



Precipitation variability and its trend detection for monitoring of drought hazard in northern mountainous region of Pakistan

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Received: 17 July 2019 / Accepted: 9 July 2020 / Published online: 18 July 2020
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Abstract

The Standardized Precipitation Index (SPI) is a powerful tool, requiring only precipitation data for calculating the intensity, duration, magnitude, severity and frequency of drought. Moreover, it provides helpful coverage of drought impacts on multi time scales. In this study, the SPI technique was applied to the dataset of 30 years (1986–2015) to detect drought condition in Northern Pakistan, which is a frequent drought-hit area. The coefficient of variability (CV) was used to analyze precipitation trend, while linear regression model was adopted to detect trend. The detected precipitation variability was spatially interpolated by applying the Inverse Distance Weighted (IDW) technique. It is evident from the analysis that there is great variability in precipitation pattern and trend in the study area. During the winter season, a positive trend in the precipitation variability was detected in the Himalaya and Karakorum region. In the Hindukush region, only Pattan weather station has observed a positive variability trend. In contrast to winter variability, pre-monsoon season has observed an increased variability in the Hindukush region, while the Karakorum and Himalayas regions observed a negative trend. The monsoon season has observed a decreased variation in precipitation throughout the study area except for Pattan. In post-monsoon, Skardu weather station of Himalayas, Gupis and Bunji of Karakorum region and Pattan of Hindukush region have witnessed increased precipitation variability. The meteorological stations of Karakoram and Himalaya have noticed a negative trend of precipitation variability, while in the Hindukush region, all the meteorological stations have witnessed a positive trend of variability except Saidu Sharif and Dir stations. The results of SPI also indicated a drought condition in the study area. Similarly, the SPI results of all return periods have shown a significant drought condition in the Himalayas followed by—in terms of frequency and magnitude—Karakoram and Hindukush, respectively. Based on the above findings, it is recommended that the agriculture experts should work on drought-resilient crops in order to cope up with the harsh prevalent climatic condition in Northern Pakistan.

Keywords SPI · Linear regression method · Drought hazard · MRP · Pakistan

Responsible Editor: Zhihua Zhang

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Introduction

Precipitation is the quantity of water deposited on earth in the form of hails, sleet, rain, mist or snow (Driscoll et al. 2003). It is a key indicator of climate and has been widely used in assessing the trend and variability of hydro-meteorological phenomena (DasGupta and Shaw 2015; Khan and Iqbal 2012). Deviation in the amount of precipitation, that is naturally prevalent in a specific geography, is referred to precipitation variability. These deviations occur both over space and time, which lead to hydro-metrological hazards across the globe (Naheed and Rasul 2011). An excessive amount of precipitation causes flooding (Yabi and Afouda 2012), while the reduced amount of precipitation may cause scarcity of water, which ultimately leads to drought (Seager et al. 2009). Over the past few decades, a changing shift in precipitation has been

observed in different regions of the world (Trenberth 2011). In recent years, the Asian continent has witnessed high spatio-temporal variability in precipitation (Ahmad et al. 2016; Cheema et al. 2011; Kumar et al. 2010). According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), there will be high spatio-temporal variability in precipitation due to climate change, which would intensify the frequency and intensity of hydro-meteorological hazards in major parts of the world. Drought being a potential hydro-meteorological hazard has a catastrophic impact on the ecosystem. Long periods of drought have a certain effect on health (Al-Hemoud et al. 2018);, dust emissions (Al-Dousari et al. 2016), albedo (El-Wahab et al. 2018), native plants, depositional fluxes of radionuclides (Aba et al. 2018), sediment supply to the marine environment (Al-Dousari et al. 2009) and economy (Al-Sudairawi and Misak 1999; Al-Dousari and Pye 2005). Long periods of drought can also have a negative effect on solar energy production (Al-Dousari et al. 2019). Therefore, monitoring precipitation and implementation of efficient control measures is an essential step towards the limitation of drought consequences (Ahmed and Al-Dousari 2013).

Over the past 3 decades, the frequency and magnitude of catastrophic floods increased due to the impacts of climate change (Khan et al. 2010). The sharp variations in precipitation may lead to hydro-metrological hazards such as riverine floods, flash floods and droughts (Gu et al. 2019; Higashino and Stefan 2019). Among these, drought is one of the complex hazards, which occurs due to a reduction in precipitation received over a prolonged timespan (Wilhite 2000). Scientifically, drought is defined as a severe water-shortage condition that arises from low or no precipitation, leaving great damages to infrastructure, socio-economic stability and environment (Chopra 2006). Drought condition is associated with a reduction in water availability from its normalcy over a long time span. The long-term changes in the primary period of occurrence, postponements or delay in the rainy season, rainfall intensity and the number of rainfall events may lead to a dry period (Wilhite 2003). Drought is a slow-onset hazard and is considered a creeping hazard; because its rising process takes long time ranging from months to years and event decades (Tsakiris et al. 2016). The severity of drought differs by the precipitation shortfall, temporal extent and length making it hard and tough to relate, associate and compare one drought to another. Moreover, the intensity of drought can be categorized based on the socio-economic, environmental and human impacts in a region (Peters et al. 2002). Being a natural and potential phenomenon, the analysis of precipitation variability and precipitation deficit, drought has always been a challenging task for the scientific community. Moreover, being a creeping and slow-onset phenomenon, drought hazard often failed to attract the attention of global scientists in the past (Keshavarz et al. 2013). So far, several attempts have been

made to study precipitation variability and monitor drought behaviours over different regions of the world (Abdulrazzaq et al. 2019; Ahmed et al. 2019b; Xie et al. 2013; Cheema et al. 2011; Han et al. 2010; Cancelliere et al. 2007; Rashid 2004; Wilhite 2000).

Precipitation-deficit drought poses potential risks to human's socio-economic setup, environment and natural ecosystem (Adnan et al. 2009). Each year, drought accounts for 22% of the global financial damage and 33% of the people affected by natural disasters (Keshavarz et al. 2013). Pakistan is one of the highly vulnerable countries to drought hazard due to sharp variability of precipitation. The country receives more than 90% of the total precipitation in two main seasons, i.e. monsoon and westerlies seasons (Naheed et al. 2013). However, the related studies stated that global warming-induced climate change has intensified the variability of precipitation over Pakistan both in the monsoon and westerlies season. Due to dynamic fluctuations, most parts of the country experience sustained dry or drought conditions (Naheed et al. 2013). Over the last few decades, the country has faced severe dry spell, which resulted in substantial human and socio-economic losses (Rasul and Chaudhry 2006). The drought event of 1998–2002 was considered the most prolonged and devastating drought disaster in the history of Pakistan (Ahmad et al. 2004). Recently, it has been reported that climate change will disturb the variability of precipitation both over space and time, which may exacerbate the intensity and frequency of drought hazard in Pakistan (Naheed et al. 2013). Moreover, the spatiotemporal changes in precipitation will lead to scarcity of freshwater in the region, which will affect a large proportion of the population. Reduced precipitation also leads to uneven exploitation of groundwater resources for irrigation (Abudu et al. 2018). Therefore, a comprehensive and systematic approach is needed to assess the precipitation variability, its trends and behaviours of precipitation-deficit drought in the country.

Study area

Geographically study area stretches from 71° 11' to 77° 41' east longitude and from 34° 30' to 37° 5' north latitude. Administratively, northern mountainous region of Pakistan roughly consists of Malakand, Dir Upper and Dir Lower, Swat, Shangla, Chitral, Kohistan, Gilgit, Hunza, Skardu, Astore and Bunji. It shares borders with Azad Kashmir to the south-east, Mardan to the south, Wakhan corridor of Afghanistan to the northwest, the Xinjiang region of China to the east and northeast and Afghanistan to the west (Fig. 1). The region is crossed by three gigantic mountain ranges of the world, i.e. Hindukush, Himalayas and Karakoram. Northern Pakistan is home to 5 peaks having height more than 8000 m and more than fifty peaks above

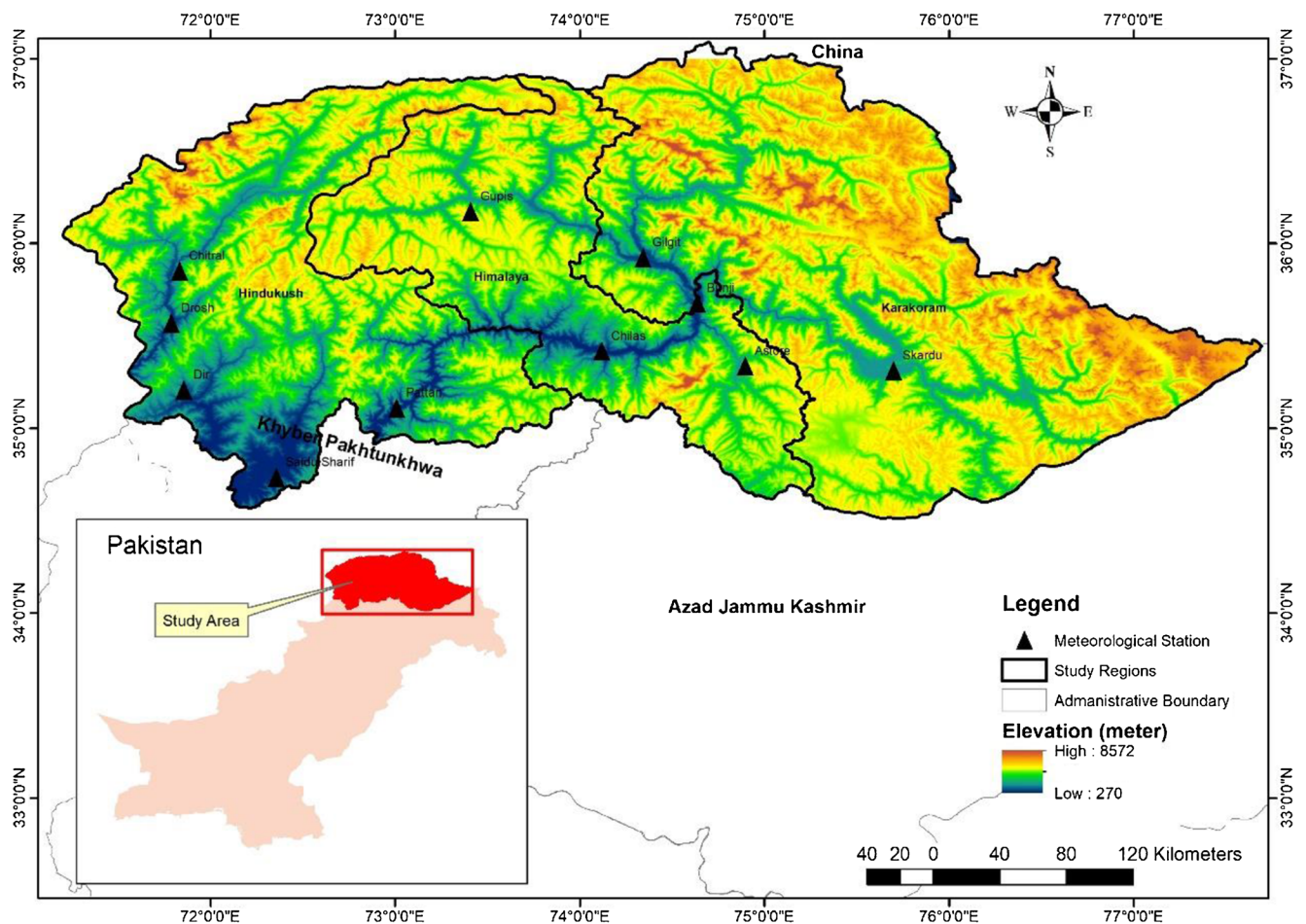


Fig. 1 Location map of the study area

7000 m. Four of the world's longest glaciers outside the Polar Regions are found in the study area, i.e. the Siachen Glacier, Biafo Glaciers, the Baltoro Glacier, the Batura Glacier and many more.

