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# Impact Assessment of Climatic Variability on the Stream Flows and Predictions for the 21st Century: Integrating Global Climate Models

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Water management needs to investigate the possible consequences of climate variability on hydrological variables. This paper presents the precipitation and temperature trend patterns and their impact on streamflow (1985-2014) for the Astore basin and streamflow predictions by the year 2100. The trend detection of the two parameters was assessed through the Man-Kendall and Sen's Slope tests. The climate station data were compared with the results of the trends analysis and reported values of two Global Climate Models (GCMs), BCC-CSM1-1 and GFDL-CM3 (each having Representative Concentration Pathway, RCP 2.6 and RCP 8.5 scenarios). No important trend was noted for the precipitation except an increasing trend in September, while there were rising trends in temperature from December to August, whereas declining trends from September to November, which shows that the summer duration is getting longer while the winter is getting shorter with an early start in September. The results indicated that precipitation trends are reciprocating the temperature. The rising trends in temperature can result in extreme events, floods, and droughts due to extensive glacier melt in the near and far future, respectively. The result of GCMs for the two chosen RCPs had a similar pattern of climatic changes all over the century, with slightly higher values for the RCP 8.5 scenario, experiencing a tendency toward less precipitation and, during some seasons, a modest increase in temperature. The stream-flow predictions using GCMs showed rising trends till the mid-21st century and declining trends by the last decade of the century and even onwards. This rise in summer flows will raise the water level in the Tarbela reservoir located on the downstream of Upper Indus River Basin (UIRB) thus providing excess water for Hydropower generation, increasing till the mid-century and there are also chances of inflows to reservoir, beyond its capacity that can cause flooding to its downstream while after 2091, a continues decrease in water level is expected, which in return, can severely affect the power generation capacity form the reservoir, also causing reducing water supply for agriculture needs.

**Keywords:** Climate Change, Global Climate Model (GCM), Mann-Kendall Test, River Indus, Sen's Slope Test

**Introduction:**

Human activities always intensify the global atmospheric concentration of greenhouse gases (GHGs). It has produced climatic changes with regard to temperature increase, rainfall trends, and an increase in the number of extreme occurrences [1], [2]. This, in turn, has affected the global water cycle. The characteristics, quantity, and spatial distribution of water are influenced across the world as a result of variation in hydrological variables [3]. The changing climate scenario of the future points out the likelihood of aggressive events that result from changes occurring in seasonal periods, realistic division of water assets [3]. Besides great development made in modeling within the past 50 years, recognizable proof of a careful environmental change at a given spot and time is still challenging [4]. A substantial rise in the highest temperature has happened both in the yearly and pre-monsoon season in more than 30% of the areas [5]. In the future, the more aggressive events will happen in the Kunhar basin as a result of rising temperatures, which results in the rise of maximum flow, whereas, fall in the least flows and more temporal and quantitative variations in peak flows [6]. Numerous studies in the Greater Himalaya showed a warming trend [7][8][9]. Previous research has also examined the temperature and precipitation patterns in the Upper Indus River Basin (UIRB). All of these investigations, meanwhile, have made more research in this area of expertise necessary [10][11][12][13][14]. All of these investigations, meanwhile, have made further research in this area of expertise necessary. Although every research has called for more investigation into this area of expertise. The climate control of the Upper Indus Basin is very change compared to the greater Himalaya. The yearly precipitation upon the UIB is influenced by the climate of the west that falls during the seasons of spring and winter. Infrequent rainfall resulted from the sudden invasion of the monsoon, yet, even during the summer season, not all the precipitation has resulted from the monsoon sources [15].

In general, it is perceived that the precipitation in the winter season has been reduced over the last 30 to 40 years, which is reflected in the variation of vegetation and variation in the closure period of the Karakorum range's high mountainous passes within winter [16].

The average annual water flows from all the significant streams and rivers of the Indus basin contribute to the requirements of the canals of the Indus Basin Irrigation System (IBIS). Pakistan's field water distribution system and the existing hydro-power generation facilities are possibly impacted by the changing climate effects on its water resources. Climate variability also drastically influences the climate in terms of extreme events of floods, drought, and low flows [17]. In the Upper Indus Basin, it is observed under the climate change scenario that the influence of differences in elevation has caused a drop in flows of the Indus River, the Swat River, and the Kabul River at the places of Alam Bridge, Nowshera, KPK, and Kalam, KPK, respectively. On the other hand, the water discharge in the Chitral, Gilgit, Hunza, Shoyk, Shigar, and Astore Rivers has gone on the higher side [18]. In such a situation, in UIB, it would be appropriate that the components of the hydrological cycle should be checked to witness the climate variation, as inspectional and previous precipitation and temperature data that are mostly utilized for designing, planning, and managing water resources related projects.

This research pinpointed the fingerprints of climate variability across the Astore basin, which is situated in the UIRB of Pakistan. Mann-Kendall (MK) test Mann (1945) is usually employed to find climatic trends in time series hydro-climatic and rainfall data, i.e., monthly or annual precipitation and temperature data sets. The degree of trends plus slope of univariate time series data is obtained by utilizing the non-parametric technique known as Sen's slope method.

GCMs are frequently used to analyze the aftershocks of worldwide changing of climate change. These are multi-dimensional mathematical depictions of the interactions between the atmosphere, seas, and continents. To predict future climate trends, GCMs often rely on emission scenarios created by the IPCC (Intergovernmental Panel on Climate Change) [19].

