Recent Patterns and Trends in Extreme River Flow Event in the Upper Indus Basin, Pakistan

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Abstract

The Upper Indus Basin (UIB), covering the Hindukush, Karakoram, and Himalayan (HKH) ranges, is a key water source for ten major rivers, including Jhelum, Kabul, Hunza, Shyok, and Shigar. This study analyzes trends in high and low streamflows from 1981 to 2016 using the Mann-Kendall test and Sen's slope estimator to assess their magnitude and timing. The results reveal a decline in high flows across key sub-basins like Jhelum, Indus, and Kabul, while glacier-fed basins such as Shigar and Shyok showed increasing trends. In contrast, nival and rainfall-fed rivers, including Jhelum, Neelum, and Kunhar, exhibited significant negative trends. For low flows, decreasing trends were observed annually and during extreme low-flow periods (one-day, seven-day, fifteen-day), especially in summer. Some stations, however, recorded increased low flows during autumn, winter, and spring. The pronounced decline in summer low flows highlights extended dry periods, raising concerns for water availability during peak demand seasons, which could adversely affect agriculture and hydropower generation in the region.

Keywords: Upper Indus Basin; streamflows; flow extremes; high and low flows; Mann-Kendall; in the Jhelum River basin and Kabul River basin; there are important trends due to climate change

1. Introduction

The increase in climate change has caused the hydrological cycle to speed up, causing more floods and droughts [1–4]. The movement of heat and the amount of rainfall greatly influence how much water is used for evapotranspiration, runs off and remains accessible [5–8]. When hydrology shifts, agriculture, industry and urban development all face major difficulties because the supply of water resources is modified [9–11].

The Upper Indus Basin is found in the Hindukush-Karakoram-Himalaya ranges, covering an area of 32,182 km² [12]. This region plays a critical role in feeding major rivers through glacial melt, snowmelt, and precipitation. In recent years, the scientific community has shown increasing interest in understanding glacier dynamics within the HKH region due to observed climate variability and its hydro-meteorological implications [13–16]. These dynamics include glacier retreat, surge events, and stability, which influence river flow regimes.

While several studies have assessed variations in precipitation, temperature, and streamflows across the UIB [17–28], most analyses have focused on annual mean flows or a limited number of gauging stations [26, 28]. Existing research has highlighted the critical role of glacial melt in feeding rivers such as the Jhelum and Kabul, which are highly sensitive to temperature and precipitation changes [17, 29]. Seasonal variations in river flows are strongly influenced by winter snow accumulation and summer ablation, with precipitation timing dictating immediate (rain-fed) or delayed (snowmelt) runoff [26, 31, 32].

Streamflow regimes reflect flow variability over time and are directly tied to climate change risks, including seasonal water availability, flooding, and droughts [38]. Pakistan has experienced several devastating floods in the past most notably in 1950, 1973, 2010, and 2013 that caused significant economic losses exceeding USD 30 billion and widespread damage to infrastructure and livelihoods [40]. Such events emphasize the need for a detailed understanding of long-term flow trends to manage water resources and mitigate future risks.

In Pakistan, changes in flow magnitudes have exacerbated water management issues, particularly in downstream provinces like Sindh, where dry-season scarcity and summer floods are recurring concerns [41, 42]. Despite the importance of flow variability, previous studies [17–19, 43, 44] have largely focused on mean flows, with limited consideration for trends in extreme high and low flows. Notably, some analyses have been restricted to short temporal records or specific sub-basins [21, 26, 27].

This research uses the daily streamflow data for 1981–2016 to evaluate peak flow date and extreme flow values at major gauging stations to fill in these gaps to date and understand spatial and temporal flow variations.

2. Study Area Location and DataSource

The Upper Indus Basin incorporates Afghanistan, China, India and Pakistan as members of the transboundary water basin. The geographical characteristics of the country comprising the generally high altitude HKH ranges gives a separate hydrological region [45]. In regions like the Hunza River Basin, snowfall predominantly occurs above 5000 meters, with snow cover extending to nearly 80% in winter and shrinking to around 30% in summer [48].

