

## Innovative Trend Analysis of Hydrometeorological Parameters in the Upper Indus Basin, Pakistan

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### Abstract

This study aims to identify climatic shifts and their implications for water resource management, particularly with the Tarbela Dam. The innovative Trend Analysis (ITA) method was used to determine key hydrometeorological parameters' monthly and seasonal trends, including precipitation, relative humidity, solar radiation, maximum and minimum temperatures, and inflows, in the Upper Indus Basin, Pakistan. Historical time series data spanning 1981 to 2024 evaluated past trends while future climate projections spanning 2025 to 2100 were obtained from the CMIP6 model using two scenarios, SSP2-4.5 and SSP5-8.5. Historical data reveals a decreasing precipitation trend in spring by  $-0.007\text{mm/year}$ . Future projections under SSP2-4.5 and SSP5-8.5 also suggest a decreasing trend of precipitation. Tmax increased by  $0.118^\circ\text{C/year}$  in Spring historically, while under SSP2-4.5 a strong increase of  $0.155^\circ\text{C/year}$  is observed in spring, and under SSP5-8.5 about  $0.2^\circ\text{C/year}$ . Tmin showed a positive trend of  $0.095^\circ\text{C/year}$  in spring, while for SSP2-4.5 dominant increase occurred in spring by  $0.137^\circ\text{C/year}$ , and for SSP5-85 increased about  $0.155^\circ\text{C/year}$ . Relative humidity slightly increased by  $0.046\%/\text{year}$  in the monsoon period and for SSP2-4.5 and SSP5-8.5 it shows a slight increase whereas in solar radiation, historical trends increased by  $6.563\text{W/m}^2/\text{year}$  for spring and SSP2-4.5 about  $7.745\text{W/m}^2/\text{year}$  and for SSP5-85 increased about  $9.028\text{W/m}^2/\text{year}$  during spring. Historical inflows increased during summer by  $0.589\text{m}^3/\text{s/month}$  and for SSP2-4.5 increased by about  $1.017\text{m}^3/\text{s/month}$  and for SSP5-85 about  $1.3\text{m}^3/\text{s/month}$  during summer. This study demonstrates ITA's effectiveness and supports sustainable water management in the Upper Indus Basin underscores the urgent importance for water resource managers to adopt adaptive reservoir management and policy adjustments at Tarbela Dam to ensure long-term water security.

**Keywords:** Innovative trend analysis (ITA); Upper Indus Basin; Tarbela Dam; Hydrometeorological trends; Climate Change; Shared Socioeconomic Pathways

### 1. Introduction

Hydro-meteorological parameters such as precipitation, temperature, and streamflow are components to be considered with aspects of water resources management. Hydro-meteorological parameters require consistent analysis to which the together river flow records, they provide timely and accurate information for flood forecasting, irrigation needs, or hydraulic structure design. In context, river streamflow data

typically acts as a spatially integrated variable, hence presenting more regional hydrologic information than just point-based precipitation data which can vary greatly in larger time steps both spatially and over time (Birsan et al., 2005). It can be quite accurate and statistically fast but usually designs need 15, or 25 years of continuous gauge records, (Mather, 1981) however this depends upon river flow characteristics and variability. Streams changing flow characteristics (low-flow, normal-flow, and high-flow, etc.), and

seasonal time trends associated with streamflow and hydro-meteorological variables need to be considered for optimum results in planning for the strategic development and sustainable management of water resources in a region. In the Upper Indus Basin (UIB): region of Pakistan surface water and groundwater are critical for potable domestic and industrial purposes, and for irrigation (Zhu and Day, 2005).

The UIB is primarily nourished by glacial and snow melt water, which makes it vulnerable to changes in climatic conditions. Analyzing trends in hydro-meteorological variables is important in the UIB to better understand changes in water availability and for the design of management practices. In the past, various statistical approaches were used to identify trends in hydro-meteorological time series observations. Parametric (to which few assumptions are required to be made about the underlying data) and non-parametric (assumptions about the data are not required) were used the most. Non-parametric approaches generally used for time series data include the Mann-Kendall (MK) and Modified MK, and Spearman's rho (SR) tests. While non-parametric approaches are good for detecting monotonic trends in hydro-meteorological time series, they have strict assumptions including that the observational data points are independent and that the dataset is normally distributed. These approaches may even require data pre-whitening, which is a statistical step to remove serial correlation, which can complicate the analysis (Hamed and Rao, 1998).

Previous regional studies in the UIB have primarily utilized traditional methods, such as the Mann-Kendall and Sen's slope estimator, to assess trends in hydro-meteorological data. For instance, Ali et al. (2017) and Bilal et al. (2021) applied the Mann-Kendall test to precipitation and temperature records in Gilgit-Baltistan and the wider UIB, highlighting significant local and annual flow variations. However, the efficacy of these methods in highly non-linear, non-normal datasets common to

glacial environments is limited, often requiring complex pre-whitening techniques. The Innovative Trend Analysis (ITA) could be applied to avoid these restrictions through the provision of a more flexible alternative. The ITA technique is not based on assumptions about data distribution or independence and does not require pre-whitening even if there is serial correlation. As a graphical approach to the data, ITA has the potential to allow trend detection providing a more intuitive insight into hydro-meteorological variability (Şen, 2012).

Several works have used the ITA method to study hydro-meteorological trends in UIB. In the UIB, hydro-meteorological trends have been widely studied because of the importance of the Basin in water security in Pakistan. This work analyzed the data from several meteorological and hydrometric stations in the UIB using the Mann-Kendall test to identify trends in temperature, precipitation, and streamflow. The research identified trends in increases in winter maximum temperatures and changes to the pattern of streamflow which influences the way rainfall runs off the Basin (Khattak et al., 2011).

The subsequent research highlights the differing hydrology associated with temperature and streamflow over space and time. For example, while some sub-Basins exhibited an increase in discharge trends with increased temperature and precipitation, other sub-Basins exhibited decreasing trends demonstrating the climatic influences across the Basin are heterogeneous (Atif et al., 2018).

A third piece of research on UIB identified that the maximum temperatures were positive in autumn, spring, and winter, while the maximum temperatures in the summer were decreasing. The study also revealed that river discharge for more elevated areas was influenced by changes in temperature compared to lower elevation areas which were influenced more by precipitation. Warming trends are greater at high elevations and precipitation trends are

mixed, with some areas positive and some areas decreasing, representing climate-water complexities in the region (Ougahi et al., 2022).

Researchers used the Mann–Kendall test with Sen’s slope estimator to analyze long-term data from meteorological and hydrological monitoring stations in UIB from 1963 to 2014. The analysis indicated a warming trend at lower elevations whereas the higher elevation stations were showing a cooling trend. Streamflow increased in winter and spring while decreasing trends were noted in summer and fall. Precipitation trends were mixed, and several stations showed decreasing precipitation trends (Yaseen et al., 2020).

These findings highlight the importance of localized and phased analyses to develop region-appropriate water management approaches. While there have been many studies employing traditional statistical methods, no studies are known that have used the ITA method in the hydro-meteorological data in the UIB. The ITA provides insights into the regimes of the data (low, medium, and high flows) and it is better able to capture complex trends, trends that conventional methods may miss. By highlighting the graphical nature of data, ITA adds value to the interpretation of trends, which is critical for stakeholders involved in water resource planning and policy. The specific aims of the study are, (i) to apply the ITA method to assess spatio-temporal trends in hydro-meteorological parameters (precipitation, temperature, solar radiation, and relative humidity), as well as streamflow throughout the Upper Indus Basin, and (ii) to interpret the water resource management and policy implications of the identified trends.

According to the literature, the future trends of hydro-meteorological parameters are not analyzed for UIB. The objective of this study was to determine the historical and future trends of hydro-meteorological parameters for 14 different stations in UIB

using the ITA approach. The information gained is anticipated to facilitate the development of adaptive management strategies to improve the resilience of water resource systems to climate variability and change, and thereby protect the socio-economic well-being of communities who are reliant on the Indus River water resources.

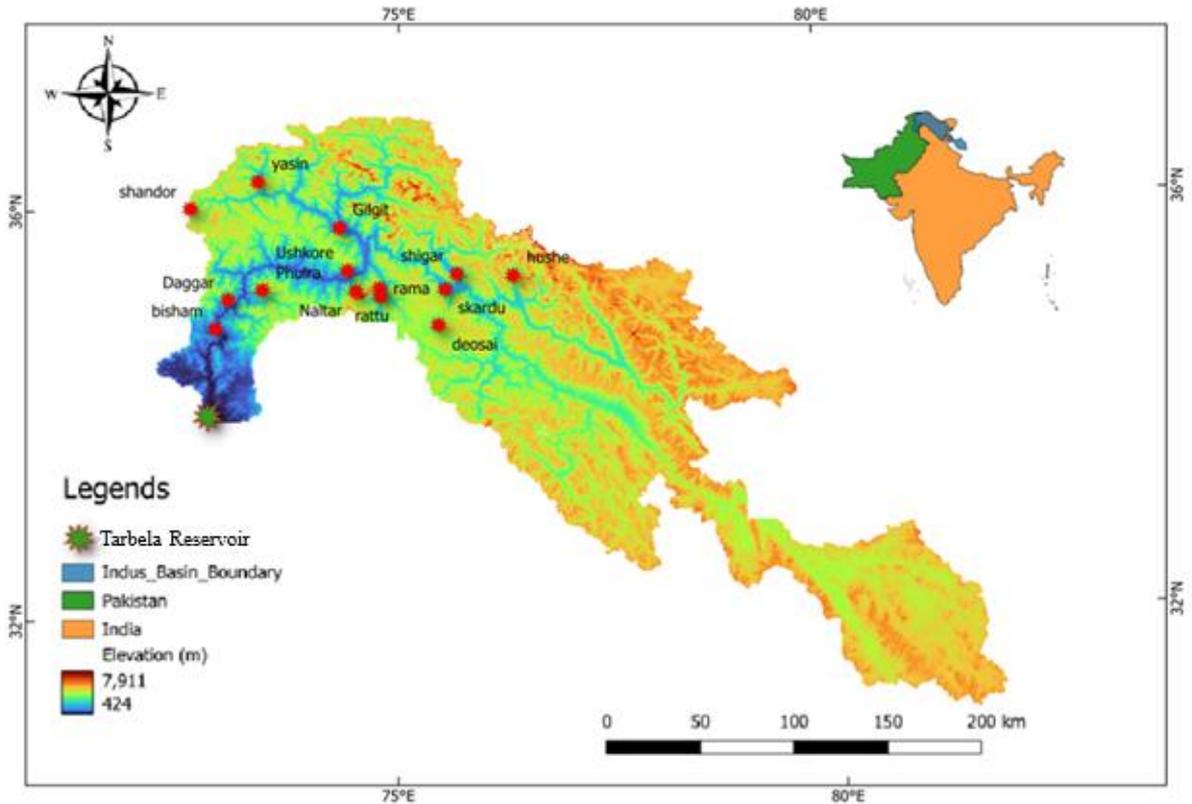
## **2. Study Area**

Tarbela Dam is the most important water resources infrastructure of Pakistan which was completed in 1976. This is one of the largest Earth and rock-filled dam located on the Upper Indus Basin in the Haripur district of Khyber Pakhtunkhwa Province as shown in Fig. 1. The total catchment area of the dam reservoir is 169,600 Km<sup>2</sup>, with an annual flow of 64 MAF (Munir et al., 2022). This is Pakistan’s most important multipurpose reservoir that covers 50% of irrigation needs and about 30% percent of energy needs and provides millions of people with potable water while preventing water scarcity and floods. The Upper Indus Basin is located in the mountain ranges of Himalaya, Hindu Kush, and Karakoram covering parts of Afghanistan, Pakistan, India, and China as a transboundary river Basin and covers a catchment area of 289,000 km<sup>2</sup> (Ahmad et al., 2023).

## **3. Materials and Methods**

### **3.1 Materials**

The daily data of hydro-meteorological parameters were collected for 14 meteorological stations within the Upper Indus Basin over the extensive period from 1981 to 2024. The parameters included in our study are precipitation, maximum temperature (T<sub>max</sub>), minimum temperature (T<sub>min</sub>), relative humidity, solar radiation, and reservoir inflow. The spatial distribution of all these stations is shown in Fig. 1.



**Fig. 1** Spatial distribution of 14 hydro-meteorological stations in the Upper Indus Basin

For the period from 1981 to 2003, the data was initially obtained from online sources. From 2003 to 2024, the data was sourced from the Water and Power Development Authority (WAPDA), which provided a continuous and consistent dataset for the entire study period. We conducted monthly and seasonal trend analyses of the key hydro-meteorological parameters for the 14 stations. Future trend analysis was carried out on monthly and seasonal scales for the period 2025–2100. This time series data has been divided into three parts. Near future from 2025-2049, Mid future from 2050-2074, and Far future from 2075-2099. Monthly and seasonal scale trend analysis was done for these three-time series data using the ITA method. Trend analysis was made using climate projections obtained from Global Climate Models (GCMs) CMIP6. The data was taken from an already published study done on the UIB and is available on a site called Hydroshare, a publicly available to be

accessed for hydro-meteorological data (Khan, 2024). Two scenarios, SSP 585 and SSP 245 were taken for analysis of trends in meteorological parameters. For inflow trends, the predicted inflow for both scenarios was taken from the best-performing machine learning model which was Support Vector Machine (SVM).

### 3.2 Methods

#### 3.2.1 Innovative Trend Analysis

The Innovative Trend Analysis (ITA) method, developed by (Sen, 2012), is a technique that is used for identifying trends in hydrometeorological data. Unlike other methods, ITA is highly advantageous because it does not rely on assumptions about serial correlation, normality, or sample size (Singh et al., 2021). In Innovative Trend Analysis, the provided time series is split into two non-overlapping segments of equal length..

