# Characterization of Interannual and Seasonal Variability of Hydro-Climatic Trends in the Upper Indus Basin

**Muhammad Usman Liaqat** ( m.liaqat@unibs.it )
University of Brescia Department of Civil Engineering Architecture Territory and Environment: Universita degli Studi di Brescia Dipartimento di Ingegneria Civile Architettura Territorio Ambiente e di Matematica
**Giovanna Grossi**
University of Brescia Department of Civil Engineering Architecture Territory and Environment: Universita degli Studi di Brescia Dipartimento di Ingegneria Civile Architettura Territorio Ambiente e di Matematica
**Shabeh ul Hasson**
University of Hamburg
**Roberto Ranzi**
University of Brescia Department of Civil Engineering Architecture Territory and Environment: Universita degli Studi di Brescia Dipartimento di Ingegneria Civile Architettura Territorio Ambiente e di Matematica

---

**Research Article**

**Keywords:** Upper Indus Basin, precipitation, hydroclimatic behaviour

**Posted Date:** April 3rd, 2021

**DOI:** https://doi.org/10.21203/rs.3.rs-376764/v1

---

**Version of Record:** A version of this preprint was published at Theoretical and Applied Climatology on December 3rd, 2021. See the published version at https://doi.org/10.1007/s00704-021-03850-3.

# Characterization of Interannual and Seasonal Variability of Hydro-Climatic Trends in the Upper Indus Basin

Muhammad Usman Liaqat*[1], Giovanna Grossi[1], Shabeh ul Hasson[2,3], Roberto Ranzi[1]

[1]Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia-DICATAM, Via Branze, 43, 25123 Brescia BS, Italy

[2]CEN, Centre for Earth System Research and Sustainability, University of Hamburg, Hamburg, Germany

[3]Department of Space Science, Institute of Space Technology, Islamabad, Pakistan

**Corresponding author**: **Muhammad Usman Liaqat*[1], *m.liaqat@unibs.it; Tel.: +393895521145**

[1]Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia-DICATAM, Via Branze, 43, 25123 Brescia BS, Italy

## Abstract

A high resolution seasonal and annual precipitation climatology of the Upper Indus Basin was developed, based on 1995-2017 precipitation normals obtained from four different gridded datasets (Aphrodite, CHIRPS, PERSIANN-CDR and ERA5) and quality-controlled high and mid elevation ground observations. Monthly precipitation values were estimated through the anomaly method at the catchment scale and compared with runoff data (1975-2017) for verification and detection of changes in the hydrological cycle. The gridded dataset is then analysed using running trends and spectral analysis and the Mann–Kendall test was employed to detect significant trends. The nonparametric Pettitt test was also used to identify the change point in precipitation and runoff time series.

The results indicated that bias corrected CHIRPS precipitation dataset, followed by ERA5, performed better in terms of RMSE, MAE, MAPE and BIAS in simulating rain gauge-observed precipitation. The running trend analysis of annual precipitation exhibited a very slight increase whereas a more significant increase was found in the winter season (DJF). A runoff coefficient value greater than one, especially in glacierized catchments (Shigar, Shyok and Gilgit) indicate that precipitation was likely underestimated and glacial melt in a warming climate provides excess runoff volumes.

As far as the streamflow is concerned, variabilities are more pronounced at the seasonal rather than at the annual scale. At the annual scale, trend analysis of discharge shows slightly significant increasing trend for the Indus River at the downstream Kachura, Shyok and Gilgit stations. Seasonal flow analysis reveals more complex regimes and its comparison with the variability of precipitation favours a deeper understanding of precipitation, snow- and ice-melt runoff dynamics, addressing the hydroclimatic behaviour of the Karakoram region.

## 1 Introduction

The hydrological cycle change at the regional and global scale is a focus of current research, being the water cycle impacted by both climatic and anthropogenic factors not easy to identify. Precipitation is a key parameter to be monitored particularly in glacial and snow-fed catchments such as the Upper Indus River Basin (UIB), where high-altitude precipitation monitoring is not continuous, showing the time series of observations some gaps, nor it is completely understood (Archer and Fowler 2004a). For this reason, a combined study of both precipitation and runoff provides a better insight into the variability of the water cycle in high mountain areas.

The Upper Indus Basin (UIB) is characterized by the confluence of the Hindukush, Karakoram and Himalayans mountain ranges (HKH) that constitute one of largest cryosphere reserves outside the poles (Soncini et al. 2015). The UIB fulfills water demands of rapidly increasing population in South Asia and feeds one of the largest irrigation system in the world. Pakistan's economy is to a large extent dependent upon agriculture and water resources of the Upper Indus Basin (UIB) feed 16.5 x $10^6$ hectares of irrigated crops. UIB just upstream of Tarbela dam (draining an area of 163,528 $km^2$) receives 70% of its annual flow from snow (26%) and glacial melt (44%) (Mukhopadhyay and Khan 2015).

Water demand in the UIB is though quite high and primary usage of water is for irrigation and hydropower production. As a matter of fact, the climate of lower Indus River basin is mainly arid and hyper-arid and the river flow mostly derives from the melt water generated in the UIB, while other South Asian basins are characterized by extensive summer monsoonal wet regimes. Immerzeel et al. (2015) marked the UIB as a climatic hotspot region, due to the wide variation in the climate anomalies, as well as to the significant rising water demand in downstream areas. The UIB is characterized by hydro-climatic regimes with changing patterns in different sub-basins and over time.

In view of assessing the hydro-climatic variability, Archer and Fowler (2004b) found rising rates in summer, winter and annual precipitation. Khattak et al. (2011) estimated mean monthly climatic trends in the UIB and found summer cooling (1967-2005) and winter warming but did not describe definite patterns of precipitation. Immerzeel and Bierkens (2012) noted the highest vulnerability of water scarcity conditions in the Indus River Basin among ten basins in Asia. They recognized that significant population increase, groundwater depletion, climate change, snowmelt and icemelt are key factors that affect the hydrological regimes of Indus. Bocchiola and Diolaiuti (2013) found a slight annual precipitation increase over northwest Karakoram and Chitral-Hindukush and a decreasing rate in the greater Himalayas side. They also observed summer cooling and winter warming which are prominent as compared to previous thoughts and can easily be checked at Bunji and Gilgit stations. Ali et al. (2015) examined current and future climatic and hydrological changes over the UIB. The results show that northern parts of the UIB experienced a larger increase in temperature and precipitation than southern parts. Projections of future changes show a consistent increase in temperature and precipitation. The rate of increase of river flow is greater in winter compared to summer season. They considered higher river flow possibly due to a larger increase in the air temperature and the consequent enhancement of the melting of the snow and ice cover. Latif et al. (2018) explored both seasonal and annual precipitation trends in the UIB using low and mid altitude stations operated by Pakistan Meteorological Department (PMD). The results exhibited significant falling rate of annual precipitation in six stations, while three stations showed a rising rate of precipitation. Overall, the UIB experienced a downward trend in precipitation both spatially and temporally.

The studies mentioned above mainly used valley-based sparse and fragmented low and mid altitude stations operated by PMD. The estimates from these stations neither represent the climatology of high altitude areas, nor provide any quantifiable mechanism that draws logical inferences between low and high altitude precipitation (Hussain et al. 2017). As a great amount of the UIB streamflow originates from the active hydrological zone in the 2500-5500 m altitude range, data from low altitude stations (even if making up long time series of observations) are not representing reliable hydro-meteorological conditions over the frozen UIB water resources (SIHP,1997).

Moreover, the Indus River basin is a transboundary basin (see Fig. 1) and observed hydro-meteorological data are mostly scattered, discontinuous and not easily accessible. Hence, it is difficult to assess the spatial and temporal variability in high altitude mountainous regions using a sparse ground-based observation network, as it cannot depict horizontal and vertical precipitation variability effectively (Lutz et al. 2014). Various gridded datasets have been developed based on satellite-based data (Huffman and Bolvin 2013), interpolated observation (Yatagai et al. 2012) and reanalysis data (Baudouin et al. 2020; Li et al. 2020) to handle this issue. Most of past studies concerning the UIB depend upon regional/global gridded datasets for mass balance and hydro-climatic studies (Baudouin et al. 2020; Dahri et al. 2016; Immerzeel et al. 2009; Iqbal et al. 2019; Krakauer et al. 2019; Lutz et al. 2014; Masood et al. 2019; Minallah and Ivanov 2019; Rizwan et al. 2019; Ullah et al. 2018).

Gridded datasets provide a better solution in terms of temporal and spatial coverage, even if they are affected by likely greater errors, in particular in high altitude areas where large bias and uncertainty may occur, especially in conditions of significant snowfall (Andermann et al. 2011) and in glacierised catchments (Wortmann et al. 2018). Uncertainties and biases in the gridded datasets are usually due to shortcomings of data sources and generation algorithms of these products (Sun et al. 2018). It is also noted that gridded datasets such as CHIRPS and Aphrodite mainly used World Meteorological Organization's Global Telecommunication System (GTS) gauge data in their production mechanism (Funk et al. 2015; Yatagai et al. 2012). WMO GTS collaborates with the Pakistan Meteorological Department (PMD) for sharing observed meteorological data. In 1995, Water and Power Development Authority (WAPDA) Pakistan collaborated with International Development Research Centre Canada to install automated weather stations known as data collection platforms (DCPs) in the UIB Pakistan. However, the data of these stations are neither publicly available, nor they are shared within WMO GTS database. Keeping in mind above issues, the primary objective of this study is to discuss biases and uncertainties in each available gridded dataset (CHIRPS, ERA5, PERSIANN-CDR and APHRODITE), before and after corrections performed using mid altitude and new high altitude WAPDA-DCPs stations. The second objective is to compare precipitation over the catchment to runoff data to identify possible sources of errors and climatic anomalies, as well as their changes over time and space.

Previous assessments on hydro-climatic trends at the annual or seasonal scale considered specific periods (Ahmad et al. 2018; Bolch et al. 2012; Fowler and Archer 2006; Janes and Bush 2012; Krakauer et al. 2019; Latif et al. 2018; Masood et al. 2019; Rahman et al. 2018; Sharif et al. 2013; Zaman et al. 2020), but they neither incorporated variations within specific temporal sub-periods, nor they described non-linear dynamics of hydro-climatic variability. In an agriculture-based country, with substantial climatic variation, it is difficult to understand the hydro-climatic phenomenology using conventional linear trend schemes. Building on the need of generating future scenarios of water sustainability, this study shows the results of a running trend analysis that covers the entire dataset period to assess hydro-climatic variability from decadal to interdecadal trends in the UIB at the sub-basin scale. More specifically, this study provides a comprehensive investigation of the detectable links of short-term (sub-decadal and decadal) and long-term (multi-decadal) precipitation and runoff variability at the seasonal and the annual scale. In this way, it supports a more detailed overview of precipitation and runoff regimes at the basin and the sub-basin level and improves the past analysis for examining hydro-climatic behaviour in a sensitive area of the earth.

Within this context, a precipitation climatology (1995-2017) for the UIB at the seasonal and the annual scale was built using the anomaly-method applied in (Crespi et al. 2018; Crespi et al. 2021). This method is briefly recalled in the second section of the paper after the description of the study area, of the collected precipitation and runoff data and of the implemented statistical analyses. In the third section, the hydro-climatic trends in each sub-basin of the UIB are examined, together with biases and uncertainties of the gridded precipitation data compared with the ground observations. A discussion of the results, also in comparison with those coming from the analysis of runoff data, follows in the fourth section.

## 2 Material and Methods

### 2.1 Description of the study area

The Upper Indus Basin (UIB), including part of western Himalayas, Karakoram, and northern Hindu Kush mountains, lies in the geographic domain with latitude 31–37° N and longitude 72–82°E and hosts 14085 small and large glaciers (according to RGI-Version 6.0), covering an area of 19338 $km^2$. The drainage area of the Indus Basin, measuring 163,528 $km^2$ at the section of Besham Qila (BQ) is shared by Pakistan, India and China with a percentage of 46% within Pakistan political boundaries (Hasson et al. 2017). The Indus River originates from Mount Kailash in the western Tibet at an elevation of 5486 m and has an overall length of 3180 km measured at the outlet into the Arabian Sea (Jain et al. 2007). The main stem flows initially through the Ladakh district in Jammu Kashmir and afterwards it enters northern Pakistan (Gilgit-Baltistan), between Himalayas and the Karakoram range. The catchment area and, consequently, the discharge of the Indus River become larger in Gilgit-Baltistan (GB) when tributaries such as Shyok, Shigar, Hunza and Gilgit River in the Karakoram Mountains and Astore River in western Himalayas merge with the main river stem. Afterwards, it turns towards south from Nanga

Parbat (8126 m asl) and flows in three provinces of Pakistan, i.e. Khyber Pakhtunkhwa (KPK), Punjab, and Sindh, and finally flows into the Arabian sea. Additionally, Chitral, Swat and Kabul rivers that are originating from the Hindu Kush Mountains also join the mainstream of Indus river in the KPK province, whereas western Himalaya rivers Jehlum, Chenab, Ravi and Sutlej join main Indus river stem at Punjnad in the Punjab province.

The basin highest elevation is set by the K2 peak, also known as "Godwin-Austen", the second highest mountain in the world (8611 m asl), whereas the lowest altitude at BQ is 542 m a.s.l and the basin average altitude is 3750 m asl. It is also noted that 35% area of this basin is above 5000 m asl. The UIB can be subdivided into seven watersheds, i.e. Gilgit, Hunza, Astore, Shigar, Shyok, Shingo-Zanskar and Indus Downstream (Mukhopadhyay and Khan 2015). Shyok and Shigar basins feed the eastern and the central part of Karakoram. Almost one-third of Shigar basin area is covered with glaciers, including world largest glaciers and ice masses. The hydro-climatic characteristics of each sub-basin are quite different. Summer monsoon and westerlies are dominant sources of annual precipitation in UIB. However, the effect and contribution of both sources vary spatially, as well as temporally.

The average annual precipitation measured at different stations within the basin ranges from 156 mm at Gilgit station to around 1514 mm in the Pir Chanasi valley. The mean annual discharge at Besham Qila is 2405 $m^3/s$ (Hussain et al. 2017). The Indus Basin receives 70% of its annual flow during June to September with a maximum value in July. October to March are distinguished as low flow months. UIB climate falls into the "cold desert" category (BWK) according to the Köppen-Geiger climate classification, i.e. an area with little precipitation and large daily temperature range. The relationship between station elevation and measured precipitation is represented in Fig.2, which shows that no significant altitudinal trend can be observed, although doubts arise about the reliability of precipitation data when snowfall occurs, as it will be discussed later.