The UIB's hydrology can be categorized into three primary flow regimes based on different moisture inputs (Figure 1). Considering the moisture sources, the study selected gauging stations. In particular, only 22 of the gauging stations had available high flow information and 35 of the stations were involved in the low flow analysis. Major sub-basins included in the study are Astore, Gilgit, and Hunza, which exhibit unique geographical features. While westerlies dominate as a moisture source, their impact varies across these basins [36]. The summer ablation season runoff is fed not only by glaciers at high altitudes but also by seasonal snowmelt, monsoon precipitation, and snow-covered areas [45]. Notably, elevations between 4500–6500 meters experience snowfall even during peak summer ablation (July–September).

Jhelum River and the Pir Panjal range is located at an elevation of 5500 feet and is a very important tributary of Indus River system. Mangla Dam is Pakistan’s second largest dam built on Jhelum River for hydropower generation as well water storage. The Jhelum River receives inflow from five major sub-catchments: Neelum/Kishanganga, Poonch, Kunhar, Kanshi, and the Jhelum itself. Out of these, most (over 85%) flow comes from the Neelum River at Domel and the Kunhar River, meeting the Jhelum at Kohala Bridge.

Streamflow data for this study were downloaded from the Water and Power Development Authority Surface Water Hydrology Project (WAPDA-SWHP), which developed a monitoring network in the 1960s [28]. The UIB comprises three main river basins are Jhelum, Indus, and Kabul with 22 sub basins monitored for high flows and 35 stations for low flows during the 1981–2016 period (Figure 2). Some stations, such as Massan, Khairabad, and Bunji, represent large drainage areas, whereas smaller areas like Chirah and Chahan are also included due to their geographical importance.

Stations with minimal flood risk or very low high-flow ranges were excluded from the high-flow analysis, whereas all 35 gauges were used for low-flow trends. Further, high flow data were not uniformly available for all gauges, and analysis was thus restricted to 1981–2016. The data consist of annual high and low flows derived from daily streamflow records. Annual maximum daily mean flow (flood magnitude) and control of the annual high flow are key flow indices. For low flows, 1-day, 7-day, and 15-day flow minima were examined to analyze extremes. Summary statistics of flow magnitudes and timings for the 1981–2016 period are presented in Table 1 from yaseen et al [69].

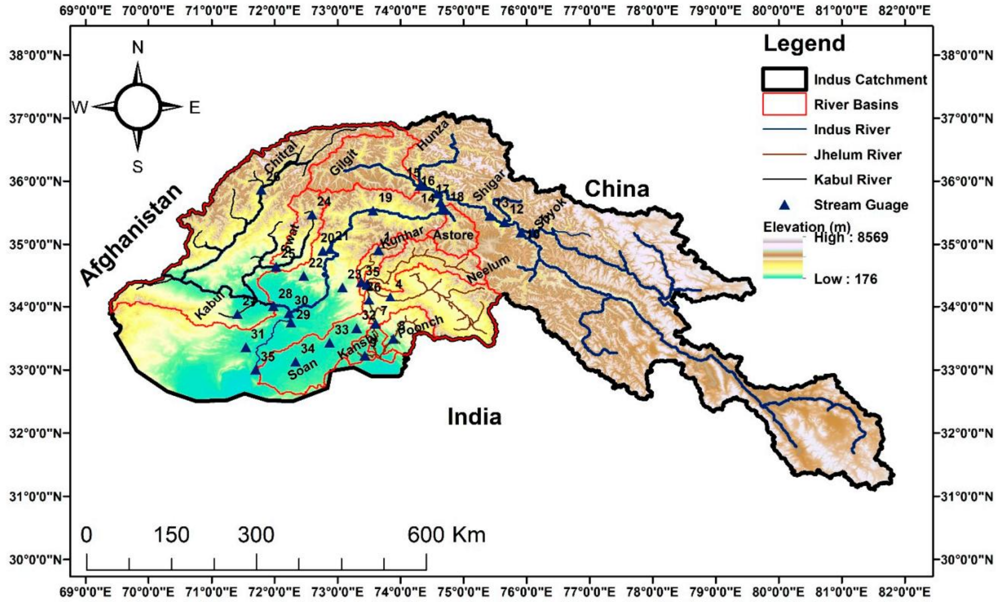

Figure 1. Indus Basin, major sub-basins & location of the gauges installed, Pakistan.

Table 1. High/low flow analysis river / stream gauges for Indus Basin.

