been observed in only one station. The magnitude of annual trends has been observed as -0.2 mm/year.

3.2.2 Precipitation Trends

The seasonal trends of the hydro climatic variables are discussed in this section, and spatial variation for hydro climatic variables are presented in Figs. S1-S4. The trend analysis results of precipitation are presented in Fig. S1 which show that *P* of UIB has presented both positive and negative trends on a seasonal basis. Winter *P* showed positive trends and four stations presented significant positive trends. During winter the magnitude of the highest increasing trend has been found as 2.9 mm/year. Spring *P* presented significant negative trends and these trends have been observed for five stations. The magnitude of the highest trend slope has been observed as -5.3 mm/year. Summer and autumn *P* presented contrasting trends, in summer 3 stations (2 positive and 1 negative) and in autumn 6 stations (4 positive and 2 negative) presented the significant trends. The results of the homogeneity test revealed that *P* of the UIB has not presented an overall homogeneous trends. The MIB stations have not presented any significant *P* trends for winter and summer season. However, only one station presented positive and negative trend for autumn and spring season respectively. The trend magnitude of a negative trend in spring (-0.9 mm/year) has been found more significant as compared to autumn trend (0.6 mm/year). The homogeneity test showed that *P* of the MIB has not presented an overall homogeneous trend. The LIB stations presented significant seasonal *P* trends, and 3 stations presented a positive trend for autumn. The trend slope of autumn season has been observed as 1 mm/year. The overall trend of season-station interaction has been found to be homogeneous for the *P* of LIB. The results of the homogeneity test for seasonal *P* trends of LIB are consistent with the trend analysis by MK and SR test as shown in Fig. S1, all stations presented an increasing trend in the autumn season.

(Archer and Fowler 2004; Khattak et al. 2011)) performed trend analysis of *P* in UIB. Comparing the current UIB stations results with these studies show both similarities and dissimilarities. In both studies increasing trends have been observed for winter which is similar with UIB stations results in this study. (Archer and Fowler 2004) found increasing annual and summer *P* trends for several stations and (Khattak et al. 2011) presented similar trends for few stations. In this study, no significant trends have been observed on an annual basis, and contrasting trends have been observed in the summer season. The possible reasons include the difference in the study period (although there is an overlap) and (Archer and Fowler 2004) did not consider the serial correlation and seasonality of the data series. Similarly, (Ahmad et al. 2014) have not found any significant annual and seasonal trends

Table 3 Results of Van Belle and Hughes homogeneity test for seasonal trends in hydro-climatic variables. Here, DF = degree of freedom

Stations sites	Total	Homogeneity	Season	Station	Season-station	Trend	Z
Precipitation (<i>P</i>)							
UIB							
χ^2	211.65	210.93	71.31*	73.14*	250.27*	0.72	0.09
DF	88	87	3	21	63	1	
MIB							
χ^2	73.06	65.57	13.31*	55.23*	85.92*	3.49	0.26
DF	88	87	3	12	36	1	
LIB							
χ^2	39.69	25.5	7.42**	8.1**	27.05**	9.61	0.52
DF	88	87	3	8	24	1	
UIB Maximum Temperature (T_{max})							
χ^2	201.4	192.35	43.83*	54.72*	106.01*	9.05	0.32
DF	88	87	3	21	63	1	
MIB							
χ^2	233.89	190.73	43.73*	94.67*	97.30*	43.16	0.91
DF	88	87	3	21	63	1	
LIB							
χ^2	125.91	125.56	32.02*	77.79*	72.95*	0.44	0.11
DF	88	87	3	21	63	1	
UIB Minimum Temperature (T_{min})							
χ^2	302.36	302.22	29.10*	95.49*	214.74*	0.14	-0.04
DF	88	87	3	21	63	1	
MIB							
χ^2	200.11	199.89	48.19*	38.75*	173.47*	0.22	-0.66
DF	88	87	3	21	63	1	
LIB							
χ^2	227.01	194.99	57.51*	23.710*	240.85*	3.3	1.79
DF	88	87	3	21	63	1	
UIB Streamflow (<i>Q</i>)							
χ^2	106.38	94.24	9.75*	90.32*	84.23*	12.14	0.5
DF	48	47	3	11	33	1	
MIB							
χ^2	62.92	58.58	19.79*	9.76**	45.59**	4.34	-0.27
DF	60	59	3	14	42	1	
LIB							
χ^2	16.22	8.99	12.45*	2.810**	10.92**	7.23	-0.77
DF	12	11	3	2	6	1	

Note: * indicate that the trends are significant and heterogeneous i.e. the given chi-square values are greater than the critical value at $\alpha = 0.01$. Whereas ** indicates trends are not significant

for *P* of LIB. In the present study *P* of LIB presented significant increasing trends in the autumn season. The possible reasons include the difference in the study period and number of stations. They analyzed data of 5 stations, but data of 9 stations have been evaluated in the present study.

3.2.3 Temperature Trends

The MK and SR test results for T_{max} data are presented in Fig. S2 which show that UIB experienced warming trends on a

seasonal basis. On a seasonal basis, seven and two stations presented positive trends in spring and summer respectively. The spring season trend magnitude varied between -0.02 °C/year and 0.08 °C/year, for summer highest trend has been observed as 0.05 °C/year. The T_{max} trends of winter (two positive, one negative) and autumn (one positive, one negative) are contrasting. In general, it can be concluded that T_{max} presented the most significant warming trends in the spring season. On the other hand, the results of trend analysis for T_{min} are presented in Fig. S3, which also presented similar trends

for UIB stations, and positive trends are more significant. On a seasonal basis, two stations presented positive trends in winter, and three stations presented similar trends in the autumn season. Winter and autumn seasons highest trend magnitude has been observed as 0.03 °C/year and 0.02 °C/year respectively. Spring presented (three positive, one negative) trends and summer presented (two positive, one negative) trends. These findings do not agree with (Khattak et al. 2011)) as they observed annual and seasonal decreasing trends in T_{\min} . It might be due to the difference of elevation as they used the data of stations at low elevation (1465–2394 m.a.s.l). However, the warming trends are found to be consistent with decreasing snow cover in spring over the Northern Hemisphere (Stocker et al. 2013). The results of the homogeneity test showed that the overall trends of T_{\max} and T_{\min} are heterogeneous for UIB stations.

