Changes In Monthly Streamflow In The Hindukush-Karakoram-Himalaya Region of Pakistan Using Innovative Polygon Trend Analysis

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Abstract

The present study explored the changes in monthly streamflow in the Hindukush-Karakoram-Himalaya (HKH) region within Pakistan using the recently developed trend analysis method known as Innovative Polygon Trend Analysis (IPTA). The monthly streamflow data of 34 gauging stations installed in the HKH region was analyzed, and the Pettitt test was applied to check the homogeneity of the time series. The entire study area was divided into 13 sub-basins, and then changes in monthly streamflow of each sub-basin were explored using the IPTA method. The streamflow of high elevated glaciated and snow/ice-covered sub-basins (e.g., Shyok, Astore, and Chitral) have increased in high flow months (June-August), where there is a downward trend for the Hunza sub-basin in these months. In the Gilgit sub-basin, a transition occurred from no trend in May to a decreasing trend from June to August. The upstream gauges of Swat and Kabul sub-basins showed an increasing trend throughout the year, while downstream gauging stations in the same sub-basins exhibited a strong decreasing trend only in high flow months (June-August). The upper reaches of the Indus part in the Upper Indus Basin (UIB) showed increasing trends in high flow months (June-August), however the downstream gauges of UIB showed decreasing trends throughout the year. Overall, only the glaciated and snow/ice-covered sub-basins experienced increasing trends, while most other sub-basins faced decreasing trends in high flow months and increasing trends in low flow months (October - March). The enhancement of the seasonal pattern of streamflow in the upper reaches of UIB is possibly due to the melting of snow and ice that potentially influence floods and hydropower generation. The results of this study can result in a better understanding of the hydrology of the HKH region and support sustainable water management.

Introduction

The Indus System of Rivers (ISR) consists of three western rivers (Indus, Jhelum, and Chenab) and three eastern rivers (Ravi, Sutlej, and Bias). According to the Indus Water Treaty (IWT) between India and Pakistan, the water of the western rivers will be used by Pakistan and the water of the eastern rivers by India. The five rivers (Jhelum, Chenab, Ravi, Sutlej, and Bias) finally join the Indus River at Panjnad Barrage, located in Punjab, Pakistan. The western rivers originate from China (Tibetan Plateau) and India (Kashmir) and finally run through Pakistan (Kalair et al. 2019). Among these, the Indus is vital as it feds 50% of the Indus basin discharge (Rao et al. 2018). The Third Polar Region (TPR) is part of the Hindukush, Karakoram, and Himalaya (HKH) ranges (Minora et al. 2013; Nie et al. 2021; Smiraglia et al. 2007), and the upper reaches of the western rivers lay in the TPR and HKH. The western rivers are fed by snow and ice melt runoff from the HKH region. The HKH region stores a substantial amount of water in the form of glaciers covering an area of about 16,300 km^2 (Akhtar et al. 2008). Immerzeel et al. (2010) stated that more than 50% of the Indus river water is contributed by glacier and snowmelt runoff from HKH, whereas the contribution of summer precipitation is relatively small (Immerzeel et al. 2009). The Upper Indus Basin (UIB) is the Indus basin upstream of Tarbela and Mangla reservoirs, and these reservoirs are the primary source of irrigation and hydropower generation for Pakistan (Nie et al. 2021; Rashid et al. 2018). The intra-annual variations in streamflow of the UIB are primarily caused by ablation and seasonal snowfall

(Forsythe et al. 2017). The changes in air temperature and humidity speed up the ablation of glaciers in this region (Harpold and Brooks 2018; Immerzeel et al. 2010).

The hydrology of the HKH region is complex and very sensitive to climate change (Fowler and Archer 2006) and susceptible to flooding (Khan 2013). In 2010, floods affected 17,553 villages with a total flooding area of 160,000 km^2 (Rahman and Shaw 2015). There are contradictions in relations between climate change and glacier mass balances within the Karakoram and Himalaya ranges. For example, the glaciers located in the Karakoram range are stable, or even some of them expanded, whereas the glaciers of the Himalaya range declined in the last two decades (Bolch et al. 2012; Brun et al. 2017; Gardelle et al. 2012; Kapnick et al. 2014; Minora et al. 2013). The behavior of glaciers located in the Karakoram range is known as the Karakoram anomaly (Gardelle et al. 2012; Hewitt 2005). The high altitudes of the Karakoram range receive about 2/3 of the total snow during the winter season triggered by synoptic western disturbances, and the remaining part is due to the contribution of monsoonal precipitation (Benn and Owen 1998; Greene and Robertson 2017; Palazzi et al. 2015). Increased winter snowfall (Farhan et al. 2015; Kapnick et al. 2014; Ridley et al. 2013; Tahir et al. 2011) and debris accumulation on glaciers also contributed to the Karakoram anomaly (Kraaijenbrink et al. 2017; Minora et al. 2013).

In the last two decades, climate-induced hydro-glaciological regime changes were investigated (Aizen et al. 2002; Hannah et al. 2005; Kehrwald et al. 2008). There has been a reduction in streamflow from the Central Karakoram sub-basins from 1961–2000 (Archer and Fowler 2004; Fowler and Archer 2006). Khattak et al. (2011) found an increasing trend in winter streamflow and a decreasing trend in summer streamflow in the UIB from 1967–2005. These studies used traditional methods (Kendall 1975; Mann 1945; Sen 1968) for trend analysis of hydro-climatic time series. A recent study in this region by Yaseen et al. (2020) also used the traditional non-parametric Mann Kendall trend test for annual and seasonal streamflow. The presence of autocorrelation in the time series influenced the Mann Kendall results (Ahmed et al. 2020b). Therefore, the modified version of the Mann Kendall trend test is prefered to overcome the autocorrelation in the time series (Hamed and Rao 1998). Else, a pre-whitening approach is recommended before applying the Mann Kendall trend test to remove the autocorrelation in the time series (Şen 2017a). These traditional trend detection methods are used for holistic trend detection, and the major limitations of these methods are assumptions such as serial independence and normality in the time series under analysis (Sen et al. 2019).

Therefore, this study used the recently introduced assumptions free trend analysis method known as the Innovative Polygon Trend Analysis (IPTA) from Sen et al. (2019) to address the trends in streamflow in the UIB. This study investigated the changes in monthly streamflow of sub-basins covering the entire UIB for 34 gauges from 1961–2013. The results of this study are relevant for flood risk assessment and sustainable water resources management in UIB and downstream riparian areas in Pakistan.

Section 2 describes the study area and streamflow gauge records used in this study, the division of the HKH region into sub-basins, characteristics of each sub-basin, and the methods applied in this study. Section 3 contains the results, and Sect. 4 the discussion. The conclusion is described in Sect. 5.

Material And Methods

2.1. Study area and data

The Upper Indus Basin (UIB) is located between latitudes 33° 40′ and 37° 12′ and longitudes 70° 30′ and 77° 30′. The total catchment area of the UIB is 286,000 km^2, with an average elevation of 3750 m Above Mean Sea Level (AMSL). In the HKH region of Pakistan, there were 34 gauging stations installed for recording of the river discharge (Fig. 1). The daily streamflow data from 1961–2013 was collected from the Water and Power Development Authority (WAPDA), Pakistan, with continuous records ranging from 30 to 52 years.

Table 1
List of streamflow gauges installed in the Hindukush-Karakoram-Himalayas (HKH) region and data period used in this study

River name @ Gauge name	Latitude	Longitude	Data Period
Shyok River @ Yugo	35.2	76.1	1974–2013
Astore Rive @ Doyian	35.5	74.7	1974–2013
Hunza River @ Dainyor Bridge	35.9	74.4	1966–2013
Gilgit River @ Alam Bridge	35.8	74.6	1966–2013
Gilgit River @ Gilgit	35.9	74.3	1970–2013
Chitral River @ Chitral	35.8	71.8	1964–2013
Swat River @ Chakdara	34.6	72	1962–2013
Swat River @ Kalam	35.5	72.6	1962–2013
Bara River @ Jhansi Post	33.9	71.4	1962–2013
Kabul River @ Nowshera	34	72	1962–2013
Kurram River @ Thal	33.4	70.5	1968–2013
Kunhar River @ Naran	34.9	73.6	1962–2013
Kunhar River @ Garhi Habib Ullah	34.4	73.4	1962–2013
Kanshi River @ Palote	33.2	73.4	1962–2013
Soan River @ Chirah	33.7	73.3	1962–2013
Sil River @ Chahan	33.5	72.9	1962–2013
Sil River @ Kharmong	33.5	72.9	1982–2013
Soan River @ Dhok Pathan	33.1	72.3	1964–2013
Neelum River @ Domel	34.5	73.5	1976–2013
Neelum River @ Muzaffarabad	34.4	73.5	1964–2013
Jhelum River @ Chinari	34.2	73.8	1970–2013
Jhelum River @ Kohala	34.1	73.5	1966–2013
Jhelum River @ Azad Pattan	33.5	73.6	1970–2013
Poonch River @ Kotli	33.5	73.6	1962–2013
Indus River @ Kachura	35.5	75.4	1970–2013
Indus River @ Bunji	35.7	74.6	1962–2013

River name @ Gauge name	Latitude	Longitude	Data Period
Indus River @ Shatial	35.5	73.6	1984–2013
Indus River @ Besham Qila	34.9	72.9	1970–2013
Gorband River @ Karora	34.6	72.8	1976–2013
Brandu River @ Daggar	34.5	72.5	1970–2013
Siran River @ Phulra	34.3	73.1	1970–2013
Indus River @ Khairabad	33.9	72.2	1982–2013
Haro River @ Garriala	33.8	72.3	1962–2013
Indus River @ Massan	33	71.7	1972–2013

2.2. Sub-basins of the HKH region within Pakistan

The entire HKH region was divided into 13 sub-basins (Fig. 2) using the modified Soil and Water Assessment Tool (SWAT+) with the QGIS tool. The main characteristics of each sub-basin and streamflow gauges installed in each sub-basin are provided in Table 2.

Table 2: Sub-basins and relevant characteristics in HKH region within Pakistan.