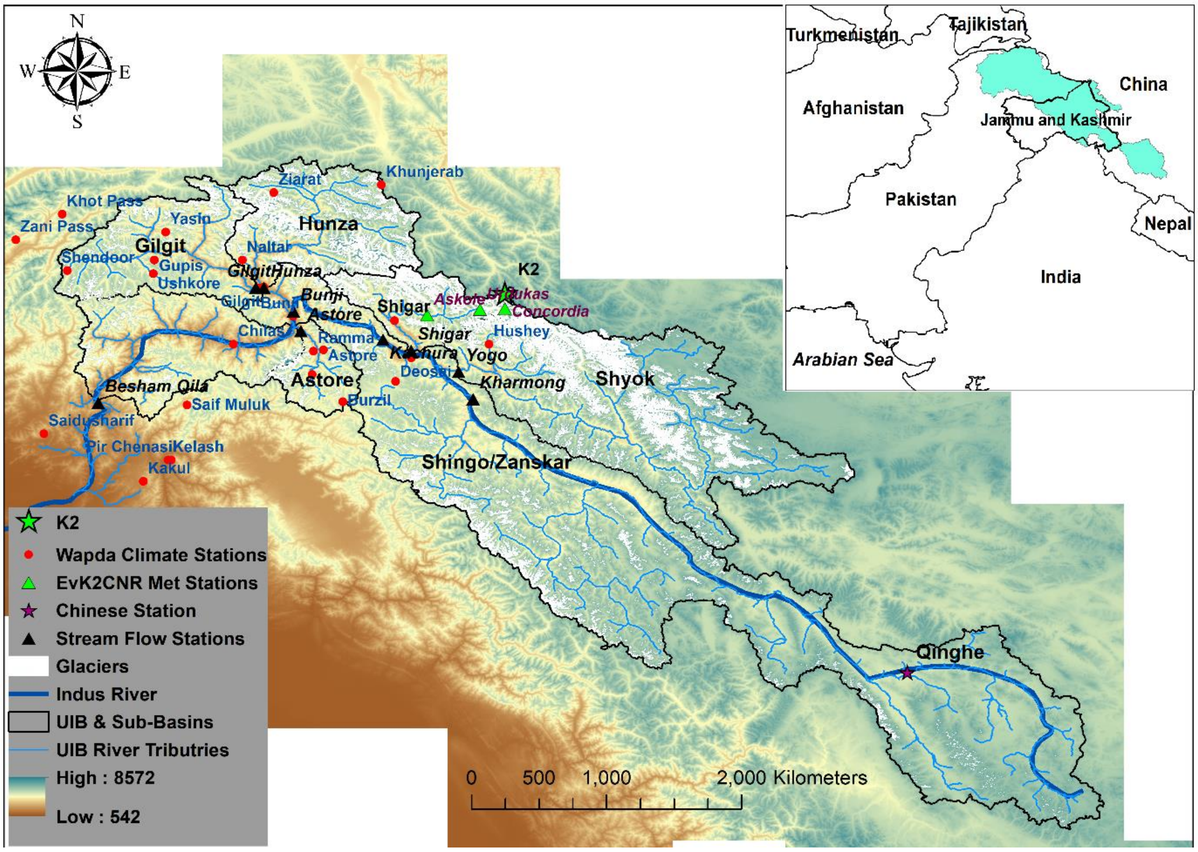


**Fig. 1** The location of the Upper Indus River Basin (UIB - light blue in the inset) and of the Hydro-Meteorological Stations used for the analysis.

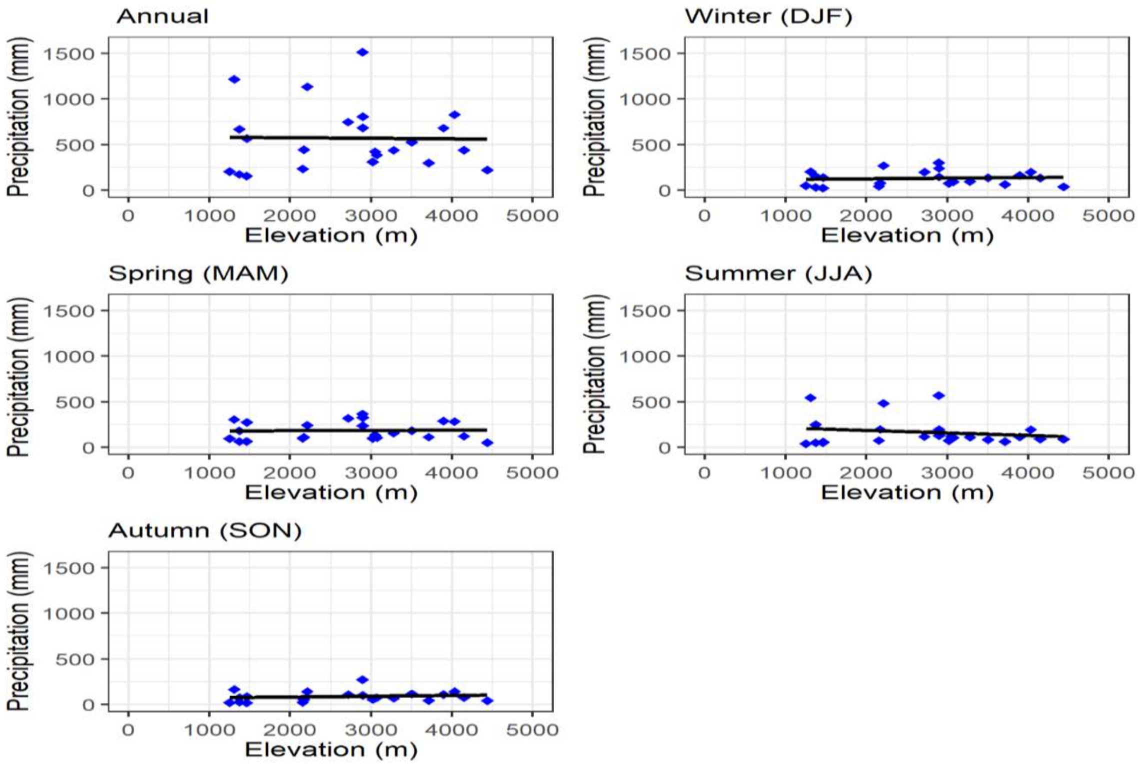


**Fig.2** Relationship between gauge precipitation and elevation observed at the annual and seasonal scale in the UIB.

## 2.2 Hydroclimatology of the Upper Indus Basin

In the Upper Indus Basin hydrology, the precipitation regime features annual-round midlatitude western disturbances. Such disturbances sometimes carry solid form of moisture, mainly during winter and spring (Hewitt 2011; Ul Hasson et al. 2016).The rate of such unusual solid form of moisture is higher during the positive phase of the North Atlantic oscillation (NAO), when western disturbances affect Afghanistan and Iran due to low heat over the area, resulting in extra moisture input from the Arabian sea (Syed et al. 2006).

UIB faced long dry spells with little rainfall from October to March. Initially, water supply is generated by melting of snow starting from the mid of March to late June. The extent of water availability mainly depends upon the concurrent temperature and accumulated snow amount (Hasson et al. 2014; Lucarini et al. 2013). Afterwards, snowmelt runoff is merged with glacier melt runoff from late June to late August as a consequence of high air temperatures. The climate of UIB is classified by winter extra-tropical cyclonic/ anticyclonic circulations (westerlies) and South Asia summer monsoon atmosphere circulations. Both winter and summer have significant impact on the climatic patterns of UIB (Hewitt 2011). The westerlies enter UIB through northwest by the end of November or early in December. Initially, these westerlies are presented in distorted and diffuse state. Afterwards, they interact with already existing orographic trough with low pressure that allow them to recover their potency and frontal structure. The topographic blocking separates these westerlies into southern and northern sections around the western Tibetan Plateau and Karakorum (Pang et al. 2014). The relationship between topography, local climate and circulation system determines the net precipitation and distribution pattern in UIB. The differential heating between land and sea is the main reason for summer precipitation (Dahri et al. 2016). The summer monsoon carries moisture from the Arabian sea that move along the Indus valley towards western Himalayas. It also brings moisture from Bay of Bengal and moves northward to the eastern Himalayas, and from Indian ocean to the western Himalayas following the path along the Indus river valley (Ahmad et al. 2012; Pang et al. 2014).

It is generally believed that the precipitation rate is increasing with elevation. However, this might not happen in UIB where (Immerzeel and Bierkens 2012; Immerzeel et al. 2015; Winiger et al. 2005) found that precipitation is increasing up to a specific elevation, i.e. 5000 m, and shows downward trend above this elevation. Most of annual precipitation falls in the winter and spring and originates from the westerlies. Although summer carries occasional rain to trans-Himalayan areas, it accounts for only one third of total annual precipitation (Madhura et al. 2015). Some other glaciological studies mentioned significant increase of precipitation rates of 1500-2000 mm at 5500 m (Soncini et al. 2015). At the high elevation zones, ice is the primary source of hydrological regimes, followed by snow melt, while the contribution of summer monsoon rainfall is small.

**Table 1** Meteorological stations and their attributes

| Basin | Stations | Period from | Period to | Agency | Latitude ($^0$) | Longitude ($^0$) | Elevation (m asl) | Precipitation (mm/year) |
|---|---|---|---|---|---|---|---|---|
| **Gligat** | Gilgit | 1981 | 2017 | PMD | 35.92 | 74.33 | 1460 | 158 |
| | Gupis | 1981 | 2017 | PMD | 36.17 | 73.4 | 2156 | 234 |
| | Ushkoor | 1995 | 2017 | WAPDA | 36.05 | 73.39 | 3051 | 423 |
| | Yasin | 1995 | 2017 | WAPDA | 36.4 | 73.5 | 3280 | 439 |
| | Shnedoor | 1995 | 2017 | WAPDA | 36.09 | 72.55 | 3712 | 300 |
| **Hunza** | Khunjerab | 1995 | 2017 | WAPDA | 36.84 | 75.42 | 4440 | 224 |
| | Ziarat | 1995 | 2017 | WAPDA | 36.77 | 74.46 | 3020 | 310 |
| | Naltar | 1995 | 2017 | WAPDA | 36.17 | 74.18 | 2898 | 685 |
| **Astore** | Astore | 1981 | 2017 | PMD | 35.37 | 74.9 | 2168 | 444 |
| | Ramma | 1995 | 2017 | WAPDA | 35.36 | 74.81 | 3179 | 806 |
| | Rattu | 1995 | 2017 | WAPDA | 35.15 | 74.8 | 2718 | 750 |
| | Burzil | 1995 | 2017 | WAPDA | 34.91 | 75.09 | 4100 | 829 |
| **Shigar** | Shigar | 1996 | 2012 | WAPDA | 35.63 | 75.53 | 2367 | 348 |
| | Askole | 2005 | 2017 | EVK2CNR | 35.68 | 76.82 | 3051 | 535 |
| | Urdukas | 2011 | 2017 | EVK2CNR | 35.74 | 76.51 | 3926 | 283 |
| | Concordia | 2011 | 2017 | EVK2CNR | 35.73 | 76.29 | 4690 | 260 |
| **Shyok** | Hushey | 1995 | 2017 | WAPDA | 35.42 | 76.37 | 3075 | 386 |
| | Skardu | 1981 | 2017 | PMD | 35.3 | 75.68 | 2210 | 237 |
| **Shingo** | Deosai | 1995 | 2017 | WAPDA | 35.09 | 75.54 | 4149 | 440 |
| | Qinghe | 1995 | 2010 | CMDC | 32.5 | 80.08 | 4279 | 238.8 |
| | Bunji | 1981 | 2017 | PMD | 35.67 | 74.63 | 1372 | 174 |
| **Indus Down Stream** | Chillas | 1981 | 2017 | PMD | 35.42 | 74.1 | 1251 | 207 |
| | Kakul | 1981 | 2017 | PMD | 34.1 | 73.2 | 1308 | 1215 |
| | Pir Chanasi | 1995 | 2017 | WAPDA | 34.387 | 73.5477 | 2872 | 1514 |
| | Saif Muluk | 1995 | 2017 | WAPDA | 34.9 | 73.65 | 2362 | 830 |
| | Saidu Sharif | 1981 | 2017 | PMD | 34.7 | 72.4 | 949 | 1070 |

## 2.3 Meteorological data

Data availability is a big issue in HKH especially in UIB where stations are neither densely nor uniformly distributed. In this study, meteorological data from 26 stations were gathered from (PMD), (WAPDA) and China Meteorological Data Sharing Network (CMDSN). Out of these 26 stations, seven are operated and maintained by the Pakistan Meteorological Department. These are valley-based stations, which are located within the altitude range of 1200–2200 m asl. These stations provide climatic time series for the period 1981-2017. The second meteorological network is maintained by Snow and Ice Hydrology Project (SIHP) of the WAPDA, which is operating 12 automated weather stations known as data collection platforms (DCPs), located in the elevation range 1479-4440 m asl and providing observations since 1995.

As Karakoram range hosts the largest snow ice reserves of the UIB, DCPs stations operated by WAPDA are particularly relevant for examining the hydro-meteorological conditions prevailing over the UIB cryosphere (Hasson et al. 2017). In addition there are also three high altitudes stations operated and maintained by EvK2-CNR (Italian based organization). The stations are Askole (3015 m asl.) and Urdukas (3926 m asl), providing values since 2005, and another one is located at Concordia (4690 m asl.) since 2011. All three stations are used to calculate standard meteorological parameters. However, data time series of these three stations show some gaps and are affected by uncertainties especially during the winter season due to sensor inefficiency in extreme weather conditions. The detailed information about climatic stations, their elevation, time period and mean precipitation are given in Table 1.

## 2.4 Streamflow Data

Upper Indus Basin is fed by three sources of streamflow i.e. glacier melt, especially in Shyok, Hunza and Shigar subbasins, followed by snow melt mainly in the Gilgit and Astore subbasins and rainfall runoff. The daily streamflow of nine hydrometric stations within the UIB have been taken from the Surface Water Hydrology Project (SWHP) of WAPDA, Pakistan from 1973-2017 for stations except Indus at Kharmong and Bunji station where data is available from 1983-2017 and 1973-2013 respectively. Discharge data of Astore at Doyian and Gilgit river at Gilgit are used in this study. Similarly, discharge of Hunza basin is collected at Dainyor station. Table 2 provides specfic information about these streamflow stations and their outflow points.

**Table 2** SWHP WAPDA stream flow gauges given in the downstream order along with their characteristics and the analyzed periods of record.

| Serial. No | Gauge River | Discharge Gauging Point | Period from | Period to | Latitude ($^0$) | Longitude ($^0$) | Elevation (m asl) |
|---|---|---|---|---|---|---|---|
| 1 | Indus | Kharmong | 1983 | 2017 | 34.93 | 76.21 | 2542 |
| 2 | Shyok | Yogo | 1973 | 2017 | 35.18 | 76.1 | 2469 |
| 3 | Indus | Kachura | 1973 | 2017 | 35.45 | 75.41 | 2341 |
| 4 | Hunza | Dainyor | 1973 | 2017 | 35.92 | 74.37 | 1370 |
| 5 | Gilgit | Gilgit | 1973 | 2017 | 35.92 | 74.3 | 1430 |
| 6 | Indus | Bunji | 1973 | 2013 | 35.73 | 74.62 | 1792 |
| 7 | Astore | Doyian | 1973 | 2017 | 35.54 | 74.7 | 1583 |
| 8 | UIB | Besham Qila | 1973 | 2017 | 34.92 | 72.88 | 542 |
| 9 | Shigar | **3-2-1** | 1983 | 2017 | 35.33 | 75.75 | 2438 |
| 10 | UIB Pakistan | **8-1** | | | | | |
| 11 | UIB Pakistan | **8-2-1** | | | | | |

### 2.5 Gridded observations

In the last decades, a great progress was made in developing analysed fields of precipitation over regional and global scale providing different gridded climatic products. These products are avaialble at regional and global scale and are used in hydro-climatic assesment studies. Precipitation products can be devided into four major different cathegories: (1) climatic model reanalysis (2) satellite estimates (3) merged satellite and station observations (4) raingauge-based observations (Sun et al. 2018). In this study we used at least one product from each of these cathegories in order to check their accuracy for hydro-climatological studies based on precipitation estimates thourgh these datasets. APHRODITE is based on station observations, CHIRPS is a combination of satellite and station observations, ERA5 is a reanalysis dataset and PERSIANN-CDR is based on remote sensing using Artifical Nureal Network. The detail information about these products are given in Table 3. For instance, APHRODITE (V1101 and V1101EX_R1) is specfically developed for summer in the Asian region with spatial resolution 0.25°× 0.25°; the products are provided by the Data Integration and Analysis System (DIAS, Japan) that is based on an interpolation of 3500 to 8000 gauge observation (Dile and Srinivasan 2014).

