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TEMPORAL AND SPATIAL VARIATIONS IN SUMMER FLOWS OF UPPER INDUS BASIN, PAKISTAN

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Muhammad Yaseen[*1,2], Haris Akram Bhatti[2], Tom Rientjes[2], Ghulam Nabi[1], and Muhammad Latif[1]

ABSTRACT

Pakistan's economy is based on agriculture that is highly dependent on water resources originating in the mountain sources of the Upper Indus. Over 70% of total flows occur in summer season (April to September). The aims of this study are to detect trends, variability analysis and assessment of changes in minimum (low), mean and maximum (high) summer flows in 35 streamflow stations in Upper Indus Basin, Pakistan. These stations are in 23 rivers in three basins (Indus, Jhelum and Kabul). Trend analyses are performed by applying Mann-Kendall, non-parametric test. Temporal variability in flows is analyzed in detail for four time windows to address the uncertainty of the temporal change in available observed data. The four time windows analyzed are: (1st) 1971- 2010, (2nd) 1981- 2010, (3rd) 1991- 2010 and (4th) all available record referred as Record Length. Sen's method was applied to estimate slope time series that indicates changes in river flows. The influence of serial correlation was eliminated from time series by applying the trend-free pre-whitening (TFPW) method prior to the trend analysis.

Results of this study revealed that trends were more common in mean and low flows compared to high flows. Statistically significant increasing and decreasing trends are noticed in different parts of UIB. Statistically significant decrease was detected mainly in the eastern parts of UIB (in Jhelum Basin) whereas the northern and western part has the increasing trends for the 40, 30 year and record length periods. The summer low and mean flows at the outlet of Jhelum (at Azad Pattan), and Kabul (at Nowshera) basins have decreased in all data time windows whereas in Indus (at Besham Qila) basin has increased. The high flows have increasing trends for the 1st period and decreasing trend for the 3rd period at outlets of all three basins. The changes in mean flows were observed upto -10%, 2% and -3% of data period average, in low flows were -3%, 10% and -15% and high flow has increased upto 3%, 1% and 4% at the outlet of Jhelum, Indus and Kabul basin respectively for the 1st period.

Keyword: Upper Indus Basin; Climate Change; Trends; Streamflows

1. INTRODUCTION

Climate change appears to accelerate the hydrological cycle and is expected to increase the frequency and impact of extreme events, such as droughts and floods. Being one of the very sensitive parameters, climate change can cause significant impacts on water resources by resulting changes in the hydrological cycle (Bates et al., 2008; Archer and Fowler, 2004). The change on temperature and precipitation can have a direct impact on the quantity of evapotranspiration and on both quality and quantity of the runoff. Consequently, the spatial and temporal water resource availability, or in general the water balance, can be significantly

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affected, which clearly amplifies its impact on sectors like agriculture, industry and urban development.

The Upper Indus Basin (UIB) makes part of the high elevated Hindukush-Karakoram-Himalaya (HKH) area with 32,182 km^2 covered by glaciers (Eriksson et al. 2009). Over the past decade, in the HKH area much attention has been on assessment of climate change and its hydro-meteorological impacts. Glacier dynamics in terms of glacier retreat or surge is assessed (Hewitt, 2004; Booghagen and Burbank, 2010; Kaab et al., 2012; among others) whereas examples of assessments on changes in precipitation, temperature and stream flow are shown in (Hewitt, 2004; Fowler and Archer, 2005, 2006; Archer and Fowler, 2008; Kehrwald et al. 2008, Cogley, 2010, Yao et al., 2007 & 2012; Archer et al. 2010, Cook et al., 2013; Sharif et al., 2013). Glacial melt waters from the Karakoram glaciers dominate the flows of the main Indus (Hewitt, 2011) and thus changes in precipitation and temperature directly affect streamflow discharges.

Streamflow (also called river flow) varies over space and time. The temporal scale ranges from minutes (e.g. in the case of flash floods) to decades (e.g. in the case of water resource assessments). River flow regimes describe the temporal patterns of flow variability. Knowledge about changing river flow regimes is vital for assessing climate change risks related to freshwater. Estimation of changes in seasonality, inter-annual variability, statistical low, mean and high flows, and floods and droughts is required to understand the impact of climate change on humans and freshwater ecosystems. River flow regime alterations affect humans with respect to water supply, navigation, hydropower generation and flooding, and they affect ecosystems with respect to habitat suitability for freshwater-dependent biota.

Trend existence in the maximum (flood) and minimum (drought) flows in rivers carries significance for different types of water resources problems. Floods and mean flows are considered in the design of flood mitigation structures and water storage reservoirs. Low flows are especially significant for the water quantity released to the downstream of a dam in order to protect the ecological sustainability. The low flow indicators are important for water resources planning and management since severe reductions in these indicators can adversely affect riparian ecology, water quality and water availability. Individual values of these indicators represent severity of hydrological droughts experienced in a year (or season) and have been generally used for designing safe water abstractions and waste load allocations in order to protect river water quality and aquatic ecosystems.

Pakistan has faced severe floods in 1950, 1956, 1957, 1973, 1976, 1978, 1988, 1992, 2010 and now in 2013 record flood peak discharges. Flood of various magnitudes occurred between 1992 and 2013. These floods affected the basins of the rivers in Punjab and Sindh. In Khyber Pakhtunkhwa (KPK), Baluchistan, FATA, Gilgit- Baltistan, Azad Jammu Kashmir (AJK) and some areas of the Punjab also, damages are caused mainly due to flash floods in secondary and tertiary rivers including from hill torrents. Pakistan has suffered a cumulative financial loss of US$ 30 billion during the past 60 years. During the period from 1950 to 2009, there was a total financial loss of US$ 20 billion, some 8887 people lost their lives, 109,822 villages were reportedly damaged / destroyed and an overall area of 407132 Km^2 was affected. In comparison, 2010-flood alone resulted into cumulative financial loss of US$ 10 billion, life loss of about 2000 people, 17533 villages and total area of 160000 km^2 was affected (FFC, 2010). In view of recent dramatic floods, detection of trends in long time series of flood data is of scientific interest and practical importance. It is essential for planning of future water resources and flood protection systems, where system design is traditionally based on the assumption of stationarity in hydrological processes such as river stage or discharge.