**Table 1:** Statistical properties of hydro-meteorological parameters data during 1981–2024.

Stations	Daggar	Gilgit	Naltar	Pulara	Ushkore	Bisham	Deosai	Hushe	Rama	Rattu	Shandor	Shigar	Skardu	Yasin
Lat (°N)	35.2	35.92	35.3	35.3	35.5	34.91	34.97	35.45	35.33	35.25	36.08	35.47	35.32	36.36
Long (°E)	73	74.3	74.5	73.4	74.4	72.86	75.47	76.35	74.78	74.79	72.53	75.69	75.55	73.33
Elevation (m)	2,284	1,500	4,478	3,134	3,302	2,425	4,114	3,048	3,300	2,676	3,720	2,230	2,228	4,267
<b>Precipitation (mm)</b>														
Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max	75.14	61.15	88.5	74.53	76.17	66.27	63.34	93.69	91.06	118.22	67.8	145.8	104.17	91.14
Avg	37.57	30.58	44.25	37.27	38.09	33.13	31.67	46.85	45.53	59.11	33.9	72.9	52.09	45.57
Frequency	Daily Data 1981-2024													
<b>Tmax (°C)</b>														
Min	5.56	-4.64	-8.61	2.22	-10.1	-5	-21.1	-18.5	-10.4	-9.12	-21.03	-9	-5.14	-13.18
Max	47.78	44.25	32.13	45	30.21	41.69	23.03	32.2	29.88	32.7	25	36.8	40	31.26
Avg	26.67	19.81	11.76	23.61	10.06	18.35	0.97	6.85	9.74	11.79	1.99	13.9	17.43	9.04
Frequency	Daily Data 1981-2024													
<b>Tmin (°C)</b>														
Min	-7.47	-9.18	-17.93	-6.67	-21.76	-12.78	-30.32	-20.21	-21.84	-19.9	-29.41	-13.79	-19.03	-20.45
Max	36.11	29.1	18.31	32.53	18.53	27.75	12.48	19.95	16.56	21.26	17.68	26.85	25.56	20.34
Avg	14.32	9.96	0.19	12.93	-1.62	7.49	-8.92	-0.13	-2.64	0.68	-5.87	6.53	3.26	-0.05
Frequency	Daily Data 1981-2024													
<b>Relative Humidity (%)</b>														
Min	1.51	1	1.86	1.18	1.77	1.1	1.17	1	1	1.15	1	1	1.2	1.42
Max	99.9	99.95	98.68	99.23	99.7	124.4	99	99.95	99.95	99.7	99.95	99.9	94.83	99.39
Avg	50.71	50.48	50.27	50.21	50.74	62.75	50.09	50.48	50.48	50.43	50.48	50.45	48.02	50.41
Frequency	Daily Data 1981-2024													
<b>Solar Radiation (Watt/m<sup>2</sup>)</b>														
Min	2,000.42	1,505.67	1,500.53	1,714.36	1,564.68	1,543.73	1,554.69	1,500.19	1,509.16	1,526.59	1,567.14	1,500.43	1,742.92	1,539.88
Max	5,249.97	5,249.97	5,249.90	5,249.97	5,249.97	5,249.97	5,249.97	5,081.33	5,249.94	5,249.90	5,249.97	5,249.97	5,249.97	5,249.97
Avg	3,625.20	3,377.82	3,375.22	3,482.16	3,407.33	3,396.85	3,402.33	3,290.76	3,379.55	3,388.24	3,408.56	3,375.20	3,496.44	3,394.92
Frequency	Daily Data 1981-2024													
<b>Reservoir Inflow (m<sup>3</sup>/s) at Station: Tarbela</b>														
Min	252.02													
Max	20,107.76													
Avg	2,327.52													
Frequency	Daily Data 1981-2024													

**Table 2:** Statistical properties of hydro-meteorological parameters data during 2024–2100 for SSP 245.

Stations	Daggar	Gilgit	Naltar	Pulara	Ushkore	Bisham	Deosai	Hushe	Rama	Rattu	Shandor	Shigar	Skardu	Yasin
Lat (°N)	35.2	35.92	35.3	35.3	35.5	34.91	34.97	35.45	35.33	35.25	36.08	35.47	35.32	36.36
Long (°E)	73	74.3	74.5	73.4	74.4	72.86	75.47	76.35	74.78	74.79	72.53	75.69	75.55	73.33
Elevation (m)	2,284.00	1,500.00	4,478.00	3,134.00	3,302.00	2,425.00	4,114.00	3,048.00	3,300.00	2,676.00	3,720.00	2,230.00	2,228.00	4,267.00
<b>Precipitation (mm)</b>														
Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max	30.78	120.1	70.24	344.23	24.72	371.6	112.33	313.69	63.6	54.67	257.91	31.28	125.09	23.58
Avg	0.56	0.99	0.84	1.57	0.81	2.62	0.47	4.15	1.68	1.23	2.53	0.65	2.01	0.3
Frequency	Daily Data 2025-2099													
<b>Tmax (°C)</b>														
Min	-15.44	-15.37	2.31	-10.82	3.27	-19.35	-18.6	-12.6	-10.55	-28.78	-22.29	-5.55	0	-16.72
Max	40.76	36.81	54.31	40.73	54.46	21.4	24.27	40.58	43.25	26.94	24.95	42.99	125.09	27.19
Avg	6.32	8.32	27.22	13.35	26.89	5.23	7.25	12.16	11.37	-3.78	-1.73	16.63	2.01	4.59
Frequency	Daily Data 2025-2099													
<b>Tmin (°C)</b>														
Min	-29.21	-18.5	-4.72	-16.89	-7.21	-36.75	-30.46	-24.2	-16.76	-38.25	-32.93	-16.21	-23.57	-27.35
Max	16.35	22.74	34.2	23.76	31.82	22.59	17.55	22.66	19.9	8.76	16.67	21.67	24.06	17.11
Avg	-2.38	2.35	14.82	4.15	13.8	-5.01	-3.69	3.03	2.54	-10.4	-6.5	5.01	6.94	-2.77
Frequency	Daily Data 2025-2099													
<b>Relative Humidity (%)</b>														
Min	7.76	8.14	8.1	7.26	7.14	9.08	8.47	8.4	8.23	7.62	8.31	7.51	8	8.01
Max	102.21	102.37	101.2	101.48	101.31	127.3	100.78	100.95	101.51	102.35	102.37	101.95	96.61	101.7
Avg	40.81	40.37	40.66	40.55	40.44	49.17	40.6	40.13	40.98	40.63	40.29	40.86	39.18	40.16
Frequency	Daily Data 2025-2099													
<b>Solar Radiation (Watt/m<sup>2</sup>)</b>														
Min	620.08	369.72	881.02	733.86	606.16	631.24	907.16	1,129.01	683.76	610.09	809.97	865.43	862.86	399.82
Max	5,174.66	5,204.48	5,215.56	5,160.68	5,223.04	5,210.21	5,194.48	5,040.00	5,196.24	5,209.47	5,195.31	5,199.54	5,219.29	5,218.34
Avg	3,298.71	3,064.78	3,074.06	3,103.51	3,204.66	3,106.69	3,307.50	3,058.05	3,202.79	3,102.29	3,387.25	3,149.33	3,220.43	3,038.49
Frequency	Daily Data 2025-2099													
<b>Reservoir Inflow (m<sup>3</sup>/s) at Station: Tarbela</b>														
Min	204.52													
Max	16,899.44													
Avg	2,154.41													
Frequency	Daily Data 2025-2099													

**Table 3:** Statistical properties of hydro-meteorological parameters data during 2024–2100 for SSP 585.

Stations	Daggar	Gilgit	Naltar	Pulara	Ushkore	Bisham	Deosai	Hushe	Rama	Rattu	Shandor	Shigar	Skardu	Yasin
Lat (°N)	35.2	35.92	35.3	35.3	35.5	34.91	34.97	35.45	35.33	35.25	36.08	35.47	35.32	36.36
Long (°E)	73	74.3	74.5	73.4	74.4	72.86	75.47	76.35	74.78	74.79	72.53	75.69	75.55	73.33
Elevation (m)	2,284.00	1,500.00	4,478.00	3,134.00	3,302.00	2,425.00	4,114.00	3,048.00	3,300.00	2,676.00	3,720.00	2,230.00	2,228.00	4,267.00
<b>Precipitation (mm)</b>														
Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max	158.64	100.34	89.26	119.04	172.11	81.12	95.46	88.54	200.87	111.14	130.85	104.24	58.88	167.08
Avg	1.68	1.89	3.99	2.57	2.6	1.14	1.58	1.93	2.04	2.63	3.13	1.28	1.63	1.4
Frequency	Daily Data 2025-2099													
<b>Tmax (°C)</b>														
Min	-13.99	-13.56	3.81	-9	4.66	-17.37	-17.24	-11.51	-8.58	-26.82	-21.12	-3.93	-8.93	-14.8
Max	41.79	38.08	55.5	42.14	56.18	22.81	25.9	41.89	44.32	28.5	26.38	44.65	44.94	28.97
Avg	7.82	9.81	28.72	14.85	28.39	6.73	8.75	13.66	12.87	-2.28	-0.23	18.13	18.82	6.09
Frequency	Daily Data 2025-2099													
<b>Tmin (°C)</b>														
Min	-27.69	-16.96	-3.42	-14.96	-6.12	-34.89	-28.95	-23.16	-15	-36.77	-31.2	-14.99	-22.53	-25.62
Max	17.44	23.81	35.59	25.08	33.07	23.85	18.59	23.98	20.99	9.78	17.99	22.94	25.59	18.31
Avg	-0.88	3.85	16.32	5.65	15.3	-3.51	-2.19	4.53	4.04	-8.89	-5	6.5	8.44	-1.27
Frequency	Daily Data 2025-2099													
<b>Relative Humidity (%)</b>														
Min	6.51	6.23	7.06	6.26	6.14	8.02	7.08	7	6.6	6.28	6.43	6.51	5.94	6.42
Max	99.9	99.95	98.68	99.23	98.42	124.4	99	99.95	99.95	99.7	99.95	99.9	94.83	99.39
Avg	37.84	37.41	37.69	37.58	37.47	46.21	37.62	37.16	38.02	37.67	37.32	37.9	36.21	37.19
Frequency	Daily Data 2025-2099													
<b>Solar Radiation (Watt/m<sup>2</sup>)</b>														
Min	637.73	377.61	901.87	751.94	609.28	647.42	925.67	1,161.16	701.29	624.09	830.11	890.07	884.99	407.09
Max	5,249.97	5,249.97	5,249.90	5,249.97	5,249.97	5,249.97	5,249.97	5,081.33	5,249.98	5,249.90	5,249.91	5,249.97	5,249.97	5,249.97
Avg	3,353.97	3,116.36	3,125.82	3,155.52	3,258.74	3,158.94	3,363.14	3,109.46	3,256.66	3,154.61	3,444.23	3,202.24	3,274.84	3,090.20
Frequency	Daily Data 2025-2099													
<b>Reservoir Inflow (m<sup>3</sup>/s) at Station: Tarbela</b>														
Min	270.72													
Max	20,054.24													
Avg	2,673.89													
Frequency	Daily Data 2025-2099													

Following this, trend series are created by arranging each value of the sub-series in ascending order Şişman and Kizilöz, 2021. The first subseries is plotted on the x-axis, while the second subseries is plotted on the y-axis. If the scatter plot of the data points lies on or very close to a 1:1 (45°) line, with a tolerance of ±5%, it indicates that there is no trend in the data. This is visually represented in Figure 2. If the data points are positioned above the 1:1 line, it indicates an upward trend over time. Conversely, points located below the 1:1 line indicate a downward trend. Moreover, the scatter plot can be divided into 'Low,' 'Medium,' and 'High' clusters. These clusters assist in identifying the trend type for each category. A cluster falling within ±5% or, at most, ±10% of the 1:1 line signifies no notable trend. Clusters situated above or below this line represent upward or downward trends, respectively (Öztopal Şen, 2017).

The slope  $S_{ITA}$  is calculated by Equation (1) (Ahmad et al., 2023):

$$S_{ITA} = \frac{2(\bar{x}_j - \bar{x}_i)}{n} \quad (1)$$

where  $\bar{x}_i$  and  $\bar{x}_j$  are the arithmetic averages of the first and the second halves of the dependent variable,  $x$ , sequence, and  $n$  is the number of data.

The trend indicator  $\Phi$  is given by Equation (2) (Cherinet, et al 2019):

$$\Phi = \sum_{i=1}^n \frac{10(x_j - x_i)}{\mu} \quad (2)$$

The trend indicator, represented by  $\Phi$ , is determined using the number of observations in the subseries ( $n$ ), the data series in the first half subseries class ( $x_i$ ), the data series in the second half subseries part ( $x_j$ ), and the mean of the data series in the first half subseries part ( $\mu$ ). A positive value of  $\Phi$  suggests an upward trend, while a negative value of  $\Phi$  indicates a downward trend. When the scatter points closely align with the 1:1 straight line, it signifies the absence of a significant trend.

## 4. Results

### 4.1 Monthly and seasonal trends of Hydro-meteorological Parameters for historical data

Trend analysis was carried out on monthly and seasonal scales for the period 1981–2024. For (ITA), the first half of time series data is taken from the period 1981 to 2002 and the second half of time series data is taken from the period 2003 to 2024. For all these 14 stations, the average values of all the parameters are calculated to get a single value. For the seasonal trend analysis, we considered four distinct seasons with winter (December, January, and February), spring (March, April, and May), summer (June, July, August), and autumn (September, October, and November) (Ahmed et al., 2018).