Sr. No.	Station Name	Lat (dd)	Lon (dd)	River	Basin	Area (km2)	Mean Annual Low Flows			Mean Date	Annual High Flows	
							1 Day	7 Days	15 Days	Mean	Highest	Date
1	Naran_Station	34.90	73.70	Kunhar_River	Jhelum_Basin	1036.0	6.30	10.40	13.40			
2	G. Habibullah_Station	34.40	73.40	Kunhar_River	Jhelum_Basin	2355.0	18.0	22.20	25.20	103.0	447.0	06-July
3	Muzaffarabad_Station	34.40	23.50	Neelum_River	Jhelum_Basin	7275.0	47.50	45.80	60.20	332.0	1417.0	14-June
4	Chinari_Station	34.20	73.80	Jhelum_River	Jhelum_Basin	13,598.0	0.20	48.70	57.40			
5	Domel_Station	34.40	73.50	Jhelum_River	Jhelum_Basin	14,504.0	56.60	52.60	611.0			
6	Kohala_Station	34.10	73.50	Jhelum_River	Jhelum_Basin	24,890.0	146.30	126.30	159.1			
7	Azad Pattan_Station	33.70	73.60	Jhelum_River	Jhelum_Basin	26,485.0	155.20	1033.0	170.40	1207.0	3155.0	14-June
8	Kotli_Station	33.50	73.90	Poonch_River	Jhelum_Basin	3238.0	19.80	21.0	30.40	126.0	1780.0	01-July
9	Palote_Station	33.20	73.40	Kanshi_River	Jhelum_Basin	1111.0	0.30	5.20	2.60	6.0	323.0	27-July
10	Kharmong_Station	35.20	75.90	Indus_River	Indus_Basin	67,858.0	93.00	80.60	122.30			
11	Yogo_Station	35.20	76.10	Shyok_River	Indus_Basin	33,670.0	37.80	36.50	67.20	358.0	2225.0	3-August
12	Shigar_Station	35.40	75.70	Shigar_River	Indus_Basin	6610.0	15.10	214.0	29.70	209.0	1108.0	29-July
13	Kachura_Station	35.50	75.40	Indus_River	Indus_Basin	112,665.0	176.60	151.0	239.70			
14	Gilgit_Station	35.90	74.30	Gilgit_River	Indus_Basin	12,095.0	62.40	58.20	848.0	309.0	1162.0	27-July
15	Dainyor Br._Station	35.90	74.40	Hunza_River	Indus_Basin	13,157.0	37.20	36.00	59.10	325.0	1494.0	2-August
16	Alam Br._Station	35.80	74.60	Gilgit_River	Indus_Basin	26,159.0	89.80	75.40	1437.0			
17	Bunji_Station	35.70	74.60	Indus_River	Indus_Basin	142,709.0	306.70	214.60	344.60			
18	Doyain_Station	35.50	74.70	Astore_River	Indus_Basin	4040.0	30.70	27.30	36.60	139.0	635.0	29-June
19	Shatial Br._Station	35.50	73.60	Indus_River	Indus_Basin	150,22.00	350.90	279.60	4395.0			
20	Karora_Station	34.90	72.80	Gorband_River	Indus_Basin	635.0	4.40	11.00	7.20	18.0	137.0	03-June
21	Besham Qila_Station	34.90	72.90	Indus_River	Indus_Basin	162,393.0	414.02	357.00	524.04	2401.0	10810.0	22-July
22	Daggar_Station	34.50	72.50	Brandu_River	Indus_Basin	598.0	2.80	8.00	5.00	6.0	98.0	30-June
23	Phulra_Station	34.30	73.10	Siran_River	Indus_Basin	1057.0	3.50	8.70	6.10	20.0	267.0	22-June
24	Kalam_Station	35.50	72.60	Swat_River	Kabul_Basin	2020.0	12.20	153.0	18.20			
25	Chakdara_Station	34.60	72.0	Swat_River	Kabul_Basin	5776.0	36.10	37.40	47.40	188.0	822.0	29-June
26	Chitral_Station	35.90	71.80	Chitral_River	Kabul_Basin	11,396.0	59.40	54.30	85.60	276.0	1091.0	28-July
27	Jhansi Post_Station	33.90	71.40	Bara_River	Kabul_Basin	1847.0	1.40	6.030	3.30			
28	Nowshera_Station	34.0	72.0	Kabul_River	Kabul_Basin	88,578.0	151.06	152.10	180.90	837.0	3218.0	04-July
29	Gurriala_Station	33.70	72.30	Haro_River	Indus_Basin	3056.0	7.20	11.60	10.20	26.0	600.0	27-July
30	Khairabad_Station	33.90	72.20	Indus_River	Indus_Basin	252,52.5	491.02	480.20	976.90			
31	Thal_Station	33.40	7150	Kurram_River	Indus_Basin	5543.0	7.60	12.30	10.80	25.0	232.0	05-July
32	Chirah_Station	33.70	73.30	Soan_River	Indus_Basin	326.0	0.10	4.90	2.20			
33	Chahan_Station	33.40	72.90	Sil_River	Indus_Basin	241.0	0.10	5.00	21.0			
34	Dhok Pathan_Station	33.10	72.30	Soan_River	Indus_Basin	6475.0	3.60	8.60	9.20	41.0	1139.0	21-July
35	Massan_Station	33.0	71.70	Indus_River	Indus_Basin	286,00.0	791.02	660.90	1317.40	3703.0	13,882.0	01-August

