Spatiotemporal Variability in the Hydrometeorological Time-Series over Upper Indus River Basin of Pakistan

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Received 2 November 2019; Revised 1 January 2020; Accepted 10 January 2020; Published 30 April 2020

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This paper investigates the spatiotemporal variability in hydrometeorological time-series to evaluate the current and future scenarios of water resources availability from upper Indus basin (UIB). Mann–Kendall and Sen’s slope estimator tests were used to analyze the variability in the temperature, precipitation, and streamflow time-series data at 27 meteorological stations and 34 hydrological stations for the period of 1963 to 2014. The time-series data of entire study period were divided into two equal subseries of 26 years each (1963–1988 and 1989–2014) to assess the overlapping aspect of climate change acceleration over UIB. The results showed a warming pattern at low altitude stations, while a cooling tendency was detected at high-altitude stations. An increase in streamflow was detected during winter and spring seasons at all hydrological stations, whereas the streamflow in summer and autumn seasons exhibited decreasing trends. The annual precipitation showed a significant decreasing trend at ten stations, while a significant increasing trend was observed at Kohat station during second subseries of the study period. The most significant winter drying trends were observed at Gupis, Chitral, Garidopatta, and Naran stations of magnitude of 47%, 13%, 25%, and 18%, respectively, during the second subseries. The annual runoff exhibited significant decreasing trends over Jhelum subbasin at Azad Pattan, Chinari, Domel Kohala, Muzaffarabad, and Palote, while within Indus basin at Chahan, Gurrial, Khairabad, Karora, and Kalam in the second time-series. It is believed that the results of this study will be helpful for the decision-makers to develop strategies for planning and development of future water resources projects.

1. Introduction

Tibetan Plateau comprises three major mountainous areas of Asia, that is, Hindukush, Karakoram, and Himalaya (HKH), also known as the “third pole” or “roof of the world” because of the massive volumes of recurrent snow and glacial ice storage in its high-altitude basins [1, 2]. The upper Indus basin (UIB) encompasses a huge constituency of hilly areas, and water resources originating from this region are of decisive significance to the interests of Pakistan. The upper Indus river system is of high importance to sustainable water supply for large populations located in the lower reaches of Indus river in Pakistan. Being an agricultural country with heavy population growth, there is a great stress on water resources to meet the food and fiber requirement for the people. The satisfaction of irrigation system, domestic consumption, and hydropower needs are dependent on water resources from the UIB and its tributaries. The huge river basins of south and southeast Asia rely on summer monsoonal wet regimes downstream, but the UIB is dependent on melted water from glaciers and snow-fed catchments [3]. If anthropogenic interventions causing greenhouse gas emissions into the atmosphere persist, the average global surface temperature may rise from 0.2 to 0.5°C/decade in the next few decades over UIB [4]. This temperature upsurge in the Himalayan region is greater than
the average global rise of 0.74°C over the last century [5]. Large-scale warming of the earth surface over the last ten decades or even more is also indicated by several researchers [6–8]. Not only did such high-scale warming affect the global circulation patterns but also direct affects occur in local climatic settings with changes in distribution and characteristics of precipitation and temperature [9]. Changes vary in space and time domains as affected by local climatic and topographic settings [10–13]. These spatiotemporal variations in the climatic variables have motivated this study in which we aim to assess possible acceleration of climate changes and related hydrological impacts over UIB.

Numerous climate change studies have been carried out over the UIB. For instance, significant decreasing temperature trends were detected during the monsoon season and warming during the premonsoon season [14–16]. Moreover, warming winter and cooling summer trends were found over UIB; however, these trends lack a definite pattern of precipitation [17, 18]. However, Bocchiola and Diolaiuti [16] argued that winter warming and summer cooling trends were overstated in earlier studies and were only restricted to Gilgit and Bunji stations, respectively. They reported increasing (insignificant) precipitation trends over the Chitral and Northwest Karakoram regions and a drying pattern over the UIB. Some recent studies have reported general increasing temperature trends during the premonsoon instead of winter warming and summer cooling trends were detected during the monsoon season and a 16% increase for the river Hunza (basin area 13.925 km²), respectively. The mean temperature in the UIB has increased over the last century; however, long-term persistent trends (>100 years) have not been detected [15, 16]. Also, the statistically significant ($p < 0.05$) increases in winter maximum temperature of 0.27°C, 0.55°C, and 0.51°C per decade were observed at Gilgit, Skardu, and Dir in the UIB. The climate change impacts are projected in a semiarid setting and altitude variations on runoff contributions from glacier melt, snow melt, and monsoon precipitation were also evaluated.

2. Description of Study Area

The Indus river basin is one of the world’s largest transboundary river basins with a total drainage area of about $1.08 \times 10^6$ km² [27, 28]. The UIB contributes to half of the surface water disposal in Pakistan depending upon the melted water resources from Hindukush-Karakoram-Himalayan (HKH) region. The URB is located within the terrestrial ranges of 33° 40’ to 37° 12’ N and 70° 30’ to 77°, 30’ E, in the mountainous ranges of Hindu-Kush, Karakoram, Himalaya, and Tibetan Plateau [12, 17]. These ranges jointly host 11,000 glaciers [29], which make it one of the world’s most glaciated areas, with roughly 22,000 km² of glacier surface area [30]. The altitude in the UIRB varies from 200 m to 8500 m.a.s.l. with an average elevation of 3750 m a.s.l., covering a catchment area of 286,000 km². The research area is considered as the prime source of fresh water for Pakistan and plays a vibrant role in the sustainable economic development of the country. The location of climatic and streamflow stations is presented in Figure 1. The major subbasins of the UIB are discussed in the following paragraphs.

2.1. Shyok and Shigar Subbasins of UIB. The eastern and central part of the Karakoram is covered by the Shyok and flows from the highest central Karakoram watersheds over the past two decades and suggested that much winter precipitation is going into long-term storage by glacier surges.
Shigar basins, respectively. About 24% of the area of the Shyok river basin is covered with snow [31]. Similarly, one-third of the area of Shigar basin is covered by glaciers including the world’s largest glaciers and ice masses and almost 25 to 90% of the area is covered with snow. The basic source of precipitation of these two basins is westerly disturbances during winter and spring seasons followed by the summer monsoon intruding during various intervals [3, 19, 32, 33]. This study used the discharge data of Shyok river at Yugo and Indus river at Shigar for the trend analysis of flows within these two basins.