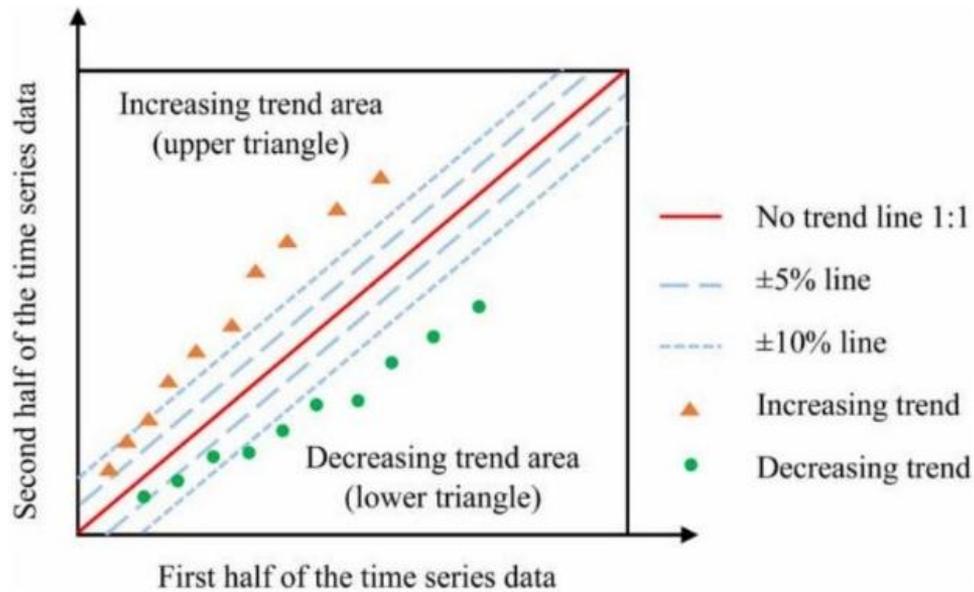
The Slope ( $S_{ITA}$ ) and trend indicator  $\Phi$  values for monthly and seasonal trends of all hydrometeorological parameters for 14 stations are calculated by using R programming language. The ITA results were obtained by using the R package ‘trendchange’ (Singh et al., 2021).

The slope and trend indicator values for monthly and seasonal trends of hydrometeorological parameters are given in Table 4 and Table 5.

### 4.2 Trend analysis on a monthly scale

#### 4.2.1 Precipitation trends in the monthly data

The evaluation of precipitation trends changes over time for 14 stations throughout the Upper Indus Basin shows an overall decline throughout the year. A few months had declines that are greater than others. The months having the highest reductions are March and May -0.062 mm/year and -0.052 mm/year. July and August experienced a decline with a slope of -0.024 mm/year and -0.031 mm/year, respectively indicating moderate reduction. Comparatively, other months like September and October experienced declines with small slope values of -0.006 mm/year and -0.012 mm/year respectively evident of almost stable conditions.



**Fig. 2** Innovative Trend Analysis graph showing positive, decreasing, and no trend.

**Table 4:** Slope and trend indicator values for Monthly trend of all Hydro-meteorological parameters

Months	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Reservoir Inflow	
	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$
Jan	-0.015	-1.476	0.063	-4.2	0.046	-1.191	-0.066	-0.249	28.725	2.433	-0.0184	-0.2552
Feb	-0.004	-0.395	0.075	9.414	0.06	-1.946	-0.106	-0.387	27.498	2.05	0.0517	0.6833
Mar	-0.062	-4.314	0.137	5.085	0.072	-6.777	-0.283	-1.002	22.226	1.408	-0.0271	-0.2666
Apr	-0.027	-2.286	0.087	1.567	0.036	2.624	-0.131	-0.489	2.688	0.144	-0.0585	-0.3960
May	-0.052	-4.306	0.109	1.413	0.034	1.034	-0.023	-0.096	-11.372	-0.56	0.0180	0.0555
Jun	-0.011	-1.472	0.065	0.651	-0.014	-0.273	0.232	1.155	-19.516	-0.932	-0.3777	-0.5604
Jul	-0.024	-2.767	0.036	0.319	-0.023	-0.342	0.236	1.167	-17.437	-0.841	-0.810	-0.7550
Aug	-0.031	-3.137	0.014	0.122	-0.038	-0.562	0.271	1.316	-15.626	-0.796	-0.401	-0.3818
Sep	-0.006	-0.862	0.017	0.176	-0.027	-0.544	0.352	1.829	-5.329	-0.3	-0.1887	-0.4046
Oct	-0.012	-1.853	0.091	1.399	0.04	2.172	-0.165	-0.699	12.461	0.854	0.0427	0.2452
Nov	-0.006	-0.935	0.055	1.471	0.028	-3.768	-0.2	-0.802	21.311	1.716	0.0680	0.6329
Dec	-0.025	-2.549	0.081	8.809	0.02	-0.731	-0.178	-0.687	28.723	2.52	0.0286	0.3432

**Table 2:** Slope and trend indicator values for the seasonal trend of Hydro-meteorological parameters

Seasons	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Reservoir Inflow	
	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$	Slope	Trend indicator, $\phi$
Winter	0.003	0.469	0.006	-4.232	-0.006	0.334	0.070	0.920	6.342	1.147	-0.023	-0.588
Spring	-0.029	-4.558	0.155	13.059	0.137	-22.711	0.056	0.734	8.045	1.062	0.772	13.511
Summer	-0.003	-1.188	0.057	1.277	0.055	2.359	0.099	1.322	-3.340	-0.388	0.763	1.965
Autumn	0.012	3.800	-0.173	-4.776	-0.161	-10.131	0.027	0.339	-11.728	-1.630	-1.073	-6.342

A few other months, namely, February (-0.004 mm/year), June (-0.011 mm/year), and November (-0.006 mm/year), had evidence that precipitation reductions are small. Overall, the data shows a significant reduction in precipitation in every month for every year included in this study with the clearest reductions found during key periods such as March and May.

#### *4.2.2 Relative Humidity trends in the monthly data*

The monthly relative humidity trend across the Upper Indus Basin for the 14 stations indicated increases and decreases throughout the year. Notable positive moisture is between June and September, with September having the largest trend slope at 0.352 %/year. July shows an important upward trend slope of 0.236%/year, and August also had an upward trend slope of 0.271%/year. In contrast, the months of February and March had the greatest downward trend, with March having the most pronounced negative slope of -0.283%/year, demonstrating a clear downward trend in relative humidity. Degrees of downward trend are also observed in October with a slope of -0.165%/year and in November with a slope of -0.2%/year. In conclusion, there is a clear pattern of an upward trend in relative humidity between June and September when compared to a downward trend in the other months, especially March, October, and November. The relative humidity trend describes the dynamic nature of this response across a year in the Upper Indus Basin.

#### *4.2.3 Solar Radiation trends in the monthly data*

The response of solar radiation trends across the 14 stations in the Upper Indus Basin, months with statistically significant trends are noted. In January, February, and December, positive strong trends are observed with slopes of 28.73 Watt/m<sup>2</sup>/year, 27.5 Watt/m<sup>2</sup>/year, and 28.72 Watt/m<sup>2</sup>/year, respectively, indicating high solar radiation. Moderate upward trends occurred in March (22.23) and November (21.31 Watt/m<sup>2</sup>/year). In contrast, the summer months displayed

rates of substantial decline. June, July, and August all displayed moderate negative trends with slopes of -19.52 Watt/m<sup>2</sup>/year, -17.4 Watt/m<sup>2</sup>/year, and -15.63 Watt/m<sup>2</sup>/year, respectively reflecting the solar radiation trend as a constant decline in these months. Overall, the patterns of the monthly trends underscored high solar Radiation in both beginning and end of the year, but also of considerable decline in solar radiation during the summer period.

#### *4.2.4 Tmax trends in the monthly data*

For the 14 stations in the Upper Indus Basin, the trend analysis of maximum temperatures (Tmax) shows consistent warming trend throughout the year. Tmax shows significant amplification in March and May with the slopes of 0.137 °C/year and 0.109 °C/year respectively. Other months also shows moderate positive trending, with higher slopes in April (0.087 °C/year), October (0.091), and December (0.081 °C/year), however, still suggest consistent upward movements over time. The July and August months have a positive trend as well, but fewer slopes of 0.036°C/year and 0.014 °C/year respectively therefore suggesting a small increase. In conclusion, the findings show persistent a positive trend in Tmax over time in all months, while March and May have had significant amplification.

#### *4.2.5 Tmin trends in the monthly data*

The assessment of the trends in daily minimum temperatures at the 14 stations in the Upper Indus Basin revealed informative monthly differences in trends. The largest upward increment is found in February and March with positive slope values of 0.060 °C/year and 0.072 °C/year. These values depict the upward trend for these months. In October, the trends show a moderate positive trend with a slope of 0.040 °C/year, thus reflecting an increase for that month. In the summer months, the values for Tmin exhibited slight downward trends. The month of August is shown to have the largest decrease while having a weak negative showing with a slope of -0.038 °C/year. Other months had slight negative trends in July (-

0.023 °C/year) and September (-0.027 °C/year). Overall, the results of the trends show distinct increment for T<sub>min</sub> during late winter and early spring and in October, while summer months are marked with slight decreases.

#### *4.2.6 Inflow trends in the monthly data*

The trends for monthly inflows in the Upper Indus Basin show a varied pattern characterized by extreme variability in inflow. Some months increased in inflows while other months shows declines which produced an ambiguous overall picture. Of this monthly distribution, February, November, and October produced positive slopes implying an increase in monthly inflows every year during each of these months as seasons change. In contrast, the July and August months produced steep negative slopes -0.810 cumecs/year and -0.401 cumecs/year respectively, and thus significant reductions in monthly inflows during the summer months. The March and April months also experienced negative trends indicating potential reductions in water contributions during those months. In contrast, the January, May, and December months show relatively small fluctuations with small positive or negative slopes and stable flow patterns with no significant rise or decline. Overall, the monthly trends show different levels of inflow for each month of the year.

### **4.3 Trend analysis on a Seasonally scale**

#### *4.3.1 Seasonal trends of precipitation*

Evaluation of precipitation trends in the Upper Indus Basin across the 14 stations also analyzed seasonal patterns. The data suggested unique trends for each season, highlighting diverse changes in precipitation. Winter: There is a weak positive trend in winter precipitation illustrated by a trend slope value of 0.003 mm/Winter and a Trend Indicator ( $\Phi$ ) of 0.912. This implies a slight increase in precipitation in the winter months, but it is a weak trend in spring and summarized by a weak slope value at -0.007 mm/Spring and a Trend Indicator ( $\Phi$ ) of -

1.778 suggesting a negative trend with a clear decline in spring precipitation. Summer: For summer, the data indicated a negligible positive trend with a seasonal trend slope value of 0.0001 mm/Summer, and a Trend Indicator ( $\Phi$ ) of -0.063, no trend change is shown in the data. Autumn: There is a slow negative trend slope for the season with a slope value of -0.001 mm/Autumn and a weak Trend Indicator ( $\Phi$ ) of -0.586 suggesting an anticipated decrease in precipitation. Overall, seasonal data shows mixed trends and changes in habits with the winter. This points to a slight decrease in precipitation in the autumn, although the trend is weak. In the end, the seasonal data show different trends in the precipitation seasonally. There seems to be a very slight positive trend in the winter component, with a weak negative trend in summer and autumn, and an apparent reduction in spring precipitation that is shown in Fig. 3.

#### *4.3.2 Seasonal Trends of Relative Humidity*

The analysis of relative humidity trends for the 14 Upper Indus Basin stations for the different seasons averaged different results. During the winter season, analysis indicates a slight increase in relative humidity data with a trend slope value of 0.033 %/Winter suggesting some degree of increase in relative humidity data during the winter months.

The analysis for spring shows a consistent decrease in relative humidity data with a trend slope value of -0.083%/Spring indicating a consistent decrease in relative humidity data in the spring. For summer there is a slight increase in relative humidity data with a trend slope value of 0.041 %/Summer indicating some upward pattern in relative humidity in the summer months. And for autumn there is a little increase in relative humidity data with a trend slope value of 0.046 %/Autumn indicating a slight upward trend in relative humidity data in the autumn. Overall, the results of the seasonal analysis indicate different trends in relative humidity data with winter, summer, and autumn showing slight increment, while spring

shows a significant decrease as shown in Fig. 4.

#### 4.3.3 Seasonal Trends of Solar Radiation

Seasonal patterns of trend changes are examined through an analysis of solar radiation trends from 14 stations in the Upper Indus Basin, and it is revealed that some of the different seasons had different patterns. In the winter season, there is a strong upward trend in the slope value of 7.373 Watt/m<sup>2</sup>/Winter of solar radiation. In spring, there is a clear upward trend in slope value of 6.563 of solar radiation. In summer, there is a downward trend in solar radiation observed with a slope value of -4.461 Watt/m<sup>2</sup>/Summer. In autumn, there is a strong downward trend in solar radiation, with a slope value of -7.540 Watt/m<sup>2</sup>/Autumn solar radiation. It is concluded from the seasonal data that the trend changes are noticeable, generally speaking, winter and spring seasons are positive upward trend solar radiation changes, while summer and autumn are negative downward trend solar radiation changes. The results provide valuable information related to the solar radiation change in the Upper Indus Basin relative to the season and are displayed in the graphs within Fig. 5.

#### 4.3.4 Seasonal Trends of Tmax

The study of the trends in maximum temperature (Tmax) for the 14 Upper Indus Basin stations for the different seasons shows different trends. In the winter season, a very minimal positive trend is found which had a slope of 0.002 °C/Winter. This indicates that maximum temperature had a very slight increase from December to February. In the spring season, there is a large increase in the trend for Tmax which had a trend slope value of 0.118 °C/Spring. This indicates that Tmax is having an increase and has a strong upward trend in the spring. In the summer season, Tmax values show a moderate positive trend with a slope of 0.028. This indicates that Max Temperature is going higher in the summer months. Autumn season is a noticeable reduction in Tmax which had a trend slope value of -0.118. This indicates that Tmax has

a very strong downward trend in the autumn season. In sum, the seasonal Tmax data displays different trends in maximum temperature having one season with a very slight to moderate increase (winter and summer), one season with a very large increase (spring), and one season with a noticeable decrease (autumn). The seasonal data provides important information based on the trends in maximum temperature changes in the Upper Indus Basin which are portrayed in figures in Figure 6.