Snow precipitation presently consists of 52% of total annual precipitation and contributes 55% to annual streamflow. Predictions under various RCPs indicate a considerable decrease in both snow precipitation and snowmelt contribution to streamflow [20]. CT and SPO approaches show an earlier snow melt runoff timing trend supported by the MSF trend [21]. The growing intensity of carbon and sulfur emissions, as well as a thorough report from Working Group 3, served as the foundation for the development of the emission scenarios from IPCC [22]. Prediction shows considerable climate variability during summer and winter. A predicted increase in temperature under various SSPs may cause melting of glaciers that will decrease snowmelt and groundwater contributions to streamflow, while the rainfall and glaciers melt component will increase [23]. Nonetheless, some uncertainties are noted in the outcomes of climate models, and they should always be taken into consideration when examining sustainable water resources [24][25][26][27]. The RCPs describe 4 different scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) based on different assumptions about population, economic growth, energy consumption [28][29][30][31][32][33] and sources and land use over this century. Details can be found in an open-access article [34]. It would be interesting to explore the similarities and differences in station data time series and various GCM results. Two GCMs, based on RCP 2.6 & RCP 8.5 emission scenarios, were used in this article to project temperature and precipitation for the period from 2015 to 2100. The selected GCM models with RCP 2.6 and RCP 8.5 have been mostly used for hydro-meteorological analysis, reported in the literature and produced appealing results for the least (RCP 2.6) and extreme (RCP 8.5) heat emission scenarios [35][36][19].

The economy of Pakistan is highly agriculture-dependent. The main water resource for irrigation comes from the Indus River [37][38]. The precipitation occurring in the Hindukush-Karakoram-Himalaya (HKH) territories is considered the primary source of water, for which the Tarbela reservoir acts as the first controlling storage. Food security and the environment of Pakistan are expected to be adversely affected by any change to the water resources because of climate variability. Thus, the temporal and spatial variability of climate within the Indus region is vital to be studied for hydro-meteorological parameters to manage water resources intelligently.

**Analysis Method:**

This section describes various methodologies for data analysis. Firstly, consistency analysis was performed using the CUSUM (Cumulative Summation) Test, and necessary corrections were made. Secondly, a non-parametric, Mann-Kendall, and Sen's slope tests were employed to identify the quantitative variability in the hydro-meteorological variables. These tests utilize an Excel macro named MAKESENS to obtain the magnitude of trends in data. Finally, to forecast the effects of climate variability on temperature and precipitation, two GCM models with two emission scenarios were utilized. The Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) was used to predict the stream flow of the Astore River using GCM-reported precipitation and temperature data of the basin as input. Microsoft Excel 2013 was used to create the trend and time series plot of the climatic variables for the study area.

**Study Area:**

UIRB is one of the sub-drains of the Indus River basin (IRB). IRB ranks among the biggest basins of the world, covering near around an area of around 970,000 $km^2$ in Pakistan. However, UIRB is situated between the starting of the Indus River and its very first reservoir of Tarbela Dam, with a total area amounting to 175,000 square kilometers [39]. The biggest river in Pakistan is the Indus River, which produces 80% of hydropower generation and is a source of approximately 75% of water for its irrigation canals annually [39]. The region of UIRB is hosting the three biggest ranges of mountains in the world, including the Himalaya, Karakorum, and Hindukush, which join together at a juncture situated almost 40 km away from the city. The flows in the Indus River and its tributaries are generated from the rainfall and snow melt over these mountains. Astore, Drosh, Gupiz, Gilgit, and Skardu rivers are the main tributaries of the basin. The lower Indus Plain stretches to the Arabian Sea, is mainly dependent on the Indus River system for its groundwater resources. The River Indus system is directly responsible for the groundwater supplies of the Lower Indus Plains to the Arabian Sea. Except for the Polar Regions, UIRB glaciers are known to be the biggest glaciers on Earth.

The Upper Indus Basin Cryosphere has been continuously monitored and studied by the Pakistan Water & Power Development Authority (WAPDA) since its establishment in 1958. For this purpose, Hydro-meteorological networks were established in the 1960s that are to be monitored through the Surface Water Hydrology Project [Figure 1]. The precipitation (P), temperature (T), and streamflow (Q) data (from 1985 – 2014) from the Astore climate and streamflow gauging station at Bisham Qila (as shown in Figure 1a and Figure 1b) have been considered for the current study.

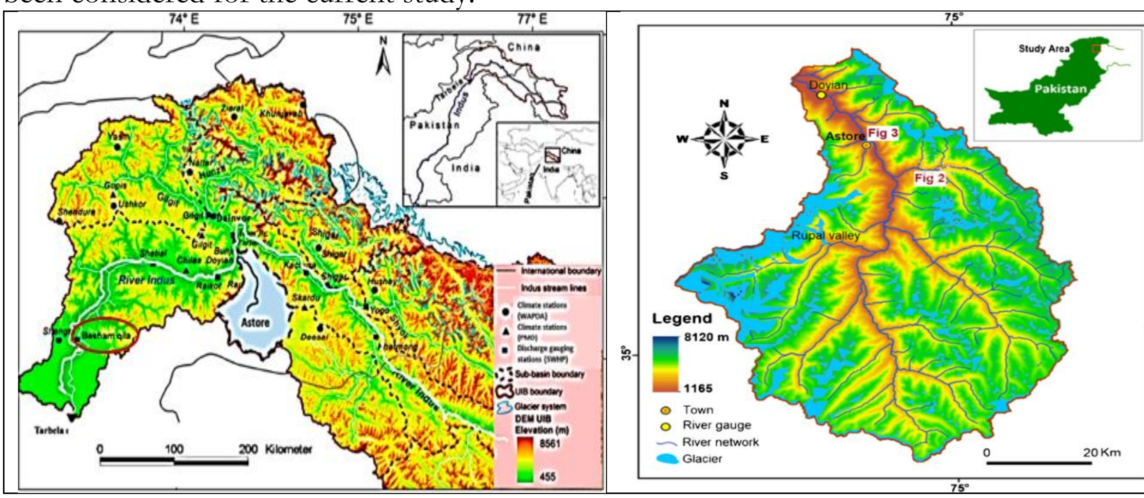


**Figure 1. (a)** Tarbela reservoir catchment and streamflow gauging station at Bisham Qila, **(b)** Locations of hydro-climatic stations in the sub-basin Astore of the Upper Indus Basin, Pakistan