Sub - basin	River name @ Gauge name	Total number of streamflow gauge (s)	Region in HKH	Catchment area (km^2)	Glacier/snow coverage (% of total catchment area)	References
Shyok	Shyok River @ Yugo	1	Central Karakoram range	33670	24	(Bhambri et al. 2013; Hewitt 2014; ul Hassan et al. 2018)
Hunza	Hunza River @ Dainyor Bridge	1	Southwest Karakoram range	13157	21	(Hewitt 2006; ul Hassan et al. 2018)
Astore	Astore Rive @ Doyian	1	Western Himalaya	3995	6.3	(Muhammad et al. 2019)
Gilgit	Gilgit River @ Alam Bridge Gilgit River @ Gilgit	2	Hindukush mountain range	26159	14.2	(Ali et al. 2017; Ul Hussan et al. 2020)
Chitral	Chitral River @ Chitral	1	Hindukush mountain range	11396		(Ahmad et al. 2020)
Swat	Swat River @ Kalam Swat @ Chakdara River	2	Hindukush mountain range	5776	-	-
Kabul	Bara River @ Jhansi Post Kabul River @ Nowshera	2	Hindukush range	33709	-	(Mack et al. 2013)
Kuram	Kuram River @ Thal	1	Hindukush range	-	-	-
Kunhar	Kunhar River @ Naran Kunhar River @ Garhi Habib Ullah	2	Southern Himalayas	2354	2.1	(Mahmood et al. 2016)
Kanshi	Kanshi River @ Palote	1	Southern Himalayas	-	-	(Mahmood et al. 2016)

Soan	Soan River @ Chirah, Sil River @ Chahan, Sil River @ Kharmong, and Soan River @ Dhok Pathan	4	Eastern Himalayas	-	-	(Ashfaq et al. 2014)
Jhelum Basin part of UIB	Neelum River @ Domel, Neelum River @ Muzaffarabad, Jhelum River @ Chinari, Jhelum River @ Kohala, Jhelum River @ Azad Pattan, and Poonch River @ Kotli	6	Southern Himalayas	4176	4.5	(Khanday et al. 2021) (Kalair et al. 2019) (Singh Jasrotia et al. 2021)
Indus Basin part of UIB	Indus River @ Kachura, Indus River @ Bunji, Indus River @ Shatial, Indus River @ Besham Qila, Gorband River @ Karora, Brandu River @ Daggar, Siran River @ Phulra, Indus River @ Khairabad, Haro River @ Garriala, and	10	Tibetan Plateau + Central Karakoram	55975	-	(Kalair et al. 2019)

	Indus River @Massan

2.3. Change point detection

A rank-based test known as the Pettitt test was used to detect (in)homogeneities (Pettitt 1979) in the annual time series of streamflow of 34 gauging stations installed across the HKH region. The advantage of this method is that it checks the homogeneity and locates the abrupt change point (year) of any time series. This method has been extensively used for hydro-climatic time series worldwide (Ahmed et al. 2020a; Ahmed et al. 2020c; Rocha and de Souza Filho 2020; Thakur et al. 2020). However, in previous studies conducted within the UIB (Ashraf et al. 2021; Yaseen et al. 2020), no data quality tests were performed to verify the reliability of the time series before using traditional trend tests (e.g Mann-Kendall, linear regression, etc.). Therefore, this study verified the reliability of the streamflow time series for 34 gauges by checking the (in)homogeneity in the time series.

2.4. Innovative Polygon Trend Analysis

Innovative Trend Analysis (ITA) developed by (Sen 2012; Şen 2014; Şen 2017a; Şen 2017b) has been widely used in many river basins of the world to analyze trends, and the advantages of the ITA method over classical methods have been well established (Caloiero et al. 2018; Guclu 2016; Güçlü 2018; Wu and Qian 2017). However, in this study, the Innovative Polygon Trend Analysis (IPTA) method, a very recently developed trend detection method introduced by Sen et al. (2019), is applied. The advantage of IPTA over ITA is that it detects the trends in a time series and describes the transition between increasing and decreasing trend months/ seasons in the form of a polygonal graphical display. Sen et al. (2019) stated that the IPTA graphical method has some advantages over traditional classical methods:

a) IPTA is a non-parametric approach and free from the serial dependency of time series;

b) IPTA provides not only trends but also their transitions (from increasing to decreasing trends and vice versa) in successive months/ seasons;

c) Trend slopes and lengths can be determined between two consecutive months/ seasons;

d) IPTA provides a good linguistic and numerical interpretation and deduction of trends in the form of a polygon(s);

e) If more than one polygon is formed, this indicates the complexity and dynamics of the hydro-meteorological events for that station (Sen et al. 2019).

In order to apply IPTA, we followed the procedure explained below:

i. The monthly streamflow data was divided into two equal time series;

ii. The monthly mean and standard deviation for each time series was calculated;

iii. The first time period is presented on the x-axis and the second time period on the y-axis in a cartesian coordinate system;

iv. The months (January up to and including December) were joined by straight lines that resulted in polygons;

v. The trend length (*TL*) and trend slope (*SL*) between every two consecutive months were calculated using the following formula

$$TL = \sqrt{(x_2 - x_1)^2 - (y_2 - y_1)^2} \quad (1)$$

$$SL = \frac{y_2 - x_2}{y_1 - x_1} \quad (2)$$

where *TL* and *SL* are trend length and trend slope, x_1 and x_2 are two consecutive months in the first period, and y_1 and y_2 are two consecutive months in the second period;

vi. Draw the no-trend line (1:1 line) at 45° in the cartesian coordinate system;

vii. The months below (above) the no-trend line shows decreasing (increasing) trends, while the months close to or on the no-trend line show no particular trend.

Figure 3 illustrates the IPTA method, where a rising streamflow trend is observed for July-December and a decreasing trend for January-June. The length and slope of the connecting lines between consecutive months show the relative changes in trend magnitude and direction. The IPTA example presented in Fig. 3 only shows one polygon. A detailed explanation of the IPTA method is available in Sen et al. (2019). The possibility to interpret periodicity and sequential behavior in a hydro-meteorological time series can also be assessed using the IPTA method. Moreover, the internal variability quantitatively and qualitatively can be explored with the IPTA method as well.

Results

5.1. Time series analysis

The annual streamflow time series for the entire HKH region under study were evaluated using the Pettitt test to ensure homogeneity. The Pettitt test results presented in Table 3 showed that all stations have inhomogeneous time series. The change point differs from station to station in each sub-basin, except for the Kunhar sub-basin. In the Kunhar sub-basin, Naran and Garhi Habib Ullah stations have the same change year (1996). In the Soan sub-basin, the change year is the same (1997) for Chahan and Dhok Pathan stations, whereas for Chirah and Kharmong stations the change years are 1995 and 2000, respectively. The Jhelum basin also has the same change year (1996) for all gauging stations except Kotli station, which has 1998 as change year. The change years are also different for all stations installed in the Indus part of the UIB (see Table 3).

Table 3
The results of the Pettitt test showing the change year in annual streamflow of sub-basins in the HKH region.

Sub-basin	River name @ Gauge name	Change Year
Shyok	Shyok River @ Yugo	1993
Astore	Astore Rive @ Doyian	1985
Hunza	Hunza River @ Dainyor Bridge	1985
Gilgit	Gilgit River @ Alam Bridge	1973
	Gilgit River @ Gilgit	2002
Chitral	Chitral River @ Chitral	1987
Swat	Swat River @ Chakdara	1989
	Swat River @ Kalam	1999
Kabul	Bara River @ Jhansi Post	1979
	Kabul River @ Nowshera	1969
Kurram	Kurram River @ Thal	1994
Kunhar	Kunhar River @ Naran	1996
	Kunhar River @ Garhi Habib Ullah	1996
Kanshi	Kanshi River @ Palote	1999
Soan	Soan River @ Chirah	1995
	Sil River @ Chahan	1997
	Sil River @ Kharmong	2000
	Soan River @ Dhok Pathan	1997
Jhelum	Neelum River @ Domel	1998
	Neelum River @ Muzaffarabad	1996
	Jhelum River @ Chinari	1996
	Jhelum River @ Kohala	1996
	Jhelum River @ Azad Pattan	1996
	Poonch River @ Kotli	1998
Indus	Indus River @ Kachura	1987
	Indus River @ Bunji	1987

Sub-basin	River name @ Gauge name	Change Year
	Indus River @ Shatial	2002
	Indus River @ Besham Qila	1975
	Gorband River @ Karora	2000
	Brandu River @ Daggar	1975
	Siran River @ Phulra	1985
	Indus River @ Khairabad	1999
	Haro River @ Garriala	1998
	Indus River @ Massan	1987

5.2. Interannual variations in streamflow

The mean monthly streamflow and its interannual variation for the entire study area are presented in Fig. 4. The spatial distribution of the monthly Coefficient of Variation (CV) for all gauges for the available data period (see Table 1) is presented in Fig. 5. It shows much clearer the intra-annual (between months), interannual (sizes of the dots) and spatial distribution of CVs. The Yogo, Kharmong, Alam Bridge to Besham Qila gauging stations have CV values ranging from 0.09–0.39. However, the highest values of CV were obtained for Chirah, Chahan, Garriala, Dhok Pathan, and Jhansi Post gauges, ranging from 0.39–2.45. The Chirah gauge has the highest CV value (2.45) in June, followed by Chahan gauge (CV = 2.12) in September. CV values ranging from 0.26–0.87 were obtained for Thal, Phulra, Kotli and Daggar gauging stations. There is less variability in CVs upstream might be caused by the storage effects of the glaciers and snow. Comparing CV values between stations for a particular month shows the similar spatial patterns in each month. All gauges have similar CV values ranging from 0.09–1.2 in January, November and October, followed by July-August (CV = 0.13–1.19) and then followed by February and March (CV = 0.09–1.27). The highest CV values were obtained in September (CV = 0.16 2.12) and June (CV = 0.19–2.45) for all gauges in the study area.

5.3. Trend Results for each sub-basin

5.3.1. Shyok, Hunza and Astore sub-basins

Figure 6 shows the changes in the mean and standard deviation of monthly streamflow of Shyok, Hunza, and Astore sub-basins. The monthly means increased in high flow months, while no trends were observed in the low flow months from October to March/April in Shyok and Astore sub-basins. There is a strong increasing trend in August and July for the Shyok sub-basin and May for the Astore sub-basin. The streamflow shows a decreasing trend from June to September in the Hunza sub-basin and no trend for the other months (October – April). A strong decreasing trend was observed in July and August, whereas the transition from May (increase) to June (decrease) in mean streamflow also occurred in the same sub-basin. For mean monthly IPTA results, the maximum trend lengths were calculated as 1198.7 m^3/s, 854.7 m^3/s, and 243.7 m^3/s for Shyok, Hunza and Astore sub-basins, respectively. The maximum trend slopes were 1.9, 1.4, and 1.6 for Shyok, Hunza, and Astore sub-basins.

The standard deviation results showed an increasing trend in May and June and a decreasing trend in July and August for the Shyok sub-basin. There is a strong decreasing trend in the Hunza sub-basin in July and August, followed by September and June. There is an increasing trend of the standard deviation in the Astore sub-basin in all months except January-March and December having no trend. The maximum trend length was 249.4 m^3/s, 197.9 m^3/s, and 74.6 m^3/s for Shyok, Hunza, and Astore sub-basins, respectively. The maximum trend slope was 6.2, 26.2, and 3.4 for Shyok, Hunza, and Astore sub-basins, respectively.

5.3.2. Gilgit, Chitral and Swat sub-basins

Figure 7 shows the changes in the mean (row one and three) and standard deviation (row two and four) of monthly streamflow in Gilgit, Chitral, and Swat sub-basins. The Gilgit River at the Gilgit gauging station showed an increasing trend from May to September, while the other months have no trend in the mean and standard deviation. There are decreasing trends for Alam Bridge gauge in high flow months (June to August), an increasing trend for May, and the other months lies on the no trend line.

In the Chitral sub-basin, the mean IPTA graphs show no trend from October to April and increases from May to September. There is a strong increasing trend for July compared to the other months in the summer period. There is a decreasing trend for the standard deviation for June and September.

In the Swat sub-basin, the mean and standard deviation of monthly streamflow for Chakdara gauge increased for all months. For the mean streamflow at Kalam gauge, an increasing trend was observed for April and May, however June, July and August show a decreasing trend and there is no trend for the other months. The standard deviation plots show increasing trends for the same station.

5.3.3. Kabul, Kurram and Kunhar sub-basins

Figure 8 shows the changes in the mean (row one and three) and standard deviation (row two and four) of monthly streamflow in Kabul, Kurram and Kunhar sub-basins. The Kabul sub-basin at the Jhansi Post gauging station showed a decreasing trend except for August (increasing trend), whereas no trend was observed in February during the entire data period. However, a strong decreasing trend exists in April. A higher trend length was found from March to April, and there is a transition from August (increase) to September (decrease) in mean streamflow for the Jhansi Post observation gauge. The standard deviation plots showed a decreasing trend in March, April, October and November with no trend for December and January, while increasing from February-September. For the Nowshera gauge of the Kabul sub-basin, a decreasing trend in June and August and an increasing trend in May are found, while other months have no trends in mean streamflow. The standard deviation showed a decrease in May and June, while the other months observed increasing trends.