3. Materials and Methods

Significant statistical trends were analyzed using parametric and non-parametric tests [33]. Hydro climatological studies are amenable to the nonparametric method because the method being robust and able to handle missing values. The Mann-Kendall (MK) test, a frequently used method for assessing trends in nonlinar river flows [11,34] were used to evaluate whether the flow magnitudes and peak controls experienced nonlinar trends. The MK test was initially developed by Mann [49] and then standardized later by Kendall and it is effective in this regard because it does not require assumptions about the distribution of data.

In order to deal with noise due to serial association in time series data, implementation of the proposed Trend-Free Prewhitening (TFPW) technique [27,28,20], recommended by recent studies, is pursued. This is to make sure that we have the correct trend detected by taking care of the autocorrelation effects. Sen's method [50] was used to calculate flow slopes which is well suited for fitting of trends to hydro-climatological data.

The MK test, TFPW and Sen's method, together, constitute a complete set of arithmetic–arithmetic methods for trend analysis of time series data [33, 51–55].

3.1. Trend Detection

Both the Mann-Kendall (MK) and Spearman tests are often compared on their ability to consistently detect trends [55]. The MK test found trends in flow indices and Sen's method calculated the slope of the trends. Various prewhitening techniques proposed in the literature were used to deal with serial correlation in time series data which often adds noise.

3.2. Serial Correlation Effect

Sequential correlation in a time series causes false significance in MK tests (lemma 56). Pre-whitening methods such as Trend-Free Pre-Whitening (TFPW) are applied to reduce this problem [57, 58]. A typical way this has been addressed in recent studies ([21], [26], [27] and [28]) is to use a version of this approach which is robust and noise free from hydro-meteorological data.

3.3. Mann-Kendall Test for Trend Detection

The MK test is a non-parametric test, here data doesn't have to follow a normal distribution, making it suitable to use for hydro climatological trend analysis [59]. Then the test statistic (Y) and the Mann-Kendall statistic (ZMK) are calculated as follows:

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

The MK statistic Y was computed using:

$$Y = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(xj - xk) \tag{2}$$

for j, k, in which n is the number of years, and xj, xk values in years j, k, respectively. The function sgn (xj − xk) decides that either the value 1, 0 or −1 should be employed depending upon the difference of (xj − xk), where j > k:

$$sgn(xj - xk) = \begin{cases} 1 & if\ (xj - xk) > 0 \\ 0 & if\ (xj - xk) = 0 \\ -1 & if\ (xj - xk) < 0 \end{cases} \tag{3}$$

Positive ZMK values indicate an increasing trend, while negative values signify a decreasing trend. Significance was assessed against a null hypothesis (H) using a standard normal table.

3.4. 3.4. Sen's Slope

Sen's slope method was used to estimate the changes of daily discharge over time. Sen's formula was used to determine the difference between the selected statistics series by value of slope's. Relative to mean daily discharge such difference over time was estimated. Because the two gauges have very different discharge it is difficult to compare as an absolute change, so the relative units were used. There is small magnitude of change in daily discharge, hence difficult to inter compare. The median of all slopes computed was Sen's estimator, (Q).

$$Q = \frac{xj - xk}{j - k} \; if \; j > k \qquad (4)$$

This method accounts for variations in discharge magnitude across stations and provides a robust estimate of trend magnitude.