**Trend Analysis:**

Trend analysis has been studied by several non-parametric and parametric methods in the literature [40]. The parametric test is considered less superior compared to the non-parametric trend test on account of its utilization of freedom and the existence of normal distribution data [41]. Unlike parametric trend tests, the behavior of outlier events/data can be allowed in non-parametric trends [42], which ultimately encourages the utilization of techniques that are non-parametric, e.g., Spearman's rho, seasonal Kendall, Sen's T, and Mann–Kendall (MK) technique. In Hydro-meteorological time series data, the trend is widely analyzed through a statistical test known as the Mann-Kendall test. This test is widely used in various parts of the world to assess trends in hydroclimate time series data without using a pre-whitening procedure [43][44][45][46][47]. The Mann-Kendall Trend Test is nonparametric, which does not require the data to possess normal distribution and is relatively less sensitive to rapid breaks because of inhomogeneity in the time series data. The Man-Kendall test is regarded as a preferred option when various stations must be tested in a single study.

**Mann-Kendal Test:**

This test supposes, in its null hypothesis H0 ¬¬, that have is no trend. This means that data is ordered randomly and independent, whereas H0 must be verified in contrast to an alternate assumption, H1, ¬which relies on the existence of a pattern.

Mann-Kendall statistic S has the following form given as equation (1) [48][37].

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn\left(x_j - x_i\right) \quad (1)$$

Where,

$x_i$ = Time series;

i = time series ranked from 1,2, 3, …n-1

$x_j$ = data points which are placed from j = i+1, 2, 3, n.

From the points of data $x_i$, each point is chosen as the point of comparison. Furthermore, it is contrasted with the remaining data points (xj) to;

$$Sgn\left(x_j - x_i\right) = \begin{cases} +1 \text{ if } (x_j - x_i) \rangle\ 0, & \text{trend increasing} \\ 0 \text{ if } (x_j - x_i) = 0, & \text{no trend} \\ -1 \text{ if } (x_j - x_i) \langle\ 0, & \text{trend decreasing} \end{cases} \quad (2)$$

For a time series, having n less than 10 points of information, the statistic S is employed, whereas, for n greater than or equal to 10, the normal distribution is utilized, i.e., E(S)=0

The statistical variance has the following mathematical form,

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2_i+5)}{18} \quad (3)$$

The ti denotes the quantity of connections to the number i. The test statistic Zc can be calculated as

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & \text{if } S \rangle\ 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & \text{if } S \langle\ 0 \end{cases} \quad (4)$$

Here, the $Z_c$ corresponds to a conventional normal distribution. A positive or negative value of Z indicates an increasing or decreasing pattern, respectively. To evaluate if a monotonic pattern is positive or negative, utilize the critical value, also known as the significance level, α. In a case where the calculated $Z_c$ value is greater than $Z_{\alpha/2,}$ where α represents the significance level, it indicates a noticeable trend.

**Sen's Slope Estimator Test:**

The size of the pattern was estimated by Sen's estimator [49]. The equation (10) below was employed to calculate the inclination ($T_i$) of every couple of data points.

$$T_i = \frac{x_j - x_k}{j-k} \quad \text{for } i = 1, 2, 3, n \quad (5)$$

The $x_j$ and $x_k$ are taken as data values at time j and k (j>k) equally [50][51][52]. Sen's estimator of slope, which represents the median of these n values of Ti, is written as under:

$$Q_i = \begin{cases} T_{\frac{n+1}{2}} & \text{If n is odd} \\ \frac{1}{2}\left(T_{\frac{n}{2}} + T_{\frac{n+2}{2}}\right) & \text{If n is even} \end{cases} \quad (6)$$

Sen's estimator is calculated as Qmed = T(n+1)/2 in case the n value is odd, whereas it is computed as Qmed = [Tn/2+T(n+2)/2]/2 for an even n. At last, Qmed is computed using a two-sided test with a 100 (1-α) % confidence interval. A true slope may then be ascertained using Sen's slope test. A +ve value of Qi indicates an upward or increasing trend, whereas a –ve value of Qi shows a decreasing or downward trend in the time series.

**GCMs Modelling:**

The US Geological Survey developed a website [53] whose purpose is to deliver visualization and access to worldwide and regional downscaled climate data. This study presented the outcomes of two GCM approaches, each with scenarios of RCP 2.6 and RCP 8.5, which aimed to investigate variability in temperature and precipitation over the Astore

River basin. Out of them, BCC-CSM1-1 is introduced by the Beijing Climate Center (BCC) of China Meteorological Administration, China, whereas the GFDL-CM3, put forward by NOAA Geophysical Fluid Dynamics Laboratory (NOAA GFDL) [54]. RCP is an abbreviation of Representative Concentration Pathways. The total negative anthropogenic GHG production following the year 2070 is assumed to be sustained by the extended RCP2.6 [55]. The negative emissions mentioned here mean that humans are absorbing more greenhouse gases from their atmosphere compared to what they produce in total. The $CO_2$ concentration estimated through the extended RCP 2.6 pathway by the year 2300 approaches almost 360 ppmv (in parts per million by volume). On the other hand, the amount of carbon dioxide is almost 7 times RCP 2.6 by the year 2250, i.e., it approaches up to 2000 ppmv of the pre-industrial level [55]. The projection made by the prolonged RCP 2.6 scenario indicates a warming of the planet of 0 °C to 1.2 °C for the late-23rd century, i.e., 2281–2300 average, concerning the period 1986-2005 [55]. Similarly, a 3.0 to 12.6 °C of global warming is predicted for the same period by the extended RCP8.5.

**Results and Discussion:**

In this section, trend patterns are presented in graphical and tabulated form for hydro-meteorological data (precipitation, temperature, and discharge) of the Astore basin that were derived from the analysis of the methods presented in past sections.