The Kuram sub-basin showed a decreasing trend in most months except July-September, which observed an increasing trend in mean streamflow. A shift in trends is found from June (July) decreasing to increasing, and September (October) increasing to decreasing.

The Kunhar sub-basin at Naran station showed no trend for most of the months except June and July, which faced decreasing trends for mean streamflow. The standard deviation showed similar results for June and July and an increasing trend from August-May. There is a shift in trends from May (increasing) to June (decreasing) and July (decreasing) to August (increasing) in mean and standard deviation for Naran station. The maximum trend length for the mean and standard deviation plots were 106 m^3/s and 26.9 m^3/s respectively, and the maximum trend slopes were 3.7 and 3.2, respectively. For Garhi Habib Ullah gauge of Kunhar sub-basin, similar trends were observed for mean streamflow, and there is only a decrease in June for the standard deviation. The maximum trend lengths are 127.4 m^3/s and 43.8 m^3/s for the mean and standard deviation plots, respectively and the trend slopes were 2.2 and 8.3 for the mean and standard deviation plots.

5.3.4. Kanshi and Soan sub-basins

In the Kanshi sub-basin, there is an increasing trend in July and a decreasing trend in August- September, while the rest of the months have no trends in mean streamflow (Fig. 9). The mean trend length is 23.4 m^3/s. A decreasing trend in the standard deviation of monthly streamflow was observed in January, March, June, August, October and November,, while the other months have increasing trends in the standard deviation. There is a transition from increasing to decreasing from July to August. The maximum trend length of the standard deviation was 21.5 m^3/s and the maximum trend slope was 9.4 in the Kanshi sub-basin.

Decreasing trends or no trends in mean streamflow were observed for all four gauging stations in the Soan sub-basin, while the standard deviation showed increasing and decreasing trends (see Fig. 9). The maximum trend length (slope) values for mean plots were recorded as 17.2 m^3/s (10.6), 6.2 m^3/s (3.1), 910.7 m^3/s (1.9), and 154.1 m^3/s (2) for Chirah, Chahan, Kharmong, and Dhok Pathan gauges in the Soan sub-basin, respectively.

5.3.5. Jhelum Basin part of UIB

Figure 10 shows the IPTA results for the Jhelum Basin of UIB for the mean and standard deviation of monthly streamflow. There is a strong decreasing trend for mean streamflow for Domel, Muzaffarabad and Chinari gauges. However, there was no trend for low flow months (September to February) for all these gauges. The maximum trend lengths for mean IPTA plots were 299.4 m^3/s, 423 m^3/s, and 268.4

m^3/s for Domel, Muzaffarabad, and Chinari stations, respectively. The maximum trend slopes were 1, 1.7, and 1.5 for Domel, Muzaffarabad, and Chinari stations, respectively. The standard deviation showed a decreasing trend for Domel (September-October) and Chinari in May, August, November, and December. However, January and February have no trend for these stations, while for Domel (Chinari) increasing trends in March to August (April June, July and September). The maximum trend length for standard deviation plots of Domel, Muzaffarabad, and Chinari stations was calculated as 130.2 m^3/s, 130.6 m^3/s, and 112 m^3/s, respectively.

The Kohala and Azad Pattan gauges have also observed decreasing trends in high flow months (June, July, and August) and no trends in mean streamflow for the rest of the months, whereas Kotli station showed an increasing trend for February, March, and September. On the contrary, standard deviation plots for Kohala, Azad Pattan, and Kotli stations resulted in a rising trend for most of the months. The maximum trend lengths were 763 m^3/s, 775.1 m^3/s, and 183.3 m^3/s for Kohala, Kotli, and Azad Patan stations, respectively.

5.3.6. Indus Basin part of UIB

For the Indus Basin part of UIB, the IPTA plots showed increasing trends in mean streamflow for Kachura, Bunji, and Shatial Bridge gauging stations in spring and summer months (May-September), whereas no trends were recorded for October-April (Fig. 11). However, the standard deviation showed a decreasing trend in June and July and a strong increasing trend in August. A transition exists from July to August from decreasing to increasing, while the rest of the months have no trends for Kachura station. The standard deviation plots for the Bunji station showed an increasing (decreasing) trend in May, August (June and July). The Shatial Bridge standard deviation plots are similar to the results of mean plots (Fig. 11). The maximum trend lengths for the mean (standard deviation) plots were 2494.6 (435.8) m^3/s, 4167.3 (547.5) m^3/s, and 4497.8 (964.2) m^3/s for Kachura, Bunji, and Shatial Bridge station, respectively.

For Besham Qila station, there is a decreasing trend in mean streamflow only in August and September and no trend in October, whereas the rest of the months showed a strong increasing trend (Fig. 11). However, this station has a complex polygon, which shows that this region has remained in non-systematic weather transitions. Similar behavior is shown in the plots for Daggar station, while Karora station showed continuous decreasing trends for most months except November to February. The standard deviation plots for Behsam Qila station showed decreasing trends from June to November and an increasing one in August. For Karora station, standard deviation plots are similar to the plots for mean streamflow. Daggar station also has a complex polygon that indicates the non-symmetry in the climatic conditions (e.g. uneven precipitation (temperature) patterns, timings and intensities) of this region. The maximum trend lengths of mean plots were 6.4 m^3/s, 24 m^3/s, and 6.2 m^3/s for Besham Qila, Karora, and Daggar stations, respectively, and the maximum trend lengths for the standard deviation were 5.6 m^3/s, 9.9 m^3/s, and 6.3 m^3/s, respectively.

For Phulra station, there are increasing and decreasing trends in mean streamflow in different months; however, these trends are very close to the no trend line. For Garraila station, decreasing trends in mean streamflow occur in most of the months and there is no trend from October to February (Fig. 11). In Khairabad station, all months show decreasing trends. The standard deviation plots for Phulra, Garraila, and Khariabad stations showed increasing trends for most of the months (Fig. 11). The maximum trend lengths were 22.2 m^3/s, 72.8 m^3/s, and 4380.5 m^3/s for mean plots, and 17 m^3/s, 77.4 m^3/s, and 1560.8 m^3/s for standard deviation plots in Phulra, Garraila, and Khairabad, respectively.

Massan hydrological station is the last streamflow gauging station in the HKH basin in UIB. The mean streamflow is decreasing in June, July and August and shows no trend in the other months (Fig. 11). For the standard deviation, an increasing trend was observed only in August. There is a sharp transition from August to September from increasing to decreasing trends. The maximum trend lengths were 4984.1 m^3/s and 2110.7 m^3/s for the mean and standard deviation, respectively. The maximum trend slopes were 2.1 and 2.5 for the mean and standard deviation plots, respectively.

Discussion

The hydrology of the Hindukush Karakoram Himalaya (HKH) region is very sensitive to climate change (Fowler and Archer 2006) and prone to flooding (Khan 2013). The flood of 2010 affected 17,553 villages and flooded an area of 160,000 km^2 (Rahman and Shaw 2015). In this study, the variations and changes in monthly streamflow in the sub-basins of the HKH region within Pakistan were analyzed using the recently developed trend analysis method known as the Innovative Polygon Trend Analysis (IPTA) method (Sen et al. 2019). Ul Hussan et al. (2020) and Sharif et al. (2013) reported that the streamflow increased for glacier and snow-fed sub-basins in the HKH region of Pakistan during December-June, whereas in our study, there is an increasing trend for all months in the glacial and snow-fed sub-basins Shyok and Astore of HKH. This contradiction is due to differences in the design of classical Mann Kendall trend test used in these studies and the recent assumptions free IPTA trend analysis method used in this study. Furthermore, Ul Hussan et al. (2020) and Sharif et al. (2013) reported that the Hunza sub-basin trends showed decreasing behavior in July and August, whereas in our study, there is also a decrease in June and September. The Gilgit sub-basin at Alam Bridge gauge showed a decreasing trend in high flow months (June-August), which is inconsistent with the findings of Ul Hussan et al. (2020) and Sharif et al. (2013) because they reported an increasing trend in high flows months for same sub-basin. For the Swat sub-basin, the trends in streamflow are increasing for May and November, which is consistent with Sharif et al. (2013), while contradictory findings were reported for the rest of the year. Our study results are also different from Yaseen et al. (2020) for Kunhar, Kanshi and Soan sub-basins due to the statistical test used in these studies. Sharif et al. (2013) reported upward trends in April and May and downward trends for the rest of the year in Kunhar and Kanshi sub-basins, however in our study, downward trends were observed from June to August. The current hydrological regimes largely depend on the timing of precipitation, its trends and duration, and additionally the snow-ice glacial reserves in the upper reaches of UIB (Archer 2003; Sharif et al. 2013). The enhancement of the seasonal pattern of streamflow in the upper reaches of

UIB is possibly due to the melting of snow and ice that potentially influence floods and hydropower generation (Biemans et al. 2019).

In the Jhelum basin, upward trends were found for Muzaffarabad station from August to May and decreasing ones for June and July (Sharif et al. 2013). However, in our study, decreasing trends are found for April-August, while other months show increasing trends except for October (which showed no trend). Lutz et al. (2016) reported an increase in streamflow of the upper river reaches in the Karakoram region and decreasing trends for lower reaches of the same region. In the Indus basin part of UIB, streamflow at Kachura and Bunji stations increased in all months and this is in agreement with Sharif et al. (2013). For Besham Qila, our findings are also consistent with (Sharif et al. 2013) for January-March, while opposite results were obtained for other months for this station. Behsam Qila station showed a decreasing trend in August-September using the IPTA method, whereas Ul Hussan et al. (2020) found an increasing trend. Karora station showed a decreasing trend throughout the year, which shows the consistency with Ul Hussan et al. (2020). Daggar station of Indus basin showed a decreasing trend in March-April, and August-September (Ul Hussan et al. 2020), while in our study, only the streamflow in August was decreasing.

Conclusion

In this study, the variations and changes in monthly streamflow of the Hindukush Karakoram Himalaya (HKH) region were investigated using the recently introduced Innovative Polygon Trend Analysis (IPTA) method. The entire HKH region of Pakistan was divided into 13 sub-basins and the IPTA method was applied to each gauging station in each sub-basin. There were 34 streamflow gauging stations installed in the study area, and change point analysis was carried out to check the (in)homogeneity in the time series. The IPTA method showed that streamflow in high elevated glaciated and snow/ice-covered sub-basins (Shyok, Astore, Gilgit, and Chitral) increased for high flow months (June-August), whereas in the Hunza sub-basin, a decreasing trend in high flow months and no trend in low flow months was observed. In the Swat and Kabul sub-basins, the upstream gauges showed an upward trend throughout the year, while the downstream gauges exhibited a strong decrease in the high flow months (June-August). In the Kunhar and Soan sub-basins, the streamflow decreased in the high flow months (June-August), while the other months showed no trend.

In the Jhelum basin part of UIB, Muzaffarabad, Chinari, and Azad Pattan gauges showed a decreasing trend in the high flow months (June-August), while in the other months, mostly no trend was observed. The Kohala and Kotli stations also showed decreasing trends in the high flow months, while increasing trends were found from February to May. In the Indus basin part of the UIB, the results showed that upstream gauges located in snow and ice-covered regions (Kachura, Bunji, Shatial Bridge and Behsam Qila) observed an upward trend in most of the months except November-February, which showed no trend. However, stations installed in the middle reaches (Daggar and Phulra) showed a mixed trend (increasing/decreasing). The lower altitude stations (Garriala, Khairabad, and Massan) of the UIB showed decreasing trends throughout the year. The results derived from this study can support decision and policy makers in sustainable water management and help to understand the complex hydrology of sub-basins in the HKH region of Pakistan.