In Pakistan changes in flow magnitudes are likely to raise tensions among the provinces, in particular with the downstream areas (Sindh province), with regard to reduced water flows in the dry season and higher flows and resulting flood problems during the wet season. The water resources estimation under climate change is important for planning and operation of hydrological installations (Shakir, et al. 2010). To quantify climate change's impacts on water resources planning and management in the basin, an analysis of possible changes in streamflow is required. However, most of studies (Sharif et al. 2013, Khattak et al. 2011, Archer and Fowler, 2004; Fowler and Archer, 2006) conducted on Upper Indus basin were on mean flow and no study has been done on minimum and maximum flows. Khattak et al. 2011 performed analysis on eight stations for period 1966-2005 and Sharif et al. 2013 performed on 19 stations for the period 1961-1998. The objective of this investigation is to trend analysis of UIB daily mean streamflow data. The trends and changes in minimum, mean and maximum streamflows were detected separately with upto date data period (1961-2010). In this study, nonparametric approach was employed for the identification of trends in flow regimes. Temporal evolutions flows were also studied in detail for four time windows in order to address the uncertainty of the temporal change in available data. The four time windows studied are: (1) 1971- 2010, (2) 1981- 2010, (3) 1991- 2010 and (4) all available record referred as Record Length. The choice of nonparametric technique is based on the fact that it is well suited in situations where minimal distributional assumptions are required to be made and where censored data and missing data problems are often encountered (Kundzewicz and Robson, 2000), as is the case with hydrological records.

2. STUDY AREA

This study was carried in the Upper Indus Basin (UIB). The catchment of this basin falls in range 33º, 40' to 37º, 12' N latitude and 70º, 30' to 77º, 30' E, longitude. The Upper Indus watershed boundary was derived from Digital Elevation Model (DEM) just upstream of Massan as shown in Fig. 1. Most of area of this catchment is lies in China and India. Due to unavailability of data from China and India, the study area was confined to the catchment falling within Pakistan boundary as shown in Fig.1. The elevation varies from 254 m to 8570 m above mean sea level. There are so many rivers which contribute water to main Indus River. The main sub basin are Chitral, Swat, Kabul, Hunza, Gilgit, Astore, Shigar, Shyok, Kunhar, Neelum, Kanshi, Poonch, Soan, Siran, Sil, Haro etc. Indus River originates from the north side of the Himalayas at Kaillas Parbat in Tibet having altitude of 18000 feet. Traversing about 500 miles in NW direction, it is joined by Shyok River near Skardu (elevation 9000 feet). After traveling about 100 miles in the same direction, it reaches Nanga Parbat and joined by the Gilgit River at an elevation of 5000 feet. Flowing about 200 miles further in SW (South West) direction, the river enters into the plains of the Punjab province at Kalabagh (800 feet). The Kabul River, a major western flank tributary, joins with Indus near Attock. The Kunar which is also called Chitral River joins Indus below Warsak. About five miles below Attock, another stream Haro River drains into the Indus River. About seven miles upstream of Jinnah Barrage, another stream called Soan River joins with Indus. The tributaries of Indus Rivers are detailed in Figure 1. One of the important Eastern River draining into the Indus River System is Jhelum River which originates from Pir Panjal and flows parallel to the Indus at an elevation of 5500 feet. Mangla basin is located between latitudes 33° 00 to 35°12' N and longitudes 73° 07' to 75°40' E with elevation ranging from 300 m to 6282 m above mean sea level (a.m.s.l.). The basin is located on the southern slope of the Himalayas and has basin area of around 33425 km^2 at Mangla dam. This dam serves hydropower generation and regulates the flow from Mangla reservoir. About 55% of the area lies in Indian held Kashmir and 45% lies in Pakistan including Azad Kashmir. There are five sub-catchments i.e. Jhelum, Poonch, Kanshi, Neelum/Kishan Ganga and Kunhar which drain water to Mangla reservoir (Fig 1.). The river Jhelum originates from Verinag Spring

situated on southern slopes of the Himalaya mountain ranges and at foot of the Pir Panjal Ranges in Jammu and Kashmir. It flows through Srinagar and the Wular Lake before entering Pakistan through a deep narrow gorge. The largest tributary of the Jhelum, Neelum River joins at Domel Muzaffarabad, as does the next largest, the Kunhar River of the Kaghan valley joins on Kohala Bridge. The flow of Jhelum River enters into the Mangla Dam reservoir in the district of Mirpur. The flows of Poonch and Kanshi Rivers also enter into Mangla reservoir.

3. DATA AVAILABILITY

Streamflows measurement in UIB is carried out by the Water and Power Development Authority—Surface Water Hydrology Project (WAPDA-SWHP) with the earliest records commencing in 1960. The stream gauges have a wide range of drainage area from 262 km^2 to 286,000 km^2 (See Fig.2a). There were only three gauges with drainage area less than 500 km^2. The study area contained three major basins namely Jhelum, Indus and Kabul. There were 21 sub-basins in all these three basins. The streamflow gauges are installed in all the sub-basins of Upper Indus Basin at different locations which are shown in Fig.1. The characteristics/information of selected flow gauges/sites are given in Table 1. The flow data of these sites were collected from Surface water Hydrology Project (SWHP), WAPDA for period (1961-2010). The mean monthly flows for each year were calculated from daily flows. Mean streamflows for Period (1961-2010) are given in Table1. The majority of gauges (89%) had more than 30 years of daily data available while 74% and 48% had more than 40 and 45 years of record (Figure 2b). Gauges with less than 20 years of data were not used for further analysis.