**Table 3** Gridded datasets used in this study for performance evaluation of climatology in Upper Indus Basin

| **Dataset** | **Resolution/frequency** | **Data Sources** | **Algorithm/Assimilation schemes** | **References** |
|---|---|---|---|---|
| APHRODITE **(Observed Values)** | 0.25°/daily | Data Integration and Analysis System (DIAS) | Interpolation with rain gauge grided precipitation | (Yatagai et al. 2012) |
| CHIRPS **(Observed+ Satellite)** | 0.05°/daily | USGS, CHG | Smart Interpolation Tech | (Funk et al. 2015) |
| PERSIANN-CDR **(Satellite)** | 0.25°/3,6 h and /daily | TRMM, NOAA, GridSat-B1 IR, Metsat-6, GOES 8, DMSP F13 | Artificial Neural Networks | (Ashouri et al. 2015) |
| ERA5 land **(Reanalysis)** | 0.25°/monthly/daily/ hourly | ECMWF | 4D-Var | (Saha et al. 2010; Tarek et al. 2019) |

The second dataset is CHIRPS which was developed by the Climate Hazards Group (CHG) and the United States Geological Survey (USGS). It is avaible from 1981 to present with spatial resolution of 0.05° and temporal resolution at daily and monthly scale. It was developed by combination of ground based gauge information and cold cloud duration measurement by the synergistic use of satellite infrared radiometers. Passive microwave and GridSat-B1 satellite data were employed to update the PERSIANN algorithim to estimate daily precipitation. It is based on remotely sensed information combination with artifical neural network (Ashouri et al. 2015).The European Center for Medium-Range Weather Forecasts (ECMWF) launched the new renalysis product ERA5 data. The analysis is developed using advanced 4Dvar assimilation scheme at temporal and spatial scale. It is available at 0.25 x 0.25 degrees and computes various atmoshphetic variables at 139 pressure levels for 1979-present time period at different temporal scale (Baudouin et al. 2020).

### 2.6 Anomaly Method: the interpolation scheme from rain-gauge network to regular grid

The precipitation ground observations in UIB are sparse and do not provide complete temporal and spatial coverage. Therefore, it is inappropriate to develop basin wide annual and seasonal precipitation climatology based on available observations directly. For this purpose, monthly precipitation records for four gridded datasets (CHIRPS, PERSIANN-CDR and ERA5 from 1995 to 2017 and for APHRODITE from 1995-2015) were selected, according to data availability. The gridded data were reconstructed over the study area by means of the anomaly method as described by Crespi et al. (2021). To develop the precipitation climatology on the seasonal and annual scale, monthly gridded and observed data were aggregated at the seasonal scale, i.e. winter (DJF), spring (MAM), summer (JJA), autumn (SON), and annual scale. In this scheme, the precipitation signal is reconstructed by superimposing the spatial fields of seasonal climatology to the spatio-temporal fields of relative anomaly i.e. deviations from the reference for a certain season. The ratio or multiplicative correction factor between referenced and gridded precipitation at each i-th specific station is computed as below:

$$\boldsymbol{P_{test\ m,i}} = \frac{\boldsymbol{p_{test_m}}}{\boldsymbol{p_{refrence,i}}} \qquad (1)$$

Here $p_{test_m}$ and $p_{refrence,i}$ are gridded and observed precipitation series at the specified time scale over the period of common data availability. It has to be pointed out that the rain gauge observations are here assumed to be 'true' reference precipitation values and the other precipitation products are adapted to them. $P_{test\ m,I}$ is the seasonal ratio anomaly or correction factor which is then interpolated as described in Crespi et al. (2018). Similarly, the interpolation method is also applied on gridded datasets on the same scale. These two fields are calculated individually and the season estimates are finally obtained by their product. The same procedure is applied on the annual scale. The anomaly-based climatology helps to develop fine-scale information provided by gridded datasets and incorporates the available records on a large area when the station distribution over the study domain does not provide complete coverage (Brunetti et al. 2012).

### 2.7 Evaluation Criteria

To evaluate the data quality of precipitation anomaly against observed precipitation for an overlapped period of 1995-2017 and 1995-2015 at seasonal and annual scale, four statistics i.e., bias (BIAS), mean absolute error (MAE), root mean square error (RMSE) and mean absolute percentage error (MAPE) were assessed in this study.

BIAS $$\frac{\sum_{i=1}^{N}(Ps_i - Po_i)}{N} \qquad (2)$$

MAE $$\frac{1}{N}\sum_{i=1}^{N}(P_{S_i} - P_{O_i}) \qquad (3)$$

RMSE $$\sqrt{\frac{\sum_{i=1}^{N}(Ps_i - Po_i)^2}{N}} \qquad (4)$$

MAPE $$\frac{1}{N} \cdot \sum_{t=1}^{N} \frac{|P_{S_i} - P_{O_i}|}{P_{O_i}} \cdot 100 \qquad (5)$$

where $PS_i$ is the value of gridded precipitation estimate for the $i_{th}$ event, $PO_i$ is the value of rain gauge observation for the $i^{th}$ event, $N$ is the number of precipitation events. Bias represents the average difference between the gridded precipitation, after the anomaly method correction, and gauge precipitation, as reference. A negative value of bias implies underestimation, while a positive value indicates overestimation of observed rainfall. The gridded precipitation datasets were also compared with observed streamflow and the runoff coefficients was computed as shown in Table 6 in order to assess the ability of runoff data to close the water balance in each sub-basin of UIB and also to verify the reliability of raingaue-based precipitation assessed at the catchment scale as pointed out, for instance, by Ranzi et al. (2021).

### 2.8 Precipitation and runoff trend analysis

The anomaly derived precipitation and streamflow discharges were used for the trend analysis in sub-basins of UIB at seasonal and annual timescales. Discharge period from 1973 to 2017 was selected for four rivers (Astore, Indus at Besham Qila, Indus at Shyok, Indus at Kachura), 1973-2013 and 1983 to 2017 were selected, respectively, for Indus at Bunji and Kharmong and Shigar due to the available data. The trend for this hydro-climatic time series were estimated using robust nonparametric regression techniques i.e. Mann–Kendall (MK) test (Kendall 1948; Mann 1945) in conjunction with Theil–Sen (Sen 1968; Theil 1950) slope method to determine the trend's slope. Mann–Kendall is a ranked based method that determines the presence of any trend irrespective of the type of sample data distribution and whether such trend is linear or nonlinear (Tabari and Talaee 2011). There are two reasons for using MK test for trend analysis. Firstly, it is not necessary for time series data to be normally distributed. Secondly, it is insensitive to missing values and data outliers and less sensitive to breaks caused by inhomogeneous time series (Bocchiola and Diolaiuti 2013) A running trend with a moving time window approach, a type of exploratory data analysis similar to that adopted by (Brunetti et al. 2012) is used to calculate and visualise trends for precipitation and discharge over different time windows and access their significance using consecutive years of the datasets as starting point (x axis in Fig.4 and 6) and ending points (y axis in Fig.4 and 6). As trends in climate change studies are expected to be analysed after 20 years of monitoring, a minimum duration of 15 years was considered for precipitation trend analysis, due to limited availability of data time series, and 20 years for discharge. However, generally, running trend analysis does not require a fix threshold on the length of time series and the threshold value can be altered according to study objectives, climatic parameters, data availability and local issues. Such analysis is not only helpful to detect non-linear hydro-climatic trends in UIB over the different temporal scales, but it also facilitates a comparison of these results with other studies which did not show overall climatic fluctuations in the study period.

### 2.9 Change Point Analysis

The nonparametric Pettitt test is also employed in this study to observe change point in hydro-climatic time series (Palaniswami and Muthiah 2018; Zhang et al. 2015). It supposes a time series $X_t$ with $t = 1,2\dots N$ has a change point at time step T. The values of $X_t$ for $t=1,2,\dots,T$ have CDF $F_1(x)$ and $t=T+1,T+2,\dots,N$ have CDF $F_2(x)$ and $F_1(x) \neq F_2(x)$. Like other statistical measures, the null hypothesis ($H_o$) depicts the absence of change point against the alternative hypothesis ($H_1$: change point present). Given the random variable k(T) defined as:

$$k(T) = \sum_i^T \sum_j^N sgn(X_i - X_j) \quad , \qquad (6)$$

the Pettitt statistics *K* is written as,

$$K = \max_{0 \leq T \leq N} |k(T)| \qquad (7)$$

And time at which change occurs in time series is determined by

$$T = arg(\max_{0 \leq T \leq N} |k(T)| \qquad (8)$$

p-values of the two-tailed Pettitt test is computed by as,

$$p \approx 2 \exp\left(- \frac{6K^2}{N^3+N^2}\right) \qquad (9)$$

The null hypothesis ($H_0$) would be rejected for $p<\alpha$, where $\alpha$ is the significance level. In our study, we keep significance level at 5%

## 3 Results

### 3.1 Climatology, anomalies and precipitation records

The annual and seasonal precipitation climatology for the study basin is shown in Fig.3. The mean annual bias corrected CHIRPS precipitation for the study domain was estimated as 536 mm $yr^{-1}$ which is closer to the results obtained by (Cheema and Bastiaanssen 2012; Reggiani and Rientjes 2015; Rizwan et al. 2019; Shafeeque et al. 2019) who suggested corrected precipitation 523, 675±100, 550 and 593 mm $yr^{-1}$ respectively in UIB using various methods. The driest area is located over the South-Western part of the study domain along the Shingo and Zanskar basins followed by the upper part of Hunza, Shigar and the central part of Gilgit, while the highest precipitation values occur over the central part of Indus downstream, Astore, Shingo, and the upper part of Shyok. Other wet conditions are also observed over the border of Gilgit/ Indus downstream Besham Qila and Astore/Shingo basin. On a seasonal scale, the driest conditions occur during the autumn season with less than 100 mm season$^{-1}$ over wider portion of the basin. In summer slightly wetter conditions occur, followed by the monsoon season which receives the major portion of rainfall. Considering the mean seasonal precipitation over the whole study basin, the precipitation rate is 96 mm in winter (DJF), 150 mm in spring (MAM), 220 mm in summer (JJA) and 70 mm in autumn (SON). It is generally believed that the precipitation rate is getting higher with elevation until an *orographic optimum*. However, the observation of this phenomenon is quite uncertain in UIB where higher precipitation values are measured at lower altitudes or no significant increase with altitude is observed (see Fig. 2). There can be two main possible reasons: the first one is related to the fact that the majority of meteorological stations are located in low lying areas and so there are significant chances of under catch snow precipitation, a common problem in windy and snow dominated areas like UIB (Petäjä et al. 2016). The second is related to the representation of precipitation with gridded datasets which are often lacking sufficient as well as reliable gauge observations.

**Table 4** Comparison of LWLR Interpolated Precipitation with previous studies

| **Sub-Basins** | **PPT mm/yr$^{-1}$** | **Dataset used** | **Reference period** |
|---|---|---|---|
| Indus-Behsam Qila | 536 | This Study (CHIRPS) | 1995-2017 |
| | 594 | This Study (ERA5) | 1995-2017 |
| | 671 | APHRODITE * 1.17 | 1998-2007 (Lutz et al. 2014) |
| | 482 | Station data + KED interpolation | 1998-2012 (Dahri et al. 2016) |
| | 675 | ERA-Interim, NCEP/NCAR | 1998-2009 (Reggiani and Rientjes 2015) |
| Gilgit | 289 | This Study (CHIRPS) | 1995-2017 |
| | 402 | This Study (ERA5) | 1995-2017 |
| | 326 | APHRODITE * 1.17 | 1998-2007 (Lutz et al., 2014) |
| | 162 | Station Observations | 1998-2007 (Akhtar et al. 2008) |
| | 575 | Station data + KED interpolation | 1998-2012 (Dahri et al. 2016) |
| Hunza | 574 | This Study (CHIRPS) | 1995-2017 |
| | 372 | This Study (ERA5) | 1995-2017 |
| | 205 | APHRODITE * 1.17 | 1998-2007 (Lutz et al. 2014) |
| | 582 | India-WRIS | 1971-2004 CWC and NRSC, 2014 |
| | 455 | Observed + SRM | 2000-2013 (Hayat et al. 2019) |
| Shyok | 245 | This Study (ERA5) | 1995-2017 |
| | 395 | This Study (CHIRPS) | 1995-2017 |
| | 175 | APHRODITE * 1.17 | 1998-2007 (Lutz et al. 2014) |
| | 342 | Station data + KED interpolation | 1998-2012 (Dahri et al. 2016) |
| Shigar | 654 | This Study (ERA5) | 1995-2017 |
| | 576 | This Study (CHIRPS) | 1995-2017 |
| | 917 | Station data + KED interpolation | 1998-2012 (Dahri et al., 2016) |
| | 550 | Model | 1980-2009 (Bocchiola et al. 2011) |
| Astore | 649 | This Study (ERA5) | 1995-2017 |
| | 868 | This Study (CHIRPS) | 1995-2017 |
| | 904 | Station data + KED interpolation | 1998-2012 (Dahri et al. 2016) |
| | 431 | APHRODITE * 1.17 | 1998-2007 (Lutz et al. 2014) |
| | 541 | Observed+ SRM | 2000-2013(Hayat et al. 2019) |
| Shingo/ Zanskar | 383 | This Study (ERA5) | 1995-2017 |
| | 302 | This Study (CHIRPS) | 1995-2017 |
| | 277 | Station data + KED interpolation | 1998-2012 (Dahri et al. 2016) |
| | 161 | APHRODITE * 1.17 | 1998-2007(Lutz et al. 2014) |