4. Results

4.1. Variability in Peak Flow Magnitudes and Trend Analysis

Annual extreme flows showed negative trends at 15 stations (10 significant) and positive trends at 7 stations (2 significant) during 1981–2016 . Decreasing trends were significant in the Jhelum River basin, including its tributaries (Kunhar, Neelum, Poonch, and Kanshi), while increases in Kabul River Basin were observed at Nowshera, albeit statistically insignificant. Glacier-fed rivers such as Shyok and Shigar exhibited significant positive trends (10.0% and 30.0%, respectively), whereas Hunza River showed a significant 7.0% decrease. Tributaries like Haro and Kurram exhibited decreasing trends of 9.0% and 12.0%, respectively, while the Indus River at Tarbela recorded a significant negative trend of 1% ($p < 00.05$).

4.2. Period analysis of Variability and Trends in Peak Flow Timing

Northern UIB rivers showed temporal sensitivity, with peak flows occurring between June and August (Table 1). Glacier-fed basins peaked in August, while snow-fed basins peaked earlier, in June. Peak timing decreased significantly at 5 stations and improved at 3 stations. Flow frequency of Jhelum and Kunhar Rivers increased, but in general no significant trends have been observed (not significant trends, negative timing trends at rates of 0.20 and 0.30 days/decade, observed in the Indus and Kabul Rivers at Tarbela). The highest significant negative trend of 2.2 days/decade occurred in the Siran River. First peak was at Kabul and Kunhar in early July and at Gilgit and Soan in late July. On the other hand, the highest flow was measured on August 2 at 229.0 m3/s at Daniyor Bridge resulting from glacier contributions (Figure 4) associated with the glacier contributions.

4.3. Analysis of Variability and Trends in Low Flow Magnitudes

During 1981–2016, low flow trends were analyzed for 35 stations for one-day, seven-day and fifteen day minima. The lowest low flow was recorded in the Soan River and the highest low in the Indus River. Daniyor Bridge was 15 days from a 34 m^3/s low flow, compared a summer maximum flow of 1400 m^3/s. Summer maximum flows of 10,700 m^3/s compared to 15-day low flow at 445 m^3/s were measured at Tarbela. Trends were most prominent decreasing in summer and autumn and slightly increasing in winter and spring. The distribution of trends is shown on spatial maps.

4.3.1. Trends in 01-Day 'Low Flows'

Annual 1-day low flows at 14 stations almost disappeared, but at 9.0 stations almost tripled. The largest decreases were observed in Indus Basin (Khairabad) [34.0%] and Kabul Basin (Jhansi Post) [14.0%] and Jhelum Basin (Palote) [10.0%]. Through seasonal analysis we found decreased summer and autumn flows, but increased winter and spring. We have highest seasonal decrease at Khairabad (57.0% winter and 42.0% autumn).

4.3.2. Analysis of Trends in 07-Day Low Flows

Seven-day low flows exhibited mixed trends, with 5 stations showing significant negative trends and 5 showing positive trends annually. Decreases were most pronounced in summer, followed by autumn. Significant decreases were recorded at Karora (36.0%), Jhansi Post (12.0%), and Muzaffarabad (8.0%). Spring increases were noted at 7.0 stations, while winter trends were nearly balanced.

There were notable differences by season, with most of the greatest decreases occuring in summer rather than winter. A decreasing trend was found at 10.0 stations in summer, and there were only increases at 2.0 stations. In 5.0 stations, flow trends tended to increase towards autumn low flows and in 9.0 stations flow has decreased to autumn low flows (Figure 7a). Almost half the stations showed winter trend increases, and one third showed increases over decreases in spring flows; seven stations showed increases during spring over decreases at five stations. The highest winter decreases were observed at Khairabad (54.00%, 99.90% significance) and Jhansi Post (10.00%, 99.00% significance). In spring, significant decreases were recorded at Khairabad (59%, 99.90%), Karora (27.00%, 99.90%), Jhansi Post (5.00%, 99.00%), and Thal (40.00%, 99.00%). In summer, reductions at Khairabad and Karora were 19.00% (99.00%) and 41.0% (99.99%), respectively. Autumn trends showed decreases at Khairabad (56.00%, 99.90%) and Jhansi Post (14.00%, 99.00%). Overall, Khairabad exhibited the most frequent and significant negative trends: 55.00% annually, 54.00% in winter, 59.00% in spring, 19.00% in summer, and 56.00% in autumn.