**Trends Analysis:**

The trend analysis suggests that no significant trends exist in precipitation (Table 1) except for the only considerable increasing trends which were observed in September. During the spring and summer seasons at Astore, statistically significant positive patterns in mean temperatures (Table 1) can be found, whereas a noteworthy declining trend was observed in September. So, significant trends are observed in temperature as compared to the precipitation that match the results reported in earlier studies performed in the study region [56][35][57]. Regarding the Discharge at Bisham Qilla (Figure 1. a, Last Gauging station on River Indus at upstream).

At Tarbela Reservoir (Table 1), a statistically significant trend was not observed, excluding July. This rise in summer flows will raise the level of water in the Tarbela reservoir. The temperature rise will boost streamflow because of the melting of glaciers in the coming years, and once the glaciers are melted, in the far future, there will be a significant decrease in streamflow as the discharge in the Astore River will only depend on precipitation.

**Table 1**. Mean monthly trend analysis results of climatic (precipitation & temperature) and hydrologic (streamflow).

| Month/variable | PPT Station data | | Temp. Station data | | Streamflow Gauging Station Data | |
|---|---|---|---|---|---|---|
| | Z-Statics | Sen's Slope | Z-Statics | Sen's Slope | Z-Statics | Sen's Slope |
| **January** | 0.463 | 0.288 | 0.79 | 0.034 | -0.71 | -0.037 |
| **February** | 0.745 | 0.562 | 1.3 | 0.046 | 0.68 | 0.07 |
| **March** | -1.46 | -1.12 | **2.05*** | **0.067** | -0.89 | -0.089 |
| **April** | -1.14 | -0.81 | 1.5 | 0.056 | -1.64 | -0.31 |
| **May** | -0.5 | -0.59 | 1.59 | 0.069 | 0.73 | 0.375 |
| **June** | 0.16 | 0.086 | **2.98*** | **0.076** | -0.52 | -0.455 |
| **July** | -0.54 | -0.2 | 0.73 | 0.021 | **-2.27*** | **-2.047** |
| **August** | -0.96 | -0.27 | 0.91 | 0.017 | 0.3 | 0.176 |
| **September** | **2.48*** | **0.54** | **-1.82** | **-0.04** | -0.09 | -0.037 |
| **October** | -1.29 | -0.34 | 1.36 | 0.03 | 0.55 | 0.074 |
| **November** | 0.11 | 0 | 0.75 | 0.017 | 1.23 | 0.045 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **December** | -1 | -0.428 | -0.14 | -0.004 | -0.87 | -0.027 |

Note: The bold values and * in the z-statistics column show the significant trend, while bold values in the Sen's slope column show the value of the significant trend.

The concluded numbers of Sen's slope estimator (Table 1) demonstrated that a connection between the intensities of the values and the trend pattern is there. The results of Sen's slope estimator show that the intensity of the values is related to the intensity of the trend pattern, although the results of the Mann-Kendall test depict such a correlation between the precipitation and temperature trend patterns because the differences in precipitation processes are generally flexible and difficult to define. In Astore, which is a sub-basin of UIB, the Precipitation and Temperature were compared for their trend pattern with the trend of streamflow determined for the inflow to the Tarbela reservoir at Bisham Qilla gauging station. The trend pattern does not show any correlation with precipitation, but in the case of temperature, the trend patterns are correlating from the month of July to September.

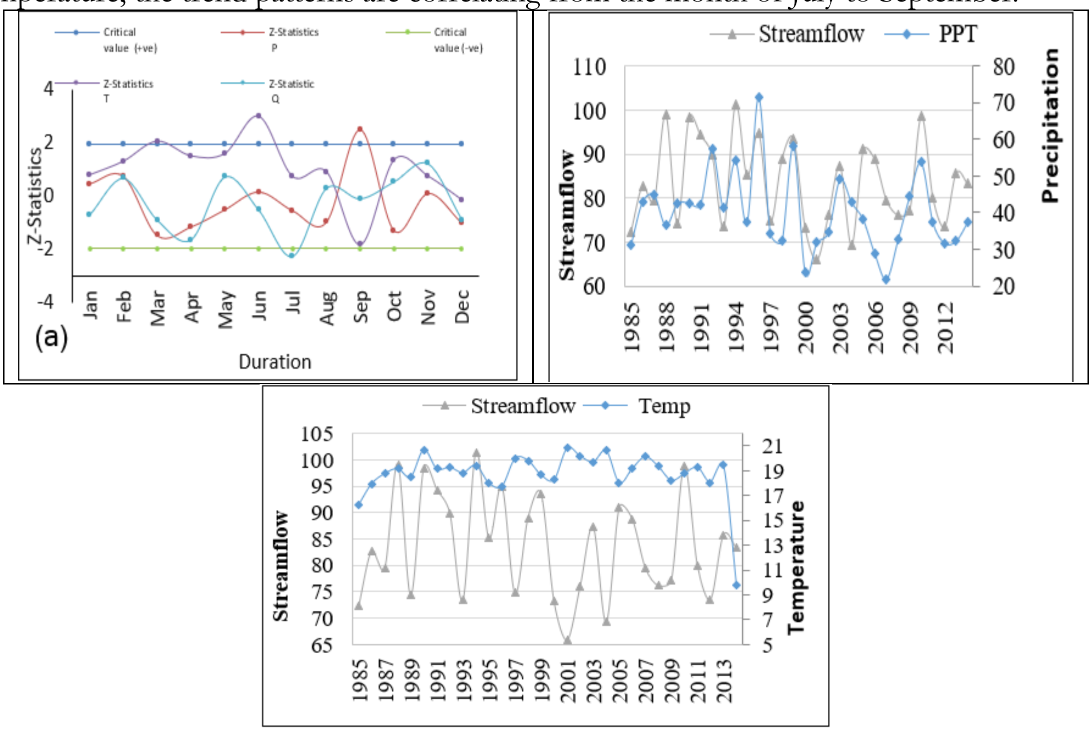


**Figure 2. (a)** Comparison of precipitation, temperature, and discharge trends. **(b)** The time series plots of precipitation vs. streamflow. **(c)** The time series plots of temperature vs. streamflow

The results in Figure 2(a) represent the trend analysis graphically, which indicates Z-statistics of trends in Precipitation and Temperature calculated for the Astore substation of UIB and Streamflow trends at Bisham Qilla on the River Indus. This pattern is compared with Z-statistics for a 5% degree of relevance, and it comes out to be ±1.96 (i.e., there is 95% less chance of rejection of the Null Hypothesis). If the outcome of Z-statistics is higher and lower than ±1.96, then this implies a +ve or -ve pattern, respectively. However, when the Z-statistic value exists in the limit, i.e., ±1.96, then this means no trend over there.