2.2. Astore and Hunza Subbasins of UIB. The Astore basin is located in the western Himalayan and Hunza basin is in the western Karakoram ranges. The glacial coverage within these basins is less than snow coverage as compared to the Shyok and Shigar basins. The glaciers and permanent ice cover within Hunza basin is 28% and 14%, which exhibits almost 21% and 3% of the total UIB glacial coverage within Hunza and Astore basins, respectively [3, 31]. Three high-altitude stations are installed within Hunza basin, that is, Khunjrab, Naltar, and Ziarat, while river discharge is measured at Danyior bridge at Hunza river. There is only one climatic station (Astore) installed in Astore basin measuring temperature and precipitation data in this basin. Discharge data of Astore river at Doyian are used in this study for the trend analysis installed by Water and Power Development Authority (WAPDA).

2.3. Gilgit Subbasin of UIB. The Gilgit subbasin ranges between 35.8 and 37° E and 72.5 to 74.4° N comprehends eastern part of Hindu Kush range and drains towards southeast to join Indus river. The discharge of Gilgit river is measured at Gilgit hydrometric station and at the confluence of Hunza and Gilgit river, which is called Alam bridge. The drainage area of this basin incorporates 12000 km² with an elevation range from 1481 to 7134 m a.s.l. Four climatic stations are installed in this area, that is, Gilgit, Gupis, Yasin, and Ushkore, by the Pakistan Meteorological Department (PMD) and WAPDA. In this study, data at two stations (Gilgit and Gupis) were used from 1960 to 2014. Hasson et al. [3] reported that the Gilgit basin receives maximum precipitation at Ushkore (3151 m) and minimum precipitation at Gilgit (1460 m) due to the westerly disturbances and summer monsoon.

2.4. Jehlum Subbasin of UIB. The Mangla basin is located on the southern slope of the Himalayas with elevation ranging from 300 m to 6282 m a.s.l. and has basin area of around 33425 km² 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 subcatchments, that is, Jhelum, Poonch, Kanshi, Neelum/Kishanganga, and Kunhar which drain water to Mangla reservoir.
2.5. Kabul Subbasin of UIB. Kabul river, in the eastern Afghanistan and northwestern Pakistan, is 700 km long, of which 560 km lies in Afghanistan. It originates in the Sanglakh ranges located 72 km west of Kabul city. It flows east through Kabul and Jalalabad, north of the Khyber Pass into Pakistan. The river has four major tributaries: the Lowgar, the Panjsher, the Konar (Kunar), and the Alingar. Most of area of this catchment lies in Afghanistan. Due to unavailability of data from Afghanistan, the study area was confined to the catchment falling within Pakistan boundary. The Kabul river, a major western flank tributary, joins with Indus near Attock.

Moreover, information of mean annual maximum and minimum temperature ($T_{\text{max}}$, $T_{\text{min}}$) and precipitation ($P$) of 27 climatic stations is shown in Table 2. Streamflow measurements in the UIB are carried out by WAPDA with the earliest records commencing from 1960. The stream gauges have a broad range of drainage area from 262 km$^2$ to 286,000 km$^2$. The study area contained three major basins, namely, Jhelum, Indus, and Kabul. The locations of different hydrological and meteorological stations are presented in Figure 1.

The hydrometeorological time-series data of entire study period (1963–2014) were divided into two equal subseries, that is, 1963 to 1988 and 1989 to 2014, to analyze the aspects of acceleration of climate change. Mean monthly, seasonal, and annual values of $T_{\text{max}}$, $T_{\text{min}}$, $P$, and $Q$ were derived from the daily time-series data. To analyze the seasonal variations in the hydrometeorological time-series data, four seasons were defined as winter (December, January, and February (DJF)), spring (March, April, and May (MAM)), summer (June, July, and August (JJA)), and autumn (September, October, and November (SON)) seasons.

### Table 1: List of stream gauges used in the present study and their characteristics (period 1: 1963–1988; period 2: 1989–2014).