Declarations

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Conflict of Interest: The authors declare no conflict of interest.

Availability of data and materials:

The streamflow data is the property of the Water and Power Development Authority (WAPDA), Pakistan, and can be requested via official channels.

Authors’ Contributions:

N. Ahmed designed the research, highlighted the problem, and formulated the research plan. N.Ahmed.and G. Ceribasi analyzed the data. G. Wang, M.J. Booij and M.S. Bhat helped with the interpretation of the results. G. Wang supervised the study and also provided the financial resources used in this study. A. I. Ceyhunlu and A. Ahmed helped in the model development and analysis of results. N. Ahmed wrote the original draft, whereasG.Wang. M.S. Bhat and M.J. Booij reviewed the draft paper. All authorsconfirm the final version of the article forsubmission to the journal. All authors have read and agreed to the publishedversion of the manuscript.

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References

1. Ahmad S, Israr M, Liu S et al. (2020) Spatio-temporal trends in snow extent and their linkage to hydro-climatological and topographical factors in the Chitral River Basin (Hindukush, Pakistan) Geocarto International **35**:711-734.
2. Ahmed K, Nawaz N, Khan N et al. (2020a) Inhomogeneity detection in the precipitation series: case of arid province of Pakistan Environment, Development and Sustainability doi:10.1007/s10668-020-00910-y
3. Ahmed N, Wang G-x, Oluwafemi A et al. (2020b) Temperature trends and elevation dependent warming during 1965–2014 in headwaters of Yangtze River, Qinghai Tibetan Plateau Journal of Mountain Science **17**:556-571. doi:10.1007/s11629-019-5438-3
4. Ahmed N, Wang G, Booij MJ et al. (2020c) Climatic Variability and Periodicity for Upstream Sub-Basins of the Yangtze River, China Water **12**:842. doi:10.3390/w12030842
5. Aizen V, Aizen E, Nikitin S (2002) Glacier regime on the northern slope of the Himalaya (Xixibangma glaciers) Quaternary International **97**:27-39.
6. Akhtar M, Ahmad N, Booij MJ (2008) The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios Journal of hydrology **355**:148-163.
7. Ali K, Bajracharya RM, Sitaula BK et al. (2017) Morphometric analysis of Gilgit river basin in mountainous region of Gilgit-Baltistan Province, Northern Pakistan Journal of Geoscience and Environment Protection **5**:70.
8. Archer D (2003) Contrasting hydrological regimes in the upper Indus Basin Journal of Hydrology **274**:198-210.
9. Archer DR, Fowler HJ (2004) Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications Hydrology and Earth System Sciences **8**:47-61.
10. Ashfaq A, Ashraf M, Bahzad A (2014) Spatial and temporal assessment of groundwater behaviour in the Soan Basin of Pakistan University of Engineering and Technology Taxila Technical Journal **19**:12.
11. Ashraf MS, Ahmad I, Khan NM et al. (2021) Streamflow Variations in Monthly, Seasonal, Annual and Extreme Values Using Mann-Kendall, Spearmen’s Rho and Innovative Trend Analysis Water Resources Management **35**:243-261. doi:10.1007/s11269-020-02723-0
12. Benn DI, Owen LA (1998) The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: review and speculative discussion Journal of the Geological Society **155**:353-363.
13. Bhambri R, Bolch T, Kawishwar P et al. (2013) Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram The Cryosphere **7**:1385-1398.
14. Biemans H, Siderius C, Lutz A et al. (2019) Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain Nature Sustainability **2**:594-601.
15. Bolch T, Kulkarni A, Kääb A et al. (2012) The state and fate of Himalayan glaciers Science **336**:310-314.

16. Brun F, Berthier E, Wagnon P et al. (2017) A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016 Nature geoscience **10**:668-673.
17. Caloiero T, Coscarelli R, Ferrari E (2018) Application of the Innovative Trend Analysis Method for the Trend Analysis of Rainfall Anomalies in Southern Italy Water Resources Management **32**:4971-4983. doi:10.1007/s11269-018-2117-z
18. Farhan SB, Zhang Y, Ma Y et al. (2015) Hydrological regimes under the conjunction of westerly and monsoon climates: a case investigation in the Astore Basin, Northwestern Himalaya Climate Dynamics **44**:3015-3032.
19. Forsythe N, Fowler HJ, Li X-F et al. (2017) Karakoram temperature and glacial melt driven by regional atmospheric circulation variability Nature Climate Change **7**:664-670.
20. Fowler H, Archer D (2006) Conflicting signals of climatic change in the Upper Indus Basin Journal of Climate **19**:4276-4293.
21. Gardelle J, Berthier E, Arnaud Y (2012) Slight mass gain of Karakoram glaciers in the early twenty-first century Nature geoscience **5**:322-325.
22. Greene AM, Robertson AW (2017) Interannual and low-frequency variability of Upper Indus Basin winter/spring precipitation in observations and CMIP5 models Climate Dynamics **49**:4171-4188.
23. Guclu YS (2016) Comments on "Comparison of Mann-Kendall and innovative trend method for water quality parameters of the Kizilirmak River, Turkey (Kisi and Ay, 2014)" and "An innovative method for trend analysis of monthly pan evaporations (Kisi, 2015)" Journal of Hydrology **538**:878-882. doi:10.1016/j.jhydrol.2016.04.064
24. Güçlü YS (2018) Multiple Şen-innovative trend analyses and partial Mann-Kendall test Journal of Hydrology **566**:685-704.
25. Hamed KH, Rao A (1998) A modified Mann-Kendall trend test for autocorrelated data Journal of Hydrology **204**:182-196. doi:10.1016/S0022-1694(97)00125-X
26. Hannah DM, Kansakar SR, Gerrard A et al. (2005) Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns Journal of Hydrology **308**:18-32.
27. Harpold AA, Brooks PD (2018) Humidity determines snowpack ablation under a warming climate Proceedings of the National Academy of Sciences **115**:1215-1220.
28. Hewitt K (2005) The Karakoram anomaly? Glacier expansion and the ‘elevation effect,’Karakoram Himalaya Mountain Research and Development **25**:332-340.
29. Hewitt K (2006) Glaciers of the Hunza Basin and related features Karakoram in Transition: Culture, Development and Ecology in the Hunza Valley:49-72.
30. Hewitt K (2014) Glaciers of the Karakoram Himalaya. Springer,
31. Immerzeel WW, Droogers P, De Jong S et al. (2009) Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing Remote sensing of Environment **113**:40-49.
32. Immerzeel WW, Van Beek LP, Bierkens MF (2010) Climate change will affect the Asian water towers Science **328**:1382-1385.

33. Kalair AR, Abas N, Ul Hasan Q et al. (2019) Water, energy and food nexus of Indus Water Treaty: Water governance Water-Energy Nexus **2**:10-24. doi:https://doi.org/10.1016/j.wen.2019.04.001
34. Kapnick SB, Delworth TL, Ashfaq M et al. (2014) Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle Nature Geoscience **7**:834-840.
35. Kehrwald NM, Thompson LG, Tandong Y et al. (2008) Mass loss on Himalayan glacier endangers water resources Geophysical Research Letters **35**
36. Kendall M (1975) Rank correlation methods Charles Griffin, London (fourth edition, 1970)
37. Khan AN (2013) Analysis of 2010-flood causes, nature and magnitude in the Khyber Pakhtunkhwa, Pakistan Natural hazards **66**:887-904.
38. Khanday SA, Bhat SU, Islam ST et al. (2021) Identifying lithogenic and anthropogenic factors responsible for spatio-seasonal patterns and quality evaluation of snow melt waters of the River Jhelum Basin in Kashmir Himalaya CATENA **196**:104853. doi:https://doi.org/10.1016/j.catena.2020.104853
39. Khattak MS, Babel MS, Sharif M (2011) Hydro-meteorological trends in the upper Indus River basin in Pakistan Climate Research **46**:103-119.
40. Kraaijenbrink P, Bierkens M, Lutz A et al. (2017) Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers Nature **549**:257-260.
41. Lutz AF, Immerzeel WW, Kraaijenbrink PD et al. (2016) Climate change impacts on the upper indus hydrology: Sources, shifts and extremes PloS one **11**:e0165630.
42. Mack TJ, Chornack MP, Taher MR (2013) Groundwater-level trends and implications for sustainable water use in the Kabul Basin, Afghanistan Environment Systems and Decisions **33**:457-467. doi:10.1007/s10669-013-9455-4
43. Mahmood R, Jia S, Babel MS (2016) Potential Impacts of Climate Change on Water Resources in the Kunhar River Basin, Pakistan Water **8**:23.
44. Mann HB (1945) Nonparametric Tests Against Trend Econometrica **13**:245-259. doi:10.2307/1907187
45. Minora U, Bocchiola D, D'Agata C et al. (2013) 2001–2010 glacier changes in the Central Karakoram National Park: a contribution to evaluate the magnitude and rate of the" Karakoram anomaly" The Cryosphere Discussions **7**:2891-2941.
46. Muhammad S, Tian L, NÜSser M (2019) No significant mass loss in the glaciers of Astore Basin (North-Western Himalaya), between 1999 and 2016 Journal of Glaciology **65**:270-278. doi:10.1017/jog.2019.5
47. Nie Y, Pritchard HD, Liu Q et al. (2021) Glacial change and hydrological implications in the Himalaya and Karakoram Nature Reviews Earth & Environment doi:10.1038/s43017-020-00124-w
48. Palazzi E, von Hardenberg J, Terzago S et al. (2015) Precipitation in the Karakoram-Himalaya: a CMIP5 view Climate Dynamics **45**:21-45.
49. Pettitt A (1979) A non-parametric approach to the change-point problem Journal of the Royal Statistical Society: Series C (Applied Statistics) **28**:126-135.