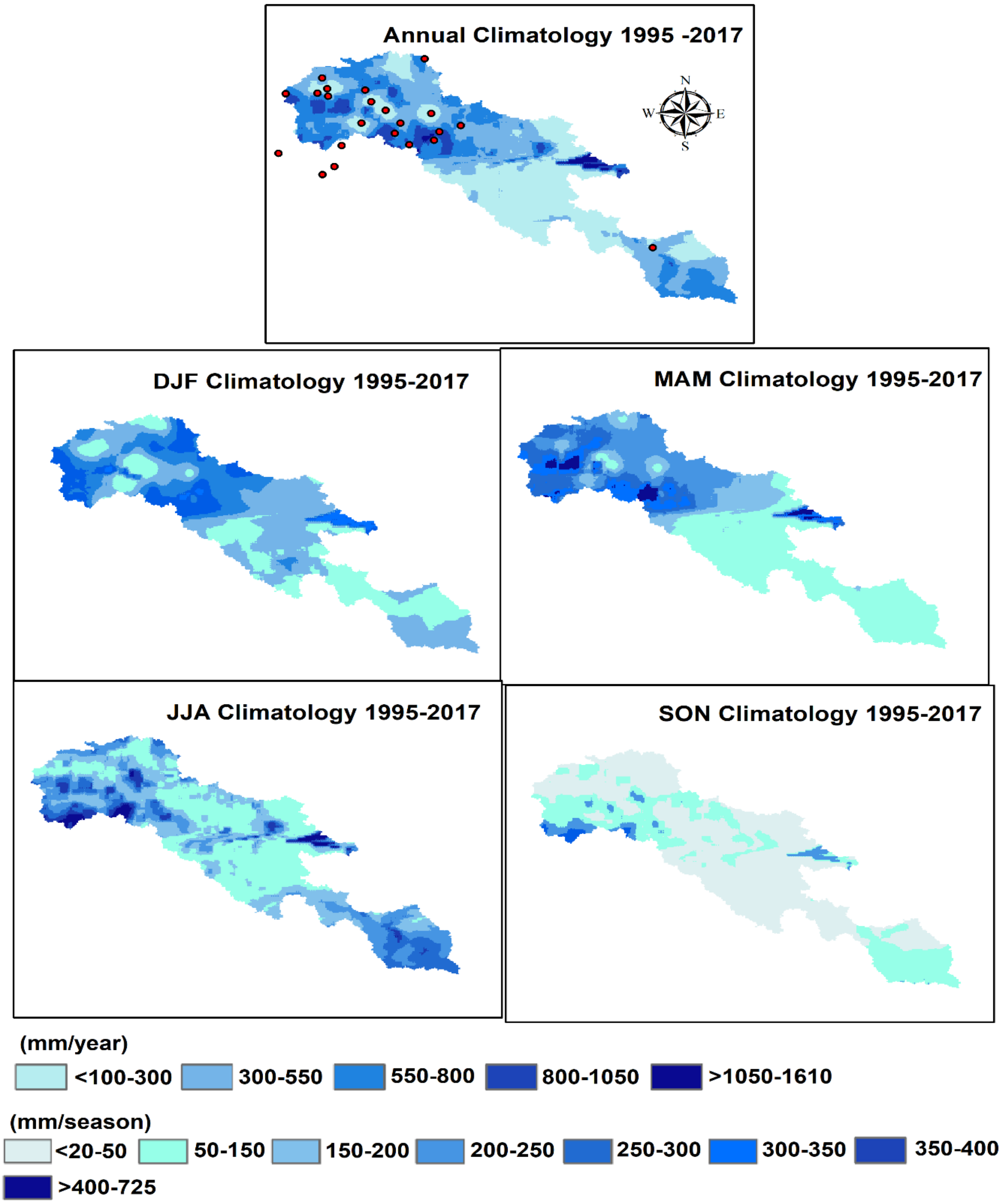


**Fig.3** Annual and seasonal precipitation climatology based on Chirps gridded datasets corrected using observed data.

The values of error statistics (2) to (5) computed with the leave-one-out method over the grid points with gauge observations are presented in Table 5. The bias corrected CHIRPS precipitation had the best performance at annual and seasonal scale followed by ERA5 whereas PERSIAN-CDR had the worst performance at both scales. The summary performance of selected gridded datasets is as follows: CHIRPS datasets is slightly underestimated before correction while ERA5 is highly overestimated before correction. However, after correction the statistical results of ERA5 are closer to CHIRPS gridded datasets. The higher values of MAE, BIAS and RMSE for ERA5 before correction due to incorporating liquid and frozen water, consisting rain and snow that falls on the earth surface. Secondly, reanalysis datasets mostly rely on coupled numerical models, ocean and atmospheric data and do not dependent upon the ground-based observations (Copernicus Climate Change Service, 2017).

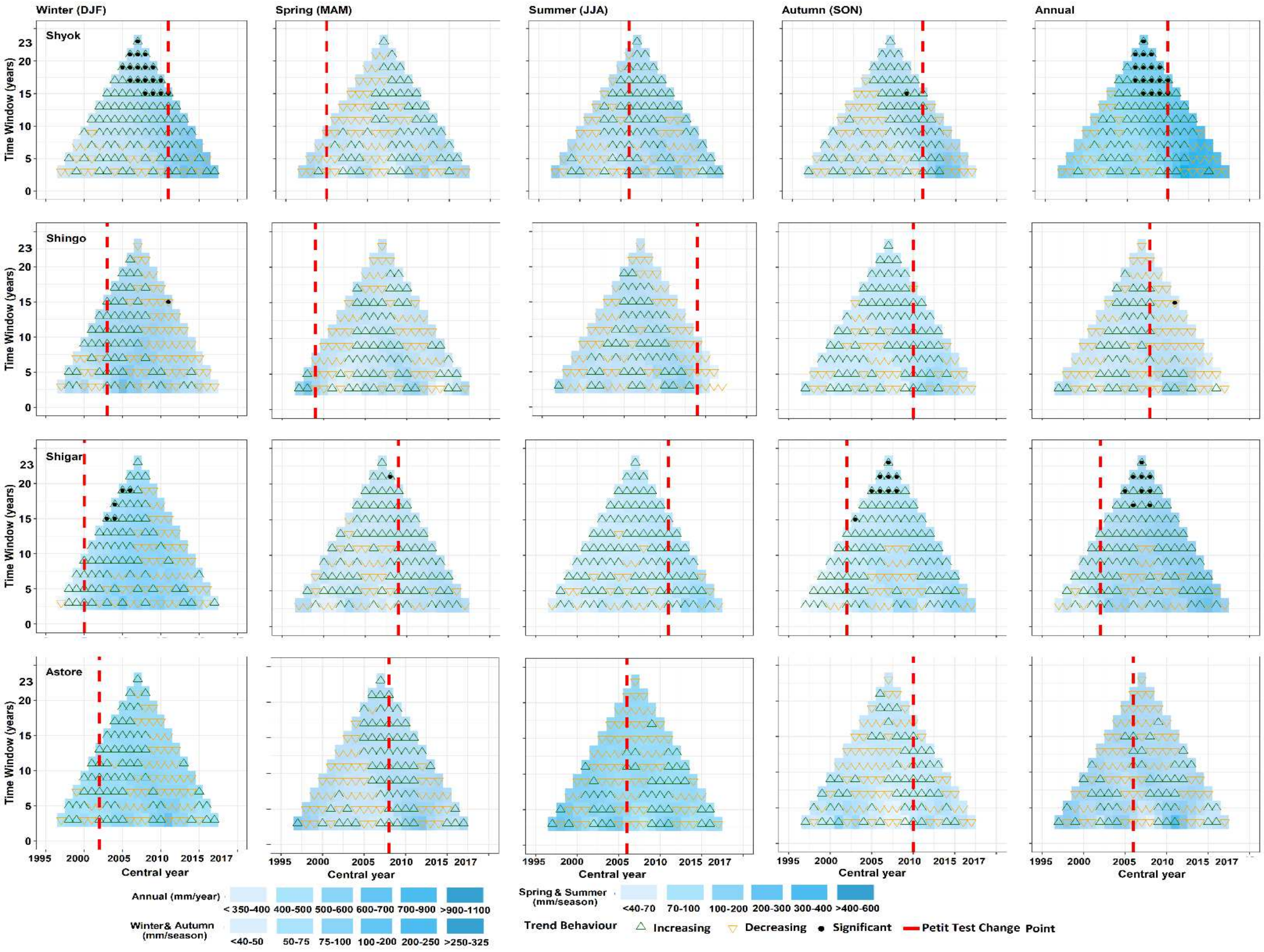
The performance of Aphrodite dataset is found to be inferior to ERA5 especially at annual scale. A great variation of PERSIAN-CDR with observed values might be associated to bias-adjustment, which is based on GPCC dataset with coarse resolution of 2.5° resolution (Fallah et al. 2019). The reliability of CHIRPS and ERA5 were also cross checked by comparing with some previous studies as shown in Table. 4. The results show reliable agreement for developing precipitation climatology using observed and gridded data series extended in space and time in UIB. The discrepancies with other studies are due to varied coverage of study area, time period and number of meteorological stations applied in the analysis.

**Table 5** Monthly leave-one-out reconstruction errors of the 1995–2017 normal for the 5 testing stations (Astore, Chilas, Deosai, Gilgit and Ziarat) included in the study domain.

| **Datasets** | **Seasons** | **MAE (mm)** | **MAPE [%]** | **BIAS (mm)** | **RMSE (mm)** |
|---|---|---|---|---|---|
| **CHIRPS** | Uncorrected Annual | 69.7 | 20.5 | -2.6 | 93.4 |
| | Annual | 50.0 | 14.0 | 21.1 | 56.9 |
| | DJF | 19.7 | 27.0 | 13.9 | 23 |
| | MAM | 27.1 | 26.3 | 15.2 | 28.4 |
| | JJA | 23.0 | 25.7 | 10.6 | 34.4 |
| | SON | 17.3 | 36.2 | -10.2 | 20.9 |
| **ERA5** | Uncorrected Annual | 516.6 | 64.8 | 516.6 | 563.8 |
| | Annual | 53.7 | 15.4 | 27.7 | 61.6 |
| | DJF | 36.7 | 35.4 | 32.6 | 41.4 |
| | MAM | 20.5 | 15.7 | 14.5 | 23.3 |
| | JJA | 25.6 | 33.2 | 14.3 | 40.3 |
| | SON | 17.4 | 33.1 | 5.0 | 22.1 |
| **APHRODITE** | Uncorrected Annual | 111.4 | 30.7 | 36.1 | 118.4 |
| | Annual | 68.4 | 19.1 | 28.2 | 75.3 |
| | DJF | 30.1 | 31.3 | 26.9 | 34.9 |
| | MAM | 36.4 | 30.8 | 12.5 | 40.1 |
| | JJA | 36.1 | 39.9 | -5.0 | 42.1 |
| | SON | 15.9 | 26.2 | -6.2 | 18.3 |
| **PERSIANN-CDR** | Uncorrected Annual | 155.6 | 28.9 | 155.7 | 195.5 |
| | Annual | 78.5 | 23.5 | 36.1 | 85.3 |
| | DJF | 40.4 | 38.1 | 28.1 | 43.2 |
| | MAM | 38.5 | 29.4 | 31.8 | 36.5 |
| | JJA | 49.4 | 33.7 | -15.7 | 53.7 |
| | SON | 26.6 | 53.9 | -9.6 | 30.8 |
| **Mean (mm)** | | | | | |
| **Observed Rain gauge** | Annual | | 358.9 | | |
| | DJF | | 86.6 | | |
| | MAM | | 131.6 | | |
| | JJA | | 86.8 | | |
| | SON | | 53.9 | | |

### 3.2 Variability and trends of the precipitation in Upper Indus Basin

The 1995-2017 annual and seasonal precipitation records for the study domain were evaluated for short and long term trends by using the Theil-Sen slope test (Theil 1950) while the trend significance was evaluated by MK test (Mann 1945). By assuming a confidence interval (C.I) 0.05 (95%), the variability of precipitation on a finer time scale was calculated using running-trend analysis or moving average window approach on the 1995-2017 records.


Winter (DJF)
Spring (MAM)
Summer (JJA)
Autumn (SON)
Annual
Shyok
Shingo
Shigar
Astore
Time Window (years)
0
5
10
15
20
23
1995
2000
2005
2010
2015
2017
Central year
Annual (mm/year)
< 350-400
400-500
500-600
600-700
700-900
>900-1100
Winter& Autumn (mm/season)
<40-50
50-75
75-100
100-200
200-250
>250-325
Spring & Summer (mm/season)
<40-70
70-100
100-200
200-300
300-400
>400-600
Trend Behaviour
△ Increasing
▽ Decreasing
● Significant
Petit Test Change Point

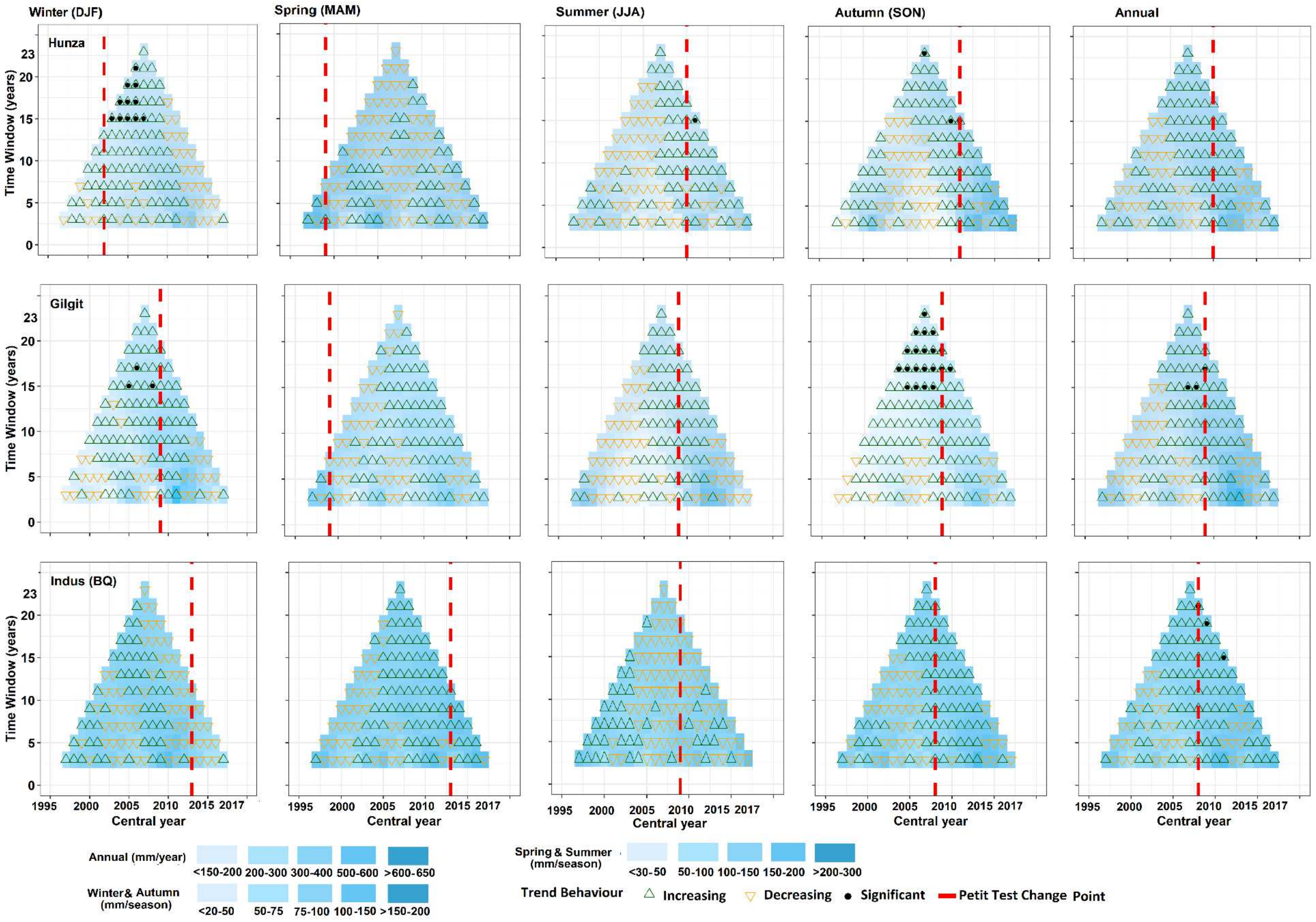

Winter (DJF)
Spring (MAM)
Summer (JJA)
Autumn (SON)
Annual
Hunza
Gilgit
Indus (BQ)
Time Window (years)
0
5
10
15
20
23
1995
2000
2005
2010
2015
2017
Central year
Annual (mm/year)
<150-200
200-300
300-400
500-600
>600-650
Winter& Autumn (mm/season)
<20-50
50-75
75-100
100-150
>150-200
Spring & Summer (mm/season)
<30-50
50-100
100-150
150-200
>200-300
Trend Behaviour
△ Increasing
▽ Decreasing
● Significant
Petit Test Change Point

**Fig.4** Running trend of annual and seasonal precipitation series. Average Precipitation values are divided into various classes (white to dark blue). Trend values are showed by upward (green) and downward triangles (yellow) while trend significance is described by filled circles (significant with at least 15 data) with Mann-Kendall p-values < 0.05). Red vertical line expresses 'change point' year (Petit Test) in the entire time series. The x axis is the starting year (central year), while the y axis is the moving window.