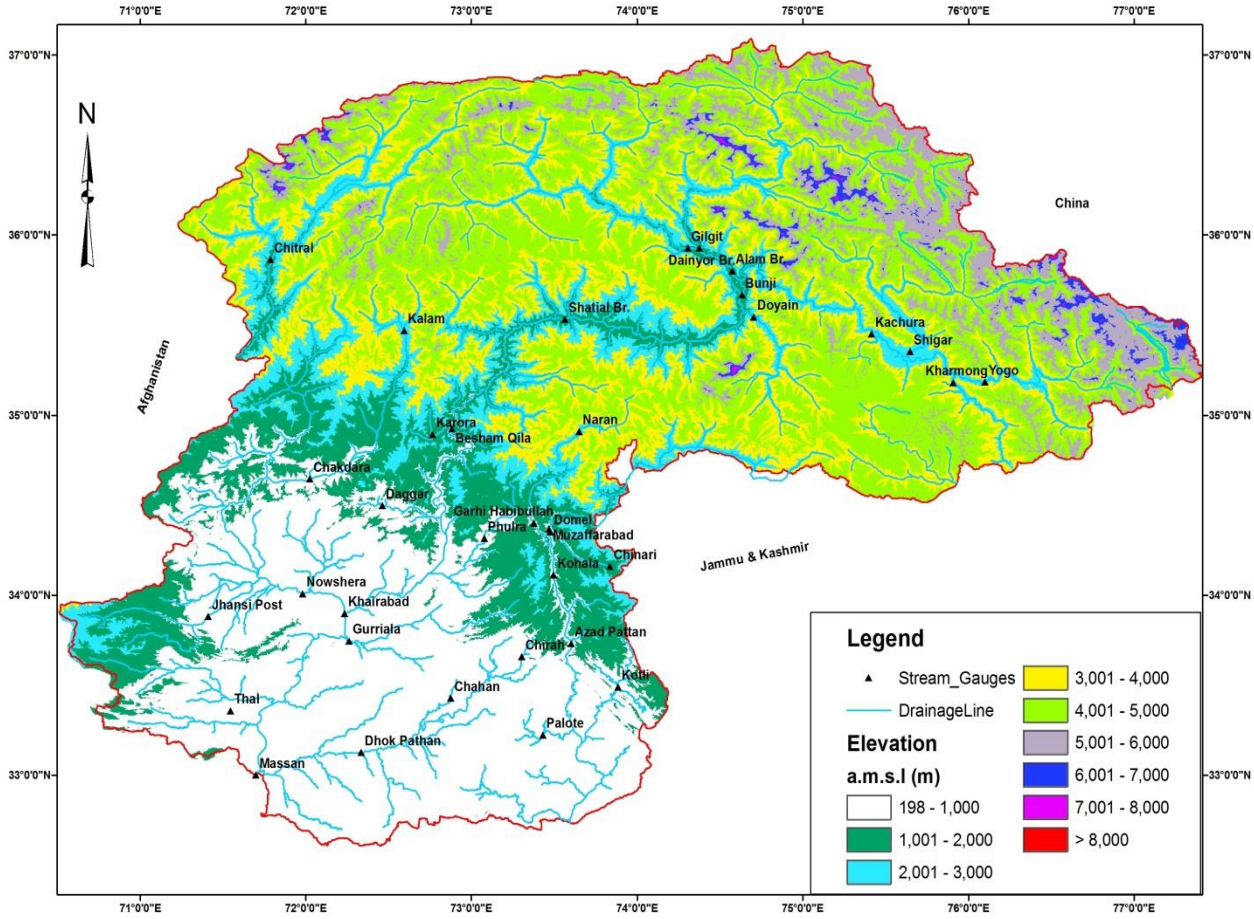


Figure-1: The Upper Indus Basin confined in Pakistan boundary showing rivers, stream gauges and elevation.

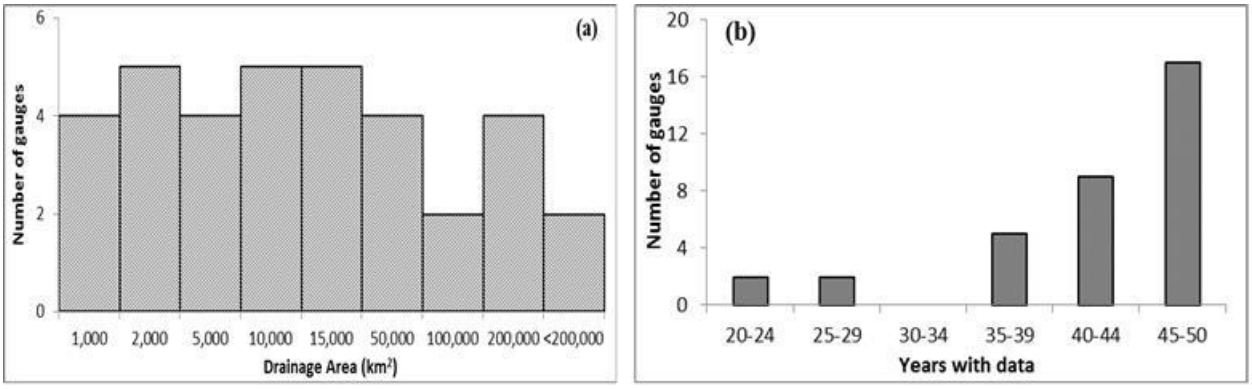


Figure-2: (a) Number of gauges by drainage basin area.
(b) Number of gauges with different length of discharge records.

Table-1: List of stream gauges used in the present study and their characteristics.

Sr.No.	Station	Lat	Lon	River	Basin	Area	Period	Means		
		dd	dd			km^2		Min.	Mean	Max.
1	Naran	34.9	73.7	Kunhar	Jhelum	1085	1961-2010	11.4	81	233
2	Garhi Habibullah	34.4	73.4	Kunhar	Jhelum	2379	1961-2010	48	172	445
3	Muzaffarabad	34.4	73.5	Neelum	Jhelum	7412	1963-2010	139	570	1394
4	Chinari	34.2	73.8	Jhelum	Jhelum	13652	1970-2010	128	444	927
5	Domel	34.4	73.5	Jhelum	Jhelum	14396	1975-2010	148	482	1146
6	Kohala	34.1	73.5	Jhelum	Jhelum	24464	1965-2010	382	1248	2725
7	Azad Pattan	33.7	73.6	Jhelum	Jhelum	25967	1970-2010	394	1869	3032
8	Kotli	33.5	73.9	Poonch	Jhelum	3210	1961-2010	48	172	1547
9	Palote	33.2	73.4	Kanshi	Jhelum	1078	1961-2010	0.3	9.4	316
10	Kharmong	35.2	75.9	Indus	Indus	66209	1983-2010	115	789	1892
11	Yogo	35.2	76.1	Shyok	Indus	33670	1973-2010	39	638	2243
12	Shigar	35.4	75.7	Shigar	Indus	6965	1982-2002	22	379	1256
13	Kachura	35.5	75.4	Indus	Indus	155402	1970-2010	192	1878	4987
14	Gilgit	35.9	74.3	Gilgit	Indus	12650	1961-2010	40	427	1316
15	Dainyor Br.	35.9	74.4	Hunza	Indus	13712	1966-2010	40	583	1681
16	Alam Br.	35.8	74.6	Gilgit	Indus	27193	1966-2010	94	1112	2925
17	Bunji	35.7	74.6	Indus	Indus	160989	1963-2010	314	3112	8019
18	Doyain	35.5	74.7	Astore	Indus	3919	1974-2010	32	238	618
19	Shatial Br.	35.5	73.6	Indus	Indus	171148	1984-2010	382	3667	9495
20	Karora	34.9	72.8	Gorband	Indus	559	1975-2010	9	25	176
21	Besham Qila	34.9	72.9	Indus	Indus	179515	1969-2010	573	4170	10684
22	Daggar	34.5	72.5	Brandu	Indus	458	1970-2010	2.8	6	78
23	Phulra	34.3	73.1	Siran	Indus	1087	1969-2010	4.9	25	214
24	Kalam	35.5	72.6	Swat	Kabul	2013	1961-2010	23	152	361
25	Chakdara	34.6	72.0	Swat	Kabul	5642	1961-2010	87	305	758
26	Chitral	35.9	71.8	Chitral	Kabul	12333	1965-2010	73	456	1114
27	Jhansi Post	33.9	71.4	Bara	Kabul	1819	1962-2010	1.7	9	63
28	Nowshera	34.0	72.0	Kabul	Kabul	85895	1961-2010	349	1385	3334
29	Gurriala	33.7	72.3	Haro	Indus	2991	1969-2010	8	36	642
30	Khairabad	33.9	72.2	Indus	Indus	252525	1988-2010	1161	4851	12198
31	Thal	33.4	71.5	Kurram	Indus	5543	1968-2010	9	32	214
32	Chirah	33.7	73.3	Soan	Indus	325	1961-2010	0.2	8	210
33	Chahan	33.4	72.9	Sil	Indus	262	1963-2010	0.1	3	77
34	Dhok Pathan	33.1	72.3	Soan	Indus	6545	1964-2010	4	66	1304
35	Massan	33.0	71.7	Indus	Indus	286000	1972-2010	1530	5689	14574

Table-2: The variation interval of statistical parameters for annual time series.