The 76 km Siachen Glacier is the longest valley glacier of the world located in the eastern Karakoram. Baltoro Glacier (63 km long) can be approached via Balti town of the Skardu, runs through part of Karakoram ranges. Shiger River, a tributary to the Indus River, originates from the Baltoro Glacier. Baltoro Glacier is fed by several tributaries from K-2, Gasherbrum and Abruzzi glaciers. The Hindukush is a standout among the most conspicuous mountain frameworks, situated in the outrageous west of Karakoram and Himalayas having a length of right around 700 km. It spreads more than two circumscribing nations; the eastern part lies in Pakistan and the rest in Afghanistan. In the Hindukush area, Pamir Bunch fills in as an intersection purpose of the Hindukush, Himalaya and Karakoram (HHK) situated in Chitral, where outskirts of Pakistan, Afghanistan and China meet. The HHK Mountains

remain snow-covered throughout the year and receive ample amount of precipitation in the form of snow during winter. Himalaya is the highest mountain ranges in the world. The western part of Himalaya is located in Pakistan, which crosses the line of control into Pakistan and reaches their western end. The highest peak of this mountain range is Nanga Parbat with 8126 m highest above sea level. These mountains are natural borders for Pakistan.

The northern mountainous region of Pakistan has micro-climatic zones due to its topology and altitude (Hussain and Lee 2009). The region has a typical highland climate, where the altitude is the main determinant of climate. The southern faces of Himalayas have a moist climate, while climate dries considerably towards Karakoram and Hindu Kush. There are towns like Gilgit, Chillas, Malakand and Lower Dir, and parts of Swat and Kohistan, which are quite warm during the summer days and cold at summer nights, i.e. Astore, Khaplu, Yasin, Deosai, Hunza, Nagar, Shangla and Lawari, where the temperatures are low even in the summer.

Materials and methods

Data

In order to achieve targeted objectives of the study, precipitation data were selected as a meteorological parameter for detecting variation and drought risk assessment. We have used a total of eleven meteorological stations. Data of all the meteorological stations in the study area were collected from the Pakistan Metrological Department for the period of 1985–2015 (Fig. 2).

Data analysis techniques

The coefficient of variability (CV) statistic was applied to assess precipitation variability in the subject area, while linear regression model was used to know the precipitation trend. Similarly, the minimum and maximum confidence intervals were calculated at 99% confidence, whereas the World Meteorological Organization's standard index SPI (Svoboda, Hayes, & Wood, 2012) was used for the drought risk assessment. This index is best applicable on such diversified topography as of the northern mountainous region of Pakistan. The

detected precipitation variability was spatially interpolated by applying the Inverse Distance Weighted (IDW) technique (Gemmer et al. 2004). These statistical techniques are discussed in detail in the following sections.

Rainfall variability assessment

The CV technique was used to analyze precipitation variability. The analysis was done the following formula (Naheed et al. 2013):

$$CV = \left(\frac{SD_i}{R_i} \right) \times 100 \quad (1)$$

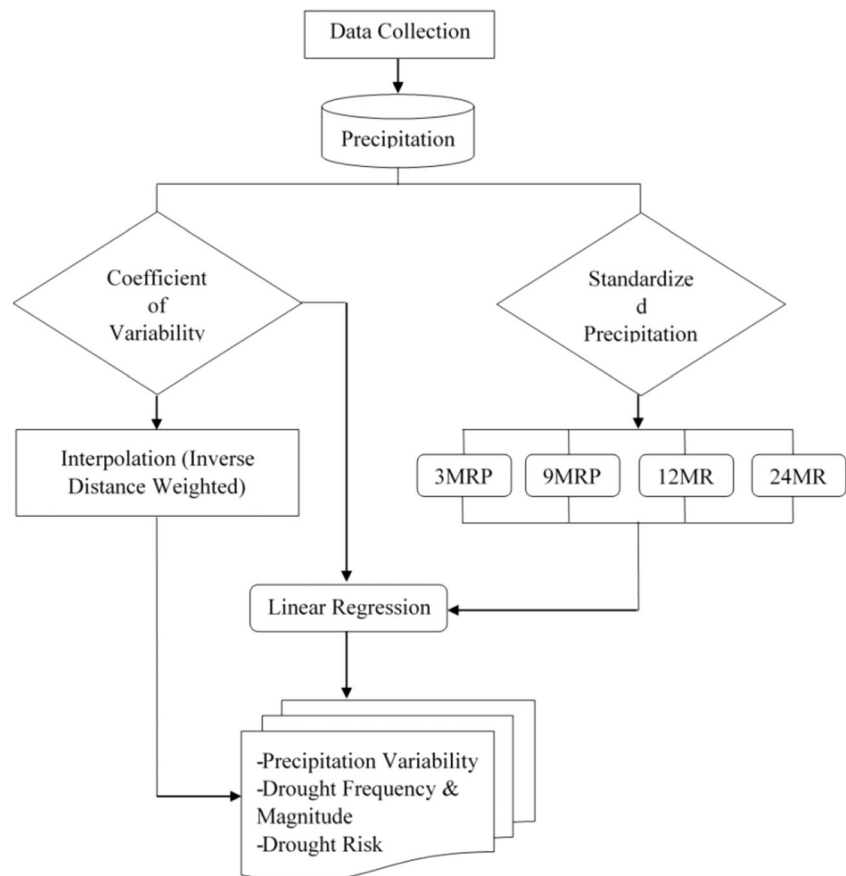
where

SD , monthly standard deviation, R is monthly rainfall average, i is the sub-index (ranging from 1 to 12), the particular month of the year.

Precipitation variability assessment was carried out as per the following procedures/steps

1. Interannual variability in precipitation
2. Seasonal and annual precipitation variability

Fig. 2 Flowchart of methodology



Standardized Precipitation Index

The SPI was developed by McKee, Deosken and Kleist (1993) at Colorado State University in 1993. The SPI can be used to monitor drought conditions on a variety of time scales. These time scales reflect the influence of drought on the availability of diverse water resources. Soil moisture conditions respond to precipitation anomalies at a relatively short scale. The groundwater, stream-flow and reservoir storage reflect the longer term precipitation anomalies. For these reasons, McKee et al. (1993) originally calculated the SPI for 3-, 6-, 12-, 24- and 48-month time scales. The SPI calculation for any location is based on the long-term precipitation record for a desired period. The positive SPI values indicate greater than median precipitation and negative values indicate less than the median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. McKee et al. (1993) used the classification system shown in the SPI values table to define drought intensities resulting from the SPI.

For the data analysis, the following techniques were applied McKee et al.(1993):

$$SPI = \frac{X - \bar{x}}{\sigma} \tag{2}$$

where X is the monthly rainfall, \bar{x} is mean of monthly rainfall data and σ represents standard deviation. SPI was calculated by using SPI_SLX6 calculator. Different stages of drought or wetter season based on SPI can be seen from Table 1.

Results and discussion

Seasonal and overall variability

The results indicate that in Gilgit of Karakoram region, the winter, pre-monsoon, monsoon, post-monsoon and annual has 136%, 90%, 140%, 214% and 129% of variability from 1986 to 2015, respectively. Similarly, Skardu in winter, pre-monsoon,

monsoon, post-monsoon and annual has 133%, 138%, 153%, 185% and 149% of variability from 1993 to 2015, respectively (Fig. 3a). The results indicate that there are more dynamic fluctuations for different seasons of the year.

In Himalayan region, Astore, it can be observed that precipitation coefficient of variability in winter was 87% that declined to 73% in pre-monsoon, and then the percentage of variability gradually increases in monsoon, post-monsoon and annual to 89%, 145% and 94%, respectively. Parallel to Astore, Bunji experienced the same phenomena with a changed percentage of variability as in winter, pre-monsoon, monsoon, post-monsoon and annual has 135%, 93%, 111%, 266% and 140% of variability respectively between 1985 and 2015. Chillas witnessed 121% of the variability in winter that declined to 103% in pre-monsoon while in monsoon, post-monsoon and annual variability has followed an increasing trend reaching 125%, 282% and 145%, respectively. In contrast to the rest of stations in the Himalayas, Gupis in winter has witnessed 146% of variability, which decreased to 133% in pre-monsoon and further declined to 115% in monsoon while it bounced back in post-monsoon and annual noticing 189% and 142%, respectively (Fig. 3b).

In Hindukush, for Dir, winter, pre-monsoon, monsoon, post-monsoon and annual has 81%, 54%, 57%, 109% and 73.18% of variability, respectively. Drosh in winter, pre-monsoon, monsoon, post-monsoon and annual has 87%, 65%, 94%, 105% and 86% of variability respectively from 1985 to 2015 period. Saidu Sharif in winter, pre-monsoon, monsoon, post-monsoon and annual has 90%, 86%, 60%, 93% and 82% of variability from 1985 to 2015, respectively. Pattan in winter, pre-monsoon, monsoon, post-monsoon and annual has 77%, 55%, 74%, 90% and 71% of variability from 2005 to 2015, respectively. Chitral in winter, pre-monsoon, monsoon, post-monsoon and annual has 89%, 81%, 146%, 137% and 109% of variability from 1985 to 2015, respectively (Fig. 3c).

In the northern mountainous region of Pakistan, winter variability is lowest in the Hindukush region followed by the Karakoram and highest variation recorded in the Himalayas. Pre-monsoonal lowest variation recorded in Hindukush followed by Himalayas and highest in the Karakorum. Monsoonal precipitation variability is lowest in Hindukush as compared with the Karakorum and Himalayas, except Chitral meteorological station. The Himalayas has observed the highest post-monsoonal precipitation variability followed by lowest in Hindukush while annual variation in precipitation was highest in the Karakorum and lowest in Hindukush.