| Sr. no. | Station  | Latitude (dd) | Longitude (dd) | Area (Km$^2$) | Mean annual streamflow (m$^3$/s) |
|---------|----------|---------------|----------------|---------------|----------------------------------|
|         |          |               |                | 1963–1988     | 1989–2014                        |
| 1       | Naran    | 34.9          | 73.7           | 1036          | 47.7                             | 45.6                             |
| 2       | Garhi Habibullah | 34.4          | 73.4           | 2355          | 105.5                           |
| 3       | Muzaffarabad | 34.4          | 73.5           | 7275          | 321.9                           |
| 4       | Chinari  | 34.2          | 73.8           | 13598         | 298.7                           | 289                             |
| 5       | Domel    | 34.4          | 73.5           | 14504         | 327.3                           | 322.3                           |
| 6       | Kobala   | 34.1          | 73.5           | 24890         | 776                             | 780.5                           |
| 7       | Azad Pattan | 33.7          | 73.6           | 26485         | 1150.7                          | 1241.8                          |
| 8       | Kotli    | 33.5          | 73.9           | 3238          | 123.9                           | 127.3                           |
| 9       | Palote   | 33.2          | 73.4           | 1111          | 6                               | 5.3                             |
| 10      | Kharmong | 35.2          | 75.9           | 67858         | 462.7                           | 465                             |
| 11      | Yogo     | 35.2          | 76.1           | 33670         | 341.2                           | 368.8                           |
| 12      | Shigar   | 35.4          | 75.7           | 6610          | 194.6                           | 220.5                           |
| 13      | Kachura  | 35.5          | 75.4           | 112665        | 962                             | 1159.6                          |
| 14      | Gilgit   | 35.9          | 74.3           | 12095         | 277.2                           | 333.7                           |
| 15      | Dainyor Br. | 35.9          | 74.4           | 13157         | 365.4                           | 295                             |
| 16      | Alam Br. | 35.8          | 74.6           | 26159         | 661.8                           | 619.3                           |
| 17      | Bunji    | 35.7          | 74.6           | 142709        | 1706                            | 1875.3                          |
| 18      | Doyain   | 35.5          | 74.7           | 4040          | 118.3                           | 149.2                           |
| 19      | Shatial Br. | 35.5          | 73.6           | 150220        | 1938.9                          | 2110.6                          |
| 20      | Karora   | 34.9          | 72.8           | 635           | 20.4                            | 17.5                            |
| 21      | Besham Qila | 34.9          | 72.9           | 162393        | 2350.2                          | 2436.8                          |
| 22      | Daggar   | 34.5          | 72.5           | 598           | 5.4                             | 5.9                             |
| 23      | Phulra   | 34.3          | 73.1           | 1057          | 18.6                            | 20.5                            |
| 24      | Kalam    | 35.5          | 72.6           | 2020          | 85.7                            | 86.2                            |
| 25      | Chakdara | 34.6          | 72             | 5776          | 169.1                           | 207.1                           |
| 26      | Chitral  | 35.9          | 71.8           | 11396         | 264.4                           | 285.4                           |
| 27      | Nowshera | 34            | 72             | 88578         | 849                             | 824.2                           |
| 28      | Gurrialal | 33.7          | 72.3           | 3056          | 26.9                            | 24.8                            |
| 29      | Khairabad | 33.9          | 72.2           | 252252        | 3222.7                          | 2834.4                          |
| 30      | Thal     | 33.4          | 71.5           | 5543          | 27.7                            | 22.6                            |
| 31      | Chirah   | 33.7          | 73.3           | 326           | 5.7                             | 4                               |
| 32      | Chahan   | 33.4          | 72.9           | 241           | 1.7                             | 1.3                             |
| 33      | Dhok Pathan | 33.1          | 72.3           | 6475          | 44                              | 38.4                            |
| 34      | Massan   | 33            | 71.7           | 286000        | 3527.2                          | 3805.9                          |
3.2. Change Detection. To detect climate impacts and possible climate change acceleration over the past 52 years, Student’s t-test was selected for sample means, whereas the “F-test” was selected to assess aspects of variability on time-series. The nonparametric Mann–Whitney U-test was used to assess aspects of the distribution of observations.

3.2.1. Student’s t-Test and F-Test. The application of Student’s t-test aims to detect the change in the mean values of two 26-year periods for statistical significance. F-test was used to detect the variability in the time-series. Both tests were performed at the 90% confidence interval. The t-statistic is calculated by using equation (1), when the variances of both time-series have similar values.

\[ t = \frac{\bar{X}_1 - \bar{X}_2}{S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \]  

(1)

where \( \bar{X}_1 \) and \( \bar{X}_2 \) are mean values of two subseries; \( n_1 \) and \( n_2 \) indicate number of observations; \( s_1 \) and \( s_2 \) are the standard deviations; subscripts 1 and 2 indicate the periods 1963–1988 and 1989–2014; and \( S_p \) is the standard deviation, which is given as

\[ S_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}. \]  

(2)

If the variances for the two periods are different, then the t-statistic is used and given in the following equation:

\[ t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\left(\frac{s_1^2}{n_1}\right) + \left(\frac{s_2^2}{n_2}\right)}}. \]  

(3)

3.2.2. Mann–Whitney U-Test. The nonparametric Mann–Whitney U test [34] is selected to detect the shift in the temperature, precipitation, and streamflow time-series data. The Mann–Whitney (MW) U test statistic [35, 36] is given in the following equation:

\[ U = \min\{U_1, U_2\}. \]  

(4)

We have

\[ U_1 = n_1n_2 + \frac{n_1(n_1 + 1)}{2} - R_1, \]  

(5a)

\[ U_2 = n_1n_2 + \frac{n_2(n_2 + 1)}{2} - R_2, \]  

(5b)

where \( U_1 \) and \( U_2 \) are the total count of samples 1 and 2; and \( R_1 \) and \( R_2 \) are the rank sums of sample 1 and sample 2, respectively. When the null hypothesis, \( H_0 \), is true and \( n_1 \) and \( n_2 \) are both larger than 8, \( U \) is considered approximately normally distributed with mean of \( E(U) \) and variance of \( V(U) \) given as

\[ E(U) = \frac{n_1n_2}{2}, \]  

\[ V(U) = \frac{n_1n_2(n_1 + n_2 + 1)}{12}. \]
3.2.3. Relative Changes. The relative change (%) in the annual and seasonal temperature, precipitation, and streamflow was assessed by using the following equation:

\[
\text{relative change} = \frac{\text{mean of 2nd period} - \text{mean of 1st period}}{\text{mean of 1st period}}.
\] (7)

3.3. Trend Analysis. For detection of trends, we (i) pre-whitened time-series to eliminate effect of serial correlation of observations, (ii) applied Mann–Kendall trend analysis to identify if trends are significant, and (iii) assessed the trend slope line by means of Sen’s estimator. Analysis is common, and reference is made to applications in [1, 2, 37–40].