The trend plot of the two climatic variables, i.e., temperature and precipitation, in Figure 2(a) clearly shows that trend patterns are changing throughout the year but mostly reciprocating each other, depicting extreme weather conditions. The rise in temperature in March, August, and October is followed by a decrease in precipitation, while in April, May, September, and November, the precipitation is increasing with the decrease in temperature. During January, February, July, and December, the precipitation trend paths are almost replicating the trend lines of temperature, which means both parameters are changing but in the same pattern; an upsurge of temperature will increase precipitation, and vice versa. The study also revealed that the climate is in a transition period at the Astore substation. A positive significant trend is detected for precipitation in September and for temperature in June, while a negative significant trend for streamflow is detected in July, when precipitation is decreasing with a decrease in temperature. The trend analysis reveals that there exists no clear relation between the obtained temperature and rainfall patterns, as modifications within the rainfall-related processes are normally multifaceted and difficult to ensure, and this relationship between the key climatic factors will seriously affect the dependents of this region.

The time series of precipitation and temperature versus stream-flow graphs are plotted to indicate the impact of these two variables on streamflow (see Figure 2(b) and Figure 2(c)). It has been observed from the graphs that the rainfall and stream flow discharge follow a similar trend of variation, which indicates the dependency of river flows on rainfall. Similarly, the comparison graphs between temperature and river discharge depict a direct relationship between them.

The seasonal analysis results in the Figure. 2(d), Figure 2(e), Figure 2(f), and Figure 2(g) showed distinct patterns observed across different climatic conditions, highlighting the influence of climatic variables on the streamflow. Seasonal variability is observed with a peak in summer, irrespective of a decreasing trend in precipitation (see Figure 2(d)). The reason behind this peak streamflow is high temperatures during summer, causing snowmelt. Conversely low flow condition is observed in winter due to lower temperatures. As precipitation has an increasing trend during the winter season, but a decreasing trend of streamflow shows that there is snow precipitation. Pre-monsoon rainfall and the onset of snow melting as a result of the gradual rise in temperature in spring cause a slight rise in streamflow. A decrease in streamflow is found during autumn due to a slight decrease in temperature.

The seasonal analysis shows that there is no considerable variability in streamflow in the winter season throughout the hydrological cycle due to low temperature and snow precipitation, which doesn't immediately contribute to streamflow. However, its effect can be observed in summer, where there is less precipitation but still a peaked discharge with high variability due to snowmelt caused by high temperatures.

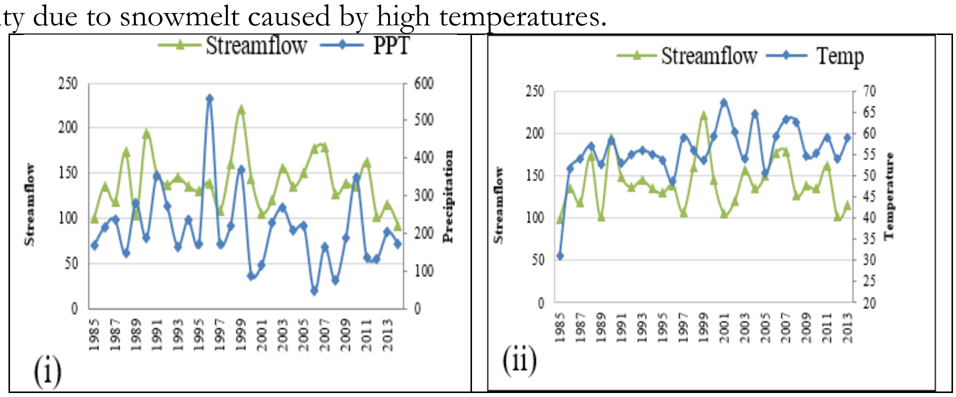


**Figure 2. (d)** The seasonal variability of time series plots for the spring season (i) Precipitation vs. Streamflow (ii) Temperature vs. Streamflow

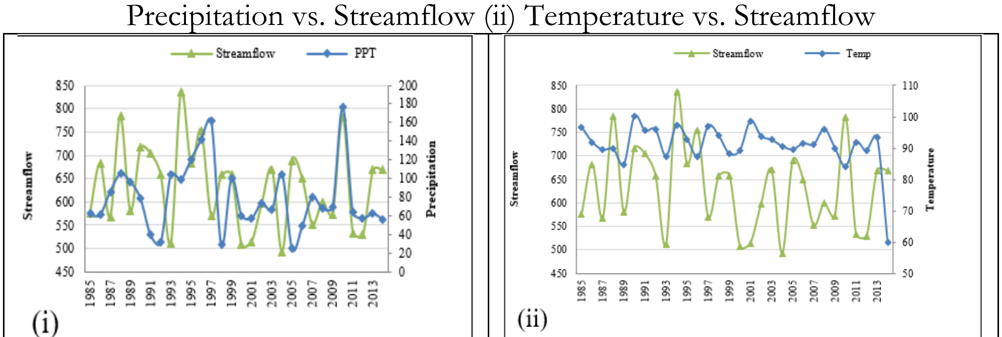

**Figure 2. (e)** The seasonal variability of time series plots for the summer season (i) Precipitation vs. Streamflow, (ii) Temperature vs. Streamflow