50. Rahman AU, Shaw R (2015) Flood Risk and Reduction Approaches in Pakistan. In: Rahman A-U, Khan AN, Shaw R (eds) Disaster Risk Reduction Approaches in Pakistan. Springer Japan, Tokyo, pp 77-100. doi:10.1007/978-4-431-55369-4_4
51. Rao MP, Cook ER, Cook BI et al. (2018) Six Centuries of Upper Indus Basin Streamflow Variability and Its Climatic Drivers Water Resources Research **54**:5687-5701. doi:https://doi.org/10.1029/2018WR023080
52. Rashid MU, Latif A, Azmat M (2018) Optimizing irrigation deficit of multipurpose Cascade reservoirs Water resources management **32**:1675-1687.
53. Ridley J, Wiltshire A, Mathison C (2013) More frequent occurrence of westerly disturbances in Karakoram up to 2100 Science of the Total Environment **468**:S31-S35.
54. Rocha RV, de Souza Filho FdA (2020) Mapping abrupt streamflow shift in an abrupt climate shift through multiple change point methodologies: Brazil case study Hydrological Sciences Journal **65**:2783-2796.
55. Sen PK (1968) Estimates of the Regression Coefficient Based on Kendall's Tau Journal of the American Statistical Association **63**:1379-1389. doi:10.1080/01621459.1968.10480934
56. Sen Z (2012) Innovative Trend Analysis Methodology Journal of Hydrologic Engineering **17**:1042-1046. doi:10.1061/(asce)he.1943-5584.0000556
57. Şen Z (2014) Trend identification simulation and application Journal of Hydrologic Engineering **19**:635-642.
58. Şen Z (2017a) Innovative trend methodologies in science and engineering. Springer,
59. Şen Z (2017b) Innovative trend significance test and applications Theoretical and Applied Climatology **127**:939-947. doi:10.1007/s00704-015-1681-x
60. Sen Z, Sisman E, Dabanli I (2019) Innovative Polygon Trend Analysis (IPTA) and applications Journal of Hydrology **575**:202-210. doi:10.1016/j.jhydrol.2019.05.028
61. Sharif M, Archer DR, Fowler HJ et al. (2013) Trends in timing and magnitude of flow in the Upper Indus Basin Hydrol Earth Syst Sci **17**:1503-1516. doi:10.5194/hess-17-1503-2013
62. Singh Jasrotia A, Baru D, Kour R et al. (2021) Hydrological modeling to simulate stream flow under changing climate conditions in Jhelum catchment, western Himalaya Journal of Hydrology **593**:125887. doi:https://doi.org/10.1016/j.jhydrol.2020.125887
63. Smiraglia, C., Mayer C, Mihalcea C et al. (2007) Ongoing variations of Himalayan and Karakoram glaciers as witnesses of global changes: Recent studies of selected glaciers Dev Earth Surf Processes **10**:235-248.
64. Tahir AA, Chevallier P, Arnaud Y et al. (2011) Modeling snowmelt-runoff under climate scenarios in the Hunza River basin, Karakoram Range, Northern Pakistan Journal of hydrology **409**:104-117.
65. Thakur B, Kalra A, Joshi N et al. (2020) Analyzing the Impacts of Serial Correlation and Shift on the Streamflow Variability within the Climate Regions of Contiguous United States Hydrology **7**:91.
66. Ul Hassan SN, Reba MNM, Hussain D et al. Elevation dependent thickness and ice-volume estimation using satellite derived DEM for mountainous glaciers of Karakorum range. In: IOP Conference Series:

Earth and Environmental Science, 2018. vol 1. IOP Publishing, p 012115

67. Ul Hussan W, Khurram Shahzad M, Seidel F et al. (2020) Comparative Assessment of Spatial Variability and Trends of Flows and Sediments under the Impact of Climate Change in the Upper Indus Basin Water **12**:730.
68. Wu H, Qian H (2017) Innovative trend analysis of annual and seasonal rainfall and extreme values in Shaanxi, China, since the 1950s International Journal of Climatology **37**:2582-2592. doi:10.1002/joc.4866
69. Yaseen M, Ahmad I, Guo J et al. (2020) Spatiotemporal Variability in the Hydrometeorological Time-Series over Upper Indus River Basin of Pakistan Advances in Meteorology **2020**:5852760. doi:10.1155/2020/5852760

Figures

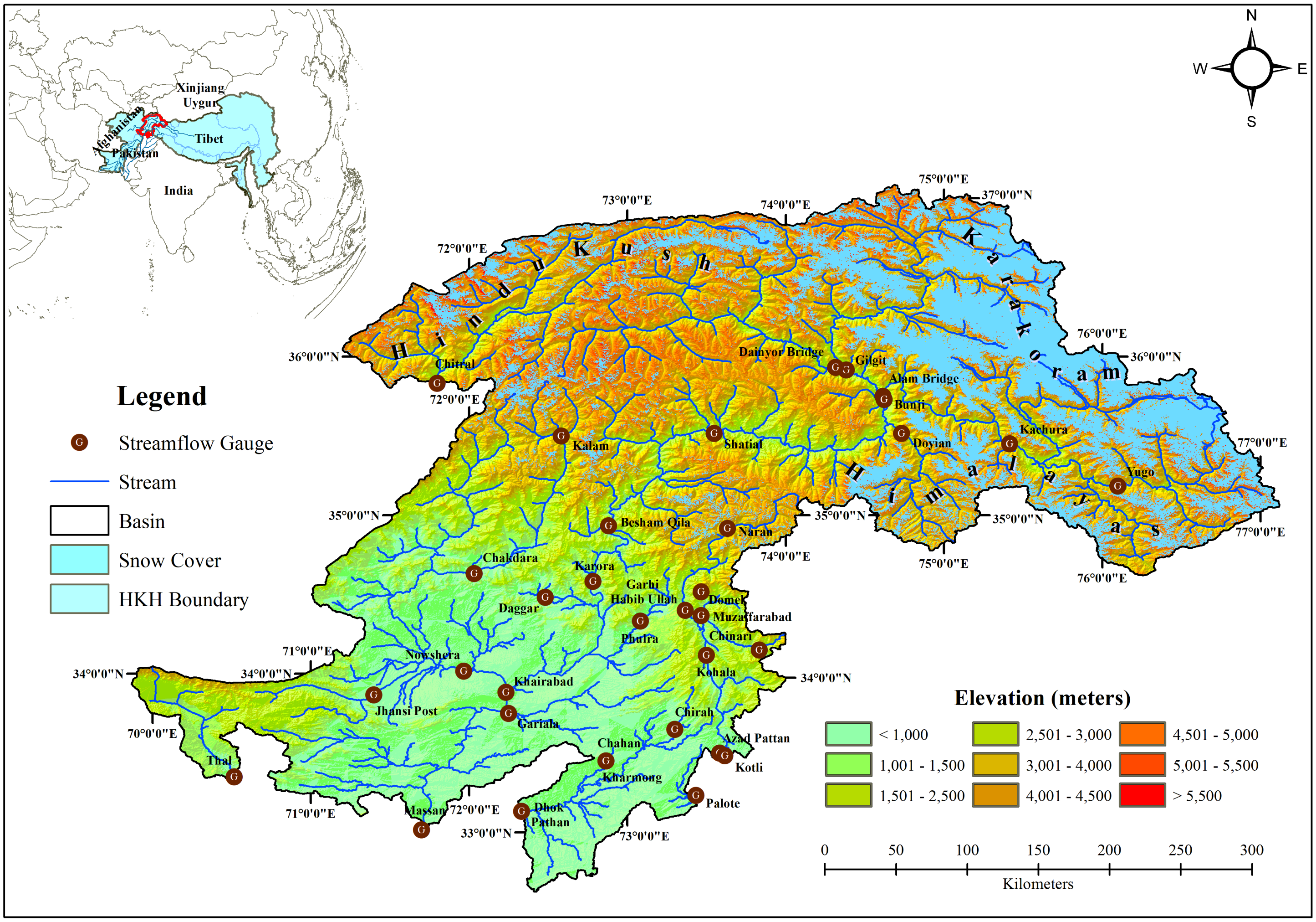

Figure 1

Location of streamflow gauges in the Hindukush Karakoram Himalayas (HKH) region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

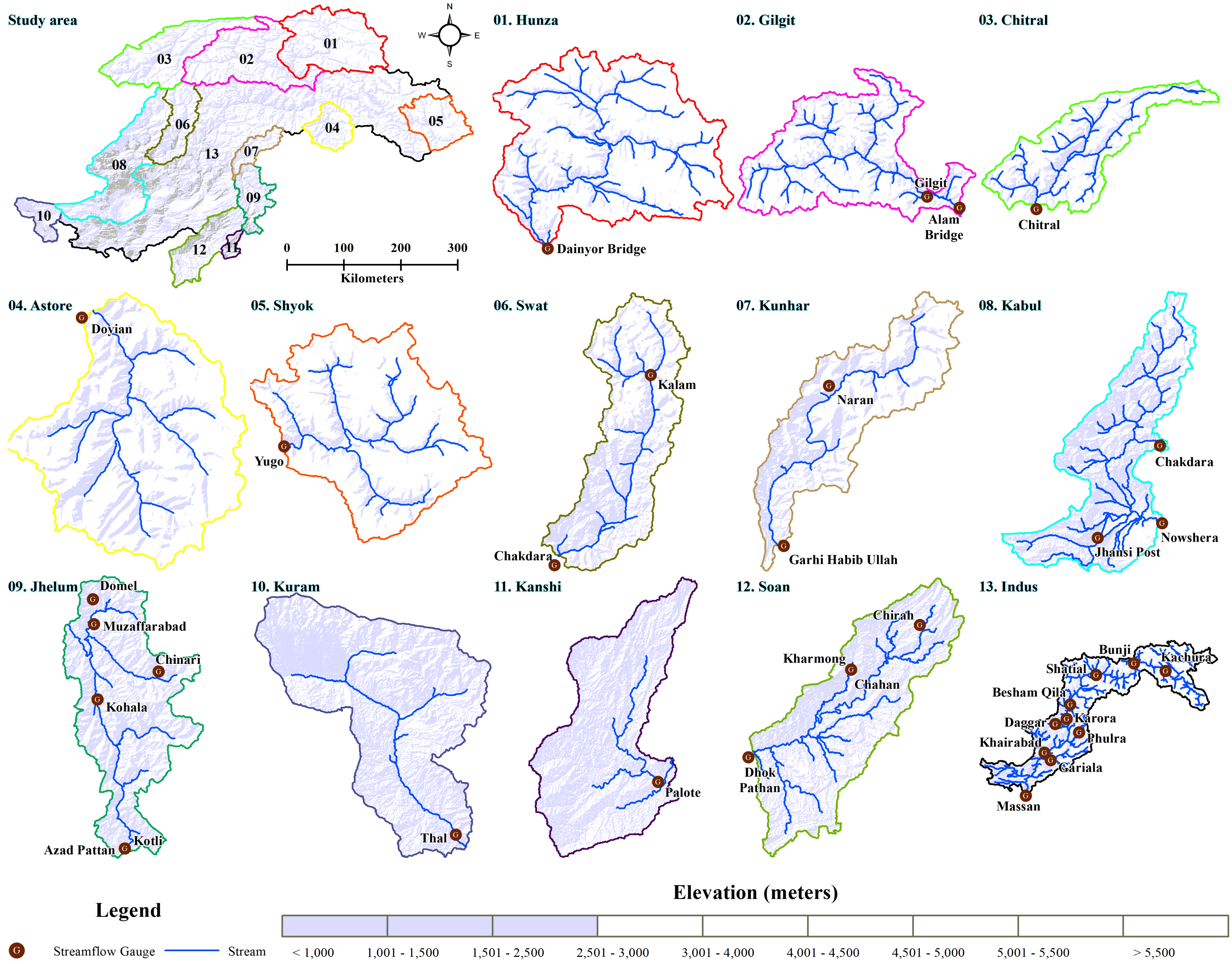

Figure 2

Sub-basin distribution in the Hindukush Karakoram Himalaya (HKH) region. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