Moreover, change point analysis of precipitation at annual and seasonal time series was also investigated using the Pettit test as shown in Fig 4, Table.S2 and Fig S1. The value of MK-Test significance is estimated on window of increasing width from 15 years up to entire period spanned by series and running from the start to the end of the record. The long-term annual precipitation series exhibited varying interdecadal rising and falling trends. For annual scale, the trend analysis revealed significant increase of precipitation for Shyok, Shigar, UIB Kharmong basins and slightly significant for Indus Downstream and Gilgit basins. Although, Hunza and overall flow at Besham Qila also depicts increasing rate of precipitation but nonsignificant whereas Astore exhibited non-significance falling rate in precipitation. The annual change point (pettit test) or sudden change in precipitation trend (drying to wetting phase) were found during 2004 year for Indus Downstream, UIB Kharmong-Shyok and Shingo basins, 2005 for UIB Kharmong. In case of Hunza Gilgit and Shyok basins, change point has been observed during 2009 and 2012, respectively. In nutshell, precipitation is increasing but non significantly and nonuniformly. It is also noted that Hunza and Shyok basins only exhibited significant change point year by Pettit Test while, all other basins depicted nonsignificant change point year. UIB is characterized by various climatic regimes like westerly disturbances and monsoonal effect orographic disturbance from Tibetan Plateu that make climatology of this region complex, nonuniform distribution and result in inconsistency in precipitation anomaly (Anjum et al. 2018).

On seasonal scale, trend analysis indicated significant increasing trend for Hunza, Shyok, UIB Kharmong, UIB Kharmong-Shyok and slightly significant rising trend of precipitation for (Gilgit, Shigar) during winter season. Astore and Indus at Besham Qila expressed non-significance increasing trend until 2008-09 followed by declining rate of precipitation. The 2003 years marked as a change point (drying to wetting phase) for Astore, Hunza (significant), Shingo, UIB Kharmong basins. Years 2009 and 2011 are noted as 5%-significant change points for Gilgit and Shyok basins. Although, Indus BQ exhibited change point for 2013 year but followed inverse phenomena i.e., wetting to drying phase. For spring season, UIB Kharmong, Astore, Shyok, Shigar and Indus BQ exhibited non-significant upward trend while, Shingo, Hunza and UIB Kharmong depicted nonsignificant decreasing trend. The change point line mainly found around the year 2003 for Gilgit, Hunza, Shingo, UIB Kharmong-Shyok and Shyok basins, 2009 for Shigar and Shyok basins. The increasing rate of precipitation during winter and falling rate during spring is possibly align with alteration in westerly precipitation regimes under climate change. The results of winter wetting also consistent with some previous studies (Cannon et al. 2015; Hasson et al. 2017; Ridley et al. 2013) who also supported rising rate in winter precipitation and drying days during spring season under climate change is mostly linked with incursion of westerly precipitation regimes and northward transfer of rainstorm trajectories in UIB.

For summer season, nonsignificant declining trend in precipitation is observed in Shingo/Zanksar, Indus Besham Qila Astore and UIB Kharmong-Shyok basins. Such fragile monsoon impacts in lower side of basins is possible cause of dryness in summer season. Although, precipitation trends are increasing gradually in remaining basins, they were non-significant. Gilgit and Hunza, also experienced dryness from 1995-2010 that support the findings (Hasson et al. 2017) regarding precipitation decreased between 1995-2012. The change point (drying to wetting phase) varies from 2005 to 2014 for all basins except Shingo that follows in inverse direction. For autumn season, Shigar and Gilgit basins revealed significant upward trend in precipitation. Similarly, Hunza, Shyok and UIB-Kharmong also shows slightly significant rising trend. Although, Indus BQ and Shingo also reveal rising trend in precipitation, they were nonsignificant. Pettit Test found significant change point year for Shyok, Shigar, Gilgit and Hunza basins while rest of basins behaved nonsignificant.

### 3.3 Long Term Temperature Trends

The trends of long term annual and seasonal minimum, maximum, average temperature and diurnal temperature range (DTR) ($T_{min}$, $T_{max}$, $T_{avg}$ and $T_{max}$- $T_{min}$) were observed in order to understand precipitation and streamflow behavior. The MK test and Theil–Sen slope were used to check the significance of trends and their slope. Table.6 shows the annual and seasonal slope values at different stations with bold values indicating trend's significance. The overall main features of minimum temperature consisted of warming during winter and spring while significant cooling was observed during summer season. The autumn and annual periods experienced a mixed response.

In case of maximum temperature, an overall significant increasing rate of temperature was noted for winter, spring and annual season while a significant cooling was noted for the summer season. Maximum and minimum winter temperature presented more warming trends than annual time series. Similarly, average temperature also followed a significant warming during winter, spring and annual season while a significant cooling is observed in the summer season. The high agreement of an upward trend for maximum and average temperature is also associated with the increasing streamflow for all stations during winter and spring season as shown in Fig.5. DTR also generally displays a significant increasing rate of temperature both for seasonal and annual scale except for the Chilas station.

**Table 6** Long-term temperature trends (°C century$^{-1}$) at seasonal to annual scale

| **Variable** | **Stations** | **DJF** | **MAM** | **JJA** | **SON** | **ANN** |
|---|---|---|---|---|---|---|
| $T_{min}$ | Astore | 1.2 | **3.7** | -1.0 | 0.2 | 0.9 |
| | Bunj | 0.5 | 0.9 | **-2.8** | -2.6 | -1.1 |
| | Chilas | **3.7** | 1.0 | **-1.8** | 0.6 | 0.9 |
| | Gilgit | 1.3 | 1.0 | **-1.9** | **-1.8** | -0.4 |
| | Gupis | -1.3 | -1.5 | **-4.9** | **-3.4** | **-2.7** |
| | Skardu | 0.4 | -0.8 | **-3.4** | **-3.1** | **-1.5** |
| $T_{max}$ | Astore | **3.2** | **5.0** | 0.0 | 1.5 | **1.7** |
| | Bunji | **3.4** | **2.7** | **-2.9** | -1.2 | 0.4 |
| | Chilas | 0.4 | 1.4 | **-3.2** | 1.1 | 0.6 |
| | Gilgit | **4.2** | **4.2** | -2.0 | 1.2 | **1.9** |
| | Gupis | **5.2** | **4.6** | -2.6 | **1.7** | **2.6** |
| | Skardu | **4.8** | **4.8** | -0.2 | **2.2** | **3.9** |
| $T_{avg}$ | Astore | **2.4** | **4.8** | -0.6 | 0.9 | **1.6** |
| | Bunji | **2.1** | 1.7 | **-2.6** | **-1.8** | -0.4 |
| | Chilas | **2.0** | 0.6 | **-2.7** | -0.4 | 0.1 |
| | Gilgit | **2.8** | **3.2** | **-2.7** | 0.2 | **1.1** |
| | Gupis | **1.8** | 1.7 | **-3.7** | -1.0 | 0.0 |
| | Skardu | **2.6** | **1.7** | **-1.8** | -0.5 | 0.5 |
| $T_{DTR}$ | Astore | 1.4 | 1.2 | **0.9** | **1.5** | **1.3** |
| | Bunji | **2.7** | 2.5 | -0.2 | 1.6 | **1.5** |
| | Chilas | **-2.9** | 0.9 | -0.8 | **-1.8** | **-1.4** |
| | Gilgit | 3.2 | **3.3** | 1.2 | **3.8** | **2.9** |
| | Gupis | **6.9** | **5.6** | **2.6** | **5.3** | **5.5** |
| | Skardu | **4.5** | **4.9** | **3.6** | **5.9** | **5.0** |

### 3.4 Variability and trends of the discharge in Upper Indus Basin

The variability and trends of the river discharge were evaluated in different sub-basins as shown in Fig.5, Table S1 and Fig.S2. The annual streamflow trends expressed strong significant increasing trend at Indus Kachura and slightly significant at Shyok and Astore stations. Although streamflow is also rising for Indus (Besham Qila), Bunji and UIB-Kharmong stations, the rates of increase were not statistically significant. In contrast, streamflow followed non-significant downward trends for Indus at Kharmong, BQ and Yogo stations. Change point analysis with Pettitt test was also studied for respective streamflow stations. The results marked year 2004 for Indus at Besham Qila, UIB at Kharmong, UIB at Kharmong and Shyok, and year 1988 and 1994, respectively, as change point (drying to wetting phase) for Kachura and Shyok stations. The Pettit test also depicted a 5%-significant change point in streamflow for Indus (Kachura and Bunji), Astore and Shyok stations.

In winter season, most of subbasins showed a significant increase in streamflow. Although Shyok and Kharmong stations also followed positive trends in streamflow they were not statistically significant. The increasing streamflow trends in winter season is consistent with the increase of winter precipitation observed in most catchments, being significant in Shyok, Hunza and Shigar and also with earlier studies (Khattak et al. 2011; You et al. 2017) that reported climate warming causing early snow melt. Our analysis of temperature also reported similar results as shown in Table 6. Similarly, the change point analysis also confirms a 5%-significance change at Besham Qila, Kachura, Shyok, Bunji and Astore in Table S1.

In case of the spring season (MAM) streamflow overall shows an increasing trend in line with the winter season and this can be explained with temperature warming and resulting earlier and more intense snow- and ice-melt. Indus at Bunji and Astore revealed statistically significant increase in streamflow. The slightly rising trend in streamflow were also observed in Indus Downstream at Besham Qila, Kachura, Shyok, UIB-Kharmong and UIB-Kharmong and Yogo. Moreover, change point analysis exhibited significant changes in streamflow for Besham Qila, Astore and Bunji shown in Fig 6.

For the summer season (JJA), the trend analysis shows a 5%-significance increase in streamflow for Indus at Kachura.The change point analysis also confirm significant variability in streamflow at Kachura. Similarly, slightly significant upward trends were also seen at Astore station. In contrast a significant decrease of streamflow were observed at Kharmong station. Although Indus at Behsam Qila and Bunji and Shyok also uncovered declining trend in streamflow, these were not significant. Such long term decrease in discharge behaviors are consistent with some previous studies for Indus at Besham Qila and Kharmong by (Arfan et al. 2019; Yaseen et al. 2020) and Indus at Kachura by (Farhan et al. 2015). Similarly trend behavior for Hunza and Shyok sub basins are also in agreement with (Mukhopadhyay and Khan 2015). The decrease of flow during the summer season can also be associated with declining temperature.

These finding demands a serious attention from policy makers and other stake holder agencies because variability of summer runoff significantly affects water availability in downstream areas in Indus Basin. In fact, about 70-75% of the Indus flow is generated during the summer season. Such changes in flow trends result in a significant reduction in water availability expected in the coming years. As a major share of this water is being used in the agricultural sector during the summer and winter season in Pakistan, if this trend of flow continues gradually in the long term, the reservoirs, farming and other water resources management operations must also be implemented and need to adapt accordingly.

In the autumn season (SON), streamflow exhibited a slightly significant rising trend for Indus at Kachura, Shyok, Astore, Bunji and Besham Qila stations. Similarly, Kharmong station showed non-significant rising trend in streamflow whereas BQ-Kharmong and BQ-Kharmong-Yogo depicted a slightly significant declining trend in streamflow. The change point analysis marked significant variation in streamflow for Bunji and Astore river. The finding of this study is also consistent with a recent study (Yaseen et al. 2020).

**Table 7** Comprehensive Explanation of Basin Characteristics of UIB-Sub-Bains

| **Sub Basins** | **Gauge Location** | **Area** | **Elevation Range** | **Glacier area** | **Glacier Area** | **Q runoff** | **P Chirps** | **P ERA5** | **Annual_RF_C Chirps** | **Annual_RF_C ERA5** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **(km$^2$)** | **m** | **(km$^2$)** | **%** | **(mm yr$^{-1}$)** | **(mm yr$^{-1}$)** | **(mm yr$^{-1}$)** | **(-)** | **(-)** |
| **UIB Down Stream** | **Besham Qila** | 163528 | 542–8572 | 19338 | 11.83 | 470 | 536 | 594 | 0.87 | 0.79 |
| **Gilgit** | **Gilgit** | 12761 | 1415-7104 | 1169 | 9.16 | 693 | 289 | 402 | 2.39 | 1.7 |
| **Hunza** | **Dainyor** | 13734 | 1420–7809 | 4285 | 31.20 | 369 | 574 | 372 | 0.642 | 0.98 |
| **Shyok** | **Yogo** | 33041 | 2389–7673 | 7388 | 22.36 | 368 | 395 | 302 | 0.931 | 1.22 |
| **Shigar** | **Kachura-Yogo-Kharmong** | 10639 | 2189–8448 | 2991 | 28.11 | 927 | 576 | 654 | 1.633 | 1.42 |
| **Astore** | **Shital Bridge/Doyian** | 3903 | 1504–8069 | 258 | 6.61 | 1146 | 876 | 1089 | 1.30 | 1.05 |
| **Shingo-Zanskar** | **Kharmong** | 69355 | 2250–7027 | 2763 | 3.98 | 205 | 302 | 383 | 0.68 | 0.53 |
| **UIB_Pakistan** | **QUIB-QKhar-QShyok** | 61132 | 569-8572 | 9187 | 15.03 | 824 | 664 | 877 | 1.24 | 0.93 |
| **UIB_Pakistan** | **QUIB-QKhar** | 94173 | 569-8572 | 16575 | 17.60 | 664 | 570 | 656 | 1.16 | 1.01 |

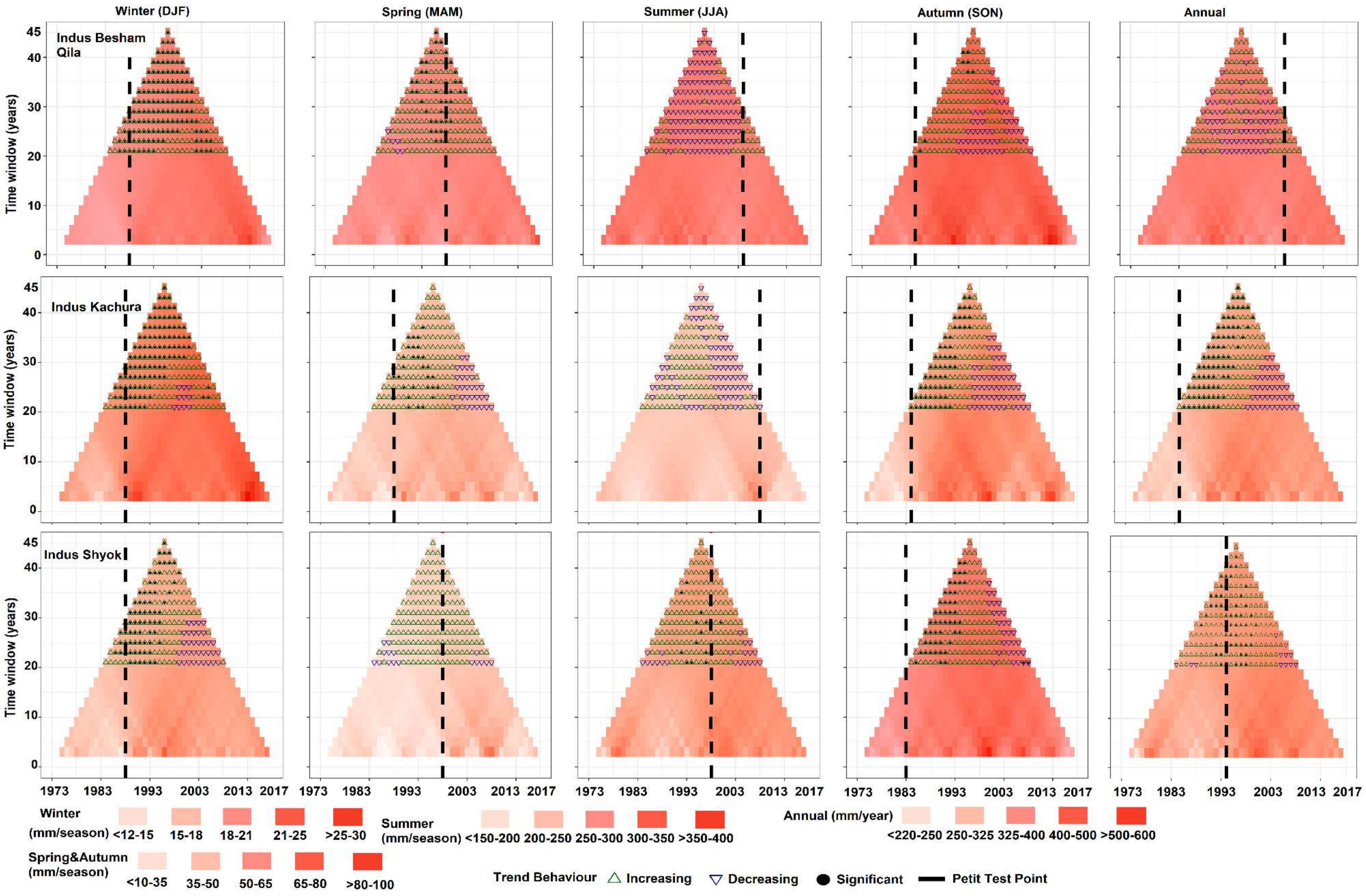

Winter (DJF)
Spring (MAM)
Summer (JJA)
Autumn (SON)
Annual
Indus Besham Qila
Indus Kachura
Indus Shyok
Time window (years)
0
10
20
30
40
45
1973
1983
1993
2003
2013
2017
Winter (mm/season)
<12-15
15-18
18-21
21-25
>25-30
Summer (mm/season)
<150-200
200-250
250-300
300-350
>350-400
Annual (mm/year)
<220-250
250-325
325-400
400-500
>500-600
Spring&Autumn (mm/season)
<10-35
35-50
50-65
65-80
>80-100
Trend Behaviour
△ Increasing
▽ Decreasing
● Significant
— Petit Test Point