Variables	Mean	Standard Deviation (SD)	Coefficient of variation (CV)	Kurtosis	Skewness
Minimum Flow	0.1….1530	0.1…528	0.1…1.0	-1.5…9.0	-1.5….3
Mean Flow	2.5….5689	1.8…1033	0.1…0.7	-1.0…12	-1.1…3.0
Maximum Flow	63….14574	45…4759	0.1…1.0	-0.8…23	-0.3…4.0

4. METHODOLOGY

The methodology which was adopted in the present study is summarized as under:

- The first step was to choose the variables to be analyzed.
- The second step was to choose the station to be investigated.
- Selection of study period for trend detection.
- The fourth step was to detect the presence of trends in variables. This was done by applying the Mann –Kendall non-parametric test.
- Estimate the trend value (changes in flow) by applying Sen's slope estimator.

4.1 Selection of Variables

Hydrological variables are important indicators of climate change. These variables tend to reflect climatic change and help to understand relationship between the hydrology and climate.

The trend analysis was applied to minimum, mean and maximum streamflows.

4.2 Selection of Stations

The selection of stations is one of the most important steps in climatic change research. The selection of gauges was based on several criteria. A gauge has must minimum of 20 years record. Record accuracy in which there were unimpaired basin conditions affecting the monthly discharge implied there must be no overt adjustment of streamflow through diversions, no regulation by control structures, and no change in land use that could have significantly affected the monthly value of streamflow.

4.3 Study Period

The trend analysis was applied to minimum, mean and maximum discharge values for three different periods: 1971–2010; 1981– 2010; and 1991–2010. In addition, a final study period corresponding to all of the available records at each station (see Table 1), subsequently referred to as the "Record Length" was also considered.

4.4 Detection of Trends

The purpose of trend testing is to determine if the values of a random variable generally increase or decrease over some period of time in statistical terms (Haan, 1977). Parametric or Non-parametric statistical tests can be used to determine whether there is a statistically significant trend. Nonparametric methods for trend detection and estimation of the magnitude of trend have been widely used in hydrology and climatology, in particular the Mann-Kendall (MK) (Kendall, 1975) and Spearman rank correlation (Dahmen and Hall, 1990) tests and Sen's robust slope estimator (SS) (Sen, 1968). Yue and Wang (2002) found no appreciable differences between the results of the MK and Spearman rank correlation tests. Therefore, the MK test is considered in this study for the detection of time trend and the SS method for the estimation of magnitude of trend in time series of flow indices. A challenging problem with the MK test is that the result of the test is affected by the autocorrelation structure of the time series being tested and therefore various approaches have been suggested in the literature to address the effect of autocorrelation on the outcome of the test. The analysis was carried out for the time series of summer minimum, mean and maximum flows; these steps essentially involve: (i) testing the serial correlation effect; (ii) Trend detection by applying the Mann–Kendall test,

4.4.1 Serial correlation effect

In time series analysis it is essential to consider autocorrelation or serial correlation, defined as the correlation of a variable with itself over successive time intervals, prior to testing for trends. Specifically, if there is a positive serial correlation (persistence) in the time series, then the non-parametric test will suggest a significant trend in a time series that is, in fact, random more often than specified by the significance level (Kulkarni and Van Storch, 1995). For this, Von Storch and Navarra (1999) suggest that the time series should be 'pre-whitened' to eliminate the effect of serial correlation before applying the Mann–Kendall test or any trend detection test. Yue and Wang (2002) showed that removal of serial correlation by pre-whitening can effectively remove the serial correlation and eliminate the influence of the serial correlation on the MK test. Yue and Wang (2004) modified the pre-whitening method as the trend-free pre-whitening to the series in which there was a significant serial correlation. The TFPW method has been applied in many of the recent studies to detect trends in hydrological and meteorological parameters (e.g., Yue et al., 2003; Aziz and Burn2006; Novotny and Stefan2007; Kumar et al., 2009; Oguntunde et al., 2011). This study incorporates this suggestion, and thus possible statistically significant trends in flow observations (x_1, x_2. . . x_n) are examined using the following procedures:

1. For a given time series of interest, the slope of the trend (β) is estimated by using the Sen's robust slope estimator method. Then the time series is de-trended by assuming a linear trend as:

$$Y_i = x_i - (\beta x\, i) \tag{1}$$

2. Compute the lag-1 serial correlation coefficient (designated by r_1).

3. If the calculated r_1 is not significant at the 5% level, then the statistical tests are applied to original values of the time series. If the calculated r_1 is significant, prior to application tests, then the 'pre-whitened' time series were obtained as:

$$\overline{Y_i} = Y_i - rY_{1-i} + (\beta x\, i) \tag{2}$$

4.4.2 Mann-Kendal Test for Trend Detection

Mann originally used this test and Kendall subsequently derived the test statistic distribution (Kendall, 1975). Mann Kendall test is a statistical test widely used for the analysis of trend in climatologic (Tabari et al. 2012, Caloiero et al. 2011, Mavromatis and Stathis, 2011, Bhutiyani, 2007, Rio del et al. 2005,) and in hydrologic time series (Yue and Wang, 2004). There are two advantages of using this test. First, it is a non-parametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to inhomogeneous time series [Tabari et al. 2011]. This test was found to be an excellent tool for trend detection.

The Mann-Kendall statistic Z_{mk}, was evaluated from as follow:

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sigma_s} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sigma_s} & \text{if} \quad S < 0 \end{cases} \tag{3}$$

The MK test statistic S can be computed from this relation:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{4}$$

where *n* is the number of years, x_j and x_k are the annual values in the year j and k respectively. The function $sgn(x_j - x_k)$ is an indicator function that takes the value 1, 0 or -1 according to sign of difference $(x_j - x_k)$, where $j > k$:

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \tag{5}$$

A positive value of Z_{mk} indicates an upward (warming) trend while negative value shows downward trend (cooling trend). The test statistic (*S*) follows the standard normal distribution and therefore if the probability, under the null hypothesis H_o, of observing a value higher than the test statistic Z_{mk} for chosen significance level α, then there is a statistically significant trend. The null hypothesis H_o is true if there is no trend and thus uses the standard normal table to decide whether to reject H_o. To test for either upward or downward trend (a two-tailed test) at α level of significance H_o is rejected if the absolute value of $Z_{mk} > Z_{1-a/2}$ at the α-level of significance.