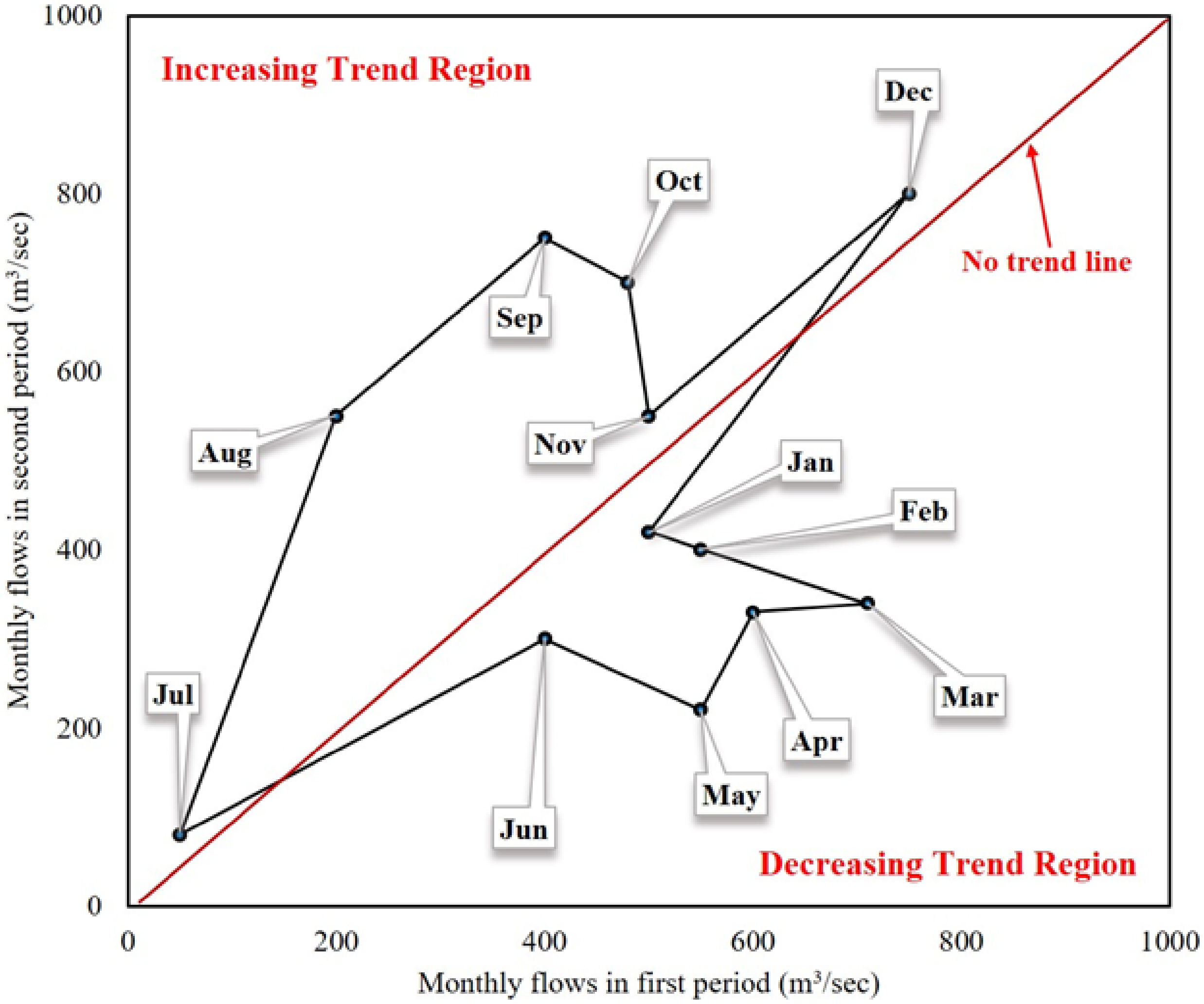

Figure 3

Innovative Polygon Trend Analysis (IPTA) graphical example.

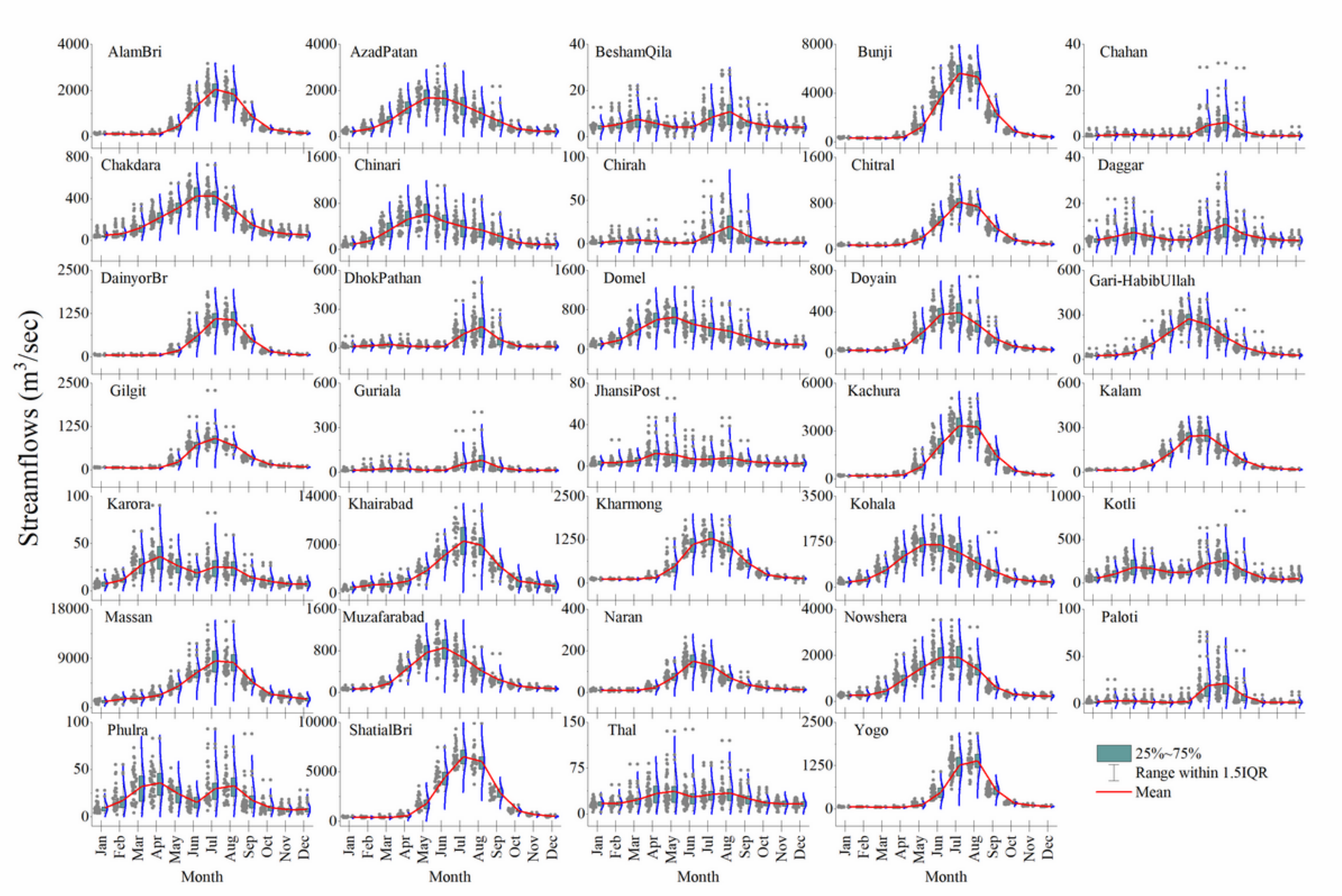

Figure 4

Monthly variation in streamflow along with the 25%-75% inter-quantile range (IQR) representing interannual variability and mean values connected by red lines for all streamflow gauges.

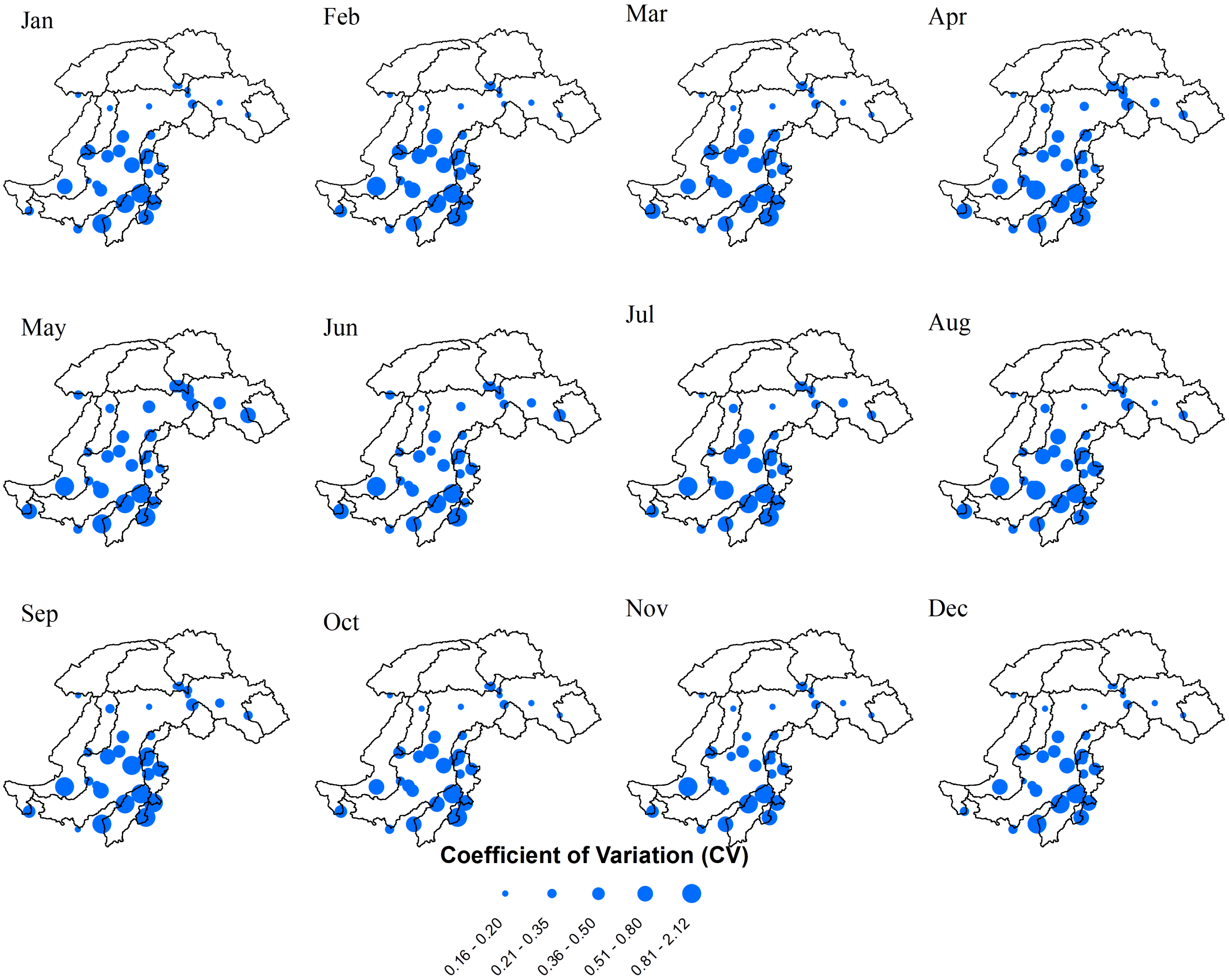

Figure 5

Coefficient of variation (CV) of monthly streamflow for all gauges in the entire data period. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