3.3.1. Mann–Kendall Test. A nonparametric rank-based Mann–Kendall (MK) trend analysis test was used to evaluate the variations in the hydrometeorological time-series data over UIB [41, 42]. The main advantage of the MK test is that there are no assumptions about the statistical distribution of the sample data. Since the method is rank-based, extreme data points in the hydrometeorological time-series will not largely affect the results. The MK test statistic (S) is given by

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(X_j - X_k) = \begin{cases} 
-1, & \text{if } (X_j - X_k) < 0; \\
0, & \text{if } (X_j - X_k) = 0; \\
1, & \text{if } (X_j - X_k) > 0; 
\end{cases}
\]

\[
\text{sgn}(X_j - X_k) = \begin{cases} 
-1, & \text{if } (X_j - X_k) < 0; \\
0, & \text{if } (X_j - X_k) = 0; \\
1, & \text{if } (X_j - X_k) > 0; 
\end{cases}
\] (8)

where “n” denotes the length of a dataset and \(X_j\) and \(X_k\) are the sequential data values at times \(j\) and \(k\). Positive value of \(S\) indicates an increasing (upward) trend, and negative value of \(S\) reveals a decreasing (downward) trend in the time-series data.

\[
\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{p} t_k (t_k - 1)(2t_k + 5)}{18}.
\] (9)

where \(t_k\) is the number of tied values in the \(q\)th group and the sign “∑” represents the summation of all the tied groups. However, if there are no tied groups in the data, then this may be ignored. After calculating the variance \(\text{Var}(S)\) from equation (4), the standardized test statistic \((Z_{mk})\) value is calculated by using the following equation:

\[
Z_{mk} = \begin{cases} 
\frac{S + 1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0, \\
0, & \text{if } (X_k - X_j) = 0, \\
\frac{S - 1}{\sqrt{\text{VAR}(S)}} & \text{if } (X_k - X_j) > 0.
\end{cases}
\] (10)

A positive value of \(Z_{mk}\) indicates an upward trend (i.e., increasing), whereas a negative value indicates a downward trend (i.e., decreasing). The test statistic (S) follows the standard normal distribution, where probability of observing a value higher than the test statistic \(Z_{mk}\) is tested under the null hypothesis, \(H_0\), that there is no trend for chosen \(\alpha\)-level of significance. \(H_0\) is rejected if the absolute value of \(Z_{mk} > Z_{1-\alpha/2}\) at the \(\alpha\)-level is significant.

3.3.2. Sen’s Estimator of Slope. Sen’s nonparametric method [43] was used to estimate the magnitude of trends in the time-series data. The slope of “n” pairs of data can be first estimated by using the following equation:

\[
Q_i = \frac{X_j - X_k}{j - k}, \quad \text{if } j > k.
\] (11)

Sen’s estimator is the median, \(Q_{med}\) of the N pairs of \(Q_i\). In the procedure, \(N\) values of \(Q_i\) are ranked from smallest to largest and Sen’s estimator is determined by using the following equation:

\[
\text{Sen’s Estimator} = \begin{cases} 
Q_{(N+1)/2}, & \text{if } N \text{ was odd}, \\
\frac{1}{2}(Q_{N/2} + Q_{[(N+2)/2]}), & \text{if } N \text{ was even.}
\end{cases}
\] (12)

\(Q_{med}\) is tested by a two-sided test at the 100(1 – \(\alpha\))% confidence interval and the true slope may be obtained by the nonparametric test. Data were processed using an Excel macro named MAKESENS [44].

4. Results and Discussions

4.1. Variability in Temperature. Student’s t-test, F-test, and Mann–Whitney U test were used to detect the percentage change between two consecutive (26-year each) hydrometeorological time-series. Table 3 showed the results of maximum and minimum temperatures (\(T_{max}\) and \(T_{min}\)) and precipitation variables at seasonal and annual scale. The results of testing are combined with assessment of relative changes as indicated by percent change. The results showed inconsistent variations in all variables at different stations and seasons. The annual Tmax during winter and spring season decreased (–22% and –27%) between two subsurbs at Bagh and Naran stations, respectively, whereas at Murree and Peshawar stations, it increased by 10% and 20%, respectively. It was noted that the changes in Tmin at seasonal scale were quite high in magnitude as compared to \(T_{min}\) during the same seasons. For \(T_{max}\), most significant
Table 3: Relative change (%) in annual and seasonal temperature and precipitation in 2nd period (1989–2014) with respect to 1st period (1963–1988) (bold, underline, and * showed significant trend with Student’s t-test, F-test, and Mann–Whitney U test, respectively, at 95% confidence level).