**Figure.5** Running trend of annual and seasonal discharge series. Average discharge values are divided into various classes (white to red). Trend values are showed by upward (green) and downward triangles (blue) while trend significance is described by filled circles (significant with at least 20 data and Mann-Kendall p-values < 0.05). Black vertical line expresses 'change point' year (Petit Test) in the entire time series. The x axis is the starting year (central year), while the y axis is the moving window (a minimum assessment duration of 10 year is selected).

### 3.5 Rainfall-runoff relationship in the Upper Indus Basin

The rainfall-runoff relationship and runoff coefficients are first order representation of under- or overestimation of precipitation in the watershed. The annual and monthly runoff coefficients at sub-basins scale were developed as shown in Table.7 and Fig.S3. The results show that both precipitation datasets (Chirps and ERA5) including observed values are not able to close the water balance because runoff coefficients (Q/P) higher than one have been calculated in the majority of sub-basins. Higher values of runoff coefficient for Gilgit, Shigar, and Shyok basins depict negative mass balance in these basins. Similarly, Astore, Hunza and Besham Qila exhibited higher precipitation values than river discharge except in summer season, because of snow and glacial melt and have natural to negative balance at monthly scale. The Indus Downstream with outlet point at Besham Qila which merges drainage of all upstream sub basins experiences positive to slight negative mass balance during summer season. These results need to search for possible explanations.

Overall, ERA5 performed better compared to Chirps precipitation dataset for closing the water balance. Although, Chirps dataset have good agreement with observed precipitation values, it is still unable to close the water balance in the majority of basins. Immerzeel et al. (2015) suggested that reanalysis products based on ECMWF IFS forecast model such as ERA5 can be used to validate atmospheric convergence. ERA5 incorporated fully coupled components of atmosphere, land surface and ocean waves that are useful for closing atmospheric water balance. Gao and Liu (2013) argued that mountain regions exhibited higher values of runoff coefficient due to greater magnitude of surface runoff, shallow soils, steep slope, permafrost and glaciers. In case of UIB, previous studies in this region and neighborhood glacierized catchments also indicated runoff coefficient values greater than one (Adnan et al. 2017; Dahri et al. 2016; Immerzeel et al. 2015; Wortmann et al. 2018). Siddique and Hashmi (2012) found 10%, 25% and 65% contribution of rainfall, snowmelt and glacier in the annual flows of Indus River at Tarbela outlet. The results of these studies about higher values of runoff coefficient also support our results. However, values are slightly changed from current study due to use of different gridded datasets, size and location of study area and in any case values higher than one are hardly acceptable.

Generally, it is believed that higher values of runoff coefficient indicate glaciers retreat and alteration of catchment hydrology. However, it is not only the single possible reason for negative mass balance. There are some other factors such as under catch observed precipitation as well as production mechanism of various gridded precipitation as reported in UIB (Immerzeel et al. 2015; Kääb et al. 2012) and it is also evident in our results as shown in Table.4 and Fig.S3. The discharge values greater than precipitation in Shigar, Shyok and Gilgit basins might also be associated with under catch precipitation due to non-availability of observed gauge stations at high elevation in UIB, where the orographic effect on enhancing precipitation could be relevant and because of possible systematic errors in measuring solid precipitation (Eccel et al. 2012). Similarly, some other mass balance studies (Brun et al. 2017; Gao and Liu 2013) also reinforce our conclusion that glacier retreat is only a partial reason for the missing water volumes in UIB for closing the water balance.

## 4. Discussion

The diverse climatic signals and contrasting hydrological regimes observed in the UIB are the main sources of the uncertainties affecting the assessment of the key components of the hydrological balance, as precipitation, snow and ice accumulation and melt and runoff. A clear example of such an inconsistent behavior is the difference between accumulation patterns based on various remote sensing data acquisition techniques and the geodetic mass balance as reported in multiple studies (Immerzeel et al. 2015; Krakauer et al. 2019; Lutz et al. 2016b).

Based on the results of the analysis, it is concluded that CHIRPS dataset performs well with respect to observed gauge precipitation with lowest BIAS, MAPE and RMSE at annual and seasonal scale, followed by ERA5.The basin wide corrected monthly precipitation values from Chirps and ERA5 and their corresponding runoff coefficient values from each sub basin are illustrated in **Fig.S3**. The results of rainfall runoff, based on novel combination of gridded datasets and comprehensive ground observations, are in good agreement with some previous studies (Dahri et al. 2016; Kääb et al. 2015).The higher values of runoff in Gilgit, Shigar, Shyok imply a significant contribution of glacier retreat and snow melt, as well as undercatch precipitation. It is also concluded that ERA5 precipitation proved to be a better dataset in-terms of closure of the water balance.

In the second part of this study, varying positive and negative trends for both precipitation and runoff at seasonal and annual scale in all sub-basins are reported. Previous knowledge about hydro-climatic trend is mainly confined up to linear trend analysis or with specific time interval, not explaining non-stationary precipitation and discharge variability within decadal to interdecadal time scale. The reliable knowledge about hydro-climatic variability over the UIB is very challenging for effective management and precise usage of available water resources in downstream areas (Böhner and Lucarini 2015). In summary, precipitation exhibited greater seasonal than annual variations. Although, precipitation is increased annually, but its behavior non-significant except Shyok and Shigar basins. Pettit test indicates that change points (drying to wetting phase) mostly lie annually from 2005 to 2010 in the majority of the basins.

An overall increasing trend of winter precipitation are found in all sub-basins. Such a rising rate of precipitation can be due to a significant contribution of winter westerlies regimes and a transfer of rainstorm trajectories in UIB. The results of higher rates in winter precipitation also consensuses with previous studies (Krakauer et al. 2019; Latif et al. 2018; Yaseen et al. 2020). In spring the majority of glacierized catchments show a downward trend in precipitation. On the other hand, Indus Besham Qila, Astore, UIB Kharmong indicate increasing rate of precipitation, but they are statically not significant. Change point analysis also did not record well any transition phase (drying to wetting) in all sub-basins. In summary, spring is drying, as it is also reported in some recent studies (Hasson et al. 2017; Yaseen et al. 2020).

In summer the basin is not showing any significant trend in the precipitation amount. On the other hand, some basins (Shyok, Gilgit, Hunza and Shigar) show a rising rate of precipitation, but none of them is statistically significant. The results showing a decreasing rate of summer precipitation align with previous studies (Cannon et al. 2015; Hasson et al. 2017; Latif et al. 2018; Rizwan et al. 2019). Lutz et al. (2016a) found a clear shift of the summer long-term rising precipitation trends to drying, revealing a transition towards weaker monsoonal influence at lower levels. In order to crosscheck this hypothesis, it would be to better to analyse seasonality in precipitation and streamflow by modeling melt water runoff in the selected area under different climatic conditions. It will be discussed in future perspective of this study. The Indus Downstream with outlet point at Besham Qila usually receives 70% of the annual rainfall in the summer season. This water is stored in two major reservoirs, Tarbela and Mangla, for next cropping season, known as Kharif and Rabi season, when rice and wheat is cultivated in major downstream areas of the UIB. If the same downfall trend of precipitation continues in the future, it will reduce the water availability, ultimately putting further stress on already dwindling water reserves of Pakistan.

Concerning streamflow, variabilities are more pronounced seasonally than annually. Results indicate that winter and spring streamflow discharge significantly or slightly significantly increased in all sub-basins, whereas it decreased in summer.Yaseen et al. (2020) suggested that a rising trend of winter discharge is mainly linked with westerly precipitation regimes, because a major portion of UIB hydrology is dominated by westerly disturbances rather than monsoon offshoots. There are also different significant interpretations about these flow dynamics. One reason could be found in the significant warming in winter and spring, as shown in Table 6, whereas summer cooling caused early snow melt during spring and less flow available during summer (i.e., decreasing trends in summer discharge show lower melting rates in summer, resulting in potential stability of glaciers and consequently positive basin storage).

## 5. Conclusions

The study presents a comprehensive hydro-climatic trend and precipitation anomaly analysis for the UIB at the sub-basin scale. The primary objective of this study is to evaluate the performance of four gridded precipitation datasets for developing a precipitation climatology and check its reliability for the UIB. The datasets were examined for an overlapping period spanning from 1995 to 2017 at the seasonal and at the annual scale. Based on results, it is found that the performance of CHIRPS dataset is good to describe the distribution of observed precipitation with lowest BIAS, MAE, RMSE and MAPE, followed by ERA5. The mean annual corrected precipitation was calculated as 536 mm yr-1 in the UIB gauged at Besham Qila. The precipitation climatology exhibited a higher rate of precipitation in the lower part of the basin for both the annual and the seasonal scale. The runoff coefficient for CHIRPS and ERA5 is though greater than one in some basins, making the water balance unrealistic. There can be two main reasons: 1) underestimate of precipitation, as most of the monitoring stations in the UIB are valley-based and do not represent the true basin hydrology in the high elevation bands 2) glacier retreat and early snow melt due to global warming and elevation-dependent warming. However, there are small chances for glacier retreat because most glaciers, especially in Karakorum, have been advancing or in stable conditions in the last decade (2008-2016) (Berthier and Brun 2019). Meanwhile, precipitation rate declines with elevation annually, rises during winter and spring season but decreases during summer season. These issues demand further investigation, as they are affecting the contribution of glacier and snow melt in total flow from each sub-basin. The findings of this study would be helpful to understand the discrepancies between the observed and the gridded precipitation datasets referring to the UIB and may have substantial impact on studies related to the designing, planning, modeling and management of the water resources under climate change. The results of the study also recommend that gridded precipitation is corrected before its usage in hydrological modeling studies, especially in those involving glacierized catchments. The anomaly method proved to be worthwhile for assessing precipitation climatology, especially in data scarce regions with a sparse monitoring network.

In the second part of this study, annual and seasonal precipitation revealed significant variability seasonally rather than annually. Summer is drying while winter is wetting. The increasing rate of precipitation was also seen during spring in some basins, but they were not statistically significant. Similarly, trend analysis of observed streamflow at various gauge stations in the UIB facilitates understanding about comprehensive water balance for the region. Like precipitation variability, streamflow one is more pronounced seasonally rather than annually. At the annual scale, trend analysis of discharge shows slightly significant increasing trend at the Indus River Kachura, Shyok and Gilgat stations, while nonsignificant decreasing trends at Kharmong stations, BQ-Kharmong and BQ-Kharmong-Shyok stations are found. Seasonal flow analysis reveals more complex regime: winter (December-February) and spring (March-May) exhibit a rising trend in streamflow, while summer (June- August) shows a declining trend. The seasonal analysis also shows an increasing rate of warming in spring and early seasonal melt discharge from most of the sub-basins, whereas field significant low flow/drying was observed during summer.

The findings of this hydro-climatic analysis are expected to support future sustainable development projects in the study area. For instance, it would be helpful to assist engineers, the government and its organizations, as well as other stakeholder agencies to set up structural and non-structural measures to handle extreme flood and other natural hazard events, such as building dams and other control structures, lining canals and water course and adopt precision agricultural techniques (drip and sprinkler irrigation). It would also be viable to bridge the gap in terms of water availability and supplies especially in the lower area of the basin, where a major share of this water is being used for growing crops. These results would facilitate farmers and other stakeholder agencies to set cropping pattern according to water availability under prevailing climatic conditions.

## Acknowledgements

The study covers one part of PhD research work funded by University of Brescia, Italy. The authors highly appreciate the Pakistan Meteorological Department (PMD), Water and Power Development Authority (WAPDA) and China Meteorological Data Sharing Network (CMDSN) for providing reliable data for our study and helping to publish valuable information.

## Declarations

**Funding:** The PhD research work funded by University of Brescia, Italy.

**Conflicts of interest:** The authors declare that they have no conflict of interest.

**Author's Contribution:** L, M.U., R.R., formal analysis, methodology, investigations, and validation. L, M.U data handling in software. L, M.U examined results, writing—original draft preparation. Ul., S.H. and G.G., visualization, verify results and contributed to writing and editing. All authors have read and agreed to the published version of the manuscript.