4.5 Sen's Slope Estimator

The changes over each period were computed from the slope estimated by Sen's method (Sen, 1968). Changes over time were estimated relative to mean daily discharge over the period. We use relative units, since discharge differs significantly from one gauge to another, and the absolute changes in discharge are difficult to compare. Daily discharges values, and especially their changes, often have very low magnitudes and are less demonstrative for inter comparison.

The slope estimates of N pairs of data were first computed by the formula:

$$Q_i = \frac{x_j - x_k}{j - k} \qquad \text{If } j > k \tag{6}$$

Where x_j and x_k are the annual values in the year j and k respectively. The Sen's estimator of slope is the median of these N values of Q. The median of the N slope estimates was obtained in the usual way. N values of Q_i were ranked from smallest to largest and the Sen's estimator was computed as follow:

$$Sen's estimator = \begin{cases} Q_{\left[\frac{(N+1)}{2}\right]} & if\ N\ was\ odd \\ \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{[(N+2)/2)]}\right) & if\ N\ was\ even \end{cases} \tag{7}$$

Finally, Q_{med} is tested by a two-sided test at the 100(1-α) % confidence interval and the true slope may be obtained by the non-parametric test. Data were processed using XLSTAT (version 2013.3.02) statistical package.

5. RESULTS

The trend analysis and changes in streamflow in various stream gauges which are installed in stream network of UIB at different locations were found over the different periods. After filtering the data for gaps and length of records 27, 30, 35 and 35 stations remained over the period 1971-2010 (1st period), 1981-2010 (2nd period), 1991-2010 (3rd period) and Record

Length (given in Table 1) respectively. The analysis was perfomed on summer times series. The percentage of stations with increasing and decreasing trends as well as significant trends are shown in Fig.3. To examine the spatial consisttency of the observed trends, maps were created displaying the locations stream gauges in all three basins (Jhelum, Indus and Kabul) with decreasing and increrasing trends. The spatial distribution of trends and changes in minimum, mean and maximum streamflow are shown in Figures 4, 5 and 6 respectively. Time series of these flows at outlets of basins are shown in Fig.7.

5.1 Trends in Minimum (Low) Flows

5.1.1 Temporal trends

The variation intervals of the statistics for the summer minimum flows of the selected stations are presented in Table 2. The mean summer minimum flow varies from 0.1 to 1530 cumec. The coefficient of variation, CV changes between 0.1 and 1.0 whereas the skewness has a minimum –1.5 and a maximum 3.0. The summer minimum flows have more increasing trends for first three periods. The increasing trends were found at 63 % (40% significant), 63 %(41%), 67 %(40%) and 43% (17%) of stations for the periods "Record Length", 1971-2010, 1981-2010 and 1991-2010 respectively as shown in Fig. 3.

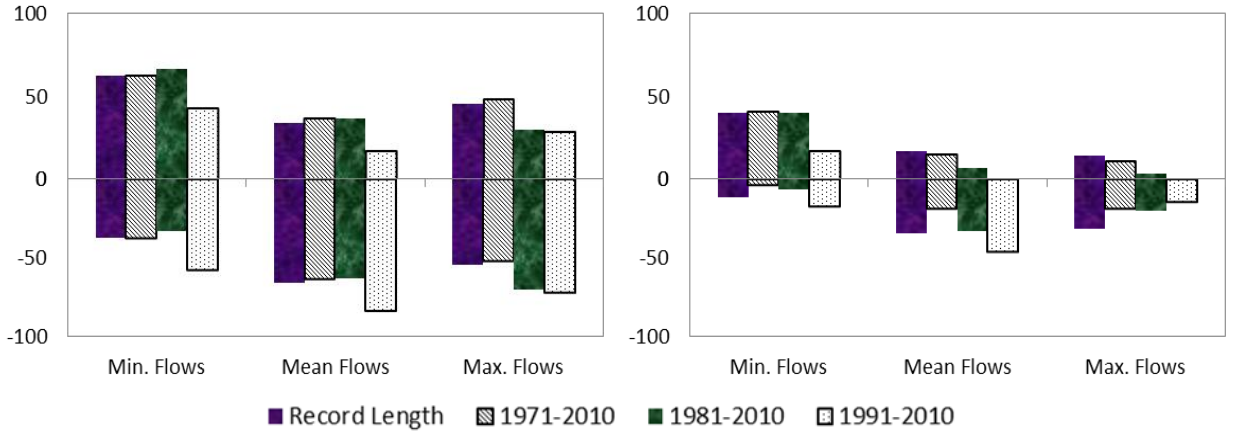


Figure-3: Percent number of stream gauges with positive and negative trends in summer time series for different periods (left) and significant trends by Mann-Kendall test (right).

5.1.2 Spatial distribution of trends

Most of decreasing trends in summer minimum flows were observed in South-East (SE) and South-West (SW) sides of the study area for all data periods. MK and Sen's slope estimator depicts that minimum flow has increased significantly ($p<0.01$) in Indus basin at Besham Qila upto 10% of mean summer flow (573 cumec) for period 1971-2010 whereas has decreased upto 15% and 3% in Kabul river at Nowshera and Jhelum river at Azat Pattan respectively but non-significant. The summer flow at the outlet of Indus and Jhelum basin has the significant increasing trends (changes are 22% and 3%) for the 2nd period (1981-2010) whereas Kabul basin has significant decreasing trend (3%). Time series of minimum flow and slope estimated by Sen's estimator at the outlets of three major basins (Jhelum, Kabul and Indus) are shown in Fig.7.