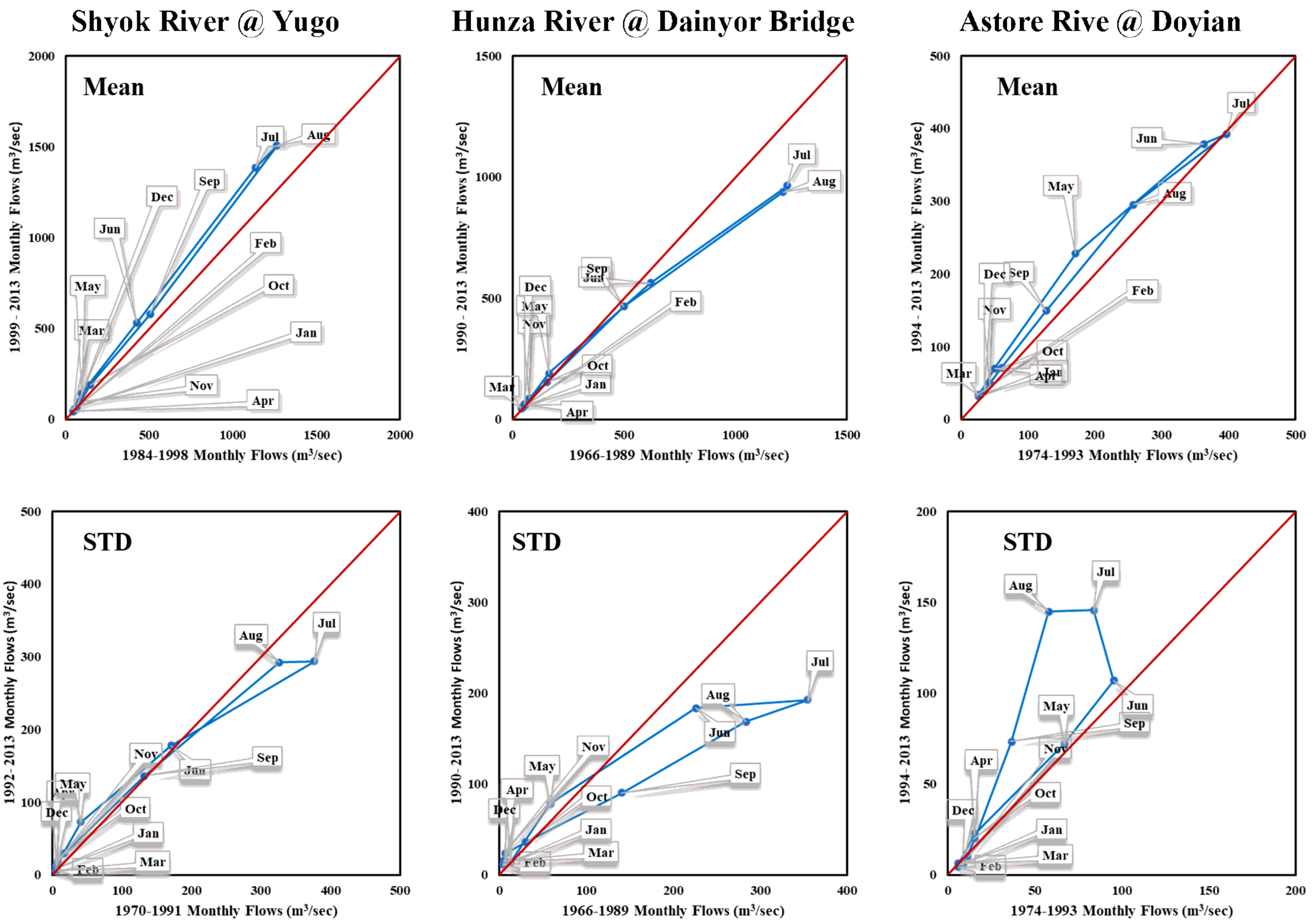

Figure 6

IPTA graphical display of changes in the mean and standard deviation of monthly streamflow for Shyok, Hunza, and Astore sub -basins of UIB.

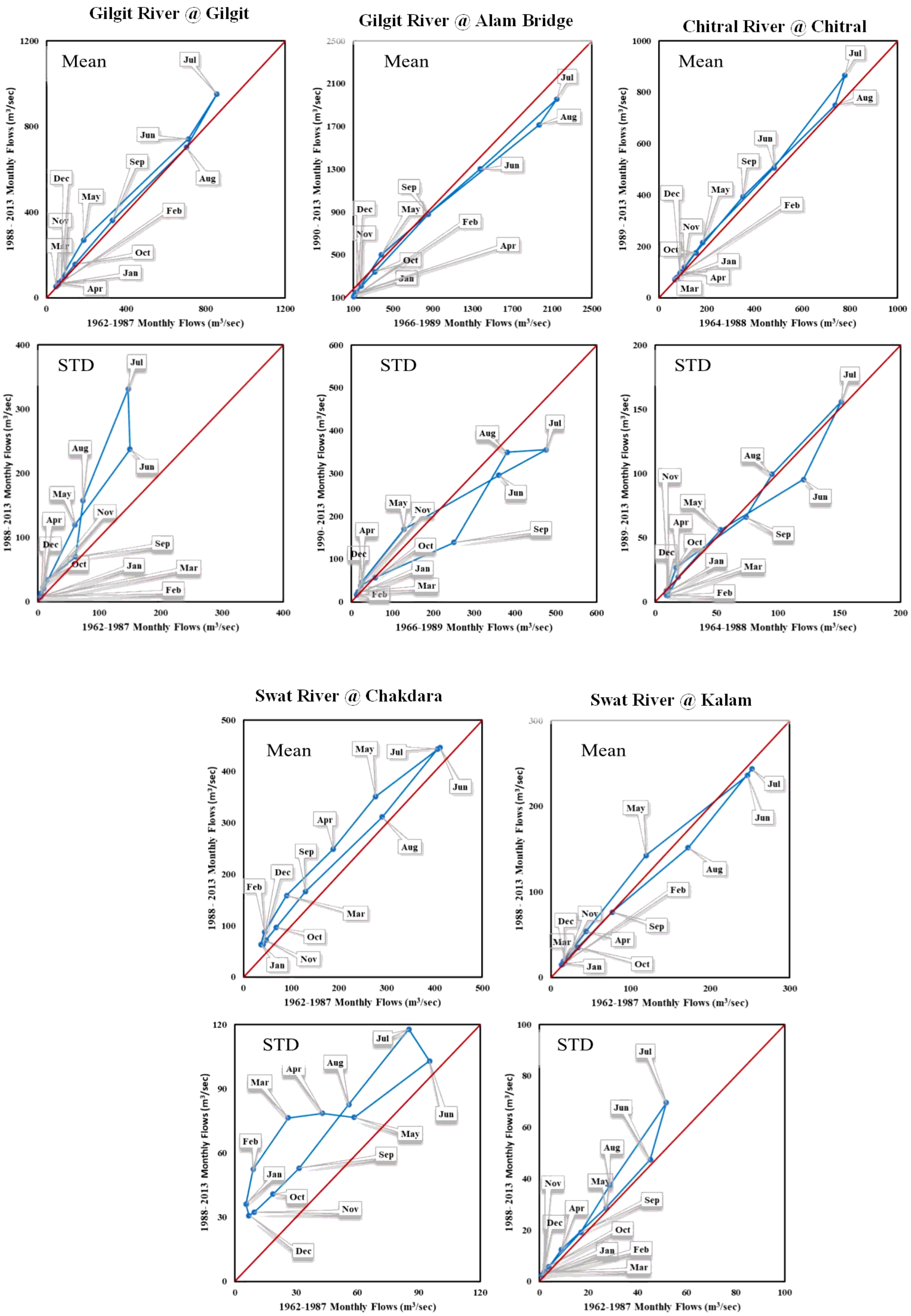

Figure 7

IPTA graphical display of changes in the mean and standard deviation of monthly streamflow for Gilgit, Chitral, and Swat sub -basins of the UIB.

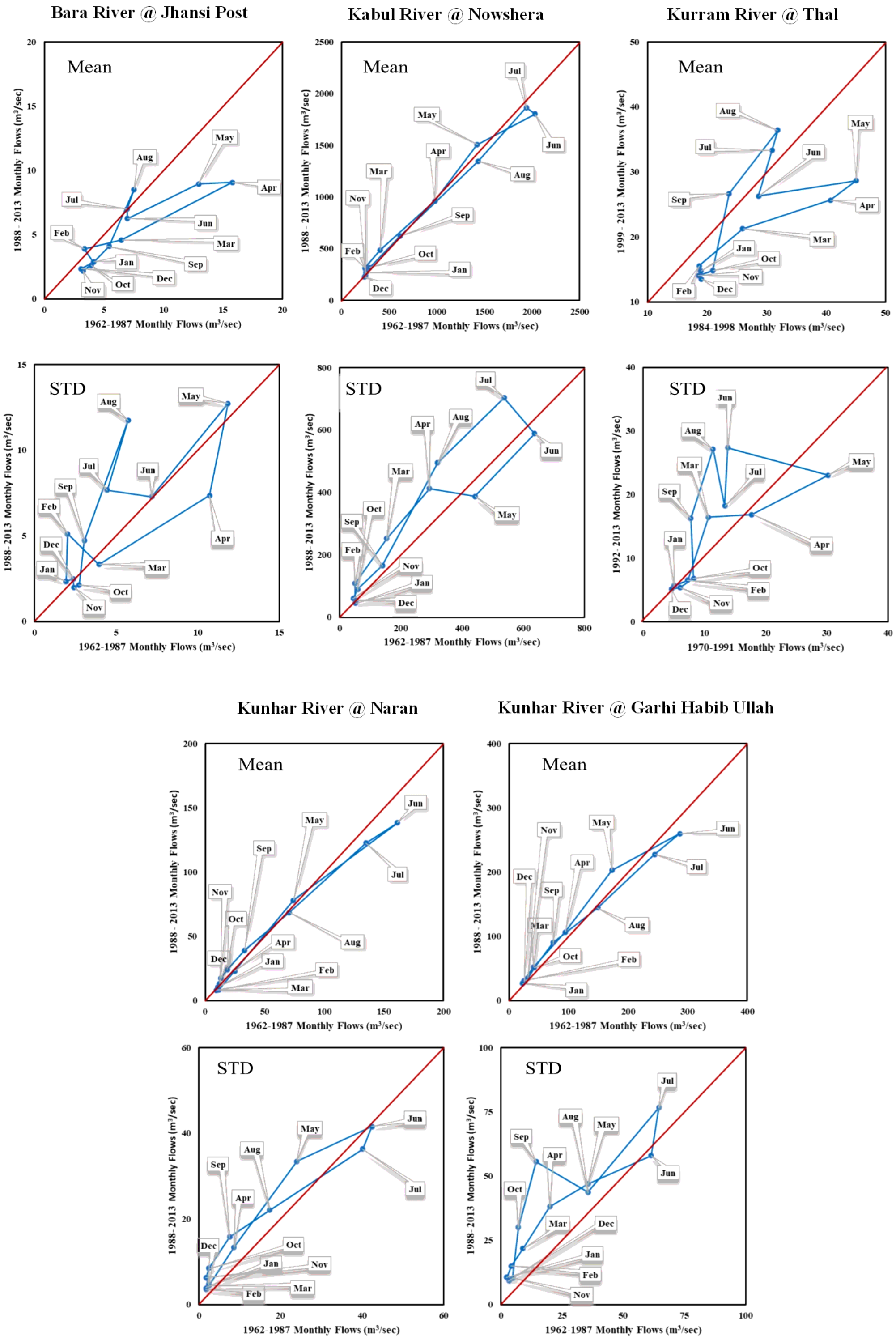

Figure 8

IPTA graphical display of changes in the mean and standard deviation of monthly streamflow for Kabul, Kurram and Kunhar sub-basins of the UIB.