Spatial distribution of seasonal precipitation and its variability

In Himalayas and Karakoram throughout the study period, low precipitation has been recorded as compared

Table 1 Drought levels according to SPI values

S. No.	Value	Condition
1	2.00 and above	Extremely wet
2	1.50 to 1.99	Very wet
3	1.00 to 1.49	Moderately wet
4	- 0.99 to 0.99	Near normal
5	- 1.00 to - 1.49	Moderate drought
6	- 1.50 to - 1.99	Severe drought
7	- 2.00 and less	Extreme drought

Source: McKee et al. (1993)

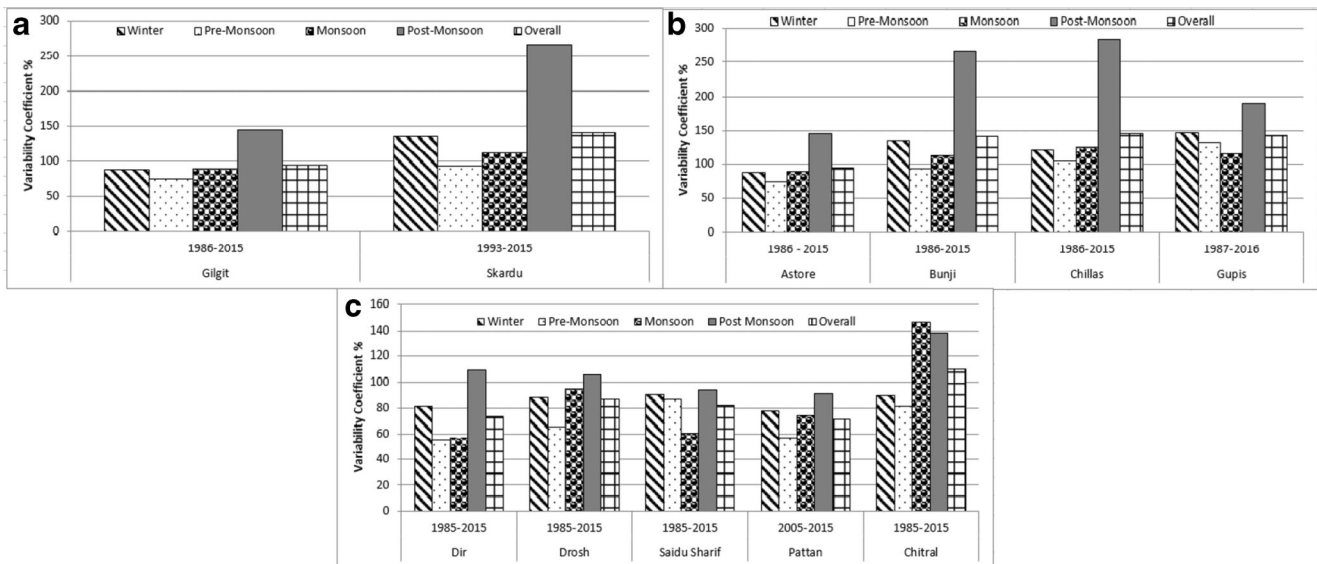


Fig. 3 Seasonal and overall variability. **a** Karakoram. **b** Himalayas. **c** Hindukush

with Hindukush region. In the study area, highest average precipitation of 610.76 mm was recorded in winter (Fig. 4a) in the Hindukush region while the lowest precipitation of 8.24 mm was recorded in post-monsoon (Fig. 4d) in Himalaya and Karakorum. In winter, except Skardu and Bunji weather stations, there detected a positive trend in the precipitation variability in Himalaya and Karakorum while in Hindukush only Pattan, meteorological station has observed a positive variability trend. In contrast to winter variability, pre-monsoon season has witnessed an increased variability in Hindukush while Karakorum and Himalayas observed a negative trend in variability (Fig. 4b). Monsoon has observed a decreased variation in precipitation variability throughout the study area except for Pattan (Fig. 4d). In post-monsoon, Skardu of Himalayas, Gupis and Bunji of Karakorum and Pattan of Hindukush have observed an increased precipitation variability which is a sign of drought in Himalaya and Karakorum and flood Pattan.

Highest average annual precipitation recorded in Hindukush was 1410 mm in Dir and lowest average annual precipitation of 480.8 mm was recorded in Chitral weather station. In the Himalayas, the highest average annual precipitation of 489.5 mm in Astore and lowest precipitation of 168.61 mm was recorded in Bunji. In Karakoram, 188.02 mm average annual precipitation was recorded in Skardu meteorological station followed by lowest precipitation of 144.9 mm in Gilgit. Weather stations of Karakoram and Himalayas have observed negative trend of precipitation variability while in Hindukush except for Saidu Sharif and Dir, rest of the meteorological stations, Chitral, Drosh and Pattan have witnessed a positive trend of variability (Fig. 5).

3-month return period

Return period of drought is the probability of occurrence of drought or the average inter-arrival time between the recurrent drought events (Ahmed et al. 2019a; Nabaei et al. 2019). Usually, it indicates the estimated time interval between drought events of a similar intensity. It is an essential to define the frequency and intensity of drought events in a particular time period (Burgess et al. 2015; Taghavi 2010). It is believed that the estimation of return period for drought hazard is extremely critical in water scarce regions, where accurate and detail knowledge is required for water resources planning and management (Adnan et al. 2018; Nabaei et al. 2019). Moreover, the estimation of return periods for drought events can provide useful information for the improvement of water systems management under dry condition (Ahmed et al. 2018). In the present study, we estimated the return periods of drought by monthly time scale.

Karakorum

In the 3MRP Karakoram, both the stations have witnessed positive drought trend. Gilgit from 1987 to 1993 has gone through a dry climatic condition in 24 months. The condition continues to be dry from 1995 to 1998 in 12 months while from 2000 to 2005, 12 months witnessed in dry climatic condition. Similarly, from 2007 to 2010, 8 months and in 2013–2014, 5 months remain dry. Parallel to Gilgit, in Skardu from 1991 to 1995 and 2000–2003, there were dry spells of 11, 11 months, respectively (Fig. 6). Gilgit, throughout the study duration, has suffered from 41 months of moderate, 15 severe and 5 months of extreme drought, while Skardu has witnessed a total of 26 months of moderate drought, 19 months of severe drought and 6 months of extreme drought (Table 2).

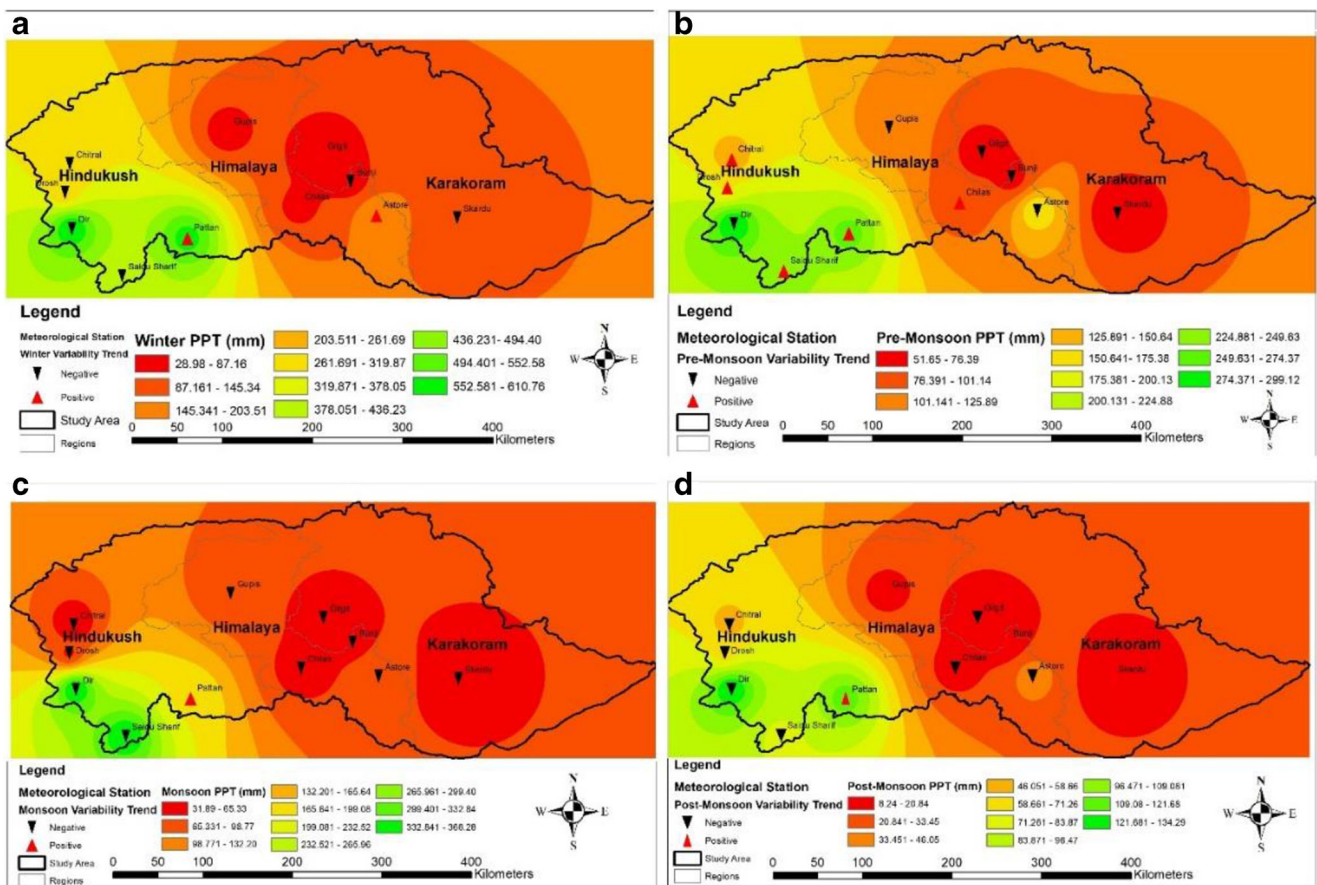


Fig. 4 Spatial distribution of seasonal precipitation and its variability trend (1985–2016) in the study area. a Winter. b Pre-monsoon. c Monsoon. d Post-monsoon