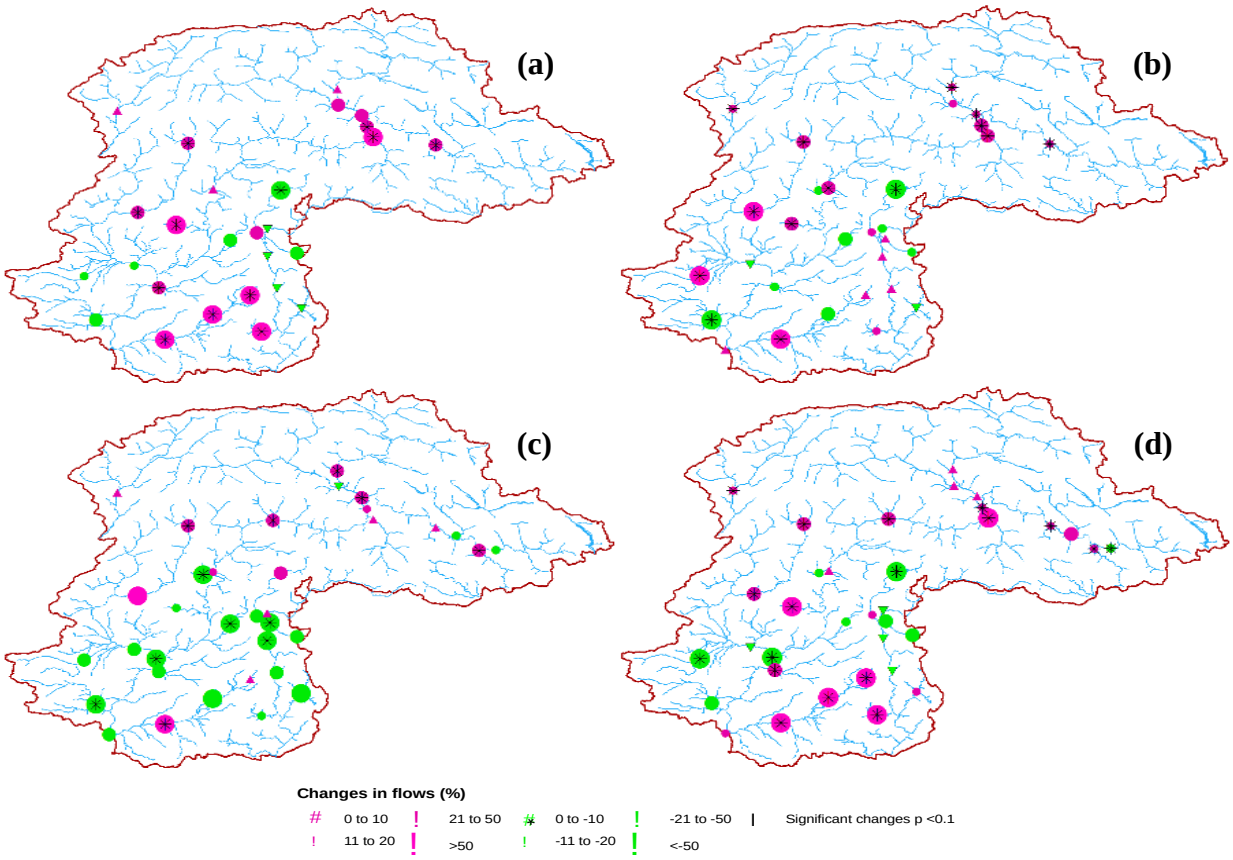


Figure-4: Spatial distribution of trends and relative changes in summer minimum flows over time windows in: (a) 1971-2010, (b) 1981-2010, (c) 1991-2010 and (d) Record Length (given in Table-1)

5.2 Trends in Mean Flows

5.2.1 Temporal trends

Trend analysis with the MK test displayed trend existence in mean summer flow at 9, 12, 16 and 18 flow stations for the period1971-2010, 1981-2010, 1991-2010 and record length respectively. The stations with trend are plotted in Fig. 5. The mean flow have more decreasing trends for all periods. The decreasing trends in mean flows were found at 63 % (19% significant), 63 %(33%), 83 %(46%) and 66% (34%) of stations for the periods 1971-2010, 1981-2010, 1991-2010 and record length respectively.

5.2.2 Spatial distribution of trends

The summer mean flow in Jhelum basin at Azad Pattan has decreasing trend with rate of 4.5 mm/year (10% of data period mean) for the record length and 1971-2010 period as well as has significantly decreasing trends in last two periods with changes in flow 26% and 52% respectively. The other three tributaries (Neelum, Kanshi and Poonch) of this basin has also significant decreasing trend for last three periods (changes in flow are given in Fig.5) whereas forth tributary Kunhar has the only positive trend at Gari-habibullah for the period 1971-2010. The mean summer flow in Indus basin at Besham Qila has the non-significant increasing trend for all periods and changes in flow were 2%, 1% and 5% for period 1971-2010, 1981-2010 and 1991-2010 respectively. The Sharif et al. (2013) also found the positive trend at Besham Qila for the period 1969-

1995. The flow at Dainyor has decreased significantly (p=0.09) upto 34% for the record length (1966-2010) and has also found decreasing trend for period 1966-1995 (Sharif et al. 2013) but in last two period (1981-2010 and 1991-2010) it has increasing trend (p=0.86 and 0.13) and flow has change with 2% and 15% respectively. The trend in Rivers Shyok at Yogo and Indus at Kharmong, Kachura and Bunji has the same trend in record length as detected by (Sharif, M. et al. 2013) with changes upto 23% -17%, 29% and 10% respectively. But for last period in Indus River at Kharmong, Kachura and Bunji has decreasing trend as shown in Fig.5. The summer mean flow in Kabul basin at Nowshera has decreased with p value 0.07 upto 20% for the whole data period 1961-2010. The River Swat Kalam and Bara at Jhansi post have decreasing trend whereas Swat River at Chakdara and River Chitral at Chitral has the increasing trend. The Chitral has decreasing trend in last period.