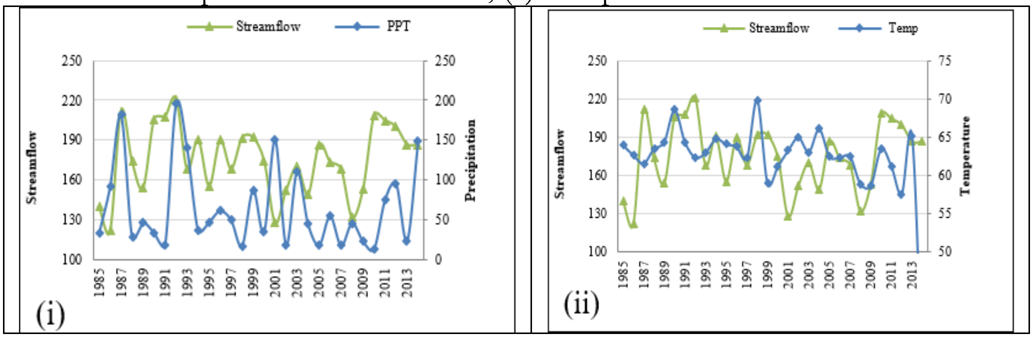


**Figure 2. (f)** The seasonal variability of time series plots for the autumn season (i) Precipitation vs. Streamflow (ii) Temperature vs. Streamflow

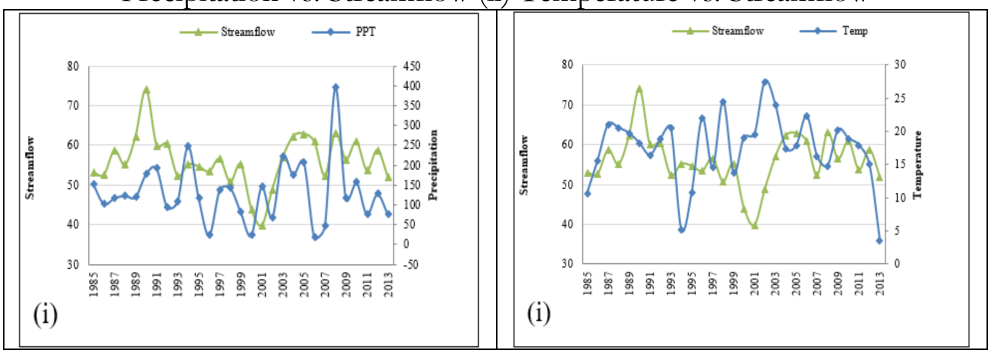


**Figure 2. (g)** The seasonal variability of time series plots for the winter season (i) Precipitation vs. Streamflow (ii) Temperature vs. Streamflow

**GCM Modelling:**

To find similarities and distinctions, the station data for the chosen UIB sub-basin was contrasted with the output of two GCMs, namely BCC-CSM1-1 and GFDL-CM3 (each against the RCP 2.6 & RCP 8.5 scenarios). The graphical representations displayed in Figure 3 demonstrate how the values simulated by GCM models and the time series data obtained from the meteorological station vary somewhat. There are several reasons for these differences. One main reason for these differences is the inaccuracy in downscaling. The climate station data was collected from the stations located at coordinates 35.33 Northing to 74.90 Easting at an altitude of 2394 m (above mean sea level), although they weren't exactly similar, the GCM modelled information was around these positions. For enhanced precision, downscaling has to be refined even more.

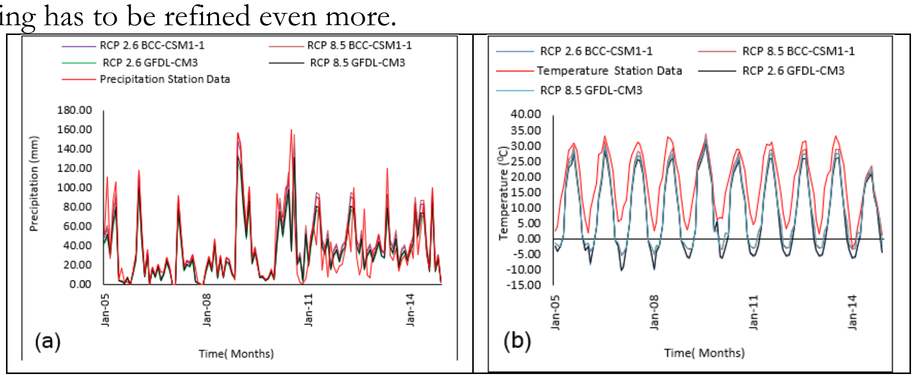


**Figure 3.** Comparison of (a) precipitation, (b) temperature, time series stations data vs. GCMs under BCC-CSM1-1 and GFDL-CM3 Scenarios RCP 2.6 and RCP 8.5.

While both the GCM scenarios and the climate monitoring rainfall show comparable growing patterns from 2010 to 2013, the temperature shows similar declining patterns from 2010 to 2014, except in 2014. The RCP8.5 has the highest heat emission as compared to other scenarios. The RCP 8.5 results have shown almost the same precipitation, but in the case of temperature, its values were higher compared to the RCP 2.6 scenario.