| Sr. no. | Climatic stations | Maximum temperature | Minimum temperature | Precipitation |
|---------|-------------------|----------------------|---------------------|---------------|
|         |                   | Annual | Winter | Spring | Summer | Autumn | Winter | Spring | Summer | Autumn | Annual | Winter | Spring | Summer | Autumn |   |
| 1       | Astore            | 3°     | 14°    | 4°     | −2°    | 5°     | −6°    | 1°     | −6°    | 15°    | −6°    | 1°     | 4°     | −12°   | 36°    | 7°   |
| 2       | Bagh              | −22°   | −25°   | −24°   | −15°   | −24°   | −8°    | 7°     | −13°   | −6°    | −8°    | 2°     | 30°    | 8°     | −9°    | −3°   |
| 3       | Balakot           | −1°    | 0°     | 0°     | −1°    | −2°    | −1°    | −15°   | 6°     | −7°    | −16°   | −6°    | −1°    | −15°   | −6°    | 8°    |
| 4       | Bunji             | −1°    | 6°     | 1°     | −5°    | −1°    | 128°   | −128°  | 68°    | 46°    | 95°    | 31°    | 66°    | −17°   | 11°    | 23°   |
| 5       | Cherat            | −4°    | −7°    | 0°     | −3°    | −6°    | −3°    | 0°     | −1°    | −6°    | 0°     | −13°   | −3°    | −24°   | −10°   | −13°  |
| 6       | Chilas            | −1°    | 0°     | 0°     | −2°    | −1°    | 2°     | 55°    | 2°     | −1°    | 1°     | 37°    | 46°    | 5°     | 91°    | 90°   |
| 7       | Chitral           | 4°     | 16°    | 7°     | 0°     | 4°     | −6°    | −36°   | −4°    | −7°    | −2°    | 14°    | 24°    | 5°     | 74°    | 66°   |
| 8       | Dir               | 3°     | 7°     | 4°     | 0°     | 1°     | −47°   | −52°   | −48°   | −33°   | −48°   | −2°    | 14°    | −12°   | 9°     | 11°   |
| 9       | Droph             | 2°     | 7°     | 4°     | 0°     | 1°     | −47°   | −52°   | −48°   | −33°   | −48°   | −2°    | 14°    | −12°   | 9°     | 11°   |
| 10      | Garisopatta       | 4°     | 10°    | 5°     | 2°     | 4°     | −6°    | −2°    | −8°    | −10°   | −16°   | 16°    | 35°    | −2°    | 30°    | 42°   |
| 11      | Gilgit            | 3°     | 12°    | 5°     | −1°    | 4°     | −6°    | −2°    | −8°    | −10°   | −16°   | 16°    | 35°    | −2°    | 30°    | 42°   |
| 12      | Gujar Khan        | 3°     | 8°     | 2°     | 1°     | 3°     | −6°    | −16°   | −8°    | −5°    | −2°    | −3°    | 3°     | −11°   | −4°    | 6°    |
| 13      | Gupis             | 1°     | 14°    | 4°     | −2°    | 0°     | −14°   | 16°    | −3°    | −12°   | −12°   | 19°    | 19°    | 16°    | 15°    | 16°   |
| 14      | Kakul             | 3°     | 6°     | 3°     | 1°     | 2°     | −11°   | −36°   | −10°   | −6°    | −15°   | 4°     | 13°    | 1°     | 1°     | 8°    |
| 15      | Kohat             | 5°     | 6°     | 7°     | 4°     | 3°     | −1°    | −2°    | −1°    | 0°     | 1°     | 40°    | 75°    | −2°    | 73°    | 18°   |
| 16      | Kolli             | 0°     | 1°     | 2°     | −1°    | −2°    | −10°   | −3°    | −21°   | −13°   | −2°    | −7°    | 4°     | −8°    | −16°   | −5°   |
| 17      | Mangla            | 2°     | 3°     | 3°     | 1°     | −36°   | −3°    | −10°   | −3°    | −1°    | 60°    | −5°    | −8°    | −22°   | 1°     | 4513  |
| 18      | Murree            | 10°    | 14°    | 4°     | 9°     | −5°    | 13°    | 64°    | −1°    | 5°     | −2°    | 6°     | −9°    | 0°     | −5°    | 2°    |
| 19      | Muzaffarabad      | 3°     | 5°     | 4°     | 1°     | 2°     | 0°     | 7°     | 2°     | −1°    | −1°    | 7°     | 25°    | 3°     | 6°     | 2°    |
| 20      | Naran             | −27°   | −65°   | −58°   | −7°    | −4°    | −9°    | 78°    | 10°    | 1°     | 10°    | 80°    | 80°    | 90°    | 72°    | 55°   |
| 21      | Palandi           | 3°     | 15°    | 4°     | 1°     | 5°     | −8°    | 78°    | 10°    | 1°     | 10°    | 80°    | 80°    | 90°    | 72°    | 55°   |
| 22      | Parachinar        | 1°     | 2°     | 4°     | 0°     | 0°     | −27°   | 38°    | −23°   | −14°   | −25°   | −3°    | 8°     | −8°    | −5°    | 2°    |
| 23      | Peshawar          | 20°    | 48°    | 2°     | 1°     | 60°    | 4°     | 20°    | 5°     | 0°     | 20°    | 48°    | 2°     | 1°     | 50°    | 2°    |
| 24      | Rawalpindi        | 6°     | 20°    | 4°     | 2°     | 6°     | 9°     | 78°    | 10°    | 1°     | 10°    | −7°    | −10°   | −11°   | −11°   | −16°  |
| 25      | Risalpur          | 1°     | 4°     | 3°     | 0°     | −1°    | −1°    | 22°    | 3°     | −2°    | −2°    | −11°   | −9°    | −13°   | −18°   | −22°  |
| 26      | Saidu Sharif      | 3°     | 9°     | 5°     | 1°     | 0°     | −3°    | 3°     | 0°     | −3°    | −6°    | 19°    | 27°    | 7°     | 26°    | 25°   |
| 27      | Skardu            | 7°     | 37°    | 8°     | 1°     | 7°     | −8°    | −11°   | −2°    | −7°    | −19°   | 30°    | 60°    | 12°    | 30°    | 20°   |
Figure 2: Percent number of stations with positive (upward) and negative (downward) trends in annual and seasonal time-series for different periods and number of stations with significant trends by Mann–Kendall test at $\alpha = 0.05$. 
decreases (−165% and −58%) were revealed at Naran station for winter and spring seasons, respectively. Bagh station exhibited a relative change of −25%, −24%, −15%, and −24% during winter, spring, summer, and autumn seasons, respectively. At Murree station, 14% and 49% relative change was observed in winter and spring seasons, while in summer and autumn, percent change values were quite smaller. Peshawar station showed largest increases of 48% and 110% in $T_{\text{max}}$ during winter and autumn seasons, respectively, while percent change values for spring and summer were negligible. Minimum temperature exhibited both positive and negative trends at different stations in different seasons. For instance, Bunji, Peshawar, and Rawalakot stations showed positive changes, whereas, at most of the stations, these variations are negative. Largest relative positive change by the $t$-test, $F$-test, and $U$ test of 128% for the Bunji station was observed in $T_{\text{min}}$ at 90% confidence level. The highest negative percent change values for the second period (−47% and 27%) at Drosh and Parachinar stations were detected, respectively. In all four seasons, varied trends were observed.
in $T_{\text{min}}$ by using Student’s $t$-test. Results of the $F$-test and $U$ test also suggested that the climate for the 2nd period was quite different from the 1st period with most changes that are statistically significant at 90% confidence level. Significant changes in variance are indicated at most of the stations over UIB in $T_{\text{min}}$ (Figure 2).