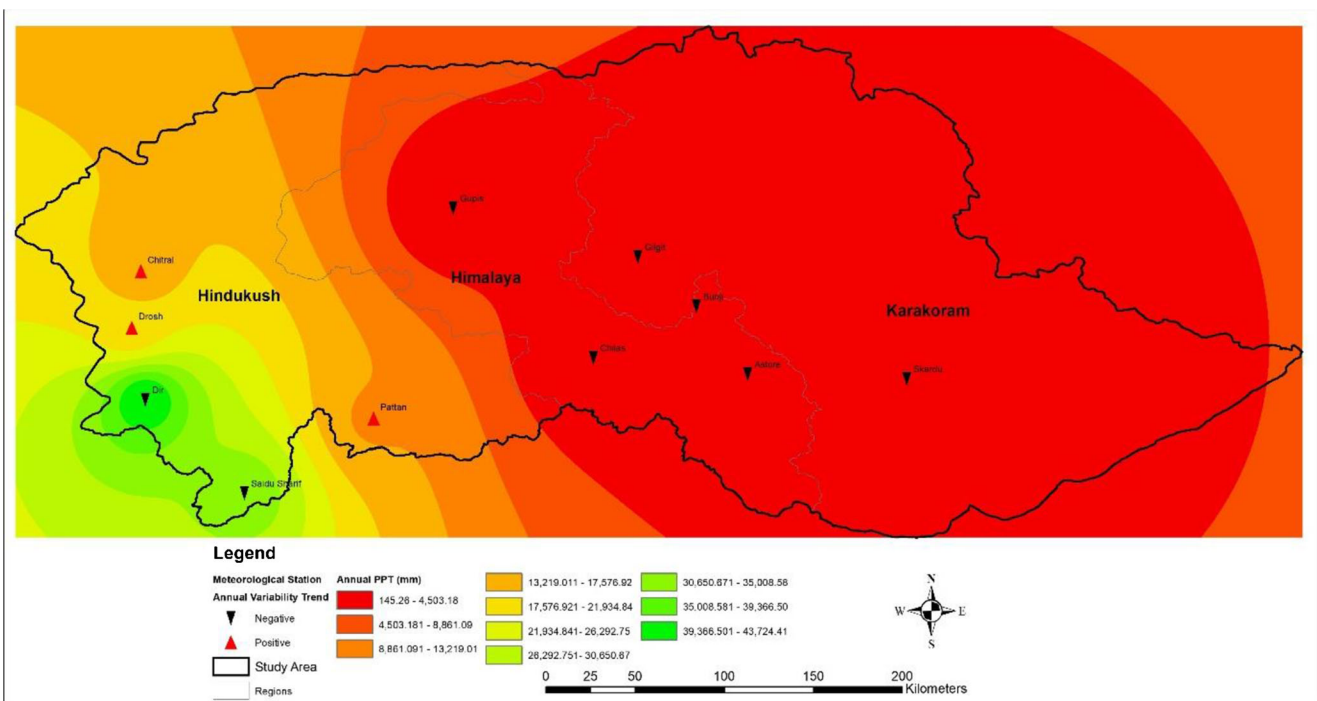
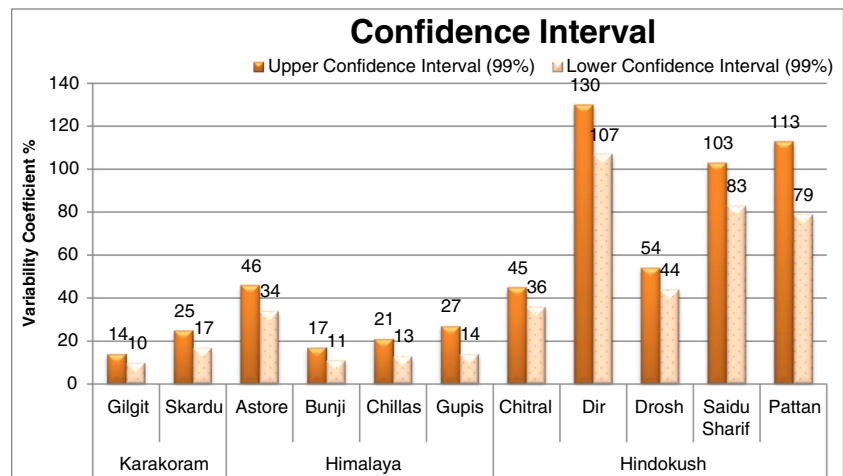


Fig. 5 Spatial distribution of annual precipitation and its variability (1985–2016) trend in the study area

Fig. 6 Confidence interval of each weather station



Himalayas

Astore and Chillas of Himalayas, in 3MRP, have witnessed a negative drought trend while Bunji and Gupis have positive drought trend. 3MRP results indicate that a total of 45 months from 1997 to 2011 in Astore have witnessed dry spell. Similarly, Bunji meteorological station experienced 26 months drought 1987–1992 while the drought period of 11 months observed from 2000 to 2001. Nine months in Chillas have observed drought from 1997 to 1998 followed by 14 months of drought from 2000 to 2003. Similarly, the drought period of 8 months was experienced in Chillas city from the years 2014 to 2015. Similar to Chillas, Gupis from 1988 to 1993 witnessed droughts in 11 months, from 1998 to 2001 in 10 months and from 2006 to 2009, the area observed drought in 17 months (Fig. 7).

Astore in 3MRP has gone through 30 months of moderate drought, 14 months of severe drought and 11 months of extreme drought. Bunji during the study period has witnessed 40 months of moderate, 16 months

of severe and 3 months of extreme drought, while in Chillas, 32 months of moderate, 23 severe and 6 months of extreme. Similarly, 24 months of moderate, 15 months of severe and 3 months of extreme drought were observed in Gupis (Table 2).

Hindukush

In Hindukush, all meteorological stations have a negative trend in SPI Values. Chitral in 1990 has witnessed 4 months of moderate drought followed by 32 months of drought witnessed from 1996 to 2008 and 7 months of drought in 2011. Dir has gone through 25 months of drought from 1997 to 2004, while 20 months in drought from 2006 to 2012. From 1990 to 1991, 8 months of drought was witnessed in Drosh followed by 19 months in dry condition from 1997 to 2002, 2004–2006 7 months, 15 months from 2009 to 2014 and 4 months in 2016 remain in drought condition. At the same time, Drosh, Saidu Sharif observatory experienced drought for

Table 2 Drought frequency and magnitude over different time scales in each meteorological station from 1985 to 2015

Region	Station	3MRP			9MRP			12MRP			24MRP		
		MD	SD	ED	MD	SD	ED	MD	SD	ED	MD	SD	ED
Karakoram	Gilgit	41	15	5	29	14	8	34	16	4	43	24	3
	Skardu	26	19	6	36	11	9	37	16	7	8	15	15
Himalaya	Astore	30	14	11	22	22	11	24	13	16	11	16	16
	Bunji	40	16	3	29	23	10	23	21	13	33	10	13
	Chillas	38	10	2	20	17	7	17	18	7	32	23	6
	Gupis	24	15	3	41	14	3	41	8	3	60	1	0
Hindukush	Chitral	32	12	8	19	9	2	10	10	1	9	8	0
	Dir	33	15	8	28	11	1	32	11	0	30	16	0
	Drosh	33	18	6	45	5	1	36	13	0	24	21	0
	Saidu Sharif	12	6	1	12	6	1	12	3	0	23	1	0
	Pattan	15	8	2	15	7	1	25	0	1	15	5	0

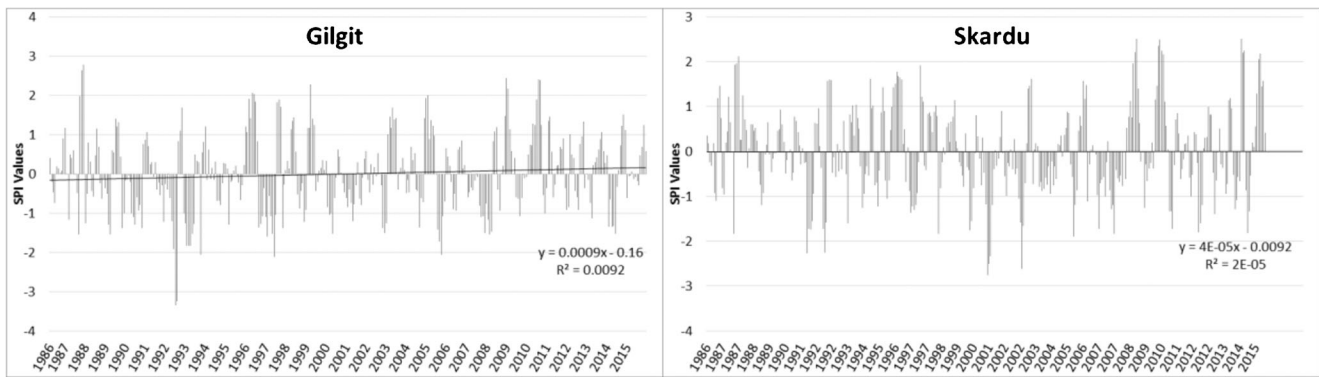


Fig. 7 Standardized Precipitation Index of Karakoram region for monthly return period of 3

8 months from 2000 to 2002 and 7 months from 2008 to 2010. Pattan meteorological station has experienced drought for 8 months from 2006 to 2008 and 8 months of drought from 2012 to 2015 (Fig. 8).

Chitral in total has experienced 32 months of moderate, 12 months of severe and 8 months of extreme drought condition. Dir has experienced 33 months of moderate, 15 months of severe and 8 months of extreme drought, while Drosh has witnessed 33 months of moderate, 18 months of severe and 6 months of extreme drought. Similarly, in Saidu Sharif, 12 months of moderate, 6 months of severe and 1 month of extreme drought. Likewise, Pattan has witnessed 25 months of moderate and 1 month of extreme drought condition throughout the study period (Table 2).

9MRP

Karakorum

Gilgit station of Karakorum has a positive drought while Skardu has a slightly negative trend. In 9MRP, Gilgit has gone through 23 months of drought from 1989 to 1993, 1997 5 months, 2000–2001 7 months, 2006–208 10 months while in 2014, 3 months remained in drought. Similarly, in Skardu, 3 months in 1991, 5 months in 1997, 15 months from 2000 to 2001, 12 months from 2003 to 2004 while from 2007 to 2008, drought were observed in 18 months (Fig. 9).

In 9MRP Gilgit, over the study period has experienced 29 months of moderate, 14 months of severe and 8 months

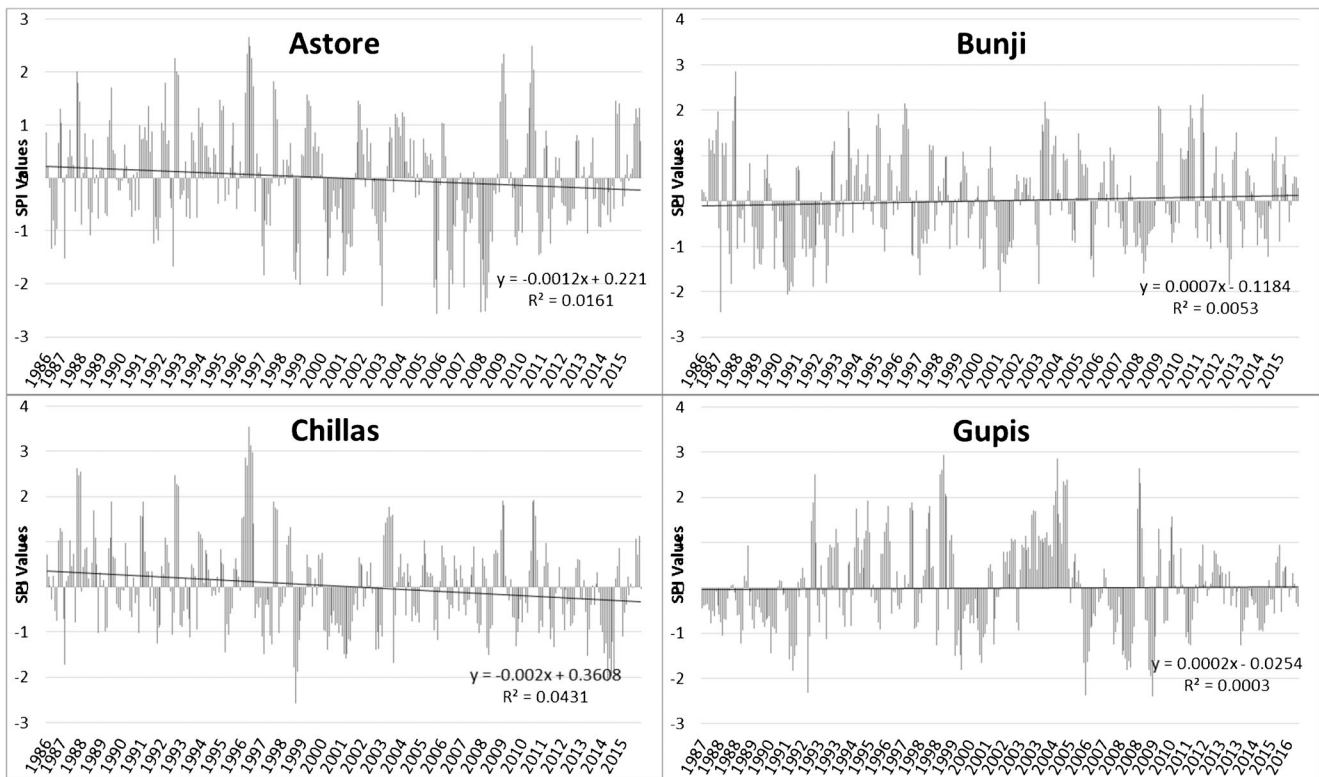


Fig. 8 Standardized Precipitation Index of Himalayan region for monthly return period of 3

of extreme drought. A total of 36 months of moderate, 11 months of severe and 9 months of extreme drought observed in Skardu (Table 2).