#### 4.3.5 Seasonal Trends of Tmin

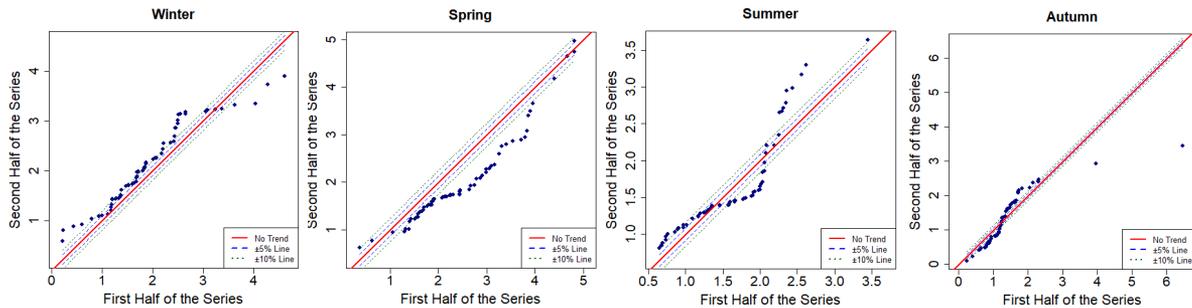
Analysis of the trends for minimum temperature (Tmin) from 14 stations across the Upper Indus Basin shows different changes across the seasons. For winter we found a very weak positive trend in minimum temperature during the winter season with a trend slope value of 0.001 °C/Winter indicating an upward trend in Tmin during the winter months. In the spring season, we found a trend slope value of 0.095°C/Spring, indicating a strong upward trend in Tmin during spring. The summer season shows a slight increase in minimum temperature, with a trend slope value of 0.029°C/Summer, indicating a small upward trend in Tmin during the summer months. We found a strong negative trend in minimum temperature during the autumn season, a trend slope of -0.116 °C/Autumn indicating a strong downward trend in Tmin during the autumn. Overall, we see that from the seasonal data, winter and summer had a slight increase, spring a strong increase, and autumn a strong decrease in Tmin. This analysis gives us valuable insights into the seasonal patterns of when Tmin amplification and decreases, and is illustrated in the graphs in Figure 7.

#### 4.3.6 Seasonal Trends of Inflow

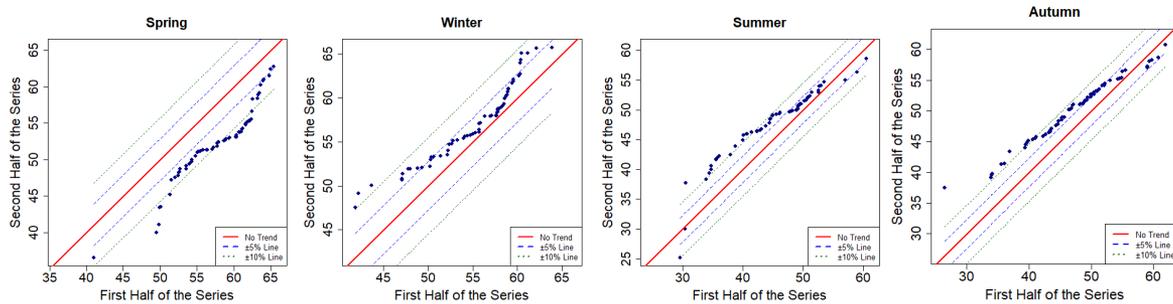
In examining the seasonal inflow trends for the Upper Indus Basin, we noted unique trends for each season with slope and Trend Indicator ( $\Phi$ ) values. Seasonal inflows during winter had a weak negative trend. The trend slope value is -0.017 cumecs/Winter and the Trend Indicator ( $\Phi$ ) value is -0.645

indicating a minor change in water availability during the winter months. Inflows from the spring season revealed a strong positive trend. The trend slope value is 0.491 cumecs/Spring and the Trend Indicator ( $\Phi$ ) value is 6.686 indicating a large amount of change from the water contributions, likely influenced by a larger rate of snowmelt. Summer is a moderate positive trend with a trend slope value of 0.589 cumecs/Summer and a Trend Indicator ( $\Phi$ ) value of 2.258. This indicates a significant rate of change from the increase in inflows heavily driven by the glacial melt when peak temperatures are observed. Inflows during autumn also

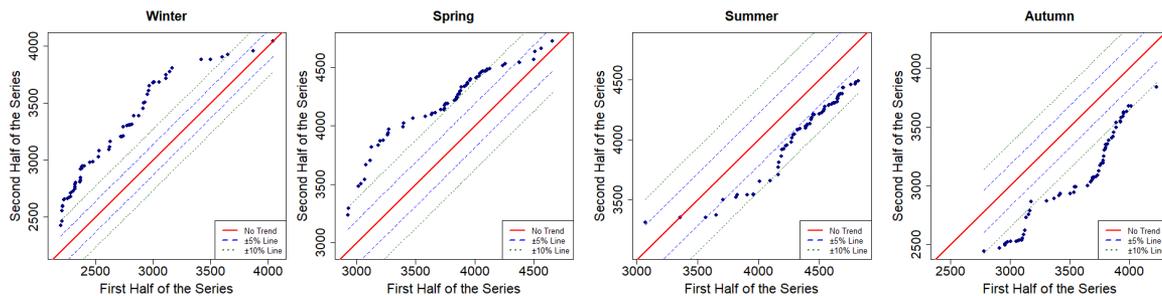
shows a strong negative trend. The trend slope value is -0.765 cumecs/Autumn and the Trend Indicator ( $\Phi$ ) value is -3.327. This indicates a significant loss in water availability as the contributions of precipitation and glacial melt decrease. In general, it is observed that both spring and summer had significant increases while spring had an apparent rise, and winter and autumn had loose trends. These trends demonstrate the critical need to improve seasonal water management strategies to account for the shifting nature of inflows to the Upper Indus Basin as seen in the graphs in Fig. 8.



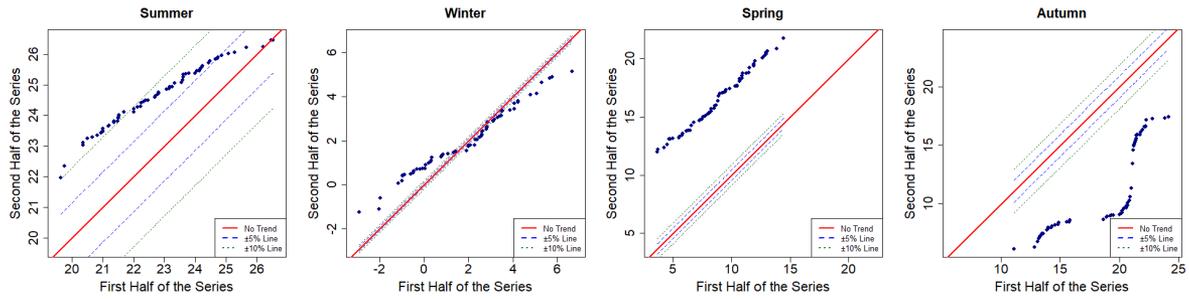
**Fig. 3** Seasonal precipitation trend for 14 stations in the Upper Indus Basin by ITA method



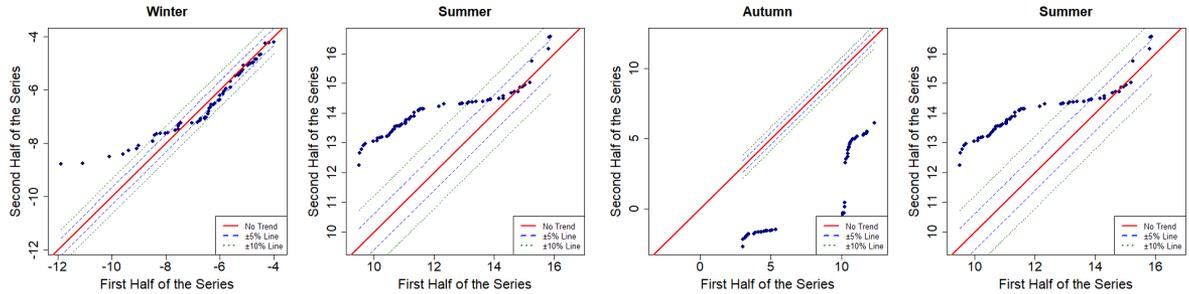
**Fig. 4** Seasonal trend of Relative Humidity for 14 stations in the upper Indus basin by ITA method



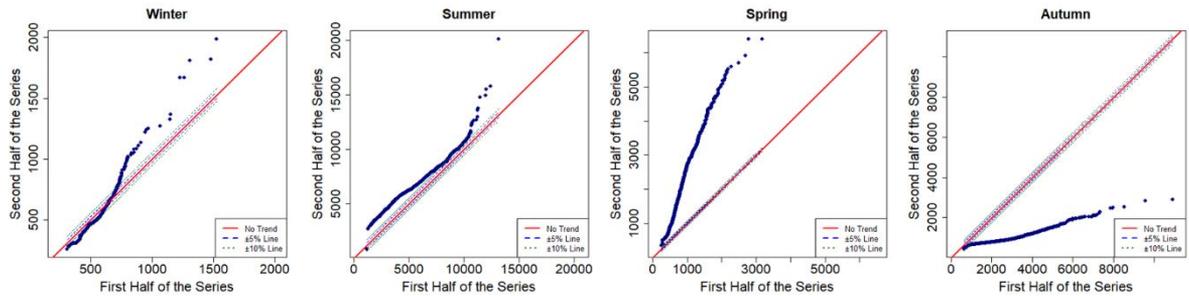
**Fig. 5** Seasonal Solar Radiation trend for 14 stations in the upper Indus basin by ITA method



**Fig. 6** Seasonal trend of Temperature Maximum for 14 stations in the upper Indus basin by ITA method



**Fig. 7** Seasonal trend of Temperature Minimum for 14 stations in the upper Indus basin by ITA method



**Fig. 4** Seasonal Inflow trend for 14 stations in the Upper Indus Basin by ITA method

#### 4.4 Monthly and seasonal trends of Hydrometeorological Parameters for the future data

Trend analysis is carried out on monthly and seasonal scales for the period 2025–2100. This time series data has been divided into three parts: near future from 2025-2049, mid future from 2050-2074, and Far future from 2075-2099.

#### 4.5 Monthly and seasonal trends of Hydrometeorological for SSP 585 Scenario

##### 4.5.1 Monthly and seasonal trends of Hydrometeorological for Near, Mid, and Far future.

Tables 6, 7, 8, 9, 10, and 11 give the slope and Trend Indicator ( $\Phi$ ) values for monthly and seasonal trends of hydrometeorological parameters in the near-future, mid-future, and far-future.

**Table 3:** Slope and Trend Indicator ( $\Phi$ ) values for Monthly trend of all Hydro-meteorological parameters for Near Future.

Months	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Jan	-0.063	-2.764	0.072	-4.388	0.063	-0.880	0.520	2.443	0.026	0.002	-0.072	-0.675
Feb	0.014	0.667	0.010	2.791	0.009	-0.163	0.390	1.762	3.052	0.160	0.057	0.516
Mar	-0.078	-3.197	0.020	0.881	0.018	-0.576	0.414	1.905	1.531	0.070	-0.045	-0.300
Apr	-0.050	-3.131	0.098	1.691	0.068	12.264	0.579	2.757	1.361	0.056	0.031	0.142
May	0.011	1.156	0.081	0.951	0.063	2.497	0.454	2.147	-0.605	-0.024	0.631	1.363
Jun	-0.012	-1.182	0.109	0.884	0.082	1.380	0.542	2.612	-0.395	-0.015	-0.165	-0.165
Jul	0.011	1.797	0.096	0.666	0.069	0.857	0.730	3.529	-2.811	-0.109	-0.929	-0.613
Aug	-0.040	-4.087	0.068	0.464	0.032	0.383	0.536	2.478	-2.065	-0.084	-0.797	-0.562
Sep	0.022	2.786	0.077	0.638	0.077	1.332	0.604	2.722	-4.770	-0.210	-0.519	-0.783
Oct	0.019	1.920	0.055	0.707	0.032	1.557	0.638	2.995	-4.115	-0.208	-0.039	-0.159
Nov	0.016	1.237	0.081	2.052	0.047	-3.126	0.545	2.658	-3.501	-0.199	0.070	0.455
Dec	-0.048	-2.422	0.057	-9.424	0.062	-1.152	0.619	3.025	-0.879	-0.054	-0.039	-0.321

**Table 4:** Slope and Trend Indicator ( $\Phi$ ) values for Seasonal trend of all Hydro-meteorological parameters for Near Future

Seasons	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Winter	0.003	0.469	0.006	-4.232	-0.006	0.334	0.070	0.920	6.342	1.147	-0.023	-0.588
Spring	-0.029	-4.558	0.155	13.059	0.137	-22.711	0.056	0.734	8.045	1.062	0.772	13.511
Summer	-0.003	-1.188	0.057	1.277	0.055	2.359	0.099	1.322	-3.340	-0.388	0.763	1.965
Autumn	0.012	3.800	-0.173	-4.776	-0.161	-10.131	0.027	0.339	-11.728	-1.630	-1.073	-6.342

**Table 5:** Slope and Trend Indicator ( $\Phi$ ) values for Monthly trend of all Hydro-meteorological parameters for Mid Future