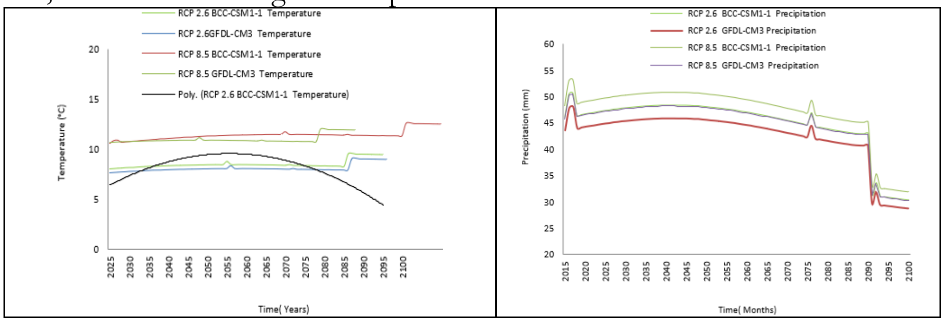


**Figure 4.** Future temperature and precipitation predicted by the GCMs

**Long-term Predictions under Climate Change Conditions:**

Forecasting of long-duration streamflow was computed till 2100 using GCM. The emissions scenarios of RCP 2.6 and RCP 8.5 were utilized to forecast the outcomes of the GCM. The two climate variables (i.e., temperature, precipitation) and streamflow of the future by GCM were demonstrated in Figures 4 and 5, respectively. It can be seen in the figures that a nearly identical pattern exists for streamflow and precipitation. Although it is understood that streamflow is reliant upon precipitation in the area, any variability within precipitation in the area will influence the streamflow of the Indus River.

The precipitation and temperature reported by GCM (RCP 2.6 and RCP 8.5), as given in Figure 4, show that both the temperature and precipitation are affected significantly by climatic changes in the selected sub-basin of the UIB. The pattern of trends for both temperature and precipitation is almost similar under both the GCM scenarios. The precipitation has a slightly increasing trend up to the mid of the 21st century, whereas it follows a decline heading to the end of the century, which is an alarming situation for UIRB, indicating that the streamflow should have a similar trend. RCP 8.5 displayed a slightly increased temperature and streamflow compared to the RCP 2.6, while the projected rise in precipitation for both scenarios is approximately alike. An average increase of 12 % in precipitation is projected from 2015-2075, while an average increase of 1.33˚C and 4.07˚C in temperature in scenarios RCP 2.6 and RCP 8.5, respectively, is observed from 2015-2100. For 2071–2100, although there is a slight difference between the two RCPs, the precipitation is decreasing under both scenarios. The temperature rise is comparatively lower in the summer than in spring and winter. Hence, the streamflow being dependent on glacier melt may have a slightly increasing trend. The probable reason for the growing trend in the flow of rivers in the middle half of the century might be due to quicker snow melting owing to the rising temperature. The outcome pointed out that the percentage increase in summer is lower than in winter.

It is shown in Figure 5 that the streamflow predicted under both the climate change RCP scenarios has an increasing trend towards the 21st century. The projection for increased streamflow was higher in RCP8.5 than in RC2.6, primarily because of the noteworthy temperature rise under RCP8.5. For in-depth analysis, the change in streamflow may be divided into various segments of time span according to an increase or decrease in it. From 2015 to 2040, the streamflow is increasing. It remains nearly constant from 2041 to 2044, and then it increases from 2055 to 2070. Then it remains constant till 2100 except for only a small period of 5 years from 2085 to 2090, where there is a slight increase in the streamflow. The streamflow for all four RCPs has a similar trend pattern with higher values in RCP8.5 than in RCP2.6, primarily because of a noteworthy rise in temperatures under RCP8.5. Overall, the streamflow has an increasing trend from 2015 to 2100 as shown by the trend line.

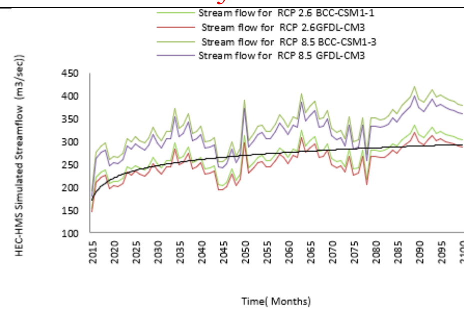


**Figure 5.**HEC-HMS predicted streamflow based on precipitation and temperature reported by GCMs.

As seen in the scattering plots in Figure 6, the anticipated outcomes of the models were then contrasted with the observed levels of temperature, precipitation, and discharge for the area under investigation. The maximum $R^2$ Pearson's correlation values and straight-line fitting equations among the GCMs are presented in Table 2. Plots show that most trends for observed against expected precipitation are close to a 45° angle, indicating that the measured and predicted values are quite similar. In contrast, most lines for temperature and stream flows are at a degree that is below 45°. It demonstrates that under different environmental change scenarios, the generated and collected statistics differ. Other research has also observed comparable differences and ambiguities surrounding GCM findings. [58][59][36]60], [36], [61]

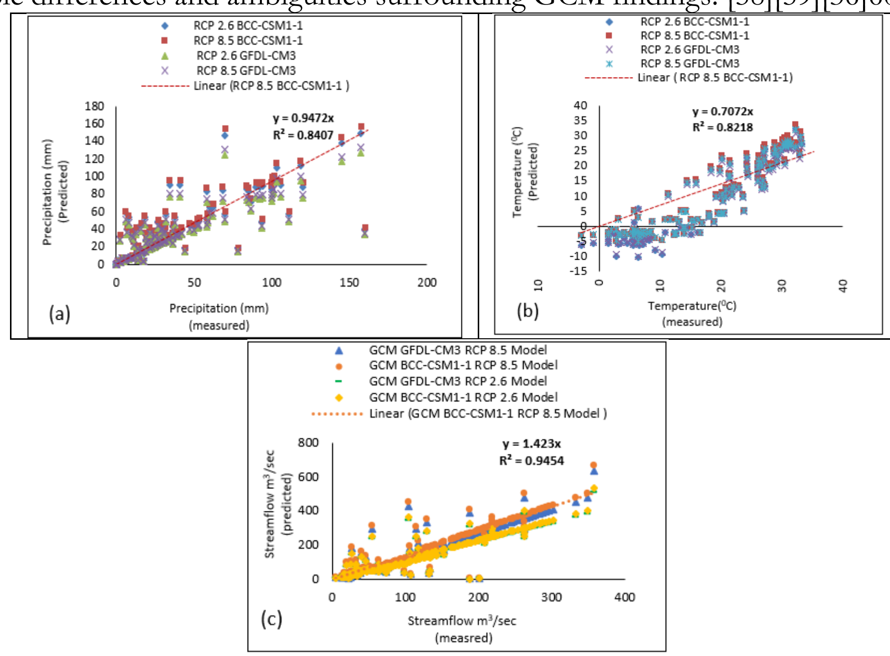


**Figure 6.** Recorded (a) precipitation, (b) temperature, and (c) water flow compared to levels estimated by several GCMs for varying emissions scenarios