The summary of the trend analyses and the spatial variation in annual, winter, spring (premonsoon), summer (monsoon), and autumn (postmonsoon) maximum and minimum temperature are presented in Figures 3 and 4. Most of the stations exhibit increasing trends in annual maximum temperature for the 1st period. The increasing trends were found at 56% stations, out of which only 4% were significant. Similarly, decreasing trends were found at 44% stations (19% significant). Cherat, Gujar Khan, and Kakul have the highest decreasing rate (1.2, 0.8, and 0.6°C per decade at 99.9%, 99%, and 95% significant level, respectively). The stations show warming trends at a magnitude of 0.1 to 0.5°C·decade$^{-1}$. In the 2nd period, increasing trends were observed at 85% stations, out of which 44% stations exhibit significant trends. The decreasing trends were found at Bagh, Gujar Khan, Naran, and Parachinar at the rates of 7.3, 0.3, 0.3, and 0.7°C per decade, respectively, but only Bagh and Parachinar exhibited significant trends at 99.9% and 95% level of confidence interval, respectively. At annual scale, almost all of the stations exhibited warming trends. However, these findings needed further validation to analyze the clear scenarios of climate change acceleration in the study area. Therefore, for more detailed trends of climate change, three-month seasonal analysis was carried out and similar warming patterns for winter, spring, and autumn were found during the 1st period (1963–1988). MK test detected significant trends at 25, 24, and 22 stations at 90%–99.9% significant level in winter, spring, and autumn temperature time-series as shown in Figures 3 and 4. Inconsistent trends were detected during the summer season. The maximum temperature has decreased at 70% stations, out of which 33% stations exhibit significant trends in summer season. The spring season showed the highest rate of warming as compared to other seasons. More increasing trends were observed during the 1st period as compared to the 2nd period. Increasing trends were also revealed at 81%, 89%, 67%, and 84% (15%, 70%, 19%, and 11% significant) during winter, spring, summer, and autumn seasons, respectively. Negative trends were observed at 19%, 11%, 33%, and 26% (11%, 4%, 15%, and 15% significant). Strong indications of climate change acceleration during second period were observed as compared to the first period. In the 1st period, trend analysis proposed the existence of decreasing trends in annual minimum temperature at 22 stations. Most of the stations exhibited decreasing trends in the annual minimum temperature at 59% stations (41% significant). Only three stations showed significant increasing trends: Bunji, Chilas, and Peshawar. Bunji station showed highest warming trend of 1.5°C per decade. In the 2nd period, trend analysis with the MK test displayed trend existence at 25 stations. More increasing trends were found as compared to the first period. These increasing trends were found at 56% (19% significant) and the decreasing trends were found at 44% (7% significant). Trend analysis in seasonal minimum temperature during the 1st period revealed that winter and spring seasons exhibited more increasing trends at 63% and 67% stations (30% and 22% significant), respectively. Meanwhile in summer and autumn there was a pattern of decreasing trends at 74% and 67% stations (41% and 41% significant), respectively. As compared to the 1st period winter and summer seasons showed decreasing minimum temperature, while spring and autumn seasons indicated increasing minimum temperature in the 2nd period (1989–2014). Figures 5 and 6 revealed that at 67% stations (26% significant) and 52% stations (11%) warming trends were found for the winter and autumn seasons. For summer season, 74% stations (67% significant) exhibited cooling trends. The cooling rates varied from 0.1°C·decade$^{-1}$ to 1.9°C·decade$^{-1}$.

### 4.2. Variability in Precipitation

Significant differences were observed at Naran and Gupis stations for all seasons, but a different pattern was revealed during winter and summer. It was observed that percent change values that are statistically significant are relatively large at few stations with values in
the range of +25% to −25%. Highest increase in percent changes of precipitation was detected at Gupis and Naran stations during all seasons but these changes became negative and quite lower at low-altitude stations.

The results of analysis by applying Mann–Kendall test and Sen’s slope estimator methods in the annual precipitation time-series were summarized for two consecutive 26-year periods, that is, 1963–1988 and 1989–2014. The annual precipitation increased significantly at five stations, while it decreased at four stations during the first period. It was noted that the Gupis station exhibited significant increasing precipitation at the rate of 32% per year with 99% level of confidence. In the 2nd period at two stations the annual precipitation has increased significantly but decreased at ten stations (Table 3). The highest increasing trend was observed with a magnitude of 47% per year with 99.9% level of significance at Kohat station, while the highest decreasing trend was revealed with a magnitude of 26% at 95% confidence.

Figure 5: Spatial distribution of trends detected by Mann–Kendall test and estimated by Sen’s method in seasonal minimum temperature showing change in °C decade$^{-1}$ (upward and downward arrows show positive and negative trends, respectively; bold (blue) arrow shows significant trend at $\alpha = 0.05$).
interval at Risalpur station as shown in Figures 7 and 8. In the 1st period the MK nonparametric test showed negative trends (Figures 7 and 8) in precipitation time-series during winter and autumn seasons at 59% stations (11% significant) and 74% stations (30% significant) during spring and summer seasons, respectively. The most significant winter drying patterns were revealed at Gupis, Chitral, Garidopatta, and Naran stations at rates of 47%, 13%, 25%, and 18%, respectively, during the second period. Spring and summer seasons showed decreasing trends at 93% stations (48% significant) and 78% stations (22% significant), respectively, during the 2nd period. It was observed that 63% stations (11% significant) exhibited increasing trends. In autumn seasons 63% insignificant stations showed decreasing trends as shown in Figures 7 and 8.

4.3. Variability in Streamflow. The annual runoff in Kurram, Soan, and Indus subbasins decreased by 18%, 13%, and 12%, respectively; however, the runoff variations are found to be statistically significant in Indus subbasin. The winter season showed the largest variations compared to other seasons. Moreover, all subbasins showed positive variations during winter season except for Kurram river subbasin as shown in Table 4. The summer flows have been decreased in all rivers. Combined change detection results for Qst at annual base only show small relative changes (~29% to 11%) at most of the stations. These results suggest that time-series have not notably changed over time. In Swat river a relative change of +22% was observed, which was found to be significant using Student’s t-test, F-test, and U test. At seasonal scale, most of the changes are positive in winter season but negative in summer. In winter season, changes are largest (up to 69%) and statistically significant, whereas in summer season changes are negative and statistically insignificant. Chakdara station of Kabul river basin showed most substantial relative change of 69% in winter season, which was significant for all three tests. In summary, analyses on change detection in general indicate acceleration of climate change.