The T_{\max} of MIB stations presented significant trends at seasonal scale. The significant warming trends have been observed in the spring, and three stations presented positive trends. The highest trend magnitude of 0.07 °C/year has been observed in the spring season. Winter and autumn presented contrasting trends, and only one station presented a negative trend in the summer season. On the other hand T_{\min} of the MIB presented positive trends in spring, summer, and autumn. The maximum positive trend has been observed in the spring, and three stations presented these trends. The highest trend magnitude of 0.03 °C/year has been observed in spring. Similarly, the T_{\max} of LIB also presented significant trends on a seasonal scale. During winter three stations (two positive and one negative) presented a significant trend. Only one station presented a positive trend in spring, and two stations presented a positive trend in autumn. The highest trend magnitude of 0.06 °C/year has been observed in autumn. On the other hand T_{\min} of LIB also presented significant positive seasonal trends. On a seasonal basis, one station in winter, three stations in spring, two stations in summer and four stations in autumn presented positive trends. The highest trend magnitude of 0.03 °C/year has been observed in the autumn season. The warming trends in MIB and LIB are consistent with the findings of (Ahmad et al. 2014)). The overall trends of T_{\max} and T_{\min} are found to be heterogeneous for MIB and LIB.

3.2.4 Streamflow Trends

The trend analysis results for streamflow are presented in Fig. S4 which show that Qof UIB has experienced significant seasonal trends. On a seasonal basis, four stations presented significant positive trends in the spring season and trend magnitude of 11 mm/year has been observed. Similarly, one station presented a positive trend in winter, and 2 stations presented a positive trend in autumn. The contrasting trend has been observed for summer where two stations presented a positive trend, and the negative trend has

been observed for one station. The homogeneity test revealed that overall trends are found to be heterogeneous for Qof UIB. The Qof MIB stations presented contrasting trends on a seasonal basis. Winter and spring presented positive trends for one and two stations respectively. The highest trend magnitude of 0.5 mm/year has been observed for spring trends. The summer and autumn presented negative trends for three and one stations respectively and most significant trend magnitude of -1.2 mm/year has been observed in summer. The Qof LIB stations also presented seasonal trends, and only one station presented a negative trend in the spring and autumn season respectively. The most significant trend magnitude of -0.5 mm/year has been observed in the spring season. The other seasons have not presented any significant trend. It has been concluded from the homogeneity test that Qof MIB and LIB presented homogeneous trends for seasons. The decreasing trends in Qof MIB and LIB are most probably due to increasing trends of temperature and other changes like industrialization, agriculture demand, urbanization, and land use change.

3.3 Analysis of Drought Condition

The SPI analysis has been performed for seasonal and annual scale. The SPI-3 (3-month scale) values in February, May, August, and November represent the winter, spring, summer and autumn respectively. The SPI-12 (12-month scale) values in December represent the whole year. Table 4 shows the trend analysis results of seasonal and annual SPI at each station of sub-basins. The annual and seasonal MK and SR statistics of SPI differed at each station, and few stations presented significant trends. In UIB, the SPI generally increased in winter and autumn season. However, it presented no significant on an annual basis and decreased in other seasons. In MIB, the SPI presented increasing trends in the autumn season, and it decreased in other seasons and annual basis. Similarly, the SPI exhibited increasing annual and seasonal trends in LIB. Thus all seasons show humid behavior for LIB. While in UIB and MIB spring and summer showed arid behavior. Although trends are not significant but SPI value of UIB and MIB are trending toward drought conditions.

The SMK statistics of all sub-basins are presented in Supplementary Figs. S5, S6. The stations of the Indus basin has not presented any abrupt change for SPI. However, it can be observed that most of the stations UF(k) curves are below the $y = 0$ line. Thus in most of the stations, there is a continuous decrease in annual SPI trends. The MK and SR tests are used to analyze the present trends while SMK is used to find abrupt trends. The rescaled range analysis R/S has been performed to understand the long-term correlation in data series (Huihui et al. 2016). The rescaled range is a statistical measure used to calculate the variability of a time series. The combination of these methods has been found useful to