Months	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Jan	-0.097	-4.053	0.063	-6.560	0.029	-0.400	-1.093	-3.129	-4.691	-0.229	0.100	0.838
Feb	-0.108	-3.726	-0.003	-0.349	0.013	-0.217	-0.837	-2.494	-5.294	-0.230	0.077	0.587
Mar	0.000	0.012	0.054	1.510	0.053	-1.800	-0.774	-2.260	-4.887	-0.186	0.333	2.056
Apr	-0.088	-4.117	0.036	0.433	-0.001	-0.080	-0.874	-2.499	-3.243	-0.111	0.176	0.695
May	-0.057	-3.632	0.136	1.167	0.065	1.628	-0.867	-2.570	-3.480	-0.114	0.139	0.255
Jun	0.001	0.040	0.068	0.390	0.044	0.497	-0.778	-2.396	-0.233	-0.008	2.203	2.012
Jul	0.008	1.156	0.096	0.483	0.014	0.120	-0.816	-2.520	-1.533	-0.050	2.940	1.807
Aug	-0.017	-1.391	0.094	0.496	0.077	0.722	-0.696	-2.181	2.250	0.078	0.244	0.148
Sep	0.010	0.961	0.032	0.189	0.009	0.106	-0.699	-2.101	1.176	0.045	0.414	0.555
Oct	0.025	1.427	0.039	0.356	0.047	1.359	-0.687	-2.039	3.553	0.155	0.044	0.148
Nov	-0.061	-2.978	0.085	1.352	0.075	-8.214	-0.707	-2.165	-0.030	-0.001	-0.007	-0.038
Dec	-0.087	-3.161	0.075	9.159	0.045	-0.877	-0.825	-2.525	-0.779	-0.040	0.059	0.407

**Table 6:** Slope and Trend Indicator ( $\Phi$ ) values for Seasonal trend of all Hydro-meteorological parameters for Mid Future

Seasons	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Winter	-0.010	-1.271	-0.004	-0.227	-0.021	1.115	-0.108	-1.056	7.093	1.081	-0.015	-0.324
Spring	-0.033	-4.360	0.190	10.588	0.155	4.307	-0.132	-1.235	8.957	0.992	0.849	8.515
Summer	-0.005	-1.190	0.051	0.824	0.047	1.424	-0.103	-1.025	-4.009	-0.393	1.338	2.980
Autumn	0.020	4.423	-0.223	-4.469	-0.198	-8.609	-0.096	-0.924	-13.261	-1.570	-1.284	-6.301

**Table 7:** Slope and Trend Indicator ( $\Phi$ ) values for Monthly trend of all Hydro-meteorological parameters for Far Future.

Months	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Jan	-0.052	-2.504	-0.027	-12.643	-0.021	0.347	0.520	1.761	1.191	0.059	0.005	0.045
Feb	-0.069	-2.737	-0.007	-0.368	-0.048	1.075	0.456	1.484	0.048	0.002	-0.029	-0.210
Mar	-0.087	-3.138	-0.017	-0.335	-0.056	4.695	0.560	1.885	1.169	0.045	-0.039	-0.229
Apr	-0.023	-0.831	0.021	0.210	0.008	0.266	0.660	2.228	-0.492	-0.017	-0.126	-0.474
May	-0.052	-3.471	-0.005	-0.035	-0.041	-0.711	0.621	2.026	0.200	0.007	-1.227	-1.869
Jun	0.024	1.875	0.037	0.194	0.027	0.270	0.623	2.125	-0.567	-0.019	-1.216	-1.020
Jul	0.012	1.336	0.069	0.318	0.033	0.270	0.420	1.404	-1.420	-0.047	0.714	0.429
Aug	-0.021	-1.700	0.023	0.108	0.019	0.148	0.099	0.304	-2.277	-0.079	1.387	0.929
Sep	0.014	1.562	0.013	0.072	0.003	0.030	0.338	1.093	-3.166	-0.121	0.455	0.653
Oct	-0.002	-0.130	0.016	0.128	0.021	0.436	0.322	0.989	-2.331	-0.102	0.167	0.596
Nov	-0.021	-1.118	-0.037	-0.449	-0.019	-2.981	0.333	1.024	-1.865	-0.092	0.082	0.437
Dec	-0.070	-3.659	-0.032	-1.578	-0.028	0.661	0.407	1.342	0.181	0.009	0.033	0.235

**Table 8:** Slope and Trend Indicator ( $\Phi$ ) values for Seasonal trend of all Hydro-meteorological parameters for Mid Future

Seasons	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Winter	0.006	0.997	-0.005	-1.079	-0.013	0.826	0.074	0.699	8.251	1.270	-0.008	-0.186
Spring	-0.028	-3.359	0.200	9.069	0.155	-5.330	0.098	0.923	9.028	1.001	0.936	6.038
Summer	-0.006	-1.342	0.054	0.809	0.056	1.526	0.056	0.520	-4.275	-0.421	1.039	2.380
Autumn	0.018	4.560	-0.235	-4.248	-0.208	-7.513	0.068	0.622	-13.670	-1.638	-1.157	-6.052

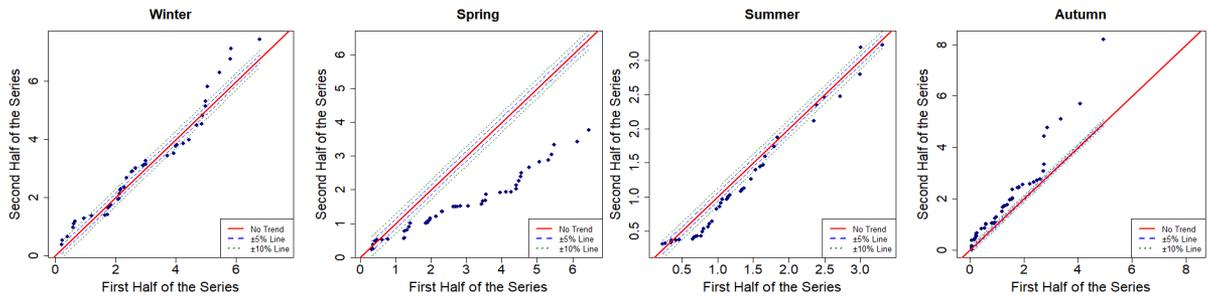
#### 4.5.2 Trends of Hydrometeorological Parameters for the Near Future.

For the near future, the trend of precipitation is negative for all seasons except for Autumn which shows a slight increase in precipitation with a slope of 0.012 mm/year. This trend of precipitation shortly is very similar to that of the historical trend. For Tmax, the trend is going up for spring and

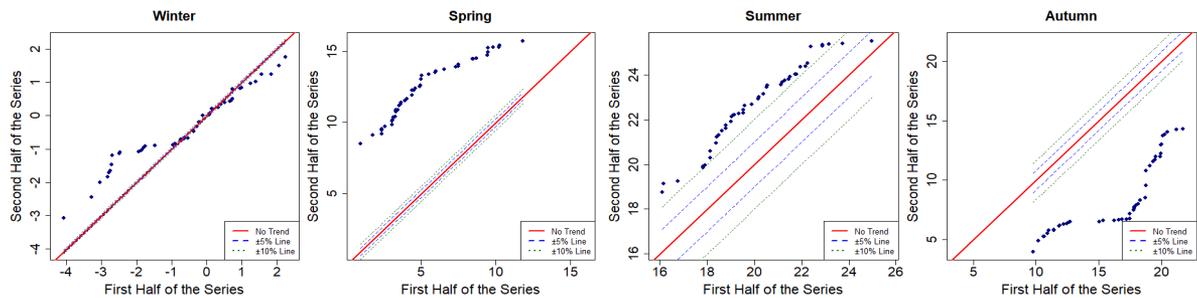
summer and negative for winter and autumn. For spring it shows a strong increase with a slope of 0.155 and for autumn it shows a strong negative trend with a slope of -0.173 mm/year. Tmin also revealed a similar trend to that of a historical trend. It shows an upwards trend in spring and summer with a strong increase in spring (0.137 mm/year) and a strong negative trend in autumn (-0.161 mm/year). Relative humidity shows a

positive trend for all seasons that is similar to that of historical trends. Solar radiation also revealed a similar trend to that of historical trend with positive in winter and spring and negative in summer and winter but with strong slope and Trend Indicator ( $\Phi$ ) values compared to that of historical. Reservoir inflow shows a strong positive trend in spring

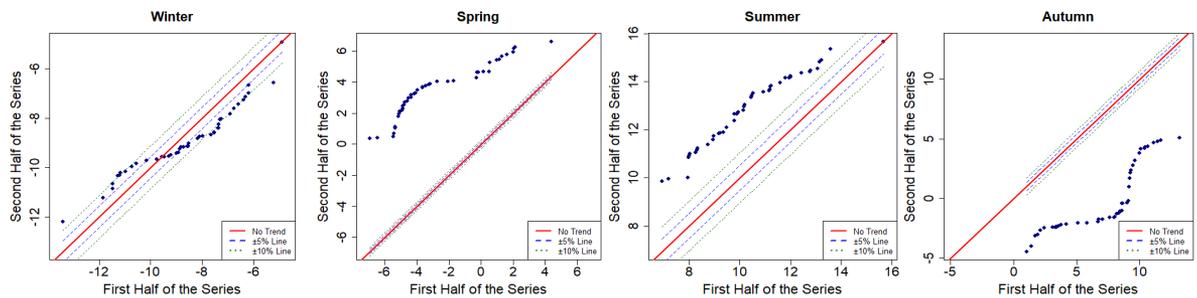
and summer with slope values of 0.772 mm/year and 0.763 mm/year respectively. It shows a negative trend in winter and autumn with slopes of -0.023 mm/year and -1.073 mm/year. Inflow also shows a similar trend to that of the historical trend but with strong values of slope and indicator.



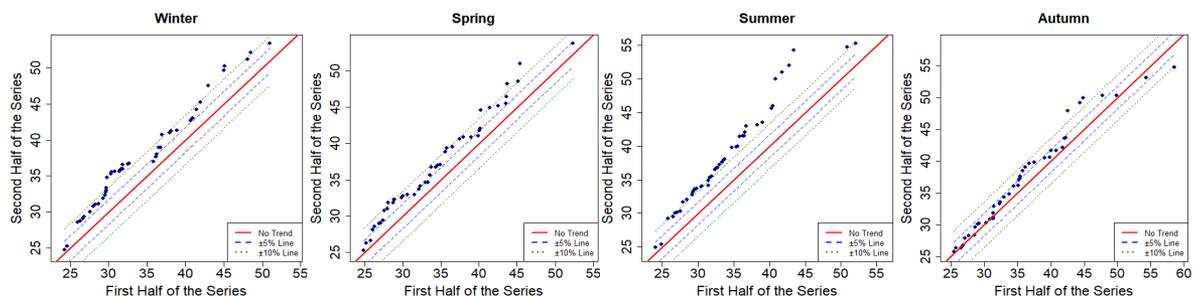
**Fig. 9** Seasonal Precipitation trend for near-future (2025-2049) SSP585 in the UIB by ITA method



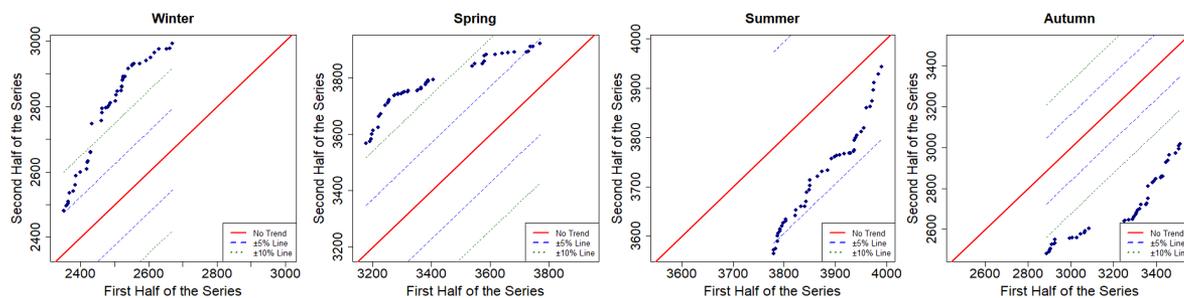
**Fig. 10** Seasonal T max trend for near-future SSP585 (2025-2049) in the UIB by ITA method



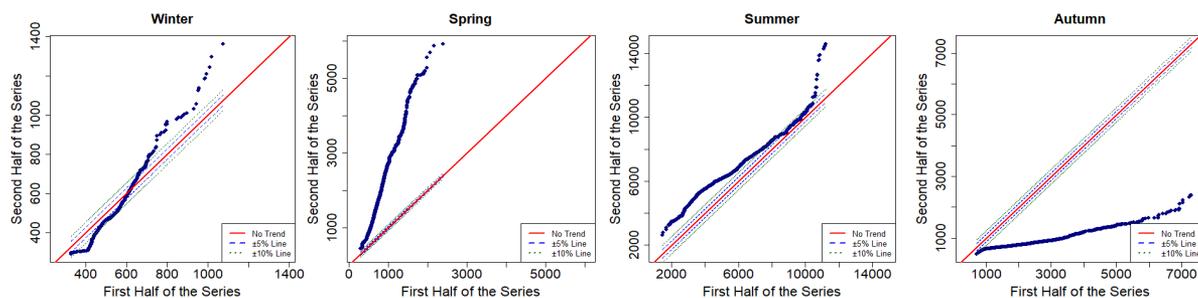
**Fig. 11** Seasonal T min trend for near-future SSP585 (2025-2049) in the UIB by ITA method



**Fig. 12** Seasonal T Relative Humidity for near-future (2025-2049) SSP585 in the UIB by ITA method



**Fig. 13** Seasonal Solar Radiation for near-future (2025-2049) SSP585 in the UIB by ITA method



**Fig. 14** Seasonal Inflow for near-future (2025-2049) SSP585 in the UIB by ITA method

#### 4.5.3 Trends of Hydrometeorological parameters for Mid-Future

For Mid future, the precipitation trend is negative for all seasons except for Autumn shows a positive slope value of 0.020 mm/year. This trend is similar to that of historical and near future. For Tmax, the trend is positive for spring and summer and negative in winter and autumn but with strong slope and indicator values of 0.190 °C/year and -0.223°C/year for spring and autumn respectively. Tmin also shows a similar trend to that of historical and near future. It shows positive in spring and summer but a strong slope value of 0.155 °C/year for spring. It shows a negative trend for winter and autumn with a strong slope value of -0.198 °C/year for autumn. Relative humidity revealed a strong negative trend for all seasons and that is different from historical and near-future trends. Solar radiation shows a positive trend in spring and summer with slope values of 7.093 Watt/m<sup>2</sup>/year and 8.957 Watt/m<sup>2</sup>/year

respectively. It shows a strong decreasing trend for winter and autumn and that is similar to the past trend. Inflow shows a strong positive trend in spring and summer with slope values of 0.849 Watt/m<sup>2</sup>/year and 1.338 Watt/m<sup>2</sup>/year respectively. It shows a decreasing trend in winter and autumn with slopes of -0.015 Watt/m<sup>2</sup>/year and -1.284 Watt/m<sup>2</sup>/year. Inflow also shows a similar trend to that of the historical trend but with strong values of slope 1.039 cumecs/year and indicator 2.380 during Summer.