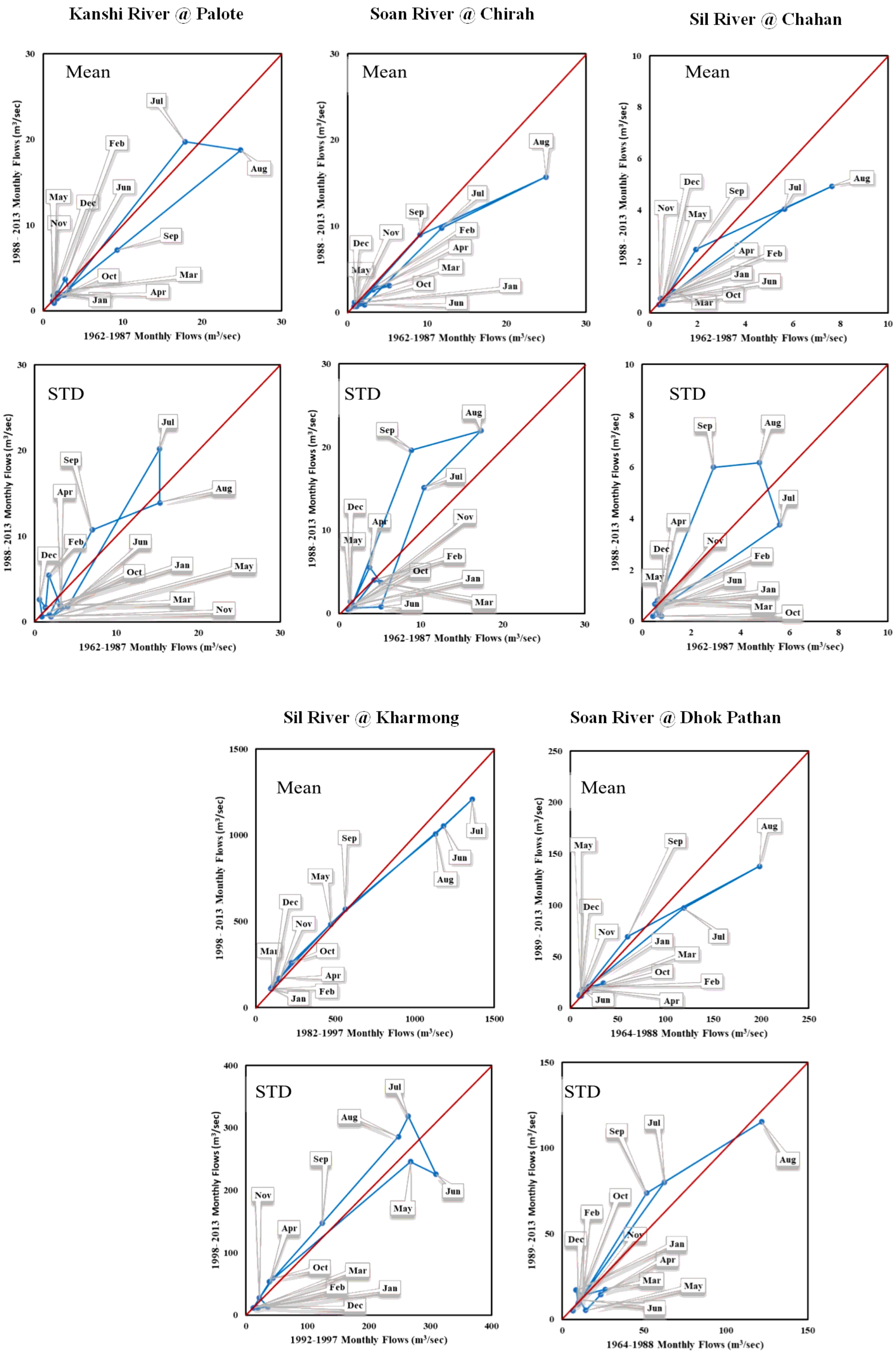

Figure 9

IPTA graphical display of changes in the mean and standard deviation of monthly streamflow for Kanshi and Soan sub-basins of the UIB.

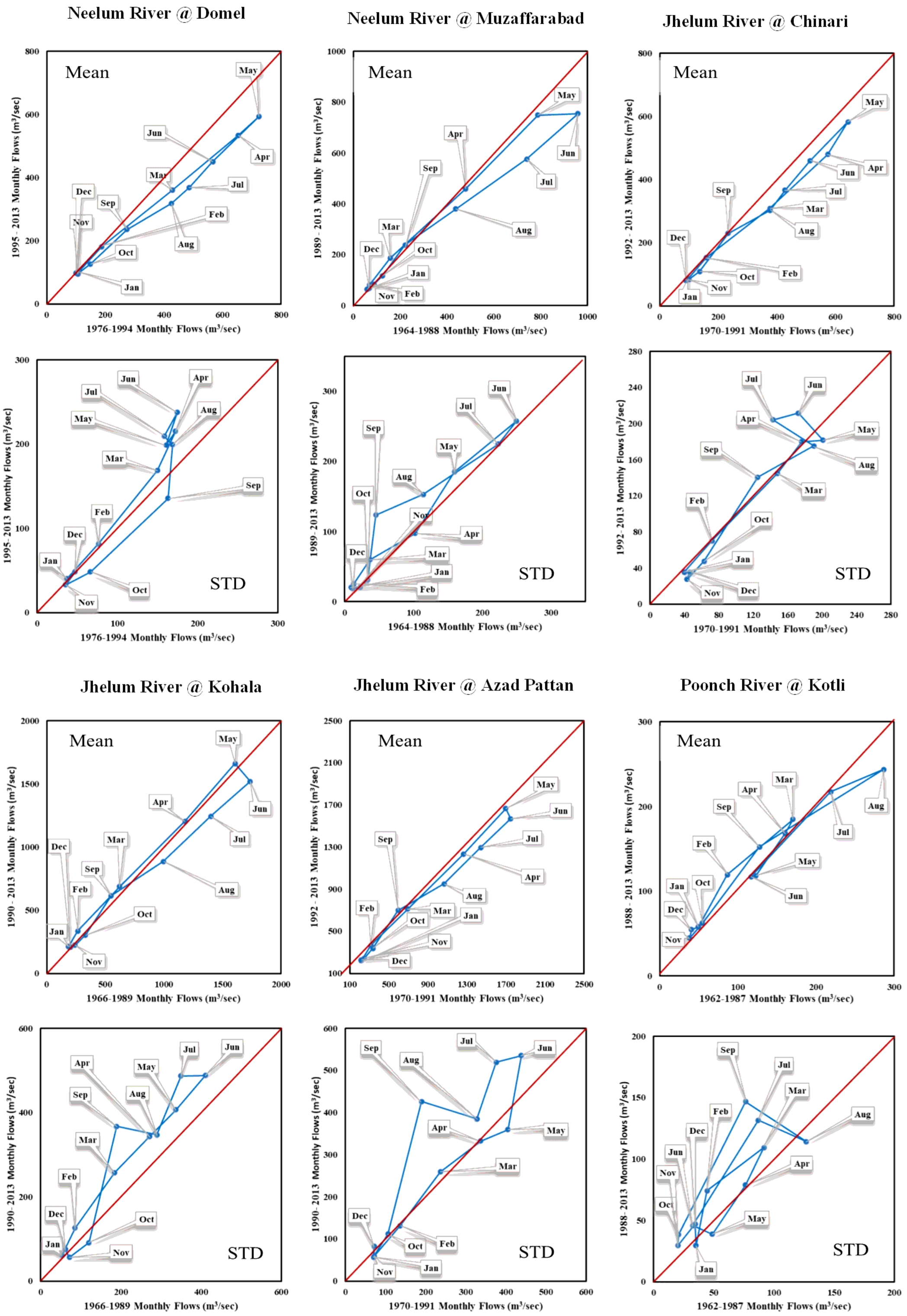

Figure 10

IPTA graphical display of changes in the mean and standard deviation of monthly streamflow for the Jhelum basin part of UIB.

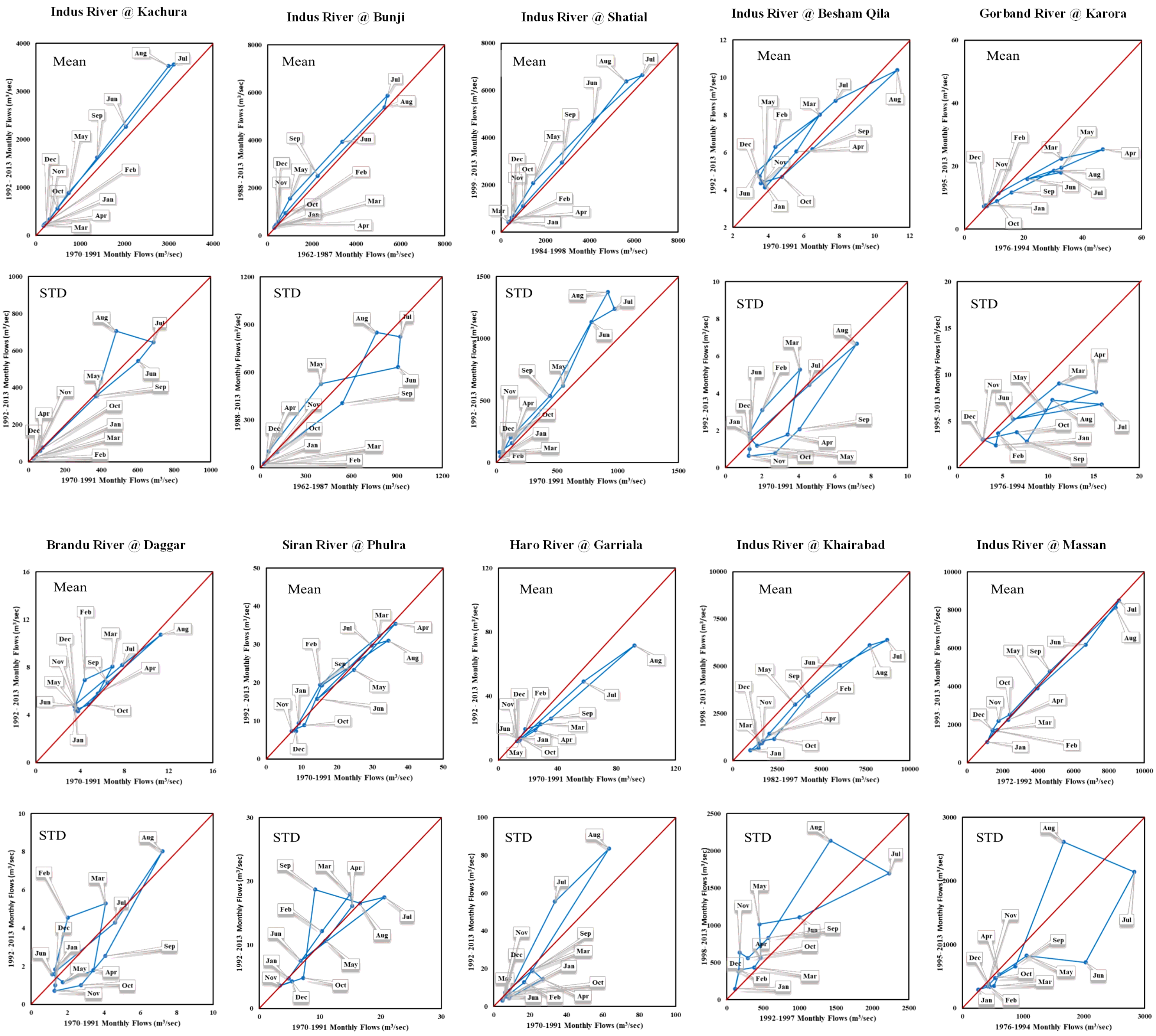

Figure 11

IPTA graphical display of changes in the mean and standard deviation of monthly streamflow for the Indus basin part of UIB.