Table 4 The trend analysis results of seasonal and annual SPI

ID	Test	Win	Spr	Sum	Aut	Ann	ID	Test	Win	Spr	Sum	Aut	Ann
MU1	S	0	-1.8	-0.7	-0.5	-1.5	MM1	S	0.8	0.8	0.9	0.9	0.8
	Z	0.2	-1.6	-0.7	-0.4	-1.5		Z	0.8	1	0.9	0.9	1
MU2	S	0.4	-2.8	-0.9	-0.1	-1.4	MM2	S	-0.6	-2.6	-1	0.1	-1.7
	Z	0.5	-2.5	-1.1	0	-1.4		Z	-0.7	-2.2	-1.1	0.2	-1.6
MU3	S	0.9	0.4	-0.1	1.7	1.1	MM3	S	0.1	-2.3	-1.5	-0.8	-2.5
	Z	1	0.3	-0.2	1.8	1		Z	0.1	-1.7	-1.6	-0.9	-2.4
MU4	S	1.8	0	-0.1	0.8	0.7	MM4	S	-1.5	-2.4	-1.5	0.3	-2.6
	Z	1.5	0.2	-0.1	0.8	1		Z	-1.5	-2	-1.5	0.3	-2.2
MU5	S	-0.7	-2.9	-1.2	0	-2.4	MM5	S	0	-1.2	0.3	1.2	-0.1
	Z	-0.5	-2.6	-1.4	0.2	-2.2		Z	-0.1	-1.2	0.2	1.3	-0.2
MU6	S	0.3	-2.2	-0.6	-0.5	-1.5	MM6	S	-1.2	-1.3	-0.9	-1.7	-3.5
	Z	0.3	-1.9	-0.8	-0.3	-1.6		Z	-1.3	-1.1	-1	-1.6	-3.1
MU7	S	-0.4	-2.7	-1	-0.4	-2.1	MM7	S	-1	-1.1	-1.4	-0.4	-1
	Z	-0.3	-2.4	-1	-0.2	-1.7		Z	-1	-1.2	-1.1	-0.2	-0.9
MU8	S	-0.1	-0.3	0.7	0.2	0.6	MM8	S	1	-0.4	1.9	0.9	1.8
	Z	-0.3	-0.4	0.6	0	0.5		Z	1	-0.4	1.8	1	1.7
MU9	S	0.1	-1.4	1.3	0.6	1.2	MM9	S	-1.1	-1.1	-0.9	0.2	-1.1
	Z	0.1	-1.4	1.3	0.7	1.4		Z	-1	-1.2	-0.7	0.1	-1
MU10	S	3.3	-0.1	3.2	2.2	3	MM10	S	-1.2	-0.4	-0.2	1	0.8
	Z	2.9	-0.1	3.0	2.2	3		Z	-1.3	-0.4	0	0.9	1
MU11	S	3.1	-1.4	-0.8	2	-0.4	MM11	S	3.4	0.3	1	2.4	2.5
	Z	2.6	-1.1	-0.6	2	-0.6		Z	2.9	0.3	1	2	2.5
MU12	S	2.9	-2.1	-0.2	0.2	0.7	MM12	S	1	1.6	1.5	0.3	2.4
	Z	2.8	-1.9	-0.1	0.3	0.4		Z	1.2	1.6	1.3	0.1	2.3
MU13	S	2.6	-0.8	-3.4	0.6	0.3	MM13	S	-0.6	-1.6	-0.3	0.2	-0.5
	Z	2.3	-0.9	-2.9	0.4	0.6		Z	-0.7	-1.6	-0.4	0.3	-0.4
MU14	S	3.4	2.5	-2.7	2.6	-1.6	ML1	S	-0.3	0.6	0.1	2.3	0.2
	Z	2.7	2.2	-2.2	2.5	-1.7		Z	-1.2	0.6	0.1	1.6	0.2
MU15	S	1	-2.6	-1.4	-0.2	-1.6	ML2	S	0.7	1.4	-0.2	2.1	0.6
	Z	1	-2.2	-1.5	-0.1	-1.7		Z	0.1	1.5	-0.4	1.8	0.6
MU16	S	2.4	-1.6	0.5	0.5	0.5	ML3	S	-0.1	0.9	0.1	2.2	0.1
	Z	2.5	-1.6	0.3	0.5	0.7		Z	-0.5	0.2	0.2	0.8	0.1
MU17	S	1.5	-2.5	-1.6	1.1	-1	ML4	S	0.7	0.3	1.3	2.4	3.5
	Z	1.3	-2.2	-1.7	1	-1.2		Z	0.5	0.3	1.3	2.4	2.9
MU18	S	-0.3	-1.3	-0.6	-2.3	-1.2	ML5	S	0.6	0.7	-0.6	1.5	1
	Z	-0.3	-1.2	-1	-2.1	-0.9		Z	0.7	0.7	-0.7	1.3	0.9
MU19	S	0.2	-0.8	-1.5	-3	-1.4	ML6	S	1.4	-0.6	0.4	0.4	1.1
	Z	0.1	-0.5	-1.7	-2.2	-1.5		Z	1.3	-0.6	0.4	0.2	1.1
MU20	S	1.7	-1.7	0.9	-2.3	0.9	ML7	S	-1.4	-3.8	0.1	1.5	-1
	Z	1.6	-1.5	1	-2.2	0.8		Z	-1.2	-3	0.2	1.5	-1
MU21	S	2.9	-0.5	0.5	4.1	1.5	ML8	S	1.1	-0.6	1.2	0	0.9
	Z	2.5	-0.4	0.1	3.2	1		Z	1.1	-0.6	1.3	-0.5	1
MU22	S	2.9	-0.7	2.1	1	1.2	ML9	S	1.1	-1.3	1.9	1.6	1.7
	Z	2.7	-0.7	1.9	1.1	1.1		Z	1.1	-1.1	1.7	1.6	1.6

Note: The terms in first row are abbreviations i.e. Win (Winter), Spr (Spring), Sum (Summer), Aut (Autumn) and Ann (Annual). The italic numbers represent the significant trends

understand the current and future trends of data series (Zhao et al. 2017). The Hurst index value of annual SPI for all sub

basins are presented in Fig. 3 and Fig. 4. It can be observed that for all stations the annual SPI Hurst index value is