4.3.3. Fifteen Day Low Flows Trends

Fifteen-day low flow trends were significantly negative at 8 stations and positive at 4. The highest annual decreases were observed at Khairabad (48%), Shigar (19%), and Naran (16%) (Figure 2a) from yaseen et al [69]. Seasonally, Khairabad recorded the largest declines across all seasons (e.g., 52% in spring and 56% in autumn) (Figures 2b–2f). They signal the flow reduction as a result of shifts in seasonality, change in precipitation and melting properties at high altitudes.

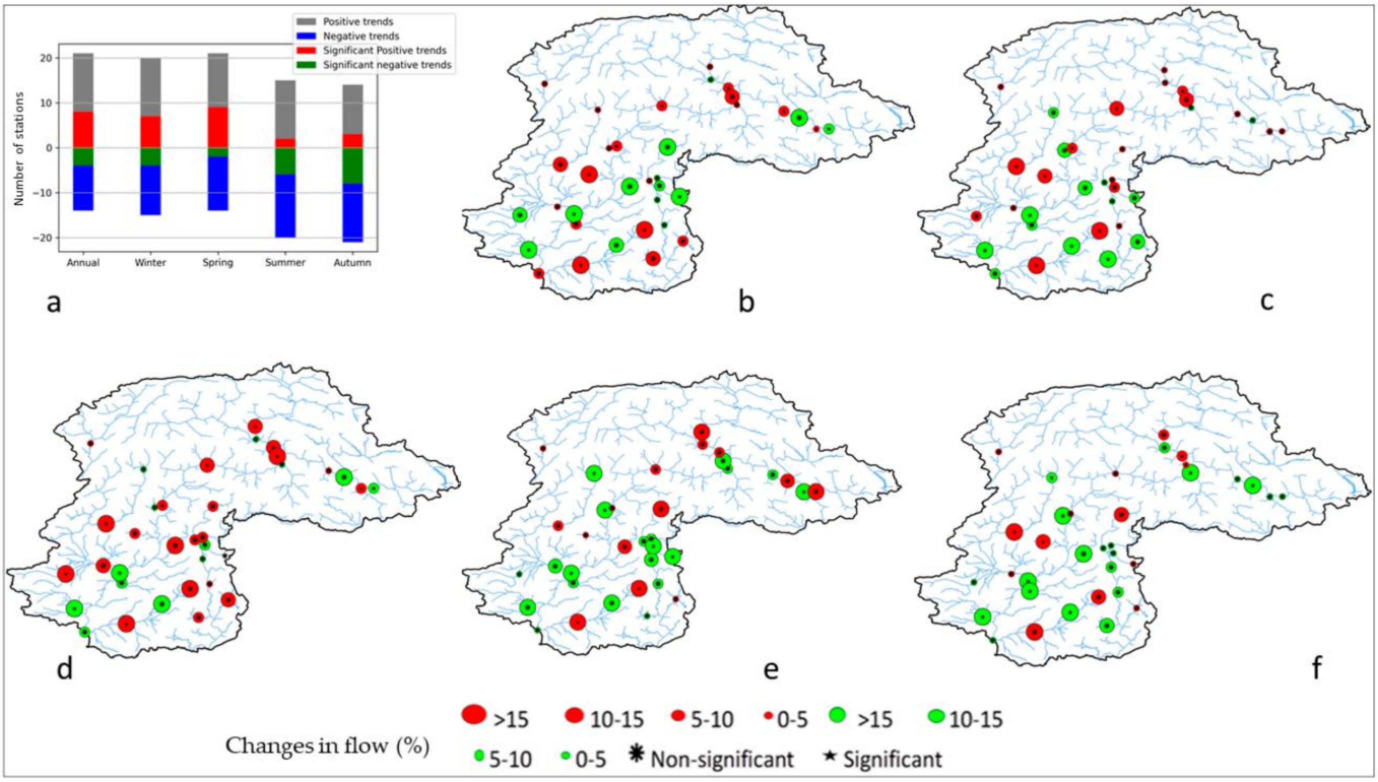

Figure 2. Seasonal and annual fifteen day low flow trends for the UIB (a) grouping of stream gauges on the basis of positive, negative and significant trends; (b) annual low flow trends; (c) winter

season shifts; (d) spring season trends; (e) summer season trends; (f) autumn season shifts. Decreasing and increasing flow patterns are highlighted red and green markers.