#### 4.5.4 Trends of Hydrometeorological Parameters for the Far Future

For Far Future, precipitation revealed a decreasing trend for spring and summer positive trend for autumn and winter with slopes of 0.018 mm/year and 0.006 mm/year and that is similar to past trends. Tmax shows a strong positive trend for spring and summer with a slope of 0.2 °C/year and 0.54 °C/year and a decreasing trend for winter and autumn with a slope of -0.005 °C/year and -0.235 °C/year respectively. Tmin shows a strong

positive trend for spring and summer and a decreasing trend for winter and autumn, similar to all past trends. Relative humidity revealed a positive trend for all seasons. Solar radiation shows a strong increase for winter and spring with a slope of 8.251 Watt/m<sup>2</sup>/year and 9.028 Watt/m<sup>2</sup>/year and a strong decrease for summer and autumn with a slope of -4.670 Watt/m<sup>2</sup>/year and -13.275 Watt/m<sup>2</sup>/year respectively. Inflow revealed a strong positive trend in spring and summer with slope values of 0.936 cumecs/year and 1.039 cumecs/year respectively. It shows a decreasing trend in winter and autumn with slopes of -0.008 cumecs/year and -1.157 cumecs/year. Inflow also shows a similar

trend to that of the historical trend but with strong values of slope and indicator.

#### 4.6 Monthly and seasonal trends of Hydrometeorological for SSP 245 Scenario

##### 4.6.1 Monthly and seasonal trends of Hydrometeorological for Near, Mid, and Far future

The slope and Trend Indicator ( $\Phi$ ) values for monthly and seasonal trends of hydrometeorological parameters for Near future, Mid-future and Far Future are given in Tables 12, 13, 14, 15, 16, and Table 17.

**Table 9:** Slope and Trend Indicator ( $\Phi$ ) values for Monthly trend of all Hydro-meteorological parameters for Near Future.

Months	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Jan	0.037	4.154	0.073	-2.746	0.063	-0.775	0.575	2.586	-1.412	-0.083	-0.026	-0.279
Feb	-0.019	-1.765	0.010	-1.042	0.010	-0.143	0.445	1.929	1.409	0.074	0.018	0.184
Mar	-0.007	-0.559	0.021	1.590	0.017	-0.424	0.469	2.070	-0.320	-0.015	-0.029	-0.246
Apr	0.021	1.598	0.098	2.036	0.068	-15.355	0.635	2.891	-0.704	-0.029	0.012	0.076
May	-0.011	-0.880	0.081	1.076	0.062	4.104	0.509	2.304	-2.740	-0.108	0.469	1.352
Jun	-0.015	-1.748	0.108	0.957	0.083	1.661	0.598	2.754	-2.558	-0.099	-0.073	-0.097
Jul	-0.027	-1.866	0.096	0.716	0.068	0.975	0.785	3.630	-4.942	-0.192	-0.700	-0.617
Aug	-0.026	-1.803	0.068	0.497	0.032	0.432	0.591	2.620	-4.093	-0.167	-0.586	-0.552
Sep	-0.001	-0.049	0.077	0.692	0.077	1.619	0.659	2.850	-6.608	-0.292	-0.374	-0.754
Oct	-0.005	-0.798	0.055	0.813	0.032	3.075	0.693	3.116	-5.714	-0.290	-0.025	-0.136
Nov	-0.011	-2.312	0.082	2.746	0.048	-1.887	0.600	2.799	-4.928	-0.282	0.043	0.370
Dec	0.005	1.695	0.057	-5.107	0.063	-0.976	0.674	3.151	-2.243	-0.138	-0.024	-0.251

**Table 10** Slope and Trend Indicator ( $\Phi$ ) values for Seasonal trend of all Hydro-meteorological parameters for Near Future.

Seasons	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Winter	0.019	6.952	0.006	-1.299	-0.007	0.289	0.076	0.953	6.123	1.116	0.009	0.281
Spring	0.003	0.737	0.155	11.158	0.137	-14.614	0.062	0.777	7.745	1.030	0.569	13.022
Summer	0.008	2.458	0.057	1.377	0.054	2.755	0.106	1.338	-3.548	-0.415	0.567	1.947
Autumn	-0.015	-4.863	-0.173	-5.260	-0.161	-12.811	0.033	0.397	-11.804	-1.653	-0.798	-6.298

**Table 11:** Slope and Trend Indicator ( $\Phi$ ) values for Monthly trend of all Hydro-meteorological parameters for Mid Future.

Months	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Jan	-0.014	-1.032	0.062	-2.881	0.062	-2.881	-1.038	-2.802	-5.102	-0.253	0.130	1.132
Feb	-0.030	-2.948	-0.003	1.563	-0.003	1.563	-0.781	-2.191	-5.662	-0.250	0.118	0.951
Mar	-0.022	-1.460	0.054	2.283	0.054	2.283	-0.718	-1.974	-5.354	-0.207	0.209	1.572
Apr	-0.045	-2.139	0.035	0.497	0.035	0.497	-0.829	-2.235	-3.790	-0.133	0.138	0.690
May	-0.007	-0.533	0.136	1.301	0.136	1.301	-0.823	-2.294	-4.168	-0.139	0.150	0.351
Jun	0.001	0.156	0.067	0.417	0.067	0.417	-0.733	-2.119	-1.009	-0.034	1.547	1.790
Jul	0.014	0.853	0.096	0.516	0.096	0.516	-0.772	-2.237	-2.285	-0.076	2.046	1.589
Aug	0.016	1.028	0.093	0.525	0.093	0.525	-0.640	-1.882	1.469	0.052	-0.009	-0.007
Sep	-0.049	-3.478	0.032	0.203	0.032	0.203	-0.643	-1.818	0.484	0.019	0.185	0.312
Oct	-0.031	-4.048	0.039	0.397	0.039	0.397	-0.632	-1.764	2.901	0.129	0.031	0.132
Nov	-0.011	-1.950	0.086	1.676	0.086	1.676	-0.651	-1.872	-0.495	-0.025	0.000	0.001
Dec	0.002	0.738	0.075	-19.734	0.075	-19.734	-0.769	-2.211	-1.261	-0.067	0.074	0.621

**Table 12:** Slope and Trend Indicator ( $\Phi$ ) values for Seasonal trend of all Hydro-meteorological parameters for Mid Future.

Seasons	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Winter	0.011	4.628	-0.001	0.291	-0.021	0.918	-0.102	-0.930	6.896	1.071	0.031	0.764
Spring	-0.009	-1.576	0.190	13.612	0.155	-12.793	-0.126	-1.100	8.709	0.983	0.662	12.202
Summer	0.020	5.331	0.051	0.881	0.047	1.622	-0.097	-0.897	-4.019	-0.401	1.017	2.883
Autumn	-0.019	-5.248	-0.223	-4.859	-0.198	-10.414	-0.090	-0.807	-13.076	-1.577	-1.001	-6.257

**Table 13:** Slope and Trend Indicator ( $\Phi$ ) values for Monthly trend of all Hydro-meteorological parameters for Far Future.

Months	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Jan	0.005	0.432	-0.027	2.755	-0.021	0.288	0.521	1.579	1.164	0.059	-0.094	-0.746
Feb	0.020	2.000	-0.007	-1.028	-0.049	0.852	0.455	1.330	0.042	0.002	-0.020	-0.150
Mar	0.010	0.533	-0.018	-0.460	-0.057	2.388	0.561	1.691	1.137	0.045	0.050	0.353
Apr	-0.020	-1.102	0.021	0.237	0.008	0.501	0.660	1.995	-0.475	-0.017	-0.080	-0.394
May	0.034	2.810	-0.006	-0.043	-0.041	-0.900	0.622	1.823	0.192	0.007	-0.926	-1.889
Jun	0.004	0.358	0.037	0.203	0.028	0.318	0.624	1.902	-0.555	-0.019	-0.930	-1.040
Jul	-0.023	-1.449	0.069	0.336	0.034	0.305	0.420	1.258	-1.384	-0.047	0.471	0.375
Aug	-0.035	-2.006	0.024	0.118	0.019	0.166	0.099	0.275	-2.224	-0.079	0.999	0.869
Sep	-0.017	-1.956	0.013	0.076	0.003	0.038	0.338	0.982	-3.088	-0.120	0.435	0.818
Oct	0.000	0.080	0.016	0.142	0.020	0.559	0.322	0.893	-2.276	-0.102	0.080	0.360
Nov	0.010	4.055	-0.036	-0.524	-0.019	3.431	0.332	0.925	-1.824	-0.092	-0.034	-0.218
Dec	0.006	2.307	-0.032	-3.784	-0.028	0.528	0.407	1.205	0.186	0.010	-0.055	-0.434

**Table 14:** Slope and Trend Indicator ( $\Phi$ ) values for Seasonal trend of all Hydro-meteorological parameters for Far Future.

Seasons	Precipitation		Tmax		Tmin		Relative Humidity		Solar Radiation		Inflow	
	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$	Slope	Trend indicator, $\Phi$
Winter	0.020	9.378	-0.005	-7.848	-0.013	0.657	0.074	0.632	8.056	1.270	0.011	0.254
Spring	-0.015	-2.282	0.200	11.085	0.155	-16.043	0.098	0.833	8.814	1.001	0.659	12.064
Summer	0.011	2.675	0.055	0.862	0.056	1.714	0.056	0.470	-4.172	-0.421	0.835	2.547
Autumn	-0.012	-5.035	-0.235	-4.580	-0.208	-8.788	0.068	0.562	-13.348	-1.638	-0.876	-5.918

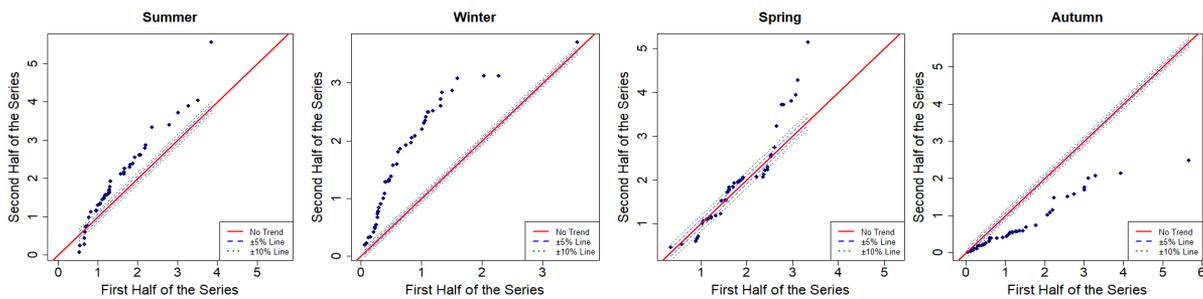
**Table 18:** Summary of Key Seasonal Trend Magnitudes ( $S_{ITA}$ ) for Historical and Future (SSP5-8.5) Scenarios.

Parameter	Season	Historical (1981–2024)	Near-Future (2025–2049)	Mid-Future (2050–2074)	Far-Future (2075–2099)
Precipitation (mm/year)	Spring	-0.007	-0.029	-0.033	-0.033
	Summer	0.0001	-0.003	-0.005	-0.006
$T_{max}$ ( $^{\circ}C/year$ )	Spring	0.118	0.15	0.190	0.200
	Autumn	-0.118	-0.173	-0.223	-0.235
Inflow ( $m^3/s/year$ )	Spring	0.490	0.772	0.849	0.936
	Summer	0.588	0.763	1.338	1.039
	Autumn	-0.764	-1.073	-1.284	-1.157

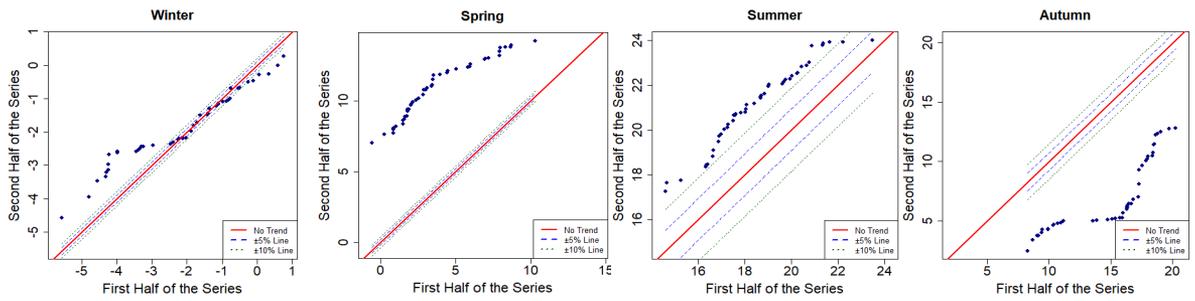
#### 4.6.2 Trends of Hydrometeorological Parameters for the Near Future

For the near future, the precipitation trend is positive for winter, spring, summer but decreases for Autumn with a slope of -0.015 mm/year. This is different than all other trends of precipitation. Tmax shows a positive trend for winter, spring, and summer but a strong decrease in autumn with a slope of -0.173  $^{\circ}C/year$ . Tmin revealed a positive trend for spring and summer and a negative trend for winter and autumn. Relative humidity shows a positive trend for all

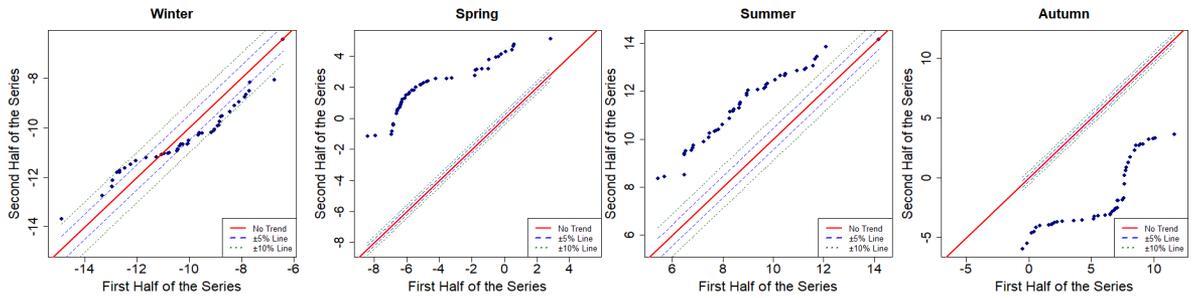
seasons that is similar to past trends. Solar radiation shows positive trend in spring and summer with slope values of 6.123  $Watt/m^2/year$  and 7.745  $Watt/m^2/year$  respectively. It shows a strong negative trend for winter and Autumn and that is similar to the past trend. Inflow shows strong positive trend in spring and summer with slope values of 0.569 cumecs/year and 0.567 cumecs/year respectively. It shows a weak positive trend for winter with slope of 0.009 cumecs/year and a strong negative trend for autumn with a slope of -0.798 cumecs/year.