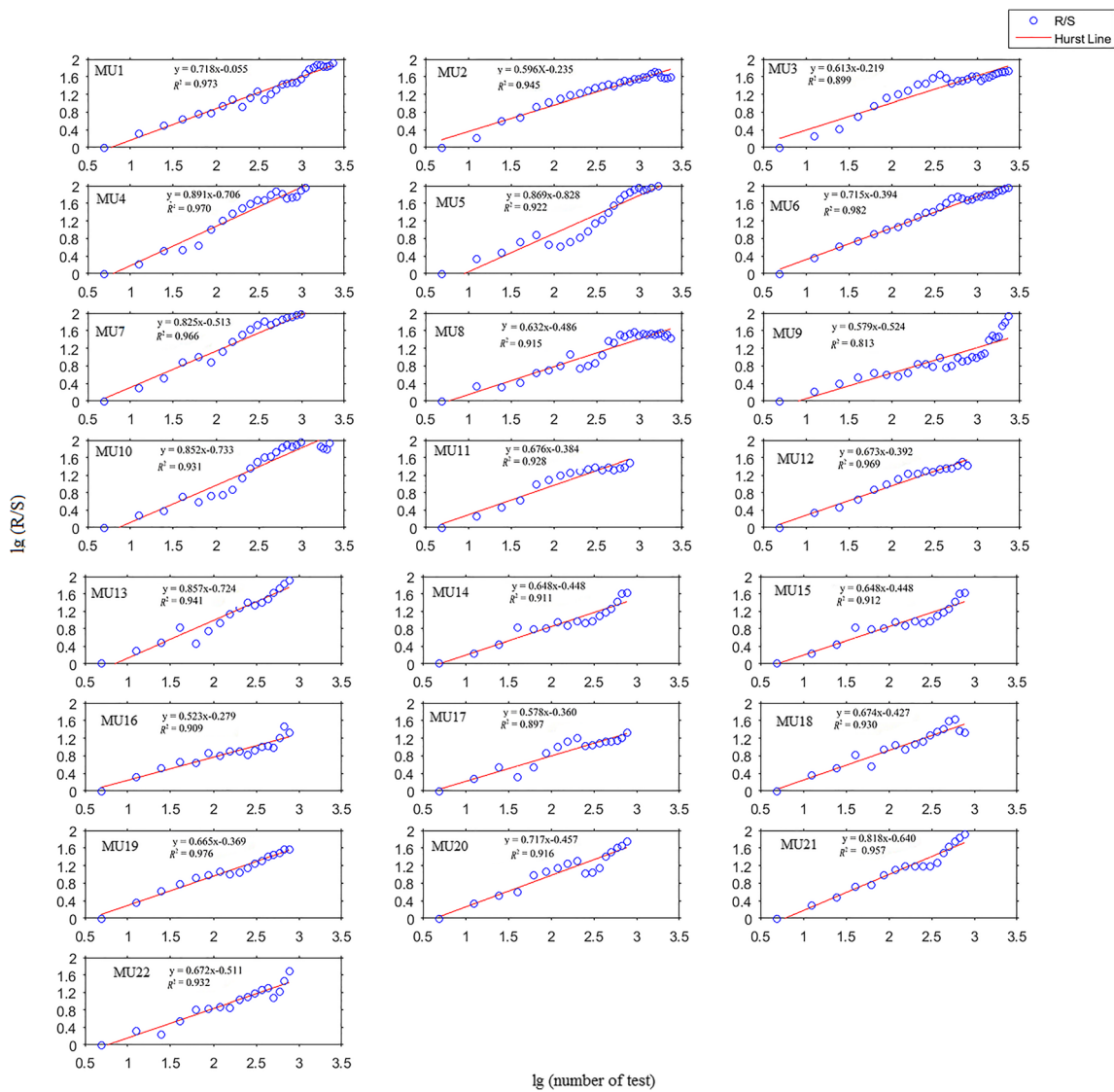


Fig. 3 Rescale range test for annual SPI of UIB. lg (number of test) and lg(R/S) represent the Log of number of test and rescale range respectively

between 0.5 to 1 which indicate that all the stations are expected to maintain current trends. The SPI-12 can be used to find the dry and wet conditions of the subsequent year. The drought frequencies of each sub-basin are presented in Fig. 5. The Fig. 5a and Fig. 5b represents the drought frequency in UIB during 1985–2015 and 1995–2013 respectively. During 1985–2015, the drought frequencies of MIB and LIB are presented in Fig. 5c and Fig. 5d respectively. The frequency of M1 station of MIB is not considered as it is the only station in MIB which have data from 1995 to 2013. Fig. 5 shows that the wet and dry year’s frequencies varied in each sub-basin and most of the years have normal frequencies. In all sub-basins, the normal frequencies year accounted for more than 60% at all stations and exceeded 56% at the majority of the stations. The dry and wet frequencies have been observed in concentrated periods, and persistent drought is dominant in recent years.

4 Conclusion

This study analyses the precipitation, temperature and streamflow trends of the Indus basin. The TFPW, SR, MK and LR, SPI, SMK, and rescaled range methods have been used to perform the analysis. The TFPW is used to remove the serial correlation in data series. The SR, MK and LR methods have been used to identify the trends in a hydro-climatic variable. The SPI method is used to calculate the drought intensity, and SMK is used to detect abrupt changes in SPI. The rescaled range method has been used to evaluate the long-term correlation of SPI.

The *P* of UIB presented the significant mixed (increasing/decreasing) trend in winter and spring and no significant trend has been observed on annual basis. The *P* of MIB has not presented any significant seasonal trend and significant negative trends have been observed on annual