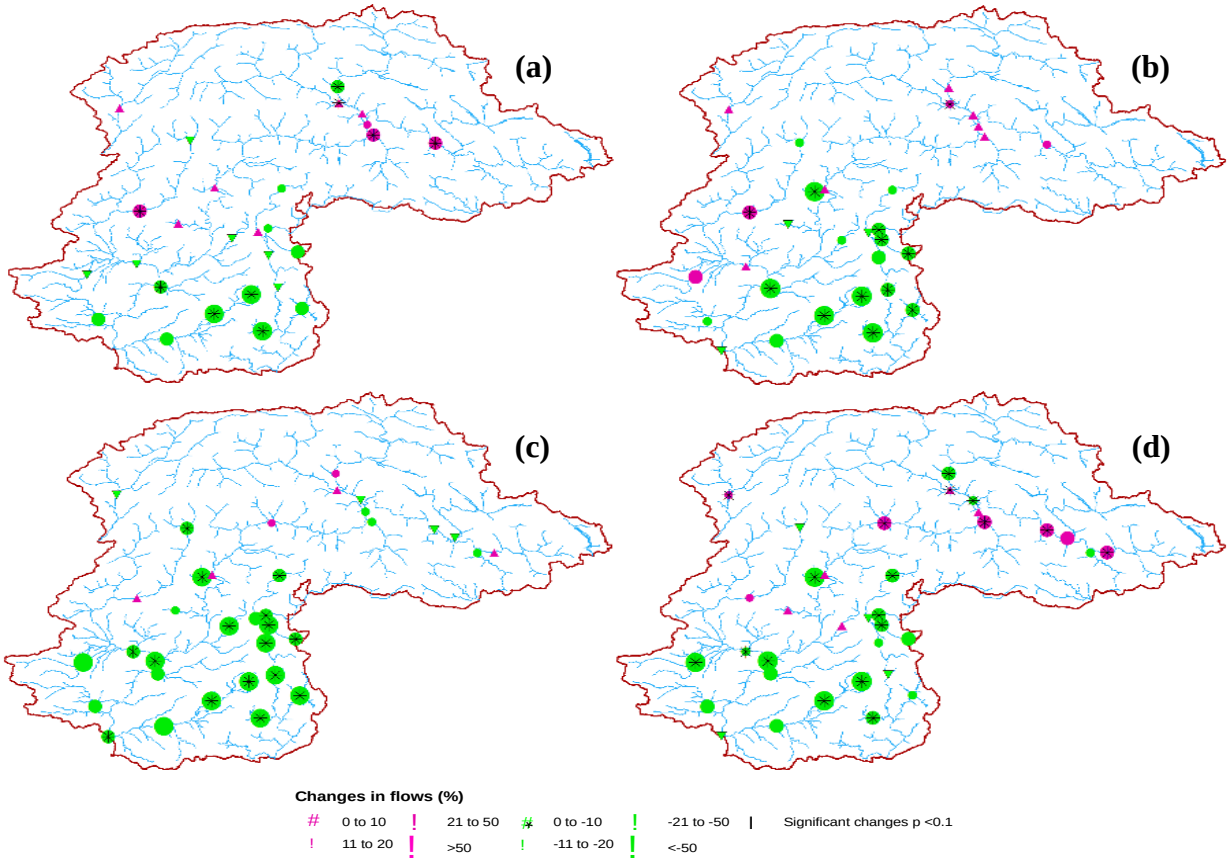


Figure-5: Spatial distribution of trends and relative changes in summer mean flows over time windows in: (a) 1971-2010, (b) 1981-2010, (c) 1991-2010 and (d) Record Length (given in Table 1)

5.3 Trends in Maximum Flows

5.3.1 Temporal trends

The variation intervals of the statistics for the maximum flows of these stations are presented in Table-2. The mean maximum varies from 67 to 14574 m/s^3. The coefficient of variation, c, changes between 0.1 and 1.0 whereas the skewness has a minimum -0.3 and a maximum 4.0. The decreasing trends in maximum flows were found at 59 % (19% significant), 60 %(17%), 69 %(14%) and 66% (29%) of stations for the periods 1971-2010, 1981-2010 , 1991-2010 and record length respectively.

5.3.2 Spatial distribution of trends

All tributaries of Jhelum basin has the decreasing trend for all periods whereas the stream gauges of main Jhelum river (at Chinari, Domel, Kohala and Azad Pattan) has the increasing trend for the record length. The changes in flows are given in Fig.6. The summer maximum flow has also the decreasing trend in Kabul basin at Nowshera for the whole data length (1961-2010) and last decade (1991-2010) and changes in flow are upto -16% and -13% respectively. The River Indus has the decreasing at Besham Qila, Khairabad and Massan for the last period. All tributaries of River Soan have also the decreasing trend for all data period analysis. The River Hunza and Gilgit have also the decreasing trend except in last period.

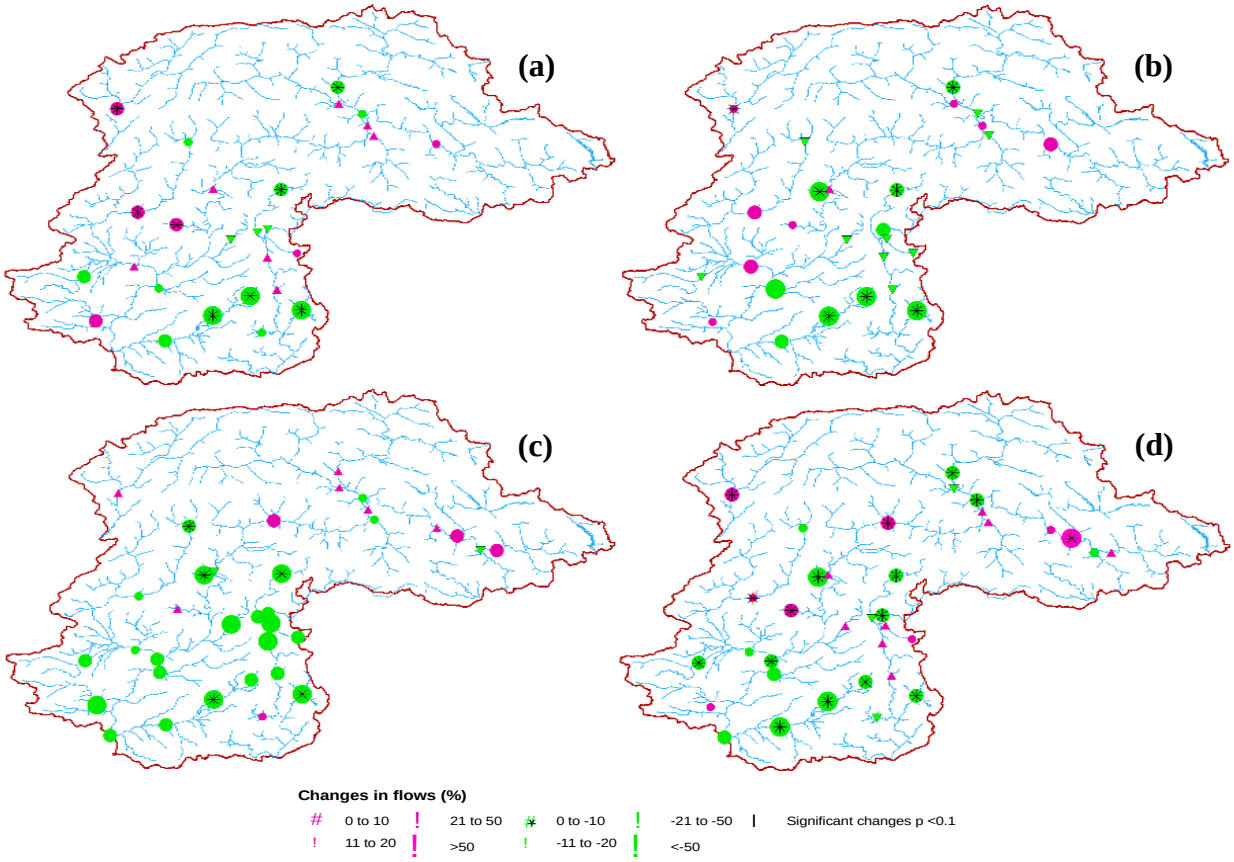


Figure-6: Spatial distribution of trends and relative changes in summer maximum flows over time windows in: (a) 1971-2010, (b) 1981-2010, (c) 1991-2010 and (d) Record Length (given in Table 1)