5. Discussion

It is revealed that annual and seasonal trends of low and high flows in the Upper Indus Basin (UIB) are mainly decreasing. Significant spatial and temporal variability in flow patterns were apparent at gauging stations across a range of diverse terrain from high glaciated mountains to more downstream areas. Annual and seasonal trends indicate a complex climatic signal in the UIB, characterized by cooler summers and contrasting hydrological regimes, as also noted in previous studies [18, 21]. Similar findings have been reported for the Indus and Jhelum basins, where a mix of positive and negative trends was observed, depending on the temporal and spatial scales [19].

Similar to earlier observations, positive trends were observed from May to August at Muzaffarabad station in the Jhelum basin and negative trends in June and July [21]. Recent studies [28] have also reported significant negative summer trends, particularly in June, across the basin. The basin is dominated by glaciers and has late summer trends (including September) that are controlled by the glacier regime and deliver peak flows in the ablation period, compared to snow fed basins where snow melts earlier in the season. This is consistent with previous research and annual and summer low flows have consistently decreased.

Trends in the Karakoram Range however were different in the gauging stations at Shigar, Shyok and Daniyor Bridge (Hunza River). Increasing flows at Shigar and Shyok and decreasing flows at Daniyor Bridge [60, 61] confirmed previous studies. Recent research confirms that snow fed basins are experiencing increasing flows [28, 62, 63], in agreement with these trends. But, for the Hunza Basin, the negative trends have been attributed to decreasing summer temperatures and negative mass balance in glaciers [21, 28, 29]. It is the winter precipitation and summer melting dynamics that lead to the increasing (negative) trend in snow fed basins [6, 21, 28, 64].

Overall, we find that grid scale hydrological changes are consistent with the global observations ascribing such changes to changes in land use and land cover (LULC) [27–29, 60, 63, 65, 66]. The results enhance our understanding of UIB hydrology and have significant practical implications. Trend detection and variability analysis of the Indus River, using tools like the copula function, can aid in developing adaptive strategies and revising regional development plans. These include irrigation management, flood protection, hydropower projects, and sustainable water resource planning.

Negative trends in mean flows also influence infrastructure dimensions and construction costs for dams, particularly regarding storage capacity and water withdrawals. The reduction in low flows, observed annually and seasonally, particularly during summer and autumn, affects water availability for irrigation, drinking, and ecological sustainability. Minimum release requirements imposed on downstream dams in order to ensure ecological balance are also affected by changes in the low flow statistics. The decrease in annual mean flows is also important for determining reservoir capacity as well as for the subsequent management strategies.

6. Conclusions

This study analyzes the patterns of magnitude and timing of high and low streamflows in key sub basins of the Upper Indus Basin (UIB) from 1981 to 2016. The data were first made trend-free pre-whitening (TFPW) to eliminate the serial correlation, and the Mann Kendall and Sen's slope method were then used to test significance and rate of change.

Results show that significant annual maximum flows and their timing decreases were recorded in the Jhelum, Indus and Kabul Rivers subbasins. Positive trends were, however, noted in the Shyok, Shigar and Gilgit basins with rates of 10, 30, 4 percent respectively. Negative trends of 0.2 and 0.3 days/decade ($p < 0.05$) were shown by the Indus at Tarbela and the Kabul river.

Low flows revealed declining trends in summer and autumn but increased during winter and spring. The most pronounced reductions occurred during summer, extending dry periods and exacerbating challenges for water-intensive activities such as irrigation and hydropower.

The study was limited to analyzing flow data up to 2016, with interpretations contextualized by recent variations in temperature, precipitation, and snow cover. Future research should incorporate more recent datasets and explore the influence of climate factors like temperature and snow cover on flow variability using advanced models. The sparse spatial distribution of some gauges presents a challenge in accurately assessing flow variability, particularly for smaller sub-basins.

Conflicts of Interest: The authors declare no conflicts of interest.

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