The results of annual mean streamflow at 34 stations using MK test of two consecutive 26-year periods are presented in Figures 9 and 10. During the 1st period, increasing trends were observed at 56% stations (11% significant) and decreasing trends at 44% stations (11% significant). However, only seven stations revealed significant decreasing trends. The highest decreasing trends were revealed at Jhansi Post at a rate of 43% during the 1st period, that is, 1963–1988. The decreasing trends in annual mean streamflows were found at 77% stations (43% significant) and the increasing trends at 23% stations, which are statistically insignificant. All nine tributaries of Jhelum basin (Naran, Garhi Habibullah, Muzaffarabad, Chinar, Domail, Kohala, Azad Pattan, Kotli, and Palote) exhibited significant decreasing trends. The five tributaries of Indus basin (Karora, Gurriala, Khairabad, Chahan, and Massan) have also shown significant decreasing trends. At Kabul basin only Kalam showed significant decreasing trends. The highest decreasing significant trends were found at Palote station at magnitude of 43% during the whole study period. Winter mean flows have significantly increased at four stations and decreased at seven stations. The highest significant increasing trend was observed at Massan station of Indus river, while decreasing trend was revealed at Jhansi Post station of Kabul river at rates of 15% and 38% for the first and second periods, respectively. All three major rivers exhibited increasing trends at Azad Pattan in Jhelum, Besham in Indus, and Nowshera in Kabul; however, significant trends were detected in the Indus river. During spring season, significant streamflow trends were detected over 10 stations (5 increasing and 5 decreasing). The Brandu river at Daggar showed significant increasing trend at a rate of 18%, whereas the Bara river exhibited decreasing trend at Jhansi Post station of 39%. Most of decreasing trends were observed in summer and autumn seasons as shown in Figures 9 and 10. In summer and autumn seasons, 57% stations (9% significant) and 60% stations (31% significant) exhibited decreasing trends, respectively. In the second period for winter season mean flows have increased at rate of 54% (14% significant) and decreased at rate of 46% (11% significant) of the data period.

Figure 6: Spatial distribution of trends detected by Mann–Kendall test and estimated by Sen’s method in annual minimum temperature showing change in °C·decade⁻¹ (upward and downward arrows show positive and negative trends, respectively; blue arrow shows significant trend at α = 0.05 and green arrow shows insignificant trend).
average for the period of 1989–2014. The highest significant increasing trend was found at Chakdara station of Swat river and decreasing trends were found at Jhansi Post station of Kabul river of 32% and 48% during the 2nd period (1989–2014), respectively. All three major rivers have shown increasing trends at Azad Pattan in Jhelum, Besham in Indus, and Nowshera in Kabul; however, only the Indus river exhibited significant trends. During spring season, sixteen stations exhibited significant trends (4 increasing and 12 decreasing). The Gilgit river at Gilgit and Alam Br.
Figure 8: Spatial distribution of trends detected by Mann–Kendall test and estimated by Sen’s method in annual precipitation showing change in % of data period averages (upward and downward arrows show positive and negative trends, respectively; blue arrow shows significant trend at $\alpha = 0.05$ and green arrow shows insignificant trend).

Table 4: Relative change (%) in annual and seasonal streamflow during the 2nd period (1989–2014) with respect to the 1st period (1963–1988) (bold, underline, and * showed significant trend with Student’s $t$-test, $F$-test, and Mann–Whitney $U$ test, respectively, at 95% confidence level).

| Stream gauge       | Annual | Winter | Spring | Summer | Autumn |
|--------------------|--------|--------|--------|--------|--------|
| Naran              | −4     | −6     | −3     | −10    | 24     |
| Garhi Habibullah   | 5      | 17     | 19*    | −5     | 21     |
| Muzaffarabad       | −6     | 13     | 3      | −16*   | 6      |
| Chinari            | −3     | 6      | 0      | −7     | −5     |
| Domel              | −2     | 13     | 2      | −8     | 0      |
| Kohala             | 1      | 21*    | 6      | −8     | 8      |
| Azad Pattan        | 8      | 37*    | 12     | 0      | 13     |
| Kotli              | 3      | 36*    | 6      | −10    | 10     |
| Palote             | −12    | 27     | −27    | −14    | −17    |
| Kharmong           | 1      | 7*     | 7      | −7     | 1      |
| Yogo               | 8*     | 4      | 19     | 6*     | 19*    |
| Shigar             | 13*    | 2*     | 5*     | 12*    | 3      |
| Kachura            | 21*    | 18*    | 24*    | 19*    | 26*    |
| Gilgit             | 20     | 14*    | 43*    | 16     | 26*    |
| Dainyor Br.        | −19*   | 8      | 5      | −25*   | −6     |
| Alam Br.           | −6     | 12*    | 21*    | −13*   | 3      |
| Bunji              | 10     | 12*    | 35*    | 5*     | 15*    |
| Doyain             | 26*    | 34*    | 28*    | 18*    | 39*    |
| Shatial Br.        | 9*     | 11*    | 19*    | 7      | 7*     |
| Karora             | −14    | 19*    | −20*   | −28*   | 14     |
| Besham Qila        | 4      | 18*    | 14*    | −1     | 13*    |
| Daggar             | 9      | 39*    | 21     | −6     | 2      |
| Phulra             | 10     | 38*    | 13     | 0      | 5      |
| Kalam              | 1      | 9*     | 20*    | −5     | 1      |
| Chakdara           | 22*    | 69*    | 36*    | 8      | 37*    |
| Chitral            | 8*     | 5*     | 15*    | 6*     | 12*    |
| Jhansi post        | −23    | −21*   | −35*   | −1     | −30*   |
| Nowshera           | −3     | 8      | 5      | −9     | 1      |
| Gurrialia          | −8     | 24     | 5      | −18*   | −11    |
| Khairabad          | −12*   | −17    | −18*   | −15    | −19    |
| Thal               | −18*   | −24*   | −31*   | −1     | −17*   |
| Chirah             | −29*   | −11    | −29*   | −35*   | −16*   |
| Chahan             | −21    | 0      | −18    | −30    | 6*     |
| Dhok Pathan        | −13    | 18     | −3     | −25*   | 15     |
| Massan             | 8*     | 28*    | 7*     | 2      | 18*    |
exhibited significant increasing trends at rates of 22% and 10%, respectively. The Indus river at Shatial Br. has shown increasing trends of 14%, whereas lower parts of Indus basin and Jhelum basin exhibited decreasing significant trends. Most of the decreasing trends were observed during summer and autumn flows as shown in Figures 9 and 10. Summer and autumn seasons exhibited increasing trends at 74% and 66% stations, out of which 40% and 37% stations showed significant decreasing trends, respectively. All three basins exhibited significant decreasing trends at Azad Pattan, Besham, and Nowshera. All the subbasins of Jhelum river exhibited decreasing trends; Kunhar, Neelum, and Kanshi
basins revealed the significant decreasing trends at the rates of 15%, 23%, and 46%, respectively. Insignificant decreasing trends were found only at Poonch river at the rate of 18%.