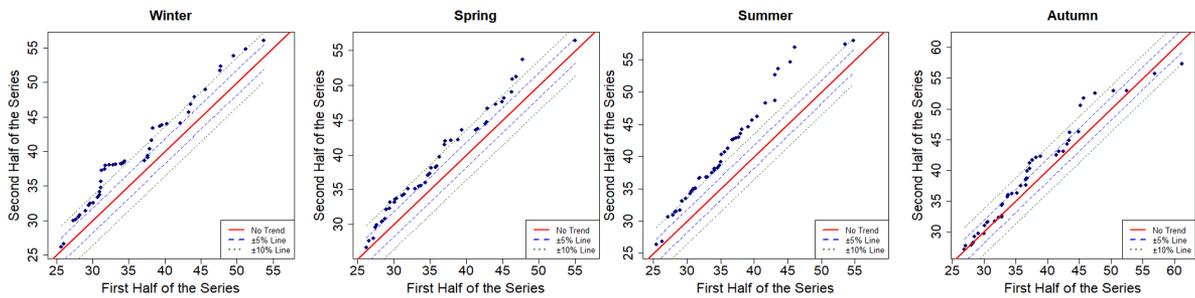
**Fig. 15** Seasonal Precipitation trend for near-future (2025-2049) SSP245 in the UIB by ITA method



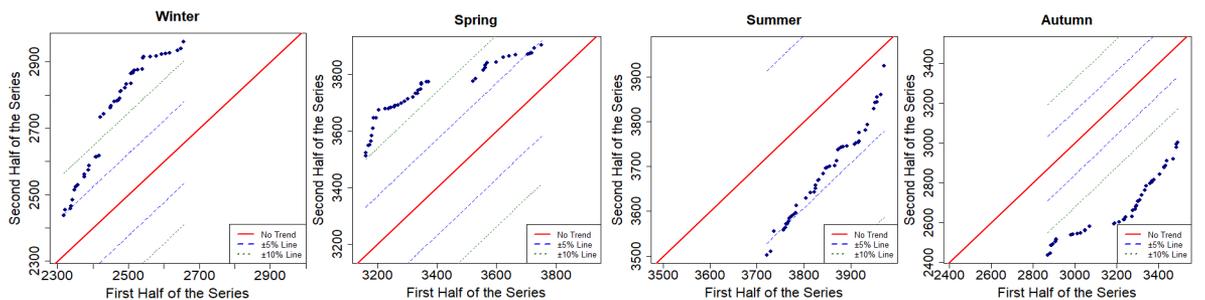
**Fig. 16** Seasonal Tmax trend for near-future SSP245 (2025-2049) in the UIB by ITA method



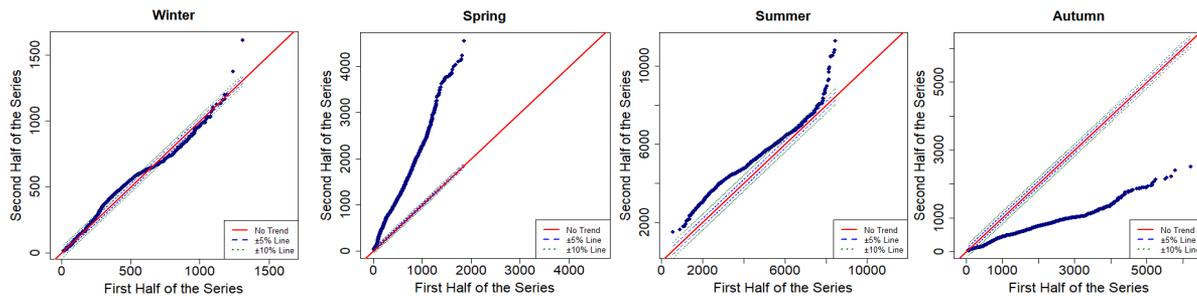
**Fig. 17** Seasonal Tmin trend for near-future SSP245 (2025-2049) in the UIB by ITA method



**Fig. 18** Seasonal Relative Humidity trend for near-future (2025-2049) SSP245 in the UIB by ITA method



**Fig. 19** Seasonal Solar Radiation trend for near-future (2025-2049) SSP245 in the UIB by ITA method



**Fig 20** Seasonal Inflow trend for near-future (2025-2049) SSP245 in the UIB by ITA method

#### 4.6.3 Trends of Hydrometeorological Parameters for Mid-Future

For mid mid-future, precipitation revealed weak positive trend for winter and summer and a weak negative trend for spring and autumn and that is different and surprising. Tmax shows similar positive trend for spring and summer and negative in winter and Autumn but with strong slope and indicator values of  $0.190\text{ }^{\circ}\text{C}/\text{year}$  and  $-0.223\text{ }^{\circ}\text{C}/\text{year}$  for spring and Autumn respectively. This is similar to Tmax of SSP 585 for mid future. Tmin revealed positive trend for spring and summer and negative trend for winter and Autumn. Relative humidity revealed strong negative trend for all seasons and that is different from historical and near future trend but is similar to SSP 585 for mid future. Solar radiation shows similar positive trend for winter and spring and negative trend for summer and Autumn. Inflow revealed weak positive trend for winter and spring. It shows strong positive trend for summer with a slope of  $1.017\text{ cumecs}/\text{year}$  and strong negative trend for autumn with a slope of  $1.001\text{ cumecs}/\text{year}$ .

#### 4.6.4 Trends of Hydrometeorological parameters for Far Future

For Far future, precipitation shows a negative trend for spring and autumn and a positive trend for winter and summer and that is different than other past trends. Tmax revealed a strong positive trend for spring with a slope value of  $0.2\text{ }^{\circ}\text{C}/\text{year}$  and an indicator of 11.085. It also said a weak negative trend for Autumn with a slope of  $-0.235\text{ }^{\circ}\text{C}/\text{year}$ . Tmin strong positive trend in

spring with a slope of  $0.155\text{ }^{\circ}\text{C}/\text{year}$ . It shows a similar trend to the past trend. Relative humidity shows a strong positive trend for all seasons. Solar radiation revealed a strong positive trend for winter and spring and a strong negative trend for summer and Autumn. Solar radiation shows similar trends in both scenarios for future data and as well as for historical trends. Reservoir Inflow shows a positive trend for winter, spring, and summer with strong increase for spring with a slope of  $0.659\text{ cumecs}/\text{year}$  and a trend indicator of 12.064. It shows strong negative trend for Autumn with a slope of  $-0.876\text{ cumecs}/\text{year}$ .

### 5. Discussion

The quantification of monthly and seasonal trends for the various hydrometeorological variables across the 14 stations of the Upper Indus Basin provided complementary information regarding the variations in environmental conditions, with each variable displaying different trends that hold significance for local hydrology and water resources, especially the Tarbela Dam.

The overall trend in precipitation has been declining, and negative slope values appear for most months; thus, we can see a decline in precipitation. It is apparent on a monthly scale that precipitation is decreasing but due to seasonality, the trends observed seem to fluctuate over the seasons. Spring and autumn have added a slight negative slope value, indicating little decline while summer and winter slightly increased with positive slope values of  $0.001\text{ mm}/\text{year}$  and  $0.003\text{ mm}/\text{year}$  respectively. Other studies of the UIB have utilized the Mann-Kendall test

and Sen's Slope method, which stated that trend analyses show both precipitation trends to be inconsistent and shows no discernible pattern (Khattak et al., 2011), we attribute the differences in results to a few reasons. First, the hydrometeorological monitoring sites used in this study vary widely from the majority of the monitoring stations used in their study. Second, they used a different time series of records, which covered a different period that included the years 1967-2005. Furthermore, they divided the Basin into different sections which affected the spatial distribution of data across the stations. Overall, the aforementioned contributed to differences in results.

More importantly, Shahid et al. (2020) observed a significant reduction in spring precipitation in the Upper Indus Basin, with a max decline of 5.3 mm/year. This matches our results for reducing precipitation trends during spring. Also, the results of Yaseen et al. (2020) noted reducing precipitation trends at several stations in the UIB, with results that differed slightly from the current results due to differences in the spatial distribution of stations and the time frame of studies. While our ITA method found declining trends in spring ( $-0.007$  mm/year) and autumn, our results align with Bilal et al. (2021) who found a significant overall annual precipitation increase, highlighting the spatial and seasonal variability across the UIB.

The work by Ali et al. (2017) also reported positive mean annual precipitation in five of six Gilgit-Baltistan stations, especially during the monsoon, validating the presence of strong positive seasonal precipitation signals in the region. The reduction in precipitation suggests there will be a reduction of water inflows into the Tarbela Dam as rainfall and snow melt account for the majority of the water storage in the reservoir. The monthly future trend of precipitation also revealed a decreasing trend for most of the months in both scenarios and that is mostly similar to the historical trend. For seasonal trend, it shows distinct variations with spring and summer revealing

a decreasing trend in most cases with a strong decrease of  $-0.033$  mm/year and  $-0.005$  mm/year.

The seasonal trend is also similar to that of the historical trend. The UIB's precipitation regime is governed by two distinct systems the Western Disturbances, which deliver the bulk of winter and spring snow, and the Summer Monsoon, which has a more limited influence on the high-altitude interior. Our finding of a slight decrease in spring precipitation ( $-0.007$  mm/year) may be linked to potential shifts in the timing, intensity, or track of the Western Disturbances under a changing climate. While the overall summer precipitation trend was negligible, this reflects the complex and often conflicting signals of monsoon dynamics in the region, which warrants further investigation.

The trends of relative humidity show different patterns seasonally as well as between months. The prior analysis confirmed positive trends for the months (June to September), and the strong positive slope values indicated moisture-rich conditions. For the remainder of the months, relative humidity declined, especially in March and Nov, with strong negative slopes through this period. Seasonal results are also supportive or indicative of the prior monthly trends suggesting a decrease in relative humidity in spring with a slope of  $-0.083\%$ /year and an increase in winter, spring, and autumn. These variations might impact evaporation rates, thus also indirectly affecting the water holding area of Tarbela Dam. For the future trend, relative humidity shows a positive trend for the near and far future in both scenarios, but it revealed a decreasing trend for mid mid-future that is different than other results.

The maximum increase is  $0.098\%$ /year for spring in the near and far future and the maximum decrease is  $-0.132\%$ /year for spring in mid future and that is very strange and different from other results of the future. Solar radiation had a distinct seasonal pattern. Strong positive

seasonal trends during the winter months are observed, with noted increases in January, February, and December, while decreases are recorded in the summer months mainly June, July, and August. Solar radiation revealed a positive trend in winter and spring with a slope of  $7.4 \text{ W/m}^2/\text{year}$  and  $6.53 \text{ W/m}^2/\text{year}$  respectively. It also shows a decreasing trend for summer and autumn. For the future, in both scenarios, the solar radiation shows a similar trend as that of historical with positive in winter and spring and decreasing in summer and autumn.

The maximum increase is  $9.028 \text{ W/m}^2/\text{year}$  for spring, and the maximum decrease is  $-13.348 \text{ W/m}^2/\text{year}$  for autumn. Again, greater solar radiation in winter months will potentially increase evaporation during water storage times, as opposed to lower solar radiation in the summer and autumn, which might marginally decrease evaporation. The decrease in solar radiation over summer could also be important for glacier melting. Decreased solar radiation during summer months indicates the potential reduction in energy available to directly heat and melt the surface layer of glaciers and thus potentially slower glacier melt rates during this important time. Maximum temperature trends show a clear increase, with all months showing positive slopes. March and May show the most intense increases, as noted by their slope values, indicating the months demonstrated the most warming. Seasonally, there is a similar increase pattern, reflecting spring as it had solidly the most increases with a slope of  $0.118^\circ\text{C}/\text{year}$ , and also Autumn revealed a decreasing trend of  $-0.118^\circ\text{C}/\text{year}$ . Our findings suggest an increase in the warming process in the study region, particularly during snowmelt periods and high-water demand periods.