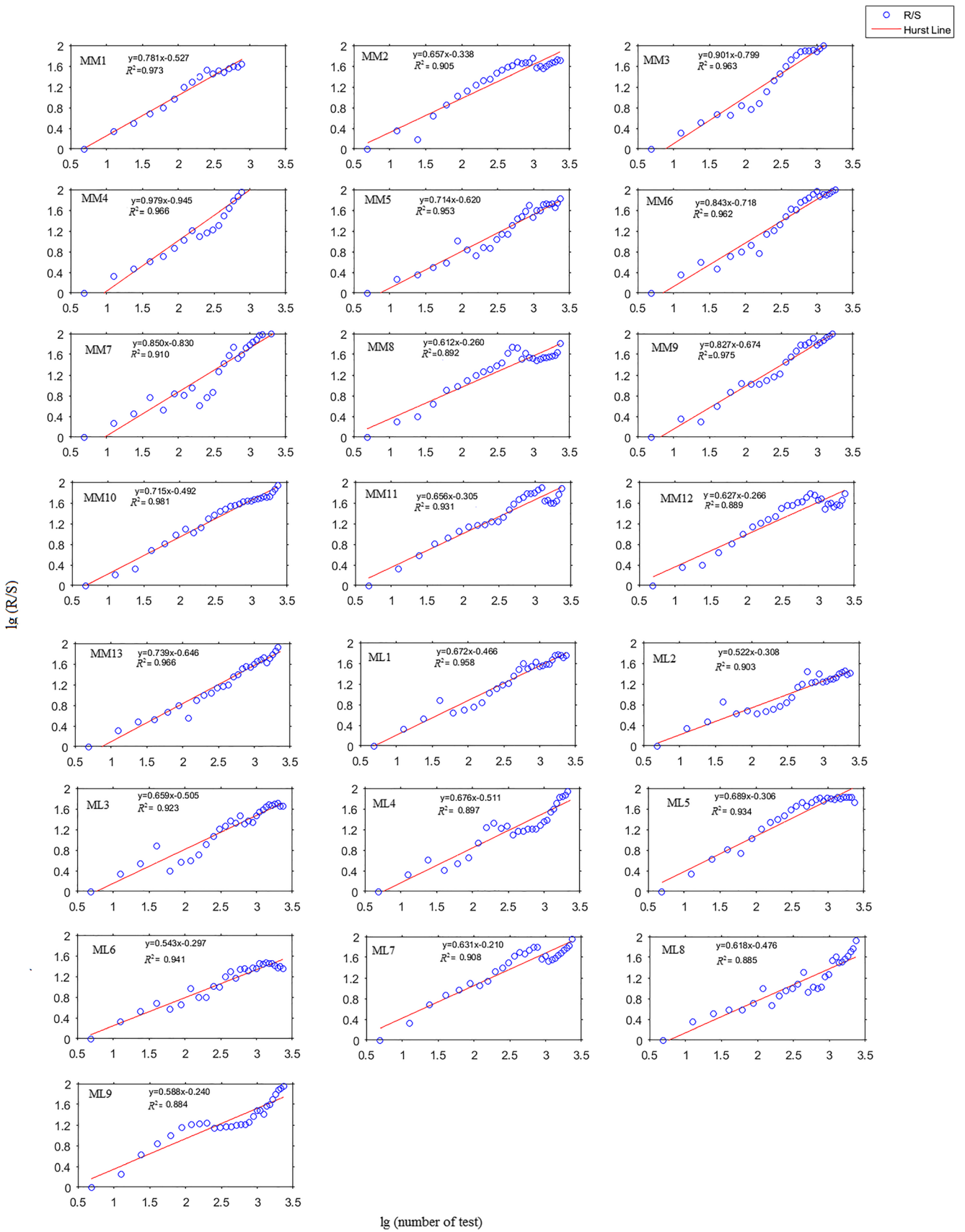


Fig. 4 Rescale range test for annual SPI of MIB and LIB. $\lg(\text{number of test})$ and $\lg(R/S)$ represent the Log of number of test and rescale range respectively

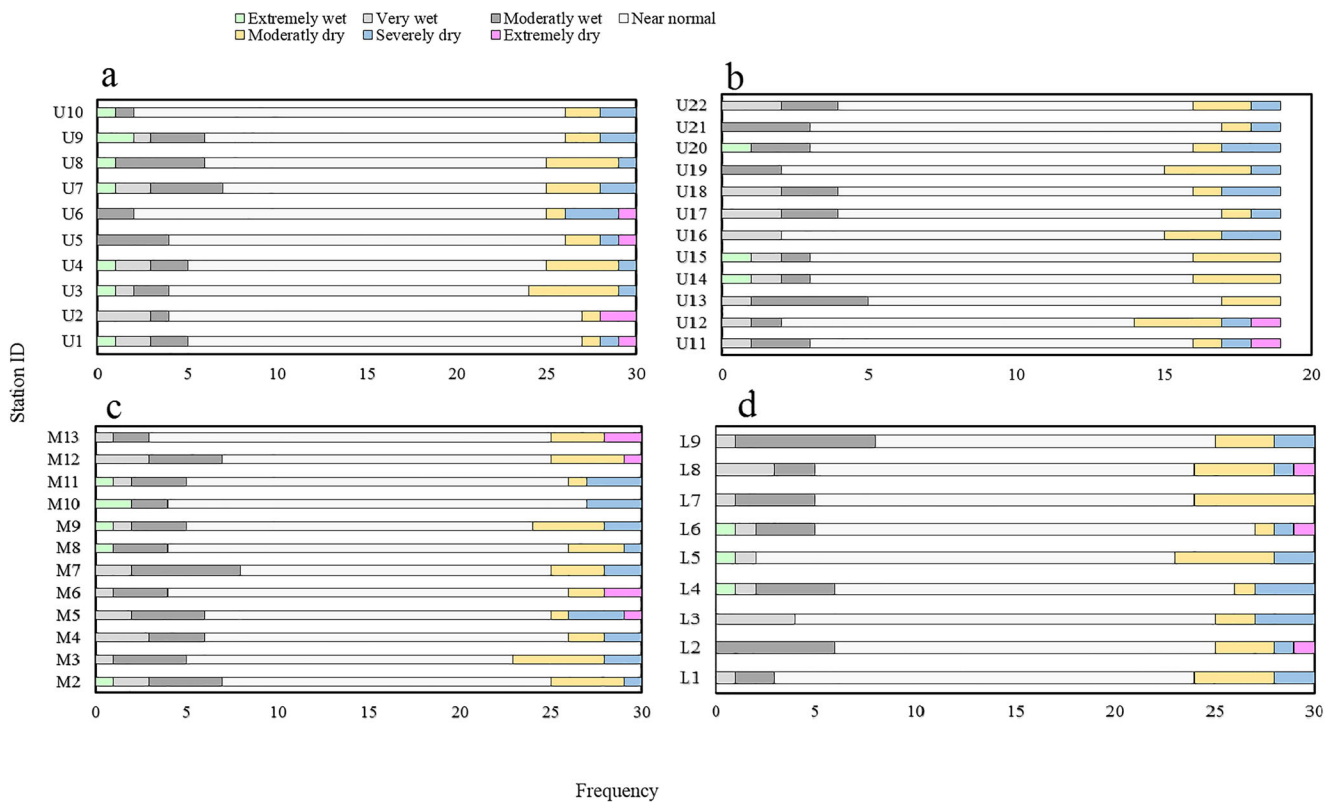


Fig. 5 Frequencies of dry and wet phenomena (a) in UIB during 1985–2015, (b) in UIB during 1995–2013. (c, d) in MIB and LIB during 1985–2015