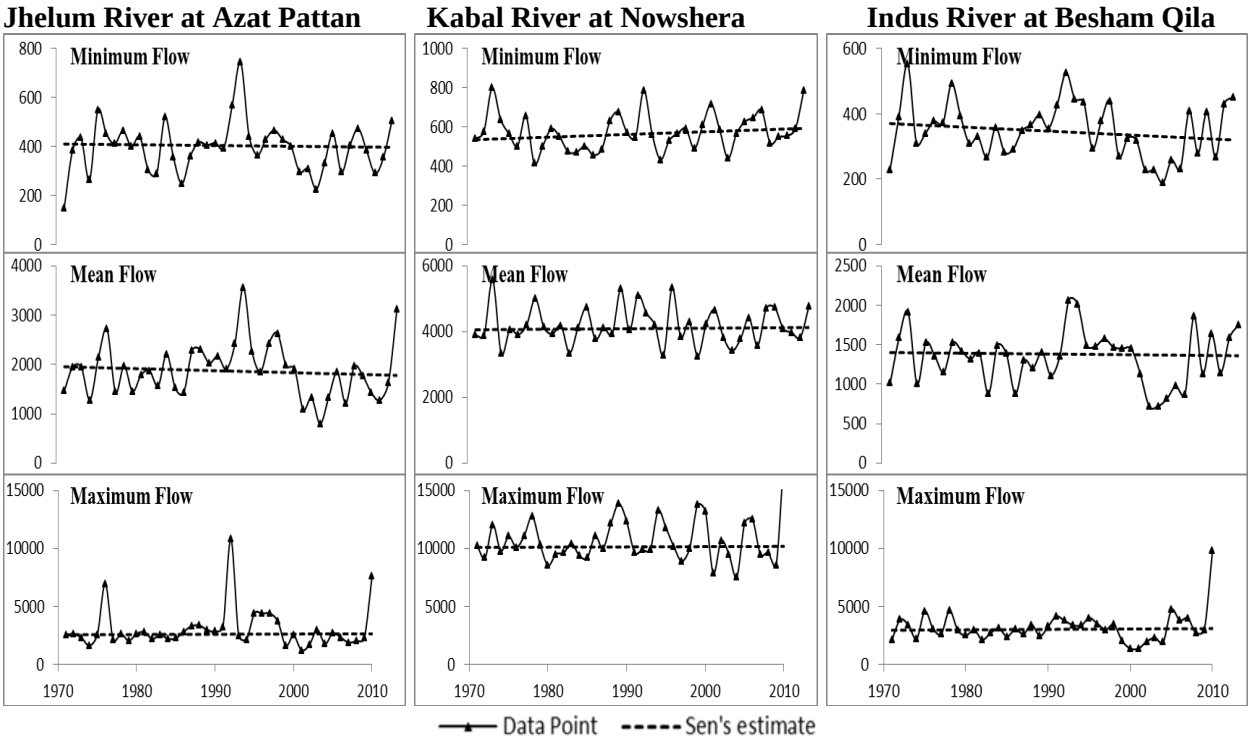


Figure-7: Time series of summer minimum, mean and maximum flows (in cumec) at outlet of three basins (Jhelum, Kabul and Indus) in Upper Indus Basin (UIB).

6. DISCUSSION AND CONCLUSIONS

The presented work covered the trend investigation of different flow statistics in Upper Indus Basin, Pakistan by applying Mann-Kendall test and Sen's method. Trend existence was more common in mean and low flows compared with maximum flows. statistically significant decreases were detected mainly in the eastern parts of UIB (in Jhelum Basin) whereas the northern and western part has the increasing trends for the 40, 30 year and record length periods. Statistically significant increasing and decreasing trends are noticed in different parts of UIB, but the exact nature of causes of these trends has not been investigated. A detailed analysis of the interaction between climatic factors and low flow regimes is beyond the scope of this paper. Overall conclusion of this study is that in the last period there were more decreasing trends in streamflows. Specific conclusions of this study are as fallow:

- The summer minimum, mean and maximum flows in Indus basin at Besham Qila (u/s of Tarbela reservoir) has significantly increasing trend as well also in Kabul basin but non-significant for the period 1971-2010 and 1981-2010.

- The maximum flow at both outlets of Indus and Kabul basins has decreasing trend with the rate of 2% and 13% of average summer maximum flow respectively for the 3rd period.

- The maximum flow in Jhelum basin at Azad Pattan (u/s of Mangla reservoir) has non-significant increasing trend for the period 1971-2010 but in last two period (1981-2010 &1991-2010), has the decreasing trends.

- The summer mean flow at outlet of Jhelum basin has decreased significantly upto 10%, 27% and 54% for the 1st, 2nd, and 3rd period respectively.

The decreasing trend in summer maximum, mean, and minimum flows carries significance in water resources engineering for different reasons. The decrease in minimum (low) flows may indicate the increase of the dry periods within a year in these rivers. This is especially true for summer months when irrigation is quite significant. Another problem would be the increase in the contaminant concentration in the case of waste water discharge to the river. The decrease in low flows is especially important for the location of the water treatment facility, the quantity of irrigation, and drinking water. The changes in low-flow also affect the minimum water quantity released by dams downstream for sustainable protection of ecological cycles.

The decrease in mean flows, on the other hand, plays a dominant role in the determination of water reservoir capacity and in the reservoir management works afterward. It can be said that the negative trend in mean flows affects the dimensions and hence the construction cost of the dam and can be also considered as a limiting factor for the water quantity withdrawn from the reservoir. A trend in maximum flows, however, is significant in particular for spillway design.

As is well known, the flood flows are considered for finding the crest height of a dam. Similarly, flood flows are also significant for the design of flood protection structures in the rivers.

Statistical tests can only indicate the significance of the observed test statistics and do not provide unequivocal findings. It is therefore important to clearly understand the interpretation of the results and to corroborate findings with physical evidence of the causes, such as land use changes or river stations influenced by human activities. Changes in streamflow drought severity and frequency might occur as a result of changes in climate (mainly precipitation and temperature) and artificial influences in the catchment such as groundwater abstraction, irrigation and urbanization (Hisdal *et al.*, 2001). Even so, low flow data are especially prone to artificial influences in a catchment, and the results presented in this paper may have been affected by this. The causes of a change in river flow behavior often do not have a simple explanation, and a further study would require a detailed analysis at the catchment scale, which is beyond the scope of this paper. However, the spatial consistency in the results does indicate some systematic factors that can be evaluated at a regional level.

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