Himalaya

Astore, Chillas and Gupis of Himalayas witnessed a negative while Bunji has a positive drought trend in 9MRP. Seventeen months from 2000 to 2001 have experienced drought in Astore followed by 26 months of drought from 2006 to 2008. Similarly, Bunji has observed 27 months of drought from 1989 to 1992, 5 months in 1997, 12 months from 2000 to 2002 and 14 months from 2006 to 2008. Chillas has gone through a dry climate in 5 months in 1997 followed by 17 months from 1999 to 2001 and 19 months of drought from 2010 to 2015. Gupis has experienced 14 months in drought

condition from 1990 to 1992, 11 months from 2000 to 2001 and 26 months from 2006 to 2011 (Fig. 10).

During the study period, in 9MRP, Astore has witnessed 22 months of moderate drought, 22 severe and 11 months of extreme drought. Twenty-nine months in Bunji suffered from moderate, 23 severe and 10 months of extreme. Twenty months of moderate drought in Chillas followed by 17 months of severe and 7 months of extreme drought. Similarly, Gupis has observed 41 months of moderate, 14 months of severe and 3 months of extreme drought (Table 2).

Hindukush

In 9MRP, all the observatories of Hindukush have witnessed a negative drought trend over the study period. However, Chitral has observed 10 months of drought from 2001 to 2004 and 13 months in drought from 2011 to 2012. Dir, from

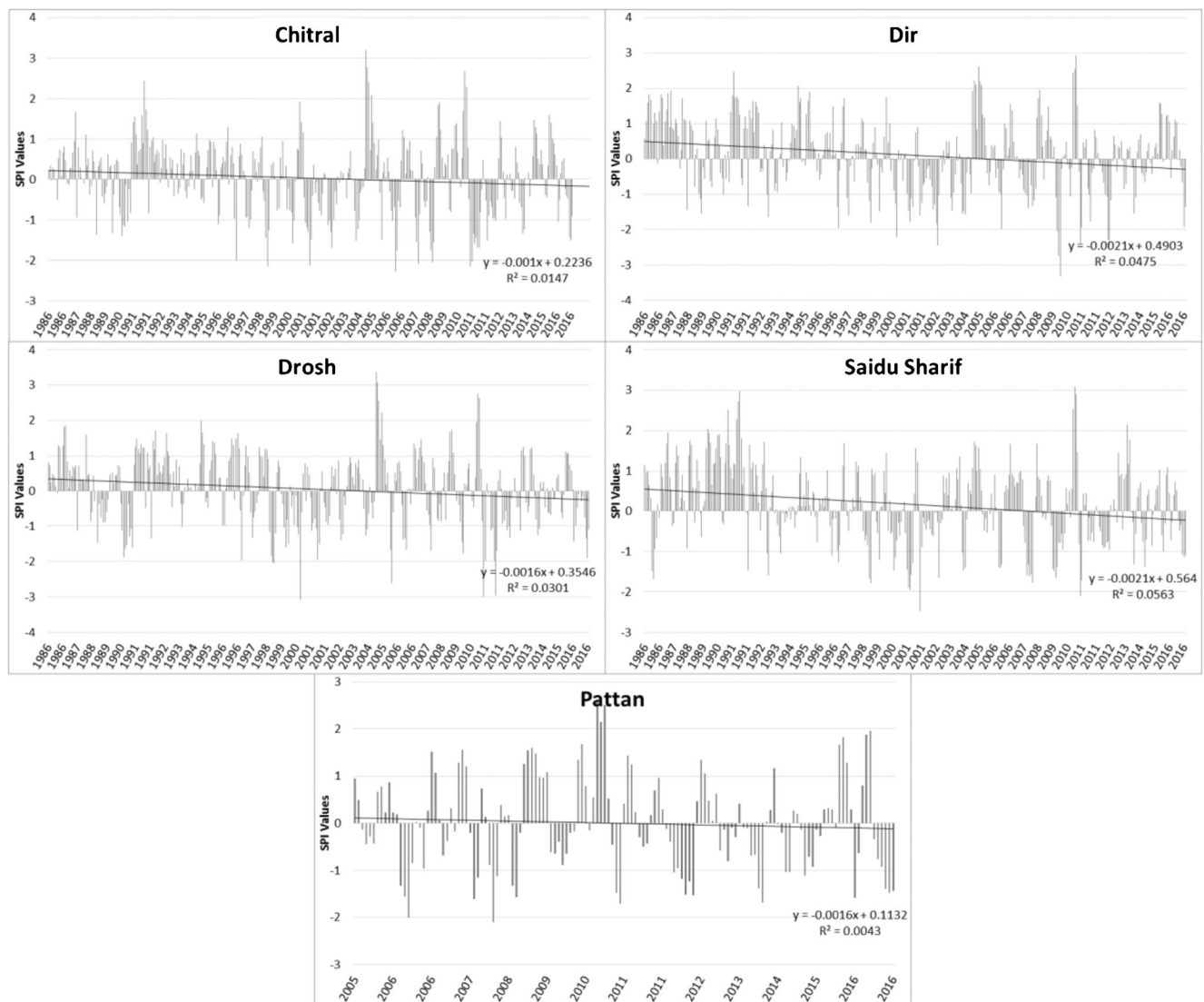


Fig. 9 Standardized Precipitation Index of Hindukush region for monthly return period of 3

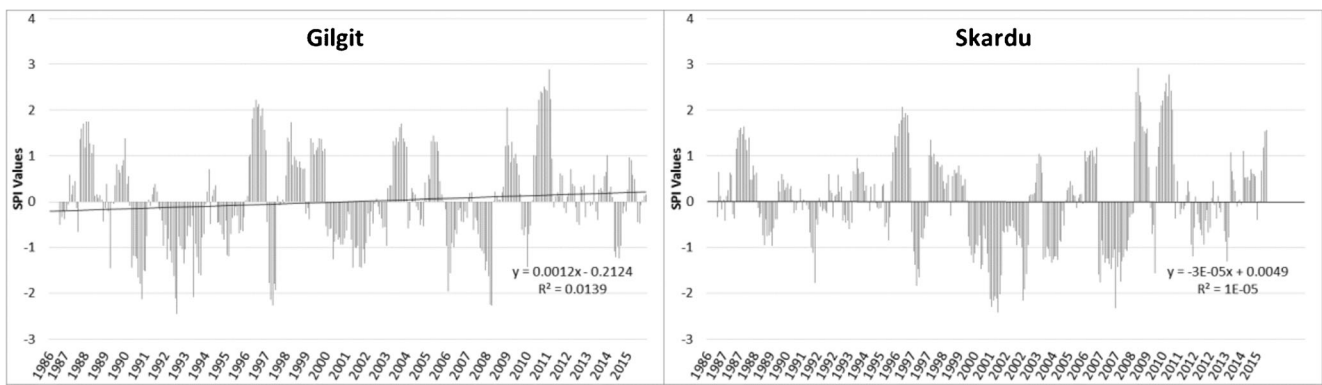


Fig. 10 Standardized Precipitation Index of Karakoram region for monthly return period of 9

2001 to 2004, has experienced 20 months of drought, 8 months in drought from 2008 to 2010 and 8 months from 2012 to 2014. From 1988 to 1990, Drosh has witnessed 9 months of drought followed by 22 months in drought from 2000 to 2004 and 18 months from 2011 to 2012. Similarly, 8 months of drought from 2000 to 2002 and 7 months of drought from 2008 to 2010 in Saidu Sharif were detected. Likewise, Pattan has suffered from 8 months of drought from 2006 to 2008 and 18 months in drought from 2012 to 2015 (Fig. 11).

During the study period, Chitral has suffered from a total of 19 months of moderate, 9 months of severe and 2 months of extreme drought. Dir has experienced 28 moderate, 11 severe and 1 month of extreme drought. Drosh was hit by 45 months of moderate, 5 severe 1 month of extreme drought. Saidu

Sharif experienced 12 moderate, 6 severe 6 and 1 month of extreme drought, while in Pattan, 25 moderate and 1 month of extreme drought (Table 2).

12MRP

Karakorum

Gilgit and Skardu stations of Karakoram region have observed positive drought trend in 12MRP. Gilgit from 1990 to 1993 suffered from 26 months of drought followed by 13 months of drought from 2000 to 2002 and 10 months in 2006–2008, while Skardu station has experienced 5 months of drought condition from 1997, 37 months from 2000 to 2005 and 17 months from 2007 to 2008 (Fig. 12).