The increased  $T_{\text{max}}$  would increase glacier melting, thus positive downstream inflows. The rapid  $T_{\text{max}}$  increase in Spring ( $0.118^\circ\text{C}/\text{year}$ ) accelerates snowmelt, pushing peak Spring inflows earlier and higher. This early water surge occurs before the peak irrigation demand of the Kharif season (late summer/early autumn). The

subsequent sharp decline in inflows during Autumn (historical decrease of  $-0.764 \text{ cumecs}/\text{month}$ ) will leave the Indus Basin Irrigation System positively reliant on reservoir storage to meet water demands for late-season crops, raising the risk of crop stress and yield losses in the fertile plains of Punjab and Sindh. This would result in higher inflow during warm periods at Tarbela Dam.

Ougahi et al. (2022) used Mann-Kendall test and Sen's slope estimator and found increases in maximum temperatures in autumn ( $0.09^\circ\text{C}/\text{decade}$ ), spring ( $0.22^\circ\text{C}/\text{decade}$ ), and winter ( $0.12^\circ\text{C}/\text{decade}$ ), with a decline in maximum temperature in summer ( $-0.07^\circ\text{C}/\text{decade}$ ), which assists in mostly not backing our results for  $T_{\text{max}}$  during these seasons. This is because they have used different methods and time series data from 1960 to 2017. The data is also not gauging data and also, they have divided UIB into sub-Basins.

Khattak et al. (2011) found significant increases in winter maximum temperatures again, not fully supporting our findings regarding the seasonal warming trends. Shahid et al. (2020) used Mann Kendall test, Spearman's rho test, the linear trend estimation method, and the Van Belle and Hughes test and reported significant warming in the Indus Basin, especially in spring, supporting our findings. Our finding of a strong increase in spring  $T_{\text{max}}$  ( $0.118^\circ\text{C}/\text{year}$ ) is consistent with the established importance of temperature as a driver of cryospheric change in the UIB.

Khan et al. (2020), in their analysis of the same region, found a strong negative correlation between monthly mean temperature and snow-covered area, underscoring how positive temperatures directly influence the timing of snow depletion and subsequent runoff. For the future trend,  $T_{\text{max}}$  revealed a positive trend for spring and summer and a decreasing trend for winter and autumn. It shows a maximum increase of  $0.2^\circ\text{C}/\text{year}$  for spring and a maximum decrease of  $-0.235^\circ\text{C}/\text{year}$  for autumn. These consistent outcomes highlight

the tight relationship between temperature and water resource relations in the UIB. Minimum temperature ( $T_{min}$ ) trends shows mixed signals. In the spring period of February to March, there is a moderate increase, indicating warming in winter and early spring.

The summer months of July and August shows small decreases, implying cooling or holding stability. Seasonal analysis also demonstrated the same variation with positive trends for winter, spring, and summer months and slight declines in autumn ( $-0.116^{\circ}\text{C}/\text{year}$ ). This changing temperature structure can have an impact on snowmelt timing and can impact the flow of water during various seasons of the year. For Tarbela Dam, the changes in  $T_{min}$  can alter the timing of water inflow, leading to a shifted timing of peak inflows during those warm months. Which can impact reservoir operations and water storage management. The results from this analysis coincide with Ougahi et al. (2022) where they had a stronger warming trend at Higher altitudes which can impact river discharge at higher elevations.

In the same way, Yaseen et al. (2020) used Mann Kendall and Sen's slope estimator tests and found warming trends in  $T_{min}$  for lower elevations, while their findings found cooling at higher elevations, which we attributed differences in station locations.

Shahid et al. (2020) documented significant warming trends across the Basin, which reflects our seasonal analysis findings. For the future trend,  $T_{min}$  revealed a positive trend for spring and summer and a decreasing trend for winter and autumn. It shows a maximum increase of  $0.155^{\circ}\text{C}/\text{year}$  for spring and a maximum decrease of  $-0.208^{\circ}\text{C}/\text{year}$  for autumn. Inflow trends for the Upper Indus Basin exhibited distinct variability with possible implications for water resource management specifically with the Tarbela Dam. Ultimately, the primary hydrological impact the temporal shift in river flow is a direct consequence of these physical drivers. The amplified regional

warming is causing a more rapid and earlier melt of the snowpack delivered by the Westerlies, leading to the surge in spring and summer inflows. The subsequent sharp decline in autumn is a result of the early depletion of this seasonal snowpack, compounded by a strong cooling trend in autumn ( $-0.118^{\circ}\text{C}/\text{year}$  for  $T_{max}$ ), which prematurely ends the melt season.

This physically driven shift from a historically stable flow regime to one of increased seasonality is the most critical finding for future water management. The winter months exhibited a weak negative trend with minor reductions in inflow, indicating consistent contributions for the winter months. Spring shows a strong positive trend of  $0.490\text{m}^3/\text{s}/\text{month}$ , associated with increased snowmelt, making a significant impact from added water resources into the system. Summer also shows a strong positive trend of  $0.588\text{m}^3/\text{s}/\text{month}$ , which correlates to increased glacier melt at high temperatures, while autumn displayed a strong negative trend of  $-0.764\text{m}^3/\text{s}/\text{month}$ , showing a sharp reduction in inflows at the end of the hydrological cycle.

The results of our study are consistent with findings found in Khattak et al. (2011), which shows that increases in maximum winter temperature had great significance to streamflow patterns, and resulted in rising inflows during spring months. In the same vein, Atif et al. (2018) used Mann-Kendall and Sen's slope methods and suggested that positive temperatures resulted in rising discharge trends in certain sub-Basins like river discharge increase with a Sen's slope value of  $1.039\text{m}^3/\text{s}/\text{year}$  for Astore Basin. Another relevant finding by Shahid et al. (2020), shows significant amplification in streamflow in spring in the UIB driven by warming and glacier melt, which supports what we observed for seasonal inflows.

One disparity, however, to Yaseen et al. (2020), is an investigation that shows decreasing streamflow trends in summer, where we show positive trends. The differing

observations could have arisen because this study has used Mann–Kendall and Sen’s slope estimator tests and also the different time series data from 1963 to 2014. For the future, inflow revealed a similar trend for both scenarios as in historical trends that it shows a positive trend for spring and summer and decreasing for winter and autumn. In the future the maximum increase is for summer which is  $1.338 \text{ m}^3/\text{s}/\text{month}$  and the maximum decrease is for autumn which is  $-1.284 \text{ m}^3/\text{s}/\text{month}$  for SSP 585 scenario. The significant future intensification of inflows, particularly the projected strong increase in summer inflow signals a heightened risk of severe downstream flooding during the melt season peak. This mandates a review of flood control protocols at Tarbela.

The concurrent and strong negative trend in Autumn inflows implies a longer and more severe low flow season. Autumn inflows, combined with a negative (though weak) trend in Winter inflows ( $-0.017 \text{ m}^3/\text{s}/\text{month}$ ), points to a longer and more severe annual low-flow period. This extends the duration of the region's dry season, increasing vulnerability to hydrological drought. Such conditions will place immense pressure on reservoir managers at Tarbela Dam to maintain minimum environmental flows, sustain year-round hydropower generation, and supply sufficient water for the vital Rabi (winter) cropping season. This shrinking water window intensifies drought vulnerability for non-irrigated and water-scarce regions and places extreme pressure on the dam's carry-over capacity. Regardless, we demonstrate that there are seasonal dynamics in our data that should be accounted for when making adaptations in reservoir operations, given the fact that we have to optimize water storage and we have declining inflows in the autumn and winter months.

## 6. Conclusions

Hydro-meteorological parameters significantly influence the use of water resources and hydrology of any Basin. The present study assesses trends in monthly and

seasonal changes for precipitation, relative humidity, solar radiation, maximum and minimum temperature, and inflows in the Upper Indus Basin (UIB) using the Innovative Trend Analysis (ITA) method on time series data from years 1981 to 2024. These findings highlight important information about climatic variability and subsequent decisions regarding water resource management, and the implications of the findings for Tarbela Dam use. The main conclusions are:

1. Historical seasonal analysis indicated declines in rainfall, with slopes of  $-0.007 \text{ mm}/\text{year}$  in spring and  $-0.001 \text{ mm}/\text{year}$  in autumn. Small increments are identified in the winter ( $0.003 \text{ mm}/\text{year}$ ) and no discernable trend in summer. In future trends, it shows distinct variations with spring and summer revealing a decreasing trend in most of the cases for both scenarios with strong decreases of  $-0.033 \text{ mm}/\text{year}$  and  $-0.005 \text{ mm}/\text{year}$ .

2. Historical relative humidity trend reported positive in the winter ( $0.033\%$  per year) and summer ( $0.041\%$  per year), while relative humidity decreased in spring ( $-0.083\%$  per year) and autumn ( $0.046\%$  per year). For future trends, maximum increase is  $0.098\%$  per year for spring in near and far future and maximum decrease is  $-0.132\%$ /year for spring in mid future.

3. Solar radiation trends displayed seasonal variability, primarily positive trends in the winter ( $7.373 \text{ W}/\text{m}^2/\text{year}$ ) and spring ( $5.563 \text{ W}/\text{m}^2/\text{year}$ ), and negative trends in the summer ( $-4.461 \text{ W}/\text{m}^2/\text{year}$ ) and autumn ( $-7.540 \text{ W}/\text{m}^2/\text{year}$ ). For the future the solar radiation shows a similar trend as that of historical with positive in winter and spring and decreasing in summer and autumn. The maximum increase is  $9.028 \text{ W}/\text{m}^2/\text{year}$  for spring and the maximum decrease is  $-13.348 \text{ W}/\text{m}^2/\text{year}$  for autumn. Basin

4. Historical Tmax had significant positive trends in spring ( $0.118^\circ\text{C}/\text{year}$ ) and summer ( $0.028^\circ\text{C}/\text{year}$ ). For the future it shows a maximum increase of  $0.2^\circ\text{C}/\text{year}$  for spring and a maximum decrease of  $-0.235^\circ\text{C}/\text{year}$  for autumn. Historical Tmin

values had significant increment in spring ( $0.095^{\circ}\text{C}/\text{year}$ ) and decrease in autumn ( $-0.116^{\circ}\text{C}/\text{year}$ ). For the future,  $T_{\text{min}}$  revealed a positive trend for spring and summer and a decreasing trend for winter and autumn. It shows a maximum increase of  $0.155^{\circ}\text{C}/\text{year}$  for spring and a maximum decrease of  $-0.208^{\circ}\text{C}/\text{year}$  for autumn.

5. Historical inflow trends had significant variability, with spring showing a strong positive trend at  $0.490 \text{ m}^3/\text{s}/\text{month}$ , likely resulting from rapid snowmelt, and summer, in contrast, positive at  $0.588 \text{ m}^3/\text{s}/\text{month}$ , likely from glacier melt. Autumn inflows are decreasing at  $-0.764 \text{ m}^3/\text{s}/\text{month}$  and winter inflows are decreasing at  $-0.017 \text{ m}^3/\text{s}/\text{month}$ , indicating a positive struggle for reliable water availability in dryer seasons. In future trends, inflow revealed similar to that of historical with positive in spring and summer and decreasing in winter and autumn. The maximum increase is for summer which is  $1.338 \text{ m}^3/\text{s}/\text{month}$  and the maximum decrease is for autumn which is  $-1.284 \text{ m}^3/\text{s}/\text{month}$  for the SSP 585 scenario.

6. The main hydrological impact is a dramatic temporal displacement of water availability in the Upper Indus Basin. The study reveals a shift toward earlier and more intense flows during the melt season (evidenced by a  $1.18^{\circ}\text{C}/\text{decade}$  increase in Spring  $T_{\text{max}}$  and a corresponding  $+0.490 \text{ m}^3/\text{s}/\text{month}$  increase in Spring Inflow) followed by a sharp, critical decline in the post-melt season in  $-0.764 \text{ m}^3/\text{s}/\text{month}$  in Autumn. The strong increase in Spring and Summer Inflows must be managed by positive carry-over storage during the melt season. Current dam operations need to be re-evaluated to capture these earlier, higher volumes for later use. The severe negative trend in Autumn inflows requires implementing strict water conservation and allocation rules during the post-melt season to maintain minimal ecological flows and produce power during the dryer months.

This research reveals the important role of hydrometeorological factors in determining UIB hydrology and sustaining Pakistan's water resources, and the need for

adaptive strategies to better manage temporal changes in precipitation, temperature, and inflows.

The findings confirm the non-stationary nature of UIB hydrology. A gradual increase in spring and summer inflows presents opportunities for water storage, while total inflow losses in fall and winter are developing a critical need for adaptive reservoir management strategies employed at Tarbela Dam. Furthermore, this study data is limited by the availability and spatial extent of hydrometeorological station data.

The 14 stations provide a valuable regional dataset, but their density may not fully capture the complex spatial heterogeneity and micro-climates present in the topographically diverse UIB in addition, relying on hydro-climatic data only is insufficient in developing our understanding of the hydrological processes and relationships, without regard to geographic and environmental conditions such as elevation or surrounding changes in land use. Further studies should consider expanding the use of spatial and temporal hydrometeorological data, upstream and downstream approaches, geographic and environmental conditions, such as elevation and land use changes (LULC) and connections between solar radiation, temperature, and glacial melt processes, among others.

Future studies must move beyond the current Basin-wide aggregation to perform a spatialized ITA across key UIB sub-Basins and elevation zones. This is critical for capturing the known heterogeneity of climate responses in mountainous regions. Research should proceed by integrating the analyzed trends with full hydrological models to simulate water availability under the explicit CMIP6 SSP2-4.5 and SSP5-8.5 scenarios.

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## Author Contributions

*Alamgir Khalil provided the study conception and design. Farjad Aziz contributed to data collection and analysis Muhammad Qasim was involved in material preparation, Mobeen Ahmad and Zabeehullah Khan did provision of relevant literature, review and proof read of the manuscript. All authors contributed to drafting and revising the manuscript and approved the final version for publication.*

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## Conflict of interest

The authors declare there is no conflict.

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