Assessing the impacts of climate change on the high altitude snow- and glacier-fed hydrological regimes of Astore and Hunza, the sub-catchments of Upper Indus Basin

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ABSTRACT

Evaluation of the impacts of prevailing climate change on rivers and water resources is significantly important in order to successfully manage water resources, particularly in snow-fed and glacier-fed catchments. The basic aim of this research was to assess the impacts of climatic variability on Astore and Hunza river-flows by employing long-term in-situ hydro-meteorological data. Times-series analysis of high- and low-altitude station data revealed consistent summer cooling, and warming in winter and spring seasons in both Karakoram and western Himalayan basins of Hunza and Astore, respectively. The intensity of these changes was not found to be identical in both basins, i.e. Hunza depicts slightly higher summer cooling rates and slightly lower annual, winter and spring warming rates as compared to Astore. Subsequently, the significant increase in annual precipitation of Hunza was also not found to be identical with Astore precipitation, which shows only a slight increase of precipitation. Notwithstanding, comparable temperature trends were observed at both high- and low-altitude stations; however, on the contrary, precipitation shows a different pattern of behavior, i.e. significantly increased winter precipitation at high-altitude Astore stations was in contrast to the precipitation recorded by low-altitude stations. The study suggested that climate change is significantly influencing the characteristics and hydrological resources of this region.

Key words | climate change, discharge, glacier-fed, precipitation, snow-fed, upper Indus basin, warming

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INTRODUCTION

There are no doubts left among climate scientists that the earth has warmed significantly over the past few decades. There may be differences of opinion regarding the magnitude of warming, but not the overall direction. Fluctuations in climate may influence almost all the processes in the biosphere to some extent (Forsythe *et al.* 2017). Similarly, climate change also has a drastic effect on thermal and hydrologic regimes of snow- and glacier-fed rivers, having a direct impact on freshwater availability, ecosystems and domestic water use (Van Tiel *et al.* 2018). Furthermore, the understanding of the impacts of prevailing climate change on rivers and water resources is of utmost importance in order to successfully manage water resources and to further improve adaptation strategies (Rees & Collins 2006).

The footprints of the prevailing warming trends can easily be observed in various global as well as local hydrological parameters, such as an intensification in the frequency and degree of extreme weather events resulting in drought and flood, as well as an alteration in seasonal hydrological cycles, particularly in snow- and glacier-fed basins (Fullerton *et al.* 2018; Xu *et al.* 2018). The latter can