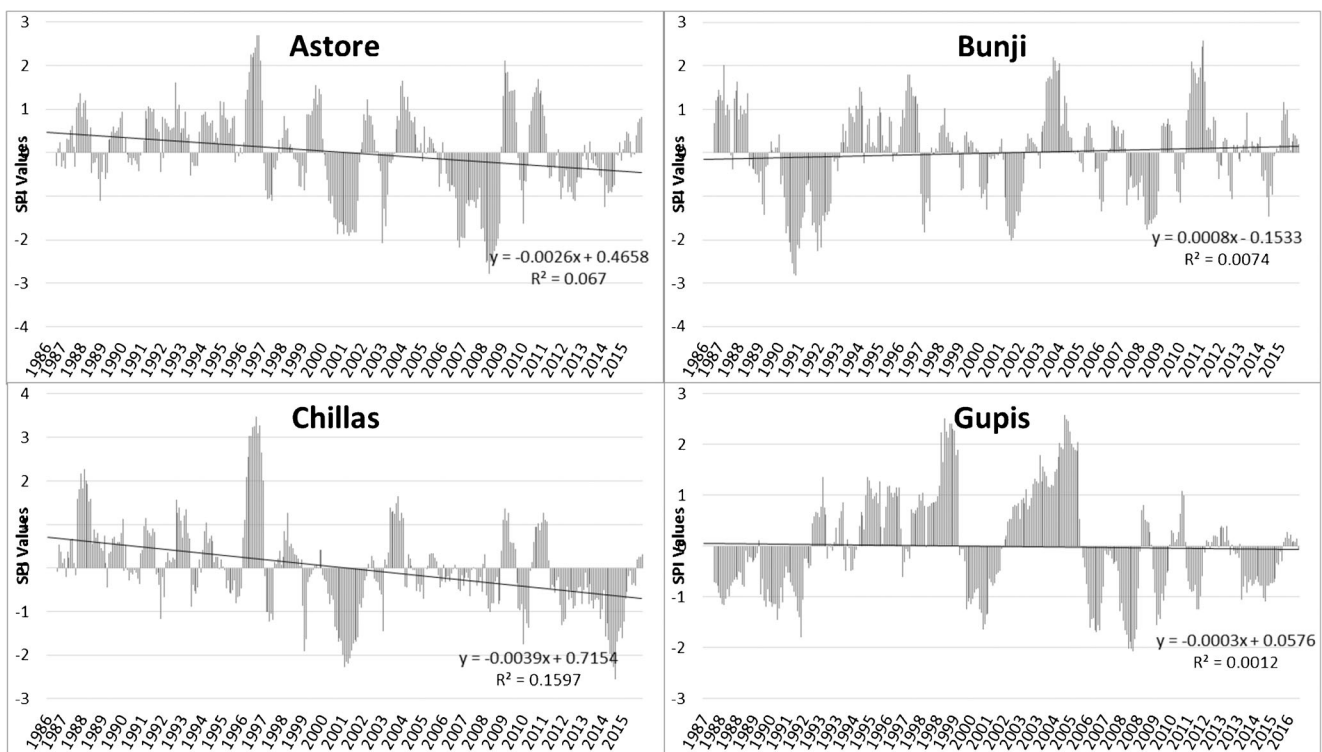


Fig. 11 Standardized Precipitation Index of Himalaya region for monthly return period of 9

Gilgit, during the study period, has been hit by 34 months of moderate, 16 severe and 4 months of extreme drought, while Skardu has suffered from 37 moderate, 16 severe and 8 months of extreme drought (Table 2).

Himalaya

Astore, Chillas and Gupis of Himalayas witnessed negative drought trend except for Bunji observatory. Fifteen months from 2000 to 2003 have experienced drought in Astore followed by 29 months of drought from 2006 to 2008 In 12MRP. Parallel to Astore, Bunji has suffered from 29 months of drought condition from 1989 to 1992, 11 months from 2000 to 2002 and 13 months from 2007 to 2008. Likewise, Chillas has witnessed 17 months of drought from 2000 to 2002 and 20 months from 2012 to 2015. Thirteen months remained in drought from 1990 to 1992 in Gupis followed

by 11 months from 2000 to 2001, 16 months from 2006 to 2008 and 7 months of drought from 2010 to 2012 (Fig. 13).

The data suggest that during the study period, in 12MRP, Astore suffered from 24 moderate, 13 severe and 16 months of extreme drought, Bunji 23 moderate, 21 severe and 13 extremes and Chillas 17 moderate 17, 18 severe 18 and 7 months of extreme drought condition. Forty-one months of moderate, 8 months of severe and 3 months of extreme drought observed in Gupis during the study period (Table 2).

Hindukush

Chitral, Dir, Drosh, Saidu Sharif and Pattan of Hindukush region, in 12MRP, have witnessed a negative drought trend; however, Chitral suffered from 5 months of drought from 2001 to 2002 and 15 months from 2011 to 2012. Dir remained in drought for 27 months from 2001 to 2004, 6 months from

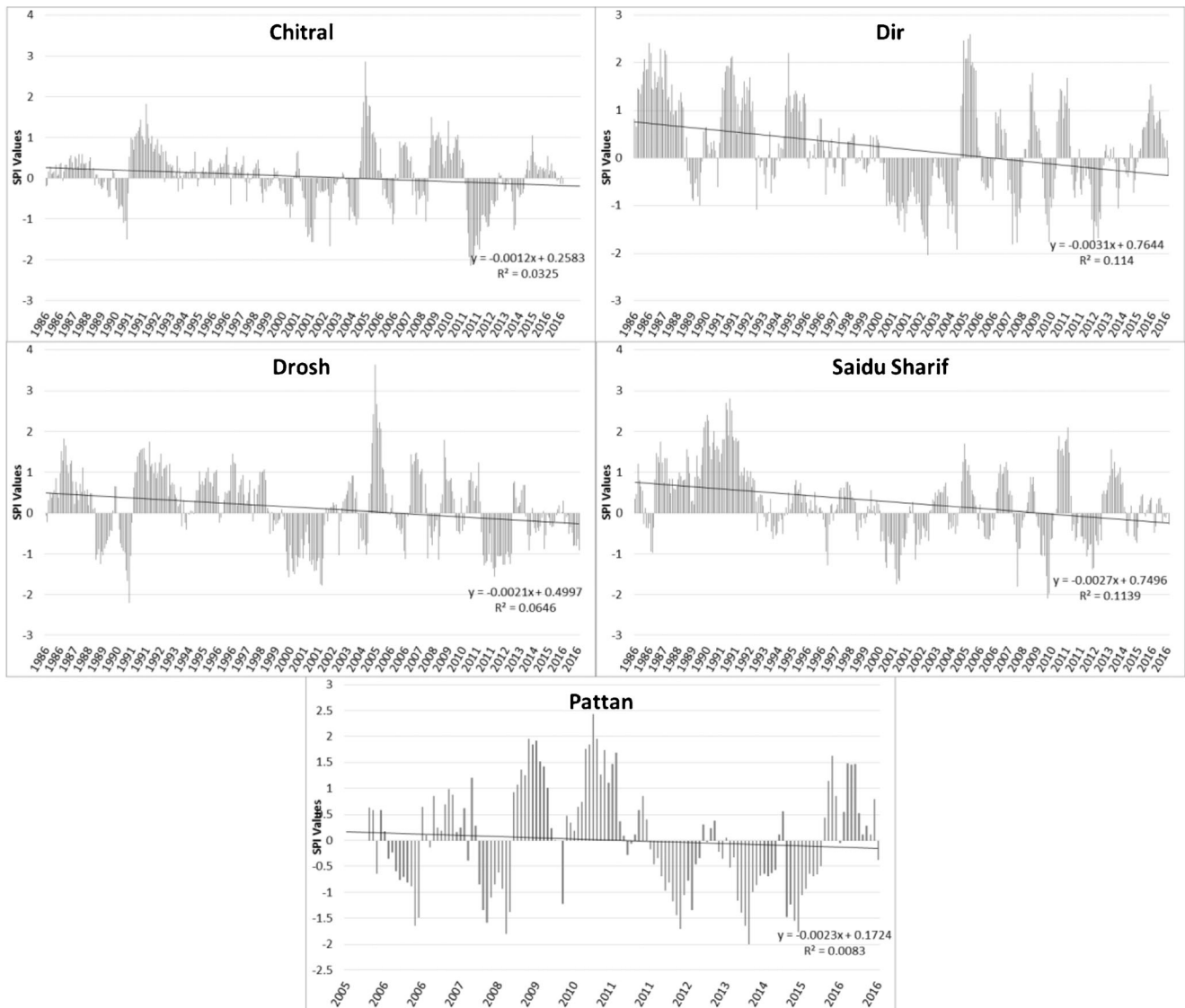


Fig. 12 Standardized Precipitation Index of Hindukush region for monthly return period of 9

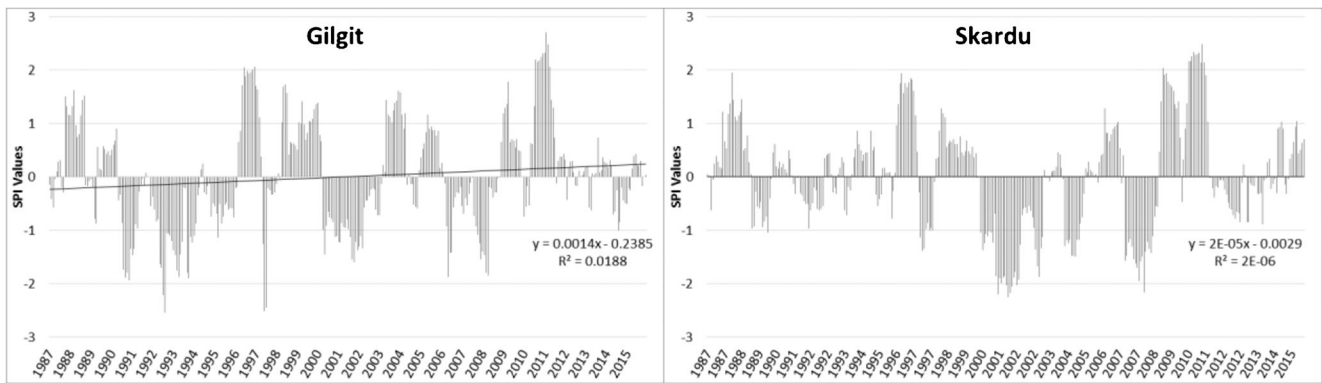


Fig. 13 Standardized Precipitation Index of Karakoram region for monthly return period of 12

2007 to 2008 and 7 months from 2012 to 2013. Similarly, Drosh has witnessed a dry condition in 7 months from 1989 to 1990, 23 months from 2001 to 2002 and 15 months of drought from 2011 to 2013. Likewise, Saidu Sharif has suffered from 7 months of drought in 2001–2003, 3 months in 2010 (3) and in 2012, 4 months remained with no precipitation, while in Pattan from 2006 to 2008, 8 months remained in drought condition followed by 18 months of drought from 2012 to 2015 (Fig. 14).

In 12MRP, during the study duration, Chitral has observed 10 moderate, 20 severe and 1 month of extreme drought. In Dir, 32 moderate and 11 months of severe drought have been observed. Drosh has moderate drought 36 and 13 months of severe drought. In Saidu Sharif, 12 moderate and 13 months of severe have been observed while in Pattan, 25 moderate

and 1 month of the extreme drought have been observed (Table 2).

24MRP

Karakoram

In 24MRP, Gilgit and Skardu stations of Karakoram region have a positive drought trend over the study period. Gilgit has been hit by 37 months of drought from 1991 to 1995, 22 months from 2001 to 2003 and 11 months from 2007 to 2008. Skardu has experienced a dry spell in 27 months from 2001 to 2003 and 9 months drought in 2008 (Fig. 15).