5. Discussions and Conclusions

UIB is a region that is famous for conflicting signals of climate and contrasting hydrological regime [15]. The basic reason for this anomalous behavior is the difference between accumulation patterns of this region as reported by various researchers on the basis of geodetic mass balance and remote sensing data acquisition studies [12, 24]. The results of this study predicted that the climate change and acceleration over UIB may seriously affect streamflow in Indus river. There are primarily three sources of streamflow in UIB, i.e., glacier melt (Hunza, Shigar, and Shyok subbasins) followed by snowmelt (Astore and Gilgit subbasins) and precipitation. The hydrology of the Karakoram and Himalayan ranges is different as reported by various authors. The basic difference is between the accumulation patterns of these two regions, Karakoram mountain receives precipitation by the westerly disturbances, and Himalayan range is controlled by the summer monsoon [23]. Climatic characteristics vary across the Indus basin by large topographic variations from very high elevated to low elevated areas facing Himalaya mountainous slopes. Himalays cover is one of the most dynamic and complex mountain ranges in the world and is also vulnerable to global warming and increasing human activities. Uncertainties in the rate and magnitude of climate change and potential impacts prevail, but there is no doubt that it is gradually and powerfully changing the ecological and socioeconomic landscape in the Himalayan region, particularly in streamsflows. The impact of warmer climate over snow fed basins is opposite to the impact on the glacier fed basins: snow fed basins are more sensitive regarding reduction in the availability of water due to a compound effect of increase in evaporation and decrease in snow melt. The present study investigated the existence of trends and relative changes in the annual and seasonal maximum and minimum temperature, precipitation, and streamflow for two consecutive 26-year periods. The results of this study revealed that climate change is occurring remarkably with warming trends in the lower part of Mangla catchment, whereas cooling trends were observed at the higher elevation regions. The prevailing trends, caused by climate change, influencing the flows should be considered by the water managers for better water management in a water-scarce country like Pakistan.

Most of the river gauges during winter (DJF) showed the significant increasing river flows during the first-time series. Mukhopadhyay and Khan [45] reported that precipitation is controlled by elevation; precipitation is almost negligible below 2500 m and there is little water yield between 1000 and 2500 m. They defined “mid-altitude melt” as water that generates due to seasonal snows during intense winter between elevations of 2500 and 3500 m. These increased river flows are more associated with increased precipitation than temperature during this period. These results are partially consistent with the findings of Khattak et al. [17] who also reported increased winter flows due to increased precipitation and temperature causing early melting of snow. But we find a significant decrease in river flows during the second, third, and fourth data periods, which is consistent with decreased mean temperature during the same periods.

We observed significant changes in the second period as compared to the first period within UIB, which are consistent and in agreement with the global warming trends reported by Hasson et al. [32]. Our results indicated high variability of trends in annual and seasonal minimum temperature, but these trends appeared to be more significant and higher in magnitude, particularly during the second period. Similarly, we observed significant wetting pattern of trends in annual and seasonal precipitation at higher altitude region, but significant drying trends were revealed by lower- or mid-altitude stations. Most of the stations within UIB exhibited significant drying trends, which are consistent with the recent studies carried out in this region [19]. The annual runoff has been decreased significantly within Jhelum river basin at Azad Pattan, Chinari, Domel Kohala, Muzaffarabad, and Palote and within Indus at Chahan, Gurrial, Khairabad, Karora, and

Figure 10: Spatial distribution of trends detected by Mann–Kendall test and estimated by Sen’s method in annual streamflow showing change in % of data period averages (upward and downward arrows show positive and negative trends, respectively; blue arrow shows significant trend at \( \alpha = 0.05 \) and green arrow shows insignificant trend).
Kalam during the second data period. Similarly, we observed that seasonal runoff has been decreased significantly in all seasons except winter during second data series. The increasing trends of winter runoff are more associated with westerly precipitation as compared to concurrent melting temperature because hydrology of the UIB is dominated by winter precipitation (westerly disturbances) as compared to summer monsoon offshoots. Moreover, the decreasing trends of summer runoff are attributed to decreased melting rate consistent with summer cooling reported by various authors [46, 47]. The decreasing trends in summer discharge show least melting rates in summer, resulting in stability of glaciers and consequently positive basin storage. Climate changes occur most noticeably in terms of temperature and precipitation over the UIB according to various authors. Moreover, this study found the spring season to be quite dry, supporting the idea of declining precipitation (reported by numerous studies carried out earlier in this area). Downstream areas in the lower portions of the drainage basin (where most of the population depends on the agriculture) are being affected by decreasing rainfall and its impacts on crop sowing and harvesting times. There will be more stress on available water resources (which are already scarce) if precipitation does not show any significant upsurge: increased dryness could further stress agricultural production. To avoid this potentially distressing situation from getting worse, water resources management must play an important role to ensure the best utilization of available resources, for example, flood control, building dams and reservoirs, lining of canals and water courses, and conservative surface irrigation (trickle and sprinkler irrigation).

**Data Availability**

The hydrometeorological time-series data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

This study was supported by the National Natural Science Foundation of China (nos. 51509141 and 51809150).

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