**Table 2.** Statistical summary of Figure 6, including straight-line fitting equations and R2, Pearson's correlation.

| RCPs/Parameter | Precipitation | | Temperature | | Streamflow | |
|---|---|---|---|---|---|---|
| | $R^2$ | Fitting Equation | $R^2$ | Fitting Equation | $R^2$ | Fitting Equation |
| 2.6 BCC-CSM 1-1 | 0.6044 | Y=0.0201x | 0.6320 | Y=0.6560x | 0.8962 | Y=1.1384x |
| 8.5 BCC-CSM 1-1 | 0.6044 | Y=0.9427x | 0.6821 | Y=0.7072x | 0.8962 | Y=1.423x |
| 2.6 GFDL-CM3 | 0.6044 | Y=0.7668x | 0.6320 | Y=0.6232x | 0.8962 | Y=1.0814x |
| 8. 5 GFDL-CM3 | 0.604 | Y=0.8051x | 0.6821 | Y=0.6718x | 0.8962 | Y=1.3518x |

**Conclusion:**

The present study employed two non-parametric tests, namely Mann-Kendall and Sen's slope estimator test, for finding out a trend in the dataset of meteorological parameters of UIRB in Pakistan. The analysis of the trend in the climatological station dataset has led to the detection of much more significant trends, which are anticipated to occur by chance. The chosen basin within UIRB demonstrated changes happening in the characteristics of temperature and precipitation.

The study results also have proven that many substantial statistical trends did not exist in precipitation, though a significant trend was witnessed within a few months only. At the Astore, a statistically identifiable positive pattern was recorded in the average temperature within spring and summer, whereas a considerable dropping trend was observed in September. It has also been observed from the results that the temperature variable has a more increasing trend in winter as compared to summer. This indicates an interesting and alarming climate change in the Indus Basin that can result in an extension of the summer season and a very short winter in the future.

Results additionally demonstrate that the two climatic variables, temperature and precipitation, fairly showed opposite trends; thus, there exists no clear relation between the obtained temperature and rainfall patterns, as modifications within the rainfall-related processes are normally multifaceted and difficult to ensure.

The precipitation and temperature reported by two GCMs (BCC-CSM1-1 and GFDL-CM3 under RPC 2.6 and RCP 8.5 scenarios) showed that both the temperature and precipitation are affected significantly by climatic changes. RCP 8.5 displayed slightly increased temperature and streamflow than the RCP 2.6, while in both scenarios, the projected precipitation increase is almost the same. An average increase of 12 % in precipitation is projected for mid-century, while an average increase of 1.33 °C and 4.07 °C in temperature in scenarios RCP 2.6 and RCP 8.5, respectively, is observed from 2015-2100. For 2071–2100, although there is a slight difference between the two RCPs, the precipitation is decreasing. The temperature rise is lower in summer as compared to spring and winter. Hence, the streamflow being dependent on glacier melt may have a slightly increasing trend. The conceivable explanation of the rising trend in the flow of rivers during the mid-portion of the century might be the quicker melting of snow because of the growing trend in temperature. It is obvious from the results percentage rise in the summer season is lower than in the winter season. The rising stream-flow projection was found to be higher in RCP8.5 than that under RC2.6, primarily because of the rise in temperatures in RCP8.5. Further, because of this rise in summer flows will raise the water level in the Tarbela reservoir located on the downstream of Upper Indus River Basin (UIRB) thus providing excess water for Hydropower generation, increasing till the mid-century and then a continues decrease in water level is expected after 2091, which in return, can severely affect the power generation capacity form the reservoir.

Overall, it is inferred here that rising trend of temperature within 3 out of 4 seasons in Pakistan along with the positive precipitation trend that was found existed in spring and summer season will lead toward longer summer season and shorter winter season and also producing more annual flow in the coming years and is going to face a dip in the long-term duration. Overall, the discharge has a growing pattern in duration 2015-2100, which will increase the inflow to the Tarbela reservoir, increasing the reservoir level and thus its hydroelectric generation capacity, although there are also chances of inflows to the reservoir beyond its capacity that can cause flooding to its downstream.

**Declarations:**

**Author Contributions:**

Conceptualization, Ateeq-ur-Rauf, and Komal Sahab Qureshi; methodology, Ateeq-ur-Rauf; software, Ateeq-ur-Rauf; validation, Ateeq-ur-Rauf; formal analysis, Ateeq-ur-Rauf;

investigation, Ateeq-ur-Rauf; resources, Ateeq-ur-Rauf; data curation, writing original draft preparation, Maaz Khan; writing review and editing, visualization, Komal Sahab Qureshi; supervision, Ateeq-ur-Rauf; project administration, Ateeq-ur-Rauf. After reading the original version of the article, all writers have given their approval.

**Data Availability Statement:**

Geospatial datasets of Digital Elevation Model (DEM) are readily accessible from USGS websites https://earthexplorer.usgs.gov. Similarly, hydro-climatic statistics comprise information from discharge, rainfall, and temperature, etc. The Pakistan Meteorological Department (PMD) provides rainfall and temperature data upon prepayment of the applicable data fees. The Surface Water Hydrology Project of the Water and Power Development Authority (WAPDA) provides the yearly discharge statistics. Discharge data can also be readily accessible from the Global Runoff Data Centre (GRDC) website https://www.bafg.de/GRDC/EN/Home/homepage_node.html.

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