**Availability of data and material:** 'Not applicable'

**Code availability (software application or custom code):** 'Not applicable'

**Ethics approval:** 'Not applicable'

**Consent to participate:** 'Not applicable’.

**Consent for publication:** 'Not applicable'

## References

Adnan M, Nabi G, Poomee MS, Ashraf A (2017) Snowmelt runoff prediction under changing climate in the Himalayan cryosphere: A case of Gilgit River Basin Geoscience Frontiers 8:941-949

Ahmad I, Zhang F, Tayyab M, Anjum MN, Zaman M, Liu J, Farid HU, Saddique Q (2018) Spatiotemporal analysis of precipitation variability in annual, seasonal and extreme values over upper Indus River basin Atmospheric Research 213:346-360

Ahmad Z, Hafeez M, Ahmad I (2012) Hydrology of mountainous areas in the upper Indus Basin, Northern Pakistan with the perspective of climate change Environmental monitoring and assessment 184:5255-5274

Akhtar M, Ahmad N, Booij MJ (2008) The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios Journal of hydrology 355:148-163

Ali S, Li D, Congbin F, Khan F (2015) Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan Environmental Research Letters 10:014007

Andermann C, Bonnet S, Gloaguen R (2011) Evaluation of precipitation data sets along the Himalayan front Geochemistry, Geophysics, Geosystems 12

Anjum MN, Ding Y, Shangguan D, Ahmad I, Ijaz MW, Farid HU, Yagoub YE, Zaman M, Adnan M (2018) Performance evaluation of latest integrated multi-satellite retrievals for Global Precipitation Measurement (IMERG) over the northern highlands of Pakistan Atmospheric Research 205:134-146

Archer DR, Fowler HJ (2004a) Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications

Archer DR, Fowler HJ (2004b) Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications Hydrology and Earth System Sciences Discussions 8:47-61

Arfan M, Lund J, Hassan D, Saleem M, Ahmad A (2019) Assessment of spatial and temporal flow variability of the Indus river Resources 8:103

Ashouri H, Hsu K-L, Sorooshian S, Braithwaite DK, Knapp KR, Cecil LD, Nelson BR, Prat OP (2015) PERSIANN-CDR: Daily precipitation climate data record from multisatellite observations for hydrological and climate studies Bulletin of the American Meteorological Society 96:69-83

Baudouin J-P, Herzog M, Petrie CA (2020) Contribution of cross-barrier moisture transport to precipitation in the upper Indus River Basin Monthly Weather Review 148:2801-2818

Berthier É, Brun FJJoG (2019) Karakoram geodetic glacier mass balances between 2008 and 2016: persistence of the anomaly and influence of a large rock avalanche on Siachen Glacier 65:494-507

Bocchiola D, Diolaiuti G (2013) Recent (1980–2009) evidence of climate change in the upper Karakoram, Pakistan Theoretical and applied climatology 113:611-641

Bocchiola D, Diolaiuti G, Soncini A, Mihalcea C, D'agata C, Mayer C, Lambrecht A, Rosso R, Smiraglia C (2011) Prediction of future hydrological regimes in poorly gauged high altitude basins: the case study of the upper Indus, Pakistan Hydrology and Earth System Sciences 15:2059-2075

Böhner J, Lucarini V (2015) Prevailing climatic trends and runoff response from Hindukush-Karakoram-Himalaya, upper Indus basin arXiv preprint arXiv:150306708

Bolch T, Kulkarni A, Kääb A, Huggel C, Paul F, Cogley JG, Frey H, Kargel JS, Fujita K, Scheel M (2012) The state and fate of Himalayan glaciers Science 336:310-314

Brun F, Berthier E, Wagnon P, Kääb A, Treichler D (2017) A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016 Nature geoscience 10:668-673

Brunetti M, Lentini G, Maugeri M, Nanni T, Simolo C, Spinoni J (2012) Projecting North Eastern Italy temperature and precipitation secular records onto a high-resolution grid Physics and Chemistry of the Earth, Parts A/B/C 40:9-22

Cannon F, Carvalho LM, Jones C, Bookhagen B (2015) Multi-annual variations in winter westerly disturbance activity affecting the Himalaya Climate dynamics 44:441-455

Cheema MJM, Bastiaanssen WG (2012) Local calibration of remotely sensed rainfall from the TRMM satellite for different periods and spatial scales in the Indus Basin International Journal of Remote Sensing 33:2603-2627

Crespi A, Brunetti M, Lentini G, Maugeri M (2018) 1961–1990 high-resolution monthly precipitation climatologies for Italy International Journal of Climatology 38:878-895

Crespi A, Brunetti M, Ranzi R, Tomirotti M, Maugeri M (2021) A multi-century meteo-hydrological analysis for the Adda river basin (Central Alps). Part I: Gridded monthly precipitation (1800–2016) records International Journal of Climatology 41:162-180

Dahri ZH, Ludwig F, Moors E, Ahmad B, Khan A, Kabat P (2016) An appraisal of precipitation distribution in the high-altitude catchments of the Indus basin Science of the Total Environment 548:289-306

Dile YT, Srinivasan R (2014) Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin JAWRA Journal of the American Water Resources Association 50:1226-1241

Eccel E, Cau P, Ranzi R (2012) Data reconstruction and homogenization for reducing uncertainties in high-resolution climate analysis in Alpine regions Theoretical and Applied Climatology 110:345-358

Fallah A, Rakhshandehroo GR, Berg P, O S, Orth R (2019) Evaluation of precipitation datasets against local observations in Southwestern Iran International Journal of Climatology

Farhan SB, Zhang Y, Ma Y, Guo Y, Ma N (2015) Hydrological regimes under the conjunction of westerly and monsoon climates: a case investigation in the Astore Basin, Northwestern Himalaya Climate Dynamics 44:3015-3032

Fowler H, Archer D (2006) Conflicting signals of climatic change in the Upper Indus Basin Journal of Climate 19:4276-4293

Funk C, Peterson P, Landsfeld M, Pedreros D, Verdin J, Shukla S (2015) The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci Data. 2015; 2: 150066. Epub 2015/12/10. https://doi. org/10.1038/sdata. 2015.66 PMID: 26646728,

Gao Y, Liu M (2013) Evaluation of high-resolution satellite precipitation products using rain gauge observations over the Tibetan Plateau Hydrology and Earth system sciences 17:837

Hasson S, Böhner J, Lucarini V (2017) Prevailing climatic trends and runoff response from Hindukush–Karakoram–Himalaya, upper Indus Basin Earth System Dynamics 8:337-355

Hasson S, Lucarini V, Khan MR, Petitta M, Bolch T, Gioli G (2014) Early 21st century snow cover state over the western river basins of the Indus River system Hydrology and Earth System Sciences 18:4077-4100

Hayat H, Akbar TA, Tahir AA, Hassan QK, Dewan A, Irshad M (2019) Simulating Current and Future River-Flows in the Karakoram and Himalayan Regions of Pakistan Using Snowmelt-Runoff Model and RCP Scenarios Water 11:761

Hewitt K (2011) Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus Basin Mountain Research and Development 31:188-200

Huffman GJ, Bolvin DT (2013) TRMM and other data precipitation data set documentation NASA, Greenbelt, USA 28:1

Hussain S, Song X, Ren G, Hussain I, Han D, Zaman M (2017) Evaluation of gridded precipitation data in the Hindu Kush–Karakoram–Himalaya mountainous area Hydrological sciences journal 62:2393-2405

Immerzeel W, Bierkens M (2012) Asia's water balance Nature Geoscience 5:841

Immerzeel W, Wanders N, Lutz A, Shea J, Bierkens M (2015) Reconciling high-altitude precipitation in the upper Indus basin with glacier mass balances and runoff Hydrology and Earth System Sciences 19:4673-4687

Immerzeel WW, Droogers P, De Jong S, Bierkens M (2009) Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing Remote sensing of Environment 113:40-49

Iqbal Z, Shahid S, Ahmed K, Ismail T, Nawaz N (2019) Spatial distribution of the trends in precipitation and precipitation extremes in the sub-Himalayan region of Pakistan Theoretical and Applied Climatology 137:2755-2769

Jain SK, Agarwal PK, Singh VP (2007) Hydrology and water resources of India vol 57. Springer Science & Business Media,

Janes TJ, Bush AB (2012) The role of atmospheric dynamics and climate change on the possible fate of glaciers in the Karakoram Journal of Climate 25:8308-8327

Kääb A, Berthier E, Nuth C, Gardelle J, Arnaud Y (2012) Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas Nature 488:495-498

Kääb A, Treichler D, Nuth C, Berthier E (2015) Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya Cryosphere 9

Kendall MG (1948) Rank correlation methods

Khattak MS, Babel M, Sharif M (2011) Hydro-meteorological trends in the upper Indus River basin in Pakistan Climate research 46:103-119

Krakauer NY, Lakhankar T, Dars GH (2019) Precipitation Trends over the Indus Basin Climate 7:116

Latif Y, Yaoming M, Yaseen M (2018) Spatial analysis of precipitation time series over the Upper Indus Basin Theoretical and applied climatology 131:761-775

Li D, Yang K, Tang W, Li X, Zhou X, Guo D (2020) Characterizing precipitation in high altitudes of the western Tibetan plateau with a focus on major glacier areas International Journal of Climatology

Lucarini V, Pascale S, Böhner J (2013) Seasonality of the hydrological cycle in major South and Southeast Asian river basins as simulated by PCMDI/CMIP3 experiments arXiv preprint arXiv:13125727

Lutz A, Immerzeel W, Kraaijenbrink P (2014) Gridded meteorological datasets and hydrological modelling in the Upper Indus Basin Final Report, for International Centre for Integrated Mountain Development (ICIMOD), FutureWater, Costerweg 1:6702

Lutz AF, Immerzeel W, Kraaijenbrink P, Shrestha AB, Bierkens MF (2016a) Climate change impacts on the upper Indus hydrology: Sources, shifts and extremes PloS one 11:e0165630

Lutz AF, Immerzeel WW, Kraaijenbrink PD, Shrestha AB, Bierkens MF (2016b) Climate change impacts on the upper indus hydrology: Sources, shifts and extremes PloS one 11:e0165630

Madhura R, Krishnan R, Revadekar J, Mujumdar M, Goswami B (2015) Changes in western disturbances over the Western Himalayas in a warming environment Climate dynamics 44:1157-1168

Mann HB (1945) Nonparametric tests against trend Econometrica: Journal of the Econometric Society:245-259

Masood M, Shakir AS, Azhar AH, Nabi G (2019) Assessment of Real Time, Multi-Satellite Precipitation Products under Diverse Climatic and Topographic Conditions Asia-Pacific Journal of Atmospheric Sciences:1-15

Minallah S, Ivanov VY (2019) Interannual variability and seasonality of precipitation in the Indus River basin Journal of Hydrometeorology 20:379-395

Mukhopadhyay B, Khan A (2015) A reevaluation of the snowmelt and glacial melt in river flows within Upper Indus Basin and its significance in a changing climate Journal of Hydrology 527:119-132

Palaniswami S, Muthiah K (2018) Change Point Detection and Trend Analysis of Rainfall and Temperature Series over the Vellar River Basin Polish Journal of Environmental Studies 27

Pang H, Hou S, Kaspari S, Mayewski P (2014) Influence of regional precipitation patterns on stable isotopes in ice cores from the central Himalayas The Cryosphere 8:289-301

Petäjä T, O'Connor EJ, Moisseev D, Sinclair VA, Manninen AJ, Väänänen R, von Lerber A, Thornton JA, Nicoll K, Petersen W (2016) BAECC: A field campaign to elucidate the impact of biogenic aerosols on clouds and climate Bulletin of the American Meteorological Society 97:1909-1928

Rahman K, Shang S, Shahid M, Li J (2018) Developing an ensemble precipitation algorithm from satellite products and its topographical and seasonal evaluations over Pakistan Remote Sensing 10:1835

Reggiani P, Rientjes T (2015) A reflection on the long-term water balance of the Upper Indus Basin Hydrology research 46:446-462

Ridley J, Wiltshire A, Mathison C (2013) More frequent occurrence of westerly disturbances in Karakoram up to 2100 Science of the Total Environment 468:S31-S35

Rizwan M, Li X, Jamal K, Chen Y, Chauhdary JN, Zheng D, Anjum L, Ran Y, Pan X (2019) Precipitation Variations under a Changing Climate from 1961–2015 in the Source Region of the Indus River Water 11:1366

Saha S, Moorthi S, Pan H-L, Wu X, Wang J, Nadiga S, Tripp P, Kistler R, Woollen J, Behringer D (2010) The NCEP climate forecast system reanalysis Bulletin of the American Meteorological Society 91:1015-1058

Sen P (1968) Estimates of the Regression Coefficient based on Kendall's Tau. J. Amer Statist Assoc 63:1379-1389

Shafeeque M, Luo Y, Wang X, Sun L (2019) Revealing Vertical Distribution of Precipitation in the Glacierized Upper Indus Basin Based on Multiple Datasets Journal of Hydrometeorology 20:2291-2314

Sharif M, Archer D, Fowler H, Forsythe N (2013) Trends in timing and magnitude of flow in the Upper Indus Basin Hydrology and Earth System Sciences 17:1503-1516

Siddique M, Hashmi D (2012) Recent trends in high altitude temperatures and river flows in the Upper Indus Basin Centenary Celebration 714:149-166

Soncini A, Bocchiola D, Confortola G, Bianchi A, Rosso R, Mayer C, Lambrecht A, Palazzi E, Smiraglia C, Diolaiuti G (2015) Future hydrological regimes in the upper indus basin: A case study from a high-altitude glacierized catchment Journal of Hydrometeorology 16:306-326

Sun Q, Miao C, Duan Q, Ashouri H, Sorooshian S, Hsu KL (2018) A review of global precipitation data sets: Data sources, estimation, and intercomparisons Reviews of Geophysics 56:79-107

Syed F, Giorgi F, Pal J, King M (2006) Effect of remote forcings on the winter precipitation of central southwest Asia part 1: observations Theoretical and Applied Climatology 86:147-160

Tabari H, Talaee PH (2011) Recent trends of mean maximum and minimum air temperatures in the western half of Iran Meteorology and atmospheric physics 111:121-131

Tarek M, Brissette FP, Arsenault R (2019) Evaluation of the ERA5 reanalysis as a potential reference dataset for hydrological modeling over North-America Hydrology and Earth System Sciences Discussions:1-35

Theil H A rank-invariant method of linear and polynominal regression analysis (parts 1-3). In: Ned. Akad. Wetensch. Proc. Ser. A, 1950. pp 1397-1412

Ul Hasson S, Pascale S, Lucarini V, Böhner J (2016) Seasonal cycle of precipitation over major river basins in South and Southeast Asia: a review of the CMIP5 climate models data for present climate and future climate projections Atmospheric Research 180:42-63

Ullah S, You Q, Ullah W, Ali A (2018) Observed changes in precipitation in China-Pakistan economic corridor during 1980–2016 Atmospheric Research 210:1-14

Winiger M, Gumpert M, Yamout H (2005) Karakorum–Hindukush–western Himalaya: assessing high-altitude water resources Hydrological Processes: An International Journal 19:2329-2338

Wortmann M, Bolch T, Menz C, Tong J, Krysanova V (2018) Comparison and correction of high-mountain precipitation data based on glacio-hydrological modeling in the Tarim River headwaters (High Asia) Journal of Hydrometeorology 19:777-801

Yaseen M, Ahmad I, Guo J, Azam MI, Latif Y (2020) Spatiotemporal Variability in the Hydrometeorological Time-Series over Upper Indus River Basin of Pakistan Advances in Meteorology 2020

Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A (2012) APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges Bulletin of the American Meteorological Society 93:1401-1415

You Q-L, Ren G-Y, Zhang Y-Q, Ren Y-Y, Sun X-B, Zhan Y-J, Shrestha AB, Krishnan R (2017) An overview of studies of observed climate change in the Hindu Kush Himalayan (HKH) region Advances in Climate Change Research 8:141-147

Zaman M, Ahmad I, Usman M, Saifullah M, Anjum MN, Khan MI, Uzair Qamar M (2020) Event-Based Time Distribution Patterns, Return Levels, and Their Trends of Extreme Precipitation across Indus Basin Water 12:3373

Zhang A, Zheng C, Wang S, Yao Y (2015) Analysis of streamflow variations in the Heihe River Basin, northwest China: Trends, abrupt changes, driving factors and ecological influences Journal of Hydrology: Regional Studies 3:106-124.