basis. In LIB, positive trends have been observed on an annual basis and seasonal basis and autumn season presented the most significant trend. The sub-basins of Indus basin presented both cooling and warming trends on an annual and seasonal basis. However, the warming trends dominated. The streamflow of the Indus basin presented contrasting trends. In UIB increasing seasonal and annual trends have been observed, MIB presented increasing streamflow trends in the spring, and it presented decreasing trends in summer. The LIB showed decreasing streamflow trends at the annual basis, and the decreasing trend has been observed in spring and autumn. The increasing streamflow trends of UIB are possible due to significant warming and glacier melt. The streamflow decrease of MIB in summer may be due to increasing temperature trends which enhance potential evapotranspiration. The decrease in LIB is possibly due to water regulation for agriculture and power generation purpose. The Van Belle and Hughes test has been used to check the general homogeneity of the trends. This test confirmed that seasons are found to be homogeneous for precipitation of LIB and streamflow of MIB and LIB. The trends of other climatic variables have been found heterogeneous. It is not difficult to explain this because of the Indus basin span different climatic zones. Moreover, the altitudinal variation of precipitation and temperature are remarkable in UIB.

The SPI of the UIB exhibited increasing trends for winter and autumn seasons. Thus both show humid behavior. However, in MIB, SPI only showed increasing trends in the autumn season, and it decreased in other seasons and annual basis. Which means except autumn all seasons exhibited arid behavior in MIB. Similarly, the SPI of LIB exhibited increasing seasonal and annual trends that illustrate annual and seasonal humid behavior for LIB. The Hurst index value indicates that all sub-basins are expected to maintain current trends and the degree of drought is expected to increase in the future. The results of the trend analysis show a relationship between streamflow and climatic variables. The increase in streamflow of UIB may be due to warming trends and glacier melt. Similarly, a decrease in streamflow on MIB is possible due to a decrease in precipitation. The decrease of LIB streamflow is possible due to water regulation in upstream. These results may not explain the streamflow variability due to catchment properties. Moreover, it is still debatable whether these trends constitute a change in climate. Why stations presented trends in some seasons and not in others. Overall, it is concluded that this study provides a useful overview of annual and seasonal hydro climatic trends in the Indus basin.

Acknowledgments The authors would like to thank the Pakistan Meteorological Department (PMD), and the Water and Power Development Authority (WAPDA) of Pakistan for providing the Hydro-climatic data.

References

- Ahmad, W., Fatima, A., Awan, U.K., Anwar, A.: Analysis of long term meteorological trends in the middle and lower Indus Basin of Pakistan—A non-parametric statistical approach. *Global and Planetary Change*. **122**, 282–291 (2014)
- Ali G, Hasson S, Khan AM (2009) Climate change: implications and adaptation of water resources in Pakistan. GCISC-RR-13, global change impact studies Centre (GCISC), Islamabad, Pakistan
- Archer, D.R., Fowler, H.J.: Spatial and temporal variations in precipitation in the upper Indus Basin, global teleconnections and hydrological implications. *Hydrol. Earth Syst. Sci. Discuss.* **8**, 47–61 (2004)
- Azmat M, Wahab A, Huggel C, Qamar MU, Hussain E, Ahmad S, Waheed A (2019) Climatic and hydrological projections to changing climate under CORDEX-South Asia experiments over the Karakoram-Hindukush-Himalayan water towers science of the Total environment:135010
- Bartels, R.: The rank von neumann test as a test for autocorrelation in regression models. *Communications in Statistics-Theory and Methods*. **13**, 2495–2502 (1984)
- Bashir F, Zeng X, Gupta H, Hazenberg P (2017) A Hydrometeorological Perspective on the Karakoram Anomaly Using Unique Valley-Based Synoptic Weather Observations *Geophysical Research Letters* **44**
- Belle, G., Hughes, J.P.: Nonparametric tests for trend in water quality. *Water resources research*. **20**, 127–136 (1984)
- Bocchiola, D., Diolaiuti, G.: Recent (1980–2009) evidence of climate change in the upper Karakoram. *Pakistan Theoretical and applied climatology*. **113**, 611–641 (2013)
- Bonaccorso, B., Bordi, I., Cancelliere, A., Rossi, G., Sutera, A.: Spatial variability of drought: an analysis of the SPI in Sicily. *Water resources management*. **17**, 273–296 (2003)
- Buishand, T.A.: Some methods for testing the homogeneity of rainfall records. *J. Hydrol.* **58**, 11–27 (1982)
- Burn, D.H., Elnur, M.A.H.: Detection of hydrologic trends and variability. *Journal of hydrology*. **255**, 107–122 (2002)
- Caloiero, T., Coscarelli, R., Ferrari, E., Mancini, M.: Trend detection of annual and seasonal rainfall in Calabria (Southern Italy). *International Journal of Climatology*. **31**, 44–56 (2011)
- Cong, Z., Shahid, M., Zhang, D., Lei, H., Yang, D.: Attribution of runoff change in the alpine basin: a case study of the Heihe Upstream Basin, China. *Hydrological sciences journal*. **62**, 1013–1028 (2017)
- de Luis M, Čufar K, Saz MA, Longares LA, Ceglar A, Kajfež-Bogataj L (2014) trends in seasonal precipitation and temperature in Slovenia during 1951–2007 Reg. Environ. Chang. **14**:1801–1810 doi:<https://doi.org/10.1007/s10113-012-0365-7>
- del Rio, S., Anjum Iqbal, M., Cano-Ortiz, A., Herrero, L., Hassan, A., Penas, A.: Recent mean temperature trends in Pakistan and links with teleconnection patterns. *International Journal of Climatology*. **33**, 277–290 (2013)
- Eckstein D, Künzel V, Schäfer L (2017) *Global Climate Risk Index 2018* Bonn, Germany: Germanwatch
- Farr TG et al. (2007) The Shuttle Radar Topography Mission Reviews of Geophysics **45** doi:<https://doi.org/10.1029/2005RG000183>
- Faruqui N (1997) Final report to CIDA: snow and ice hydrology (Pakistan)
- Fathian, F., Morid, S., Kahya, E.: Identification of trends in hydrological and climatic variables in Urmia Lake basin, Iran. *Theoretical and Applied Climatology*. **119**, 443–464 (2015)
- Forsythe N, Archer DR, Pritchard D, Fowler H (2019) A Hydrological Perspective on Interpretation of Available Climate Projections for the Upper Indus Basin. In: *Indus River Basin*. Elsevier, pp 159–179
- Forsythe, N., Hardy, A., Fowler, H., Blenkinsop, S., Kilsby, C., Archer, D., Hashmi, M.: A detailed cloud fraction climatology of the Upper Indus Basin and its implications for near-surface air temperature. *Journal of Climate*. **28**, 3537–3556 (2015)
- Fowler, H.J., Archer, D.R.: Hydro-climatological variability in the Upper Indus Basin and implications for water resources. *Regional Hydrological Impacts of Climatic Change—Impact Assessment and Decision Making*. **295**, 131–138 (2005)
- Fowler, H.J., Archer, D.R.: Conflicting Signals of Climatic Change in the Upper Indus Basin. *Journal of Climate*. **19**, 4276–4293 (2006). <https://doi.org/10.1175/jcli3860.1>
- Gan, T.Y.: Hydroclimatic trends and possible climatic warming in the Canadian prairies. *Water Resour. Res.* **34**, 3009–3015 (1998)
- Gocic, M., Trajkovic, S.: Analysis of precipitation and drought data in Serbia over the period 1980–2010. *J. Hydrol.* **494**, 32–42 (2013)
- Han, W., Liang, C., Jiang, B., Ma, W., Zhang, Y.: Major natural disasters in China, 1985–2014: occurrence and damages. *International journal of environmental research and public health*. **13**, 1118 (2016)
- Hartmann, H., Buchanan, H.: Trends in extreme precipitation events in the Indus River Basin and flooding in Pakistan. *Atmosphere-Ocean*. **52**, 77–91 (2014)
- Hasson S, Böhner J, Lucarin V (2017) Prevailing climatic trends and runoff response from Hindukush–Karakoram–Himalaya, upper Indus Basin earth system Dynamics **8**
- He, Y., Ye, J., Yang, X.: Analysis of the spatio-temporal patterns of dry and wet conditions in the Huai River Basin using the standardized precipitation index. *Atmospheric Research*. **166**, 120–128 (2015)
- Helsel DR, Hirsch RM (1992) *Statistical Methods in Water Resources Vol 49*. Elsevier
- Hewitt, K.: Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus Basin. *Mountain Research and Development*. **31**, 188–200 (2011)
- Huihui, Z., Na, T., Qingfeng, Z.: Spatial heterogeneity of loess contour tilled microtopographic slope in rainfall erosion. *Soil Science and Plant Nutrition*. **62**, 409–415 (2016)
- Immerzeel WW, van Beek LPH, Bierkens MFP (2010) Climate Change Will Affect the Asian Water Towers Science **328**:1382–1385 doi:<https://doi.org/10.1126/science.1183188>, Climate change will affect the Asian water towers
- Jiang, R., Gan, T.Y., Xie, J., Wang, N., Kuo, C.-C.: Historical and potential changes of precipitation and temperature of Alberta subjected to climate change impact: 1900–2100. *Theoretical and applied climatology*. **127**, 725–739 (2017)
- Kahya, E., Kalaycı, S.: Trend analysis of streamflow in Turkey. *Journal of Hydrology*. **289**, 128–144 (2004)
- Kang, H.M., Yusof, F.: Homogeneity tests on daily rainfall series. *Int J Contemp Math Sciences*. **7**, 9–22 (2012)
- Karmeshu N (2012) Trend detection in annual temperature & precipitation using the Mann Kendall test—a case study to assess climate change on select states in the northeastern United States
- Khan A (2015) Hydrological modelling and their biases: constraints in policy making and sustainable water resources development under changing climate in the Hindukush-Karakoram-Himalayas brief for GSDR
- Khan A, Richards KS, Parker GT, McRobie A, Booij MJ Impact of Warming Climate on the Monsoon and Water Resources of a Western Himalayan Watershed in the Upper Indus Basin. In: *EGU General Assembly Conference Abstracts*, 2015a
- Khan A et al. Spatial and Altitudinal Variation of Precipitation and the Correction of Gridded Precipitation Datasets for the Upper Indus Basin and the Hindukush-Karakoram-Himalaya. In: *EGU General Assembly Conference Abstracts*, 2015b
- Khan, M., Daityari, S., Chakrapani, G.: Factors responsible for temporal and spatial variations in water and sediment discharge in Ramganga River, Ganga Basin. *India Environmental Earth Sciences*. **75**, 283 (2016a)
- Khan, M.Y.A., Gani, K.M., Chakrapani, G.J.: Assessment of surface water quality and its spatial variation. A case study of Ramganga