Gilgit in 24MRP, during the study period, has observed moderate drought in 43, 24 severe and 3 months of extreme

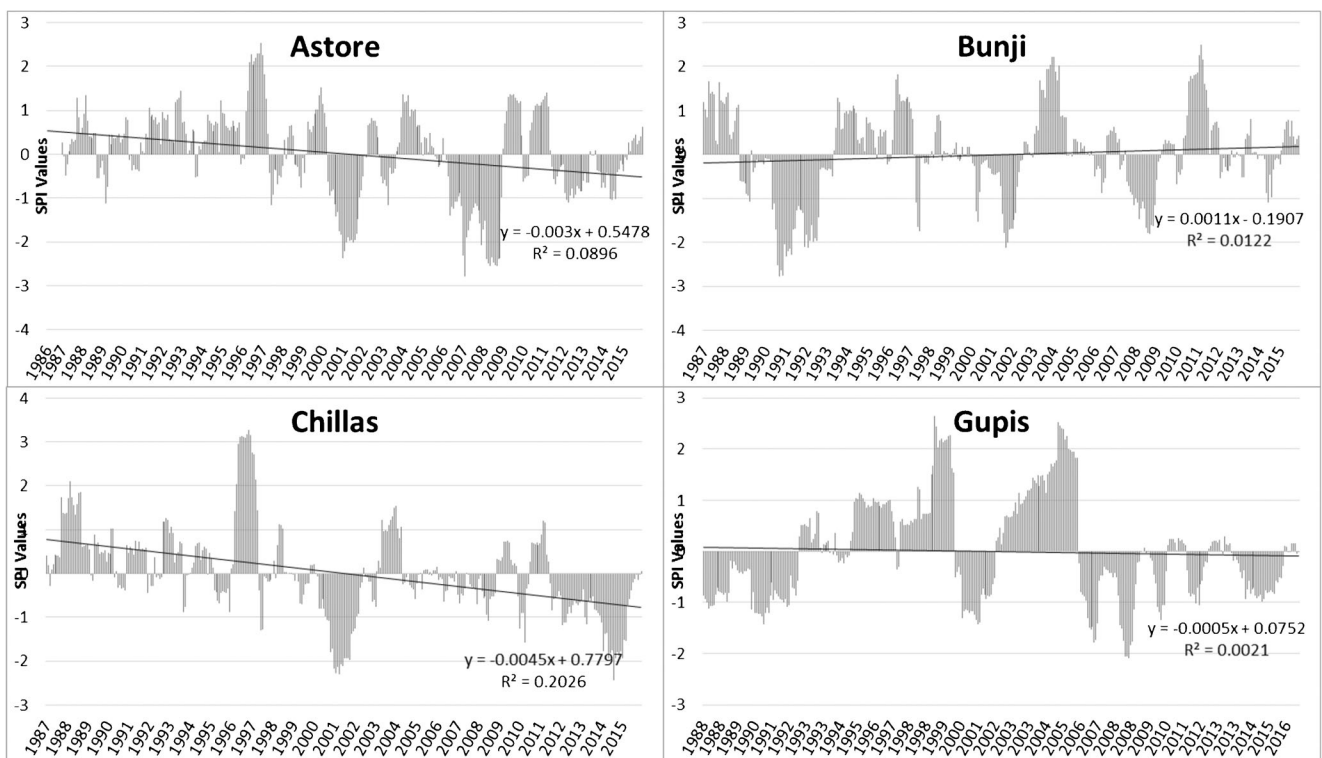


Fig. 14 Standardized Precipitation Index of Himalaya region for monthly return period of 12

drought, while in Skardu, 8 moderate, 15 severe and 15 months of extreme drought observed (Table 2).

Himalaya

The Himalayas has witnessed negative drought trend except for Bunji observatory. Astore from 2001 to 2002 has suffered from drought condition in 12 months and 24 months of drought from 2007 to 2008. Bunji experienced 31 months of drought from 1990 to 1992, 14 months from 2001 to 2003 and 6 months from 2008 to 2009. Similarly, the Chillas station was remained in drought in 27 months from 2000 to 2003 and 34 months from 2012 to 2015. Gupis from 22 months of drought during 1989–1992, 12 months during 2000–2001, 22 months during 2007–2009 and 6 months in 2015 (Fig. 16).

Astore, in 24MRP, has been hit by a total of 11 moderate, 16 severe and 16 months of extreme drought. In Bunji, 33 moderate, 10 severe and 13 months of extreme and in Chillas, 32 moderate, 23 severe 23 and 6 months of extreme drought observed. Gupis during the study duration observed 60 months of moderate and 1 month of severe drought (Table 2).

Hindukush

In 24MRP, Chitral, Dir, Drosh, Saidu Sharif and Pattan meteorological stations of Hindukush have negative drought trend. During 2002–2003, Chitral experienced 3 months of drought condition followed by 14 months of drought from 2012 to 2013. From 2001 to 2004, Dir has suffered from 34 months of drought and in 2012–2014, 7 months remained dry. Parallel to Dir, Drosh has witnessed 10 months of a dry weather in

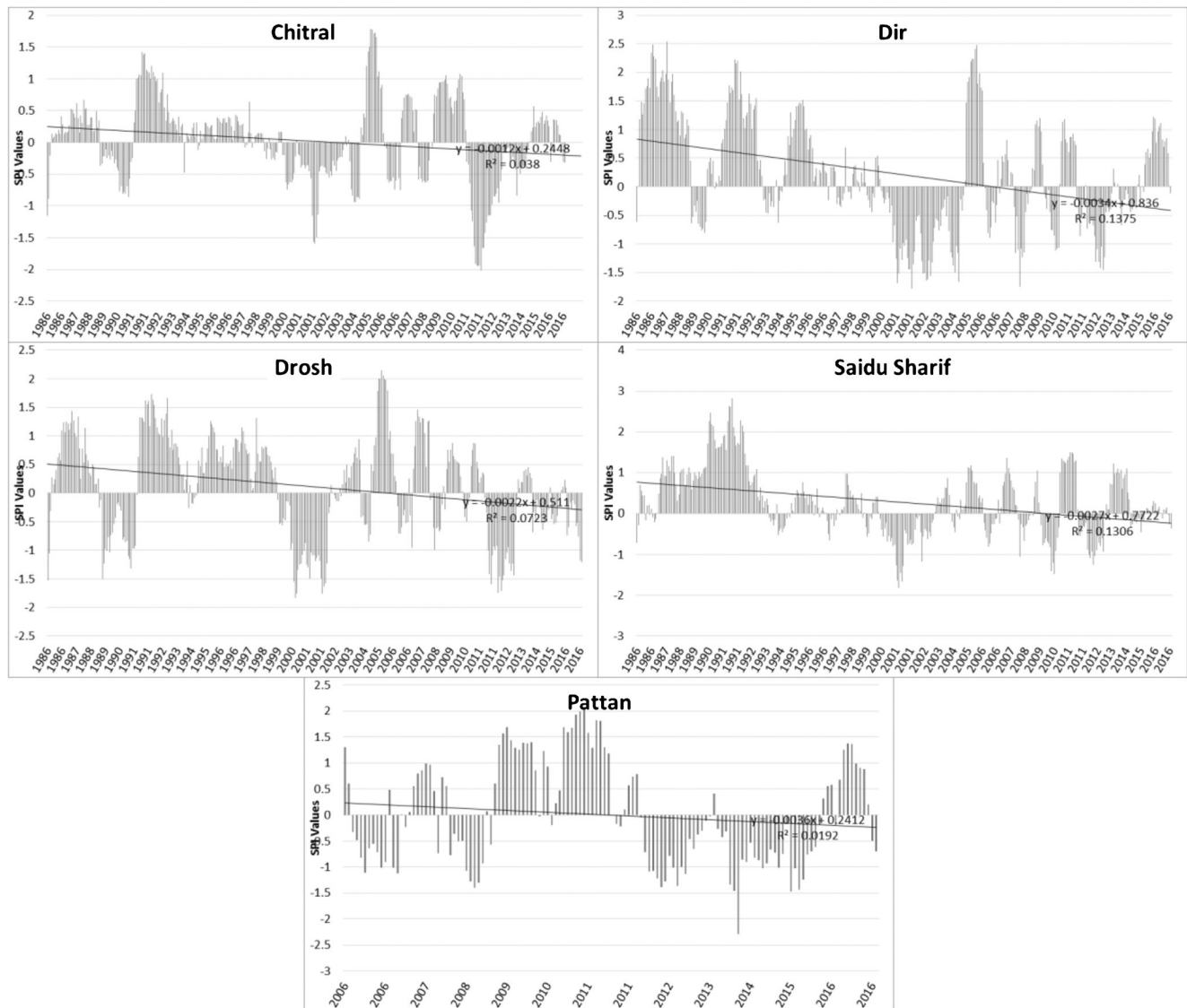


Fig. 15 Standardized Precipitation Index of Hindukush region for monthly return period of 12

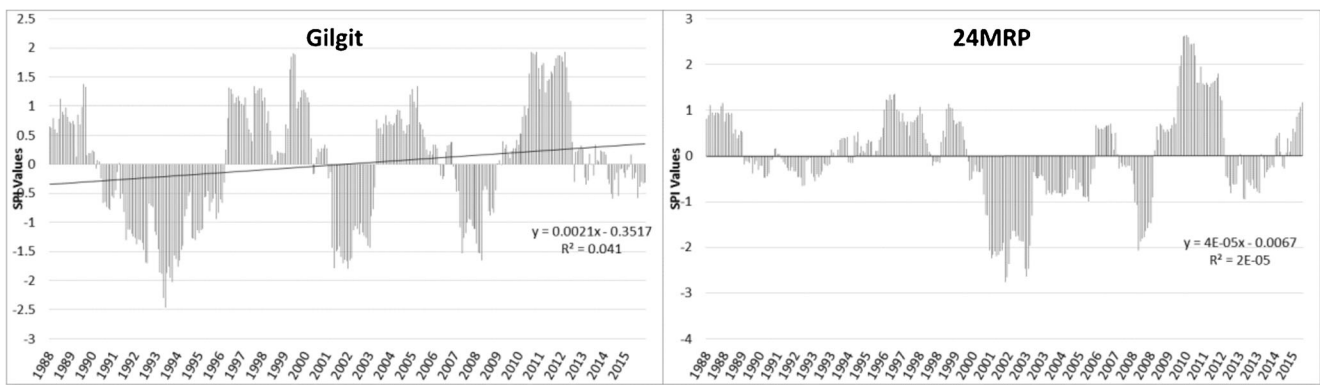


Fig. 16 Standardized Precipitation Index of Karakoram region for monthly return period of 24

1990, 23 months during 2000–2002 and 11 months during 2012–2013. Similarly, Saidu Sharif from 2001 to 2002 has suffered from 20 months of drought while Pattan remained in a dry climate for 20 months during the span from 2012 to 2015 (Fig. 17).

During the study period, Chitral has been caught by 9 months of moderate drought and 8 months of severe drought. Dir has remained moderately drier for 30 and 16 months in severe drought. Drosh has been caught by moderate drought in 24 months and severe drought in 21 months. In Saidu Sharif, 23 moderate and 1 month severe drought have been observed, while Pattan has suffered from 15 months of moderate and 5 months of severe drought (Table 2).