# Figures

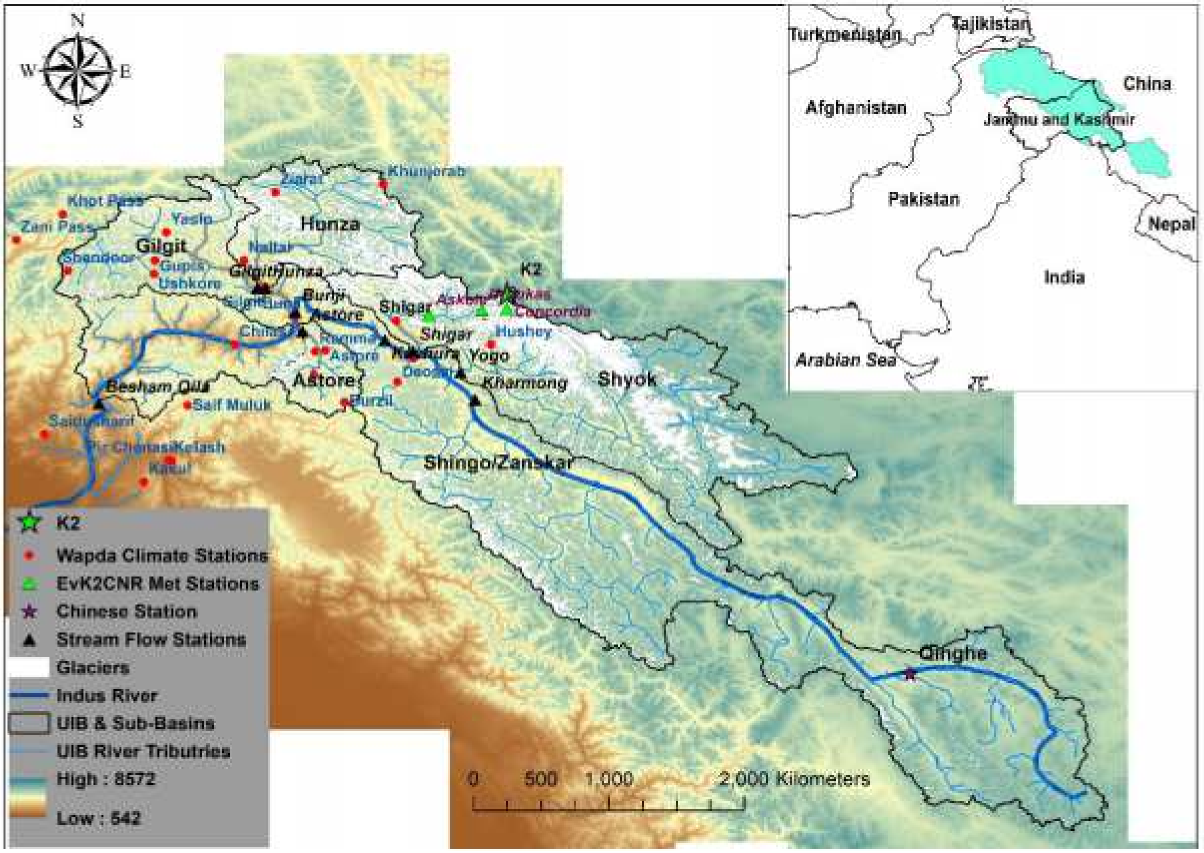


Figure 1

The location of the Upper Indus River Basin (UIB - light blue in the inset) and of the Hydro-Meteorological Stations used for the analysis. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

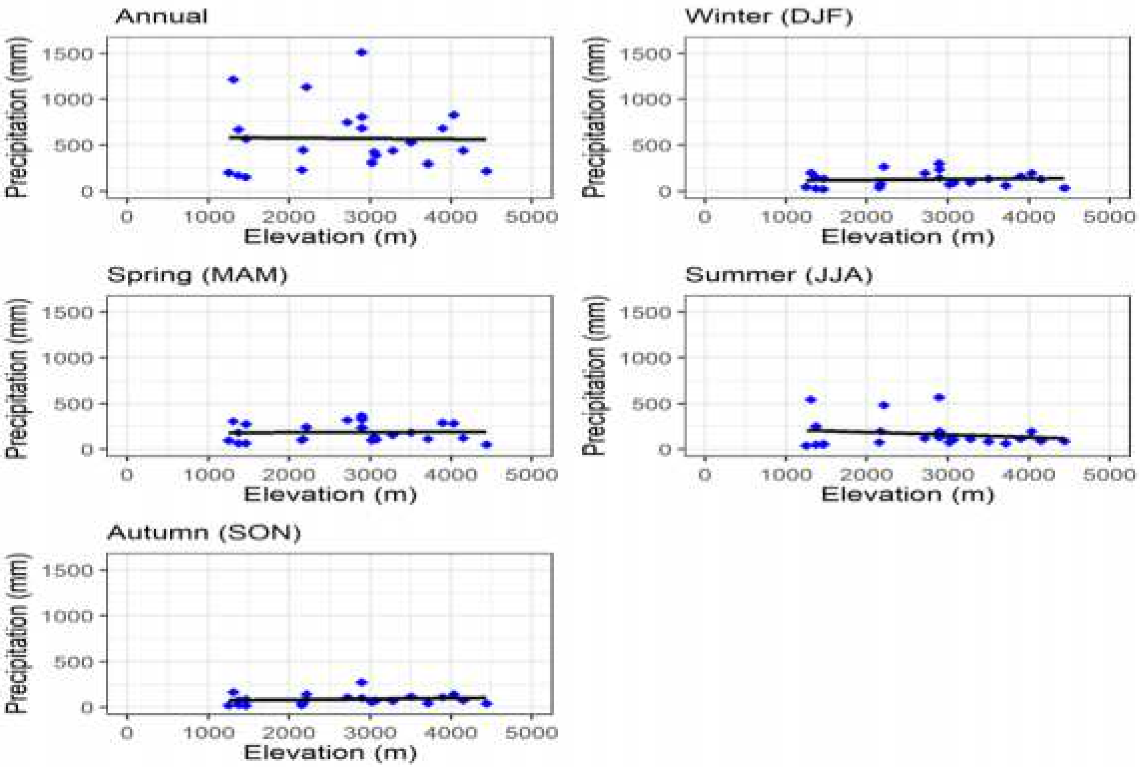
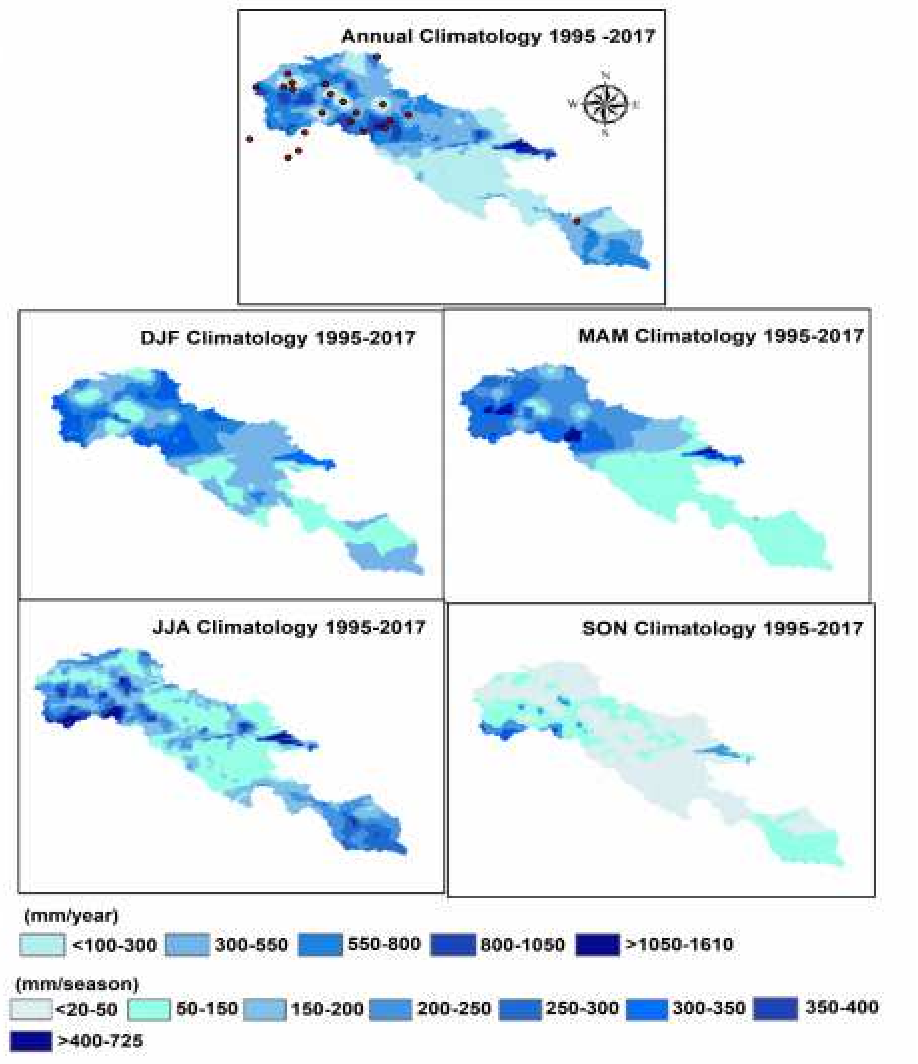


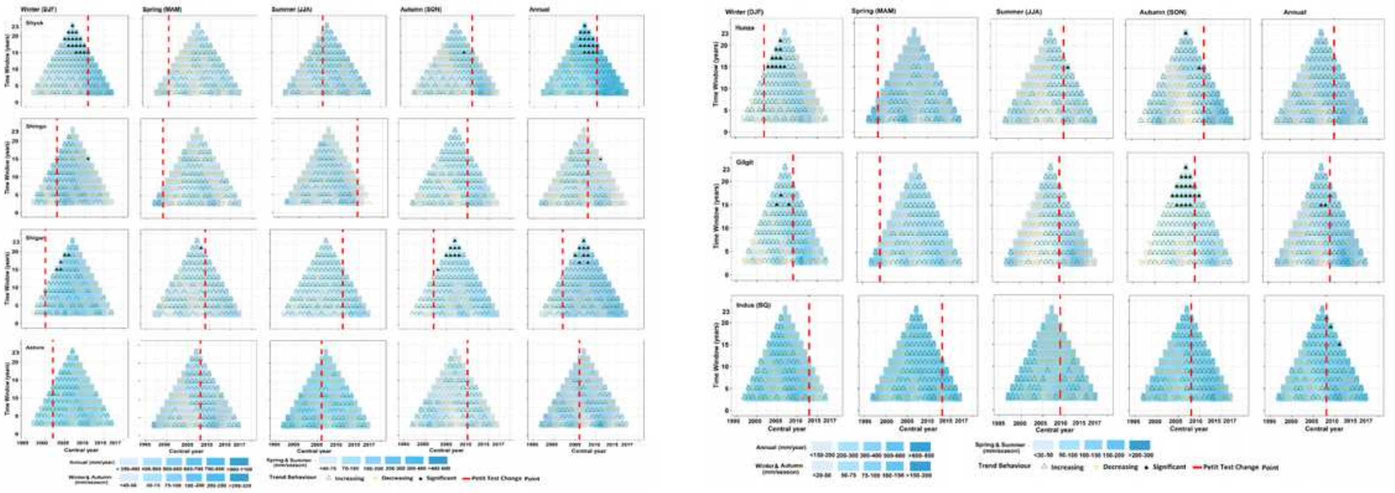
**Figure 2**

Relationship between gauge precipitation and elevation observed at the annual and seasonal scale in the UIB.



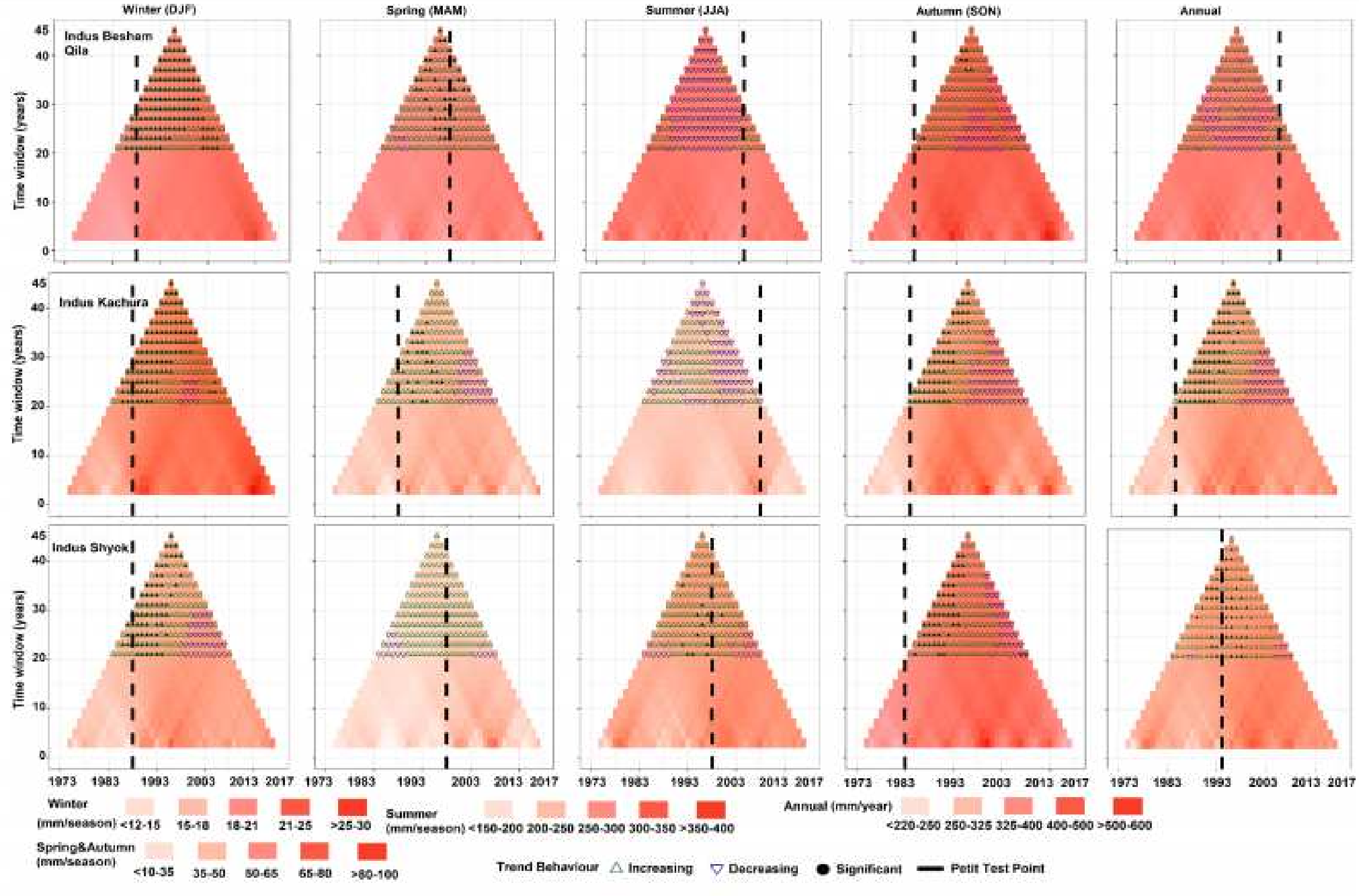
## Figure 3

Annual and seasonal precipitation climatology based on Chirps gridded datasets corrected using observed data.



## Figure 4

Running trend of annual and seasonal precipitation series. Average Precipitation values are divided into various classes (white to dark blue). Trend values are showed by upward (green) and downward triangles (yellow) while trend significance is described by filled circles (significant with at least 15 data) with Mann-Kendall pvalues < 0.05). Red vertical line expresses ‘change point’ year (Petit Test) in the entire time series. The x axis is the starting year (central year), while the y axis is the moving window.



## Figure 5

Running trend of annual and seasonal discharge series. Average discharge values are divided into various classes (white to red). Trend values are showed by upward (green) and downward triangles (blue) while trend significance is described by filled circles (significant with at least 20 data and Mann-Kendall p-values < 0.05). Black vertical line expresses ‘change point’ year (Petit Test) in the entire time series. The x axis is the starting year (central year), while the y axis is the moving window (a minimum assessment duration of 10 year is selected).

# Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplymentaryMaterial.pdf