- River, Ganga Basin, India. *Arabian Journal of Geosciences*. **9**, 28 (2016b)
- Khattak, M.S., Babel, M., Sharif, M.: Hydro-meteorological trends in the upper Indus River basin in Pakistan. *Climate research*. **46**, 103–119 (2011)
- Laghari, A., Vanham, D., Rauch, W.: The Indus basin in the framework of current and future water resources management. *Hydrology and Earth System Sciences*. **16**, 1063 (2012)
- Langat, P.K., Kumar, L., Koech, R.: Temporal variability and trends of rainfall and Streamflow in Tana River basin, Kenya. *Sustainability*. **9**, 1963 (2017)
- Latif, Y., Yaoming, M., Yaseen, M.: Spatial analysis of precipitation time series over the Upper Indus Basin. *Theoretical and applied climatology*. **131**, 761–775 (2018)
- Lu, H., Bryant, R.B., Buda, A.R., Collick, A.S., Folmar, G.J., Kleinman, P.J.: Long-term trends in climate and hydrology in an agricultural, headwater watershed of Central Pennsylvania, USA. *Journal of Hydrology: Regional Studies*. **4**, 713–731 (2015)
- Mahmood, R., Jia, S.: Spatial and temporal hydro-climatic trends in the transboundary Jhelum River basin. *Journal of Water and Climate Change*. **8**, 423–440 (2017)
- Mahmood, R., Jia, S., Babel, M.: Potential impacts of climate change on water resources in the Kunhar River basin, Pakistan. *Water*. **8**, 23 (2016)
- McKee TB, Doesken NJ, Kleist J The relationship of drought frequency and duration to time scales. In: *Proceedings of the 8th Conference on Applied Climatology*, 1993, vol 22. American Meteorological Society Boston, MA, pp 179–183
- Melillo JM (2014) *Climate Change Impacts in the United States: the Third National Climate Assessment*. Government Printing Office
- Mukhopadhyay B, Khan A, Gautam R (2015) Rising and falling river flows: contrasting signals of climate change and glacier mass balance from the eastern and western Karakoram *Hydrological Sciences Journal* 60
- Negi SS (1991) *Himalayan Rivers, Lakes, and Glaciers*. Indus Publishing Nepal, S., Shrestha, A.B.: Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature. *International Journal of Water Resources Development*. **31**, 201–218 (2015)
- Ouyang, Y., Parajuli, P.B., Li, Y., Leininger, T.D., Feng, G.: Identify temporal trend of air temperature and its impact on forest stream flow in Lower Mississippi River Alluvial Valley using wavelet analysis. *Journal of environmental management*. **198**, 21–31 (2017)
- Oyerinde, G.T., Hountondji, F.C., Wissler, D., Diekkrüger, B., Lawin, A.E., Odofin, A.J., Afouda, A.: Hydro-climatic changes in the Niger basin and consistency of local perceptions. *Regional environmental change*. **15**, 1627–1637 (2015)
- Pettitt A (1979) A non-parametric approach to the change-point problem *Applied statistics*:126–135
- Porter JR et al. (2014) Food security and food production systems
- Qin, Y., Smith, B., Lei, Q.: Test for homogeneity in normal mixtures with unknown means and variances. *Journal of Statistical Planning and Inference*. **139**, 4165–4178 (2009)
- Ragetti, S., Immerzeel, W.W., Pellicciotti, F.: Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proceedings of the National Academy of Sciences*. **113**, 9222–9227 (2016). <https://doi.org/10.1073/pnas.1606526113>
- Safi Ullah, Qinglong You, Waheed Ullah, Amjad Ali (2018) Observed changes in precipitation in China-Pakistan economic corridor during 1980–2016 *Atmos. Res*. 210
- Salomao, L., Campanha, J., Gupta, H.: Rescaled range analysis of pluviometric records in Sao Paulo state Brazil. *Theoretical and Applied Climatology*. **95**, 83–89 (2009)
- Seyam, M., Othman, F.: Long-term variation analysis of a tropical river's annual streamflow regime over a 50-year period. *Theoretical and applied climatology*. **121**, 71–85 (2015)
- Shahid M, Cong Z, Zhang D (2017) Understanding the impacts of climate change and human activities on streamflow: a case study of the Soan River basin, Pakistan *Theoretical and Applied Climatology*:1–15
- Shahid S, Wang X-J, Harun SB, Shamsudin SB, Ismail T, Minhans A (2016) Climate variability and changes in the major cities of Bangladesh: observations, possible impacts and adaptation *Regional Environmental Change* 16
- Sheikh M, Manzoor N, Adnan M, Ashraf J, Khan A (2009) Climate profile and past climate changes in Pakistan, GCISC-RR-01
- Shrestha AB, Wagle N, Rajbhandari R (2019) A Review on the Projected Changes in Climate over the Indus Basin. In: *Indus River Basin*. Elsevier, pp 145–158
- Soncini, A., et al.: Future hydrological regimes in the upper Indus Basin: a case study from a high-altitude Glacierized catchment. *Journal of hydrometeorology*. **16**, 306–326 (2015). <https://doi.org/10.1175/jhm-d-14-0043.1>
- Stocker T et al. (2013) IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, 1535 pp. Cambridge Univ. press, Cambridge, UK, and New York,
- Svoboda M, Hayes M, Wood D (2012) *Standardized precipitation index user guide* World Meteorological Organization Geneva, Switzerland
- Tehrani EN, Sahoo H, Booi M (2018) Trend analysis of hydro-climatic variables in the north of Iran *Theoretical and Applied Climatology*: 1–13
- Vousoughi, F.D., Dinpashoh, Y., Aalami, M.T., Jhajharia, D.: Trend analysis of groundwater using non-parametric methods (case study: Ardabil plain). *Stochastic Environ. Res. Risk Assess*. **27**(2), 547–559 (2013)
- Wolf AT, Natharius JA, Danielson JJ, Ward BS, Pender JK (1999) International river basins of the world *International Journal of Water Resources Development* 15:387–427
- Yang, Z., Yan, Y., Liu, Q.: The relationship of streamflow-precipitation-temperature in the Yellow River Basin of China during 1961–2000. *Procedia Environ. Sci*. **13**, 2336–2345 (2012)
- Yue, S., Pilon, P., Phinney, B., Cavadias, G.: The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological processes*. **16**, 1807–1829 (2002)
- Zeleňáková M, Vido J, Portela MM, Purez P, Blišťán P, Hlavatá H, Hlušík P (2017) Precipitation trends over Slovakia in the period 1981–2013 *water* 9:922
- Zhao X, Li Z, Zhu Q (2017) Change of precipitation characteristics in the water-wind erosion crisscross region on the loess plateau, China, from 1958 to 2015 *scientific reports* 7:8048