The southern and central parts of Pakistan are highly vulnerable to drought due to their arid and hyper-arid climates

(Ahmed et al., 2019; Bhatti et al. 2020; Ullah et al. 2019b); however, recent studies suggested that the dynamic variability in precipitation over northern mountainous parts has significantly triggered the drought events (Ahmed et al. 2017; Ullah et al. 2018a). In a recent study, Baig et al. (2020) reported that the transboundary of the Chitral Kabul River Basin (CKRB) has experienced both meteorological and agricultural droughts between 2000 and 2018, which is expected to be continued in the future with more drastic intensity. In another study, Adnan and Ullah (2020) indicated that the northern mountainous parts of Pakistan were dominated by moderate drought events during 1951–2010, which could be attributed to dynamic changes in westerlies-dependent precipitation and warming tendency of temperature (Ullah et al. 2018b; Ullah et al. 2019a). Rahman et al. (2018) reported

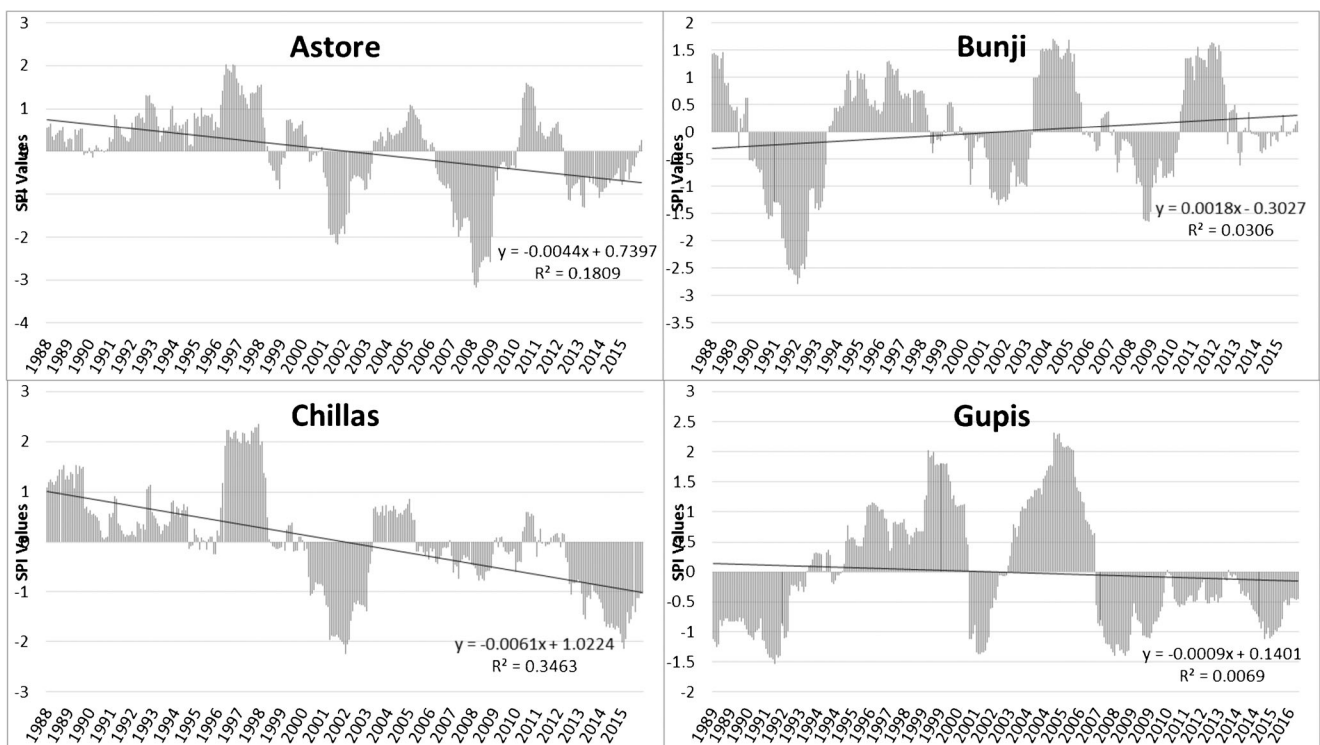


Fig. 17 Standardized Precipitation Index of Himalaya region for monthly return period of 24

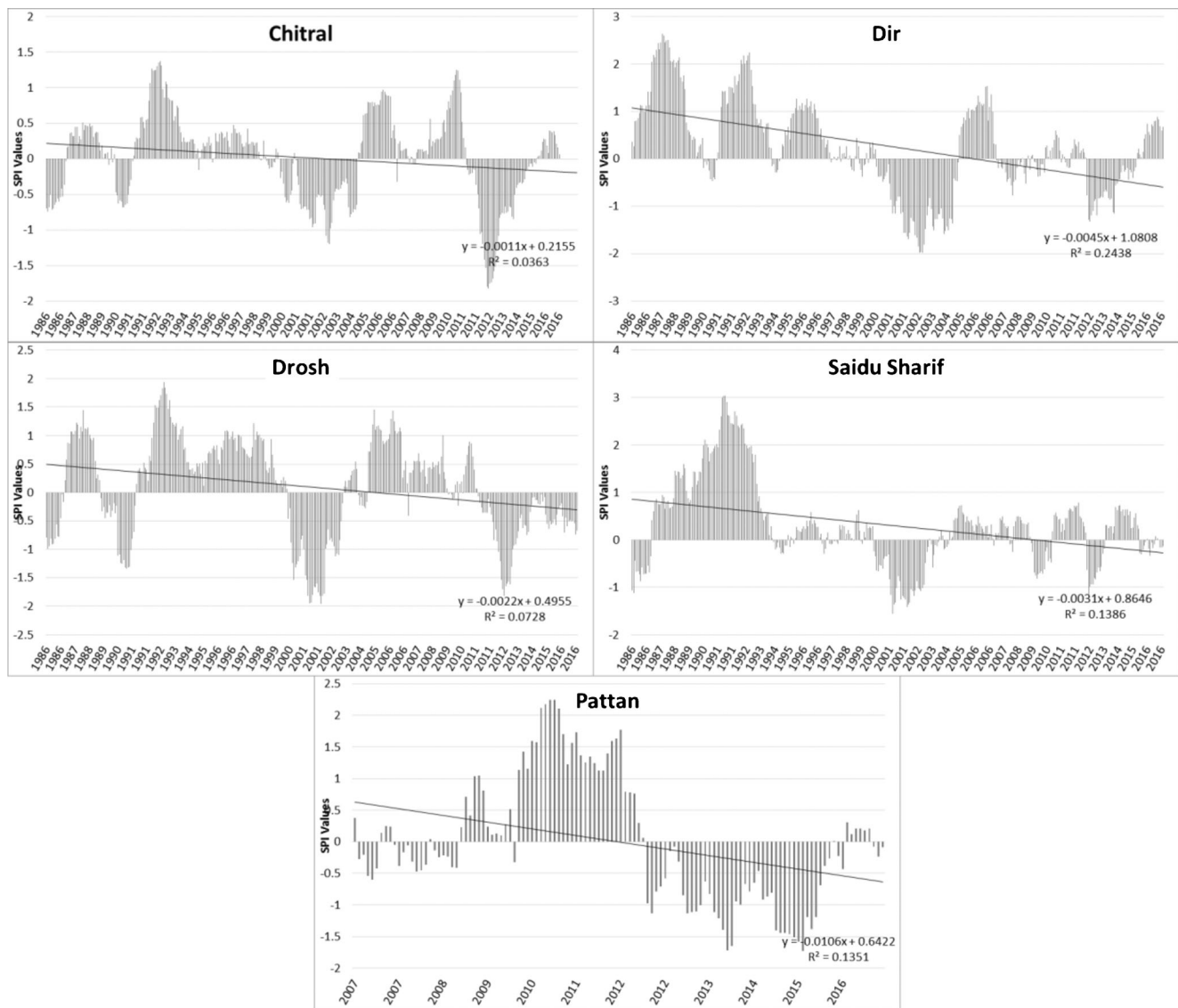


Fig. 18 Standardized Precipitation Index of Hindukush region for monthly return period of 24

two distinct severe drought periods in Khyber Pakhtunkhwa province of Pakistan, i.e. 1984–1989 and 1998–2002, with maximum intensity in the northern parts covering the current study region. According to Mazhar et al. (2015), the northern parts of Pakistan have experienced consistent patterns of moderate to extreme droughts in recent decades. Similarly, Parvaze et al. (2016) estimated the severity and duration of drought events in Srinagar Kashmir and indicated that the study observed moderate drought events in 1989, 1998, 2003 and 2008, severe droughts in 2000 and 2001 severe, while extreme drought in the year 1999 (Fig. 18).

Conclusion

It is evident from the analysis that there is great variability in precipitation pattern and trend as well as drought condition in

the study area (Northern Khyber Pakhtunkhwa and Gilgit-Baltistan). In Himalayas and Karakoram throughout the study period, low precipitation was recorded as compared with the Hindukush region. In the study region, highest average precipitation of 610.76 mm was recorded in winter in the Hindukush region, indicating the impact of western depressions, while the lowest precipitation of 8.24 mm was recorded in post-monsoon in Himalaya and Karakoram. In winter, except Skardu and Bunji meteorological stations, a positive trend was detected in the precipitation variability in Himalaya and Karakoram while in Hindukush, only Pattan weather station has observed a positive variability trend. In contrast to winter variability, pre-monsoon season has witnessed an increased variability in Hindukush while Karakoram and Himalayas have observed a negative trend in pre-monsoonal variability. Monsoon has experienced a decreased variation in precipitation variability throughout the

study area except for Pattan. In post-monsoon, Skardu of Himalayas, Gupis and Bunji of Karakorum and Pattan of Hindukush have witnessed increased precipitation variability, which is a sign of drought in Himalaya and Karakorum. Weather stations of Karakoram and Himalayas observed to have a negative trend of precipitation variability while in Hindukush except for Saidu Sharif and Dir, rest of the meteorological stations Chitral, Drosh and Pattan have witnessed a positive trend of variability. At the same time, results of SPI also indicated drought risk in the study area. In 3 months return period, Himalayas of Pakistan was at high risk in terms of drought frequency and magnitude, followed by Hindukush and Karakoram, while in 9 months return period, Himalaya is followed by the Karakoram and Hindukush in terms of drought risk, whereas 12 months return period indicated that Karakoram region of Pakistan is at high risk of drought followed by Himalaya and Hindukush. Parallel to the 9 months return period, 24 months return period reflected that Himalaya is followed by the Karakoram and Hindukush in terms of drought frequency and magnitude. Overall, it can be concluded that past climatic data for Northern Pakistan indicate risks of drought due to less than normal precipitation as well as probabilities of the flood as a result of higher than normal precipitation.

Suggestions and recommendations

It is recommended for the researchers to develop more studies to quantify drought risk and precipitation variation by utilizing temperature data as well to achieve a more in-depth understanding of the role of temperature on precipitation and drought. The government should invest in drought-resilient seeds to cope with drought risk in the country.

Acknowledgements We are extremely thankful to the Pakistan Meteorological Department for providing precipitation data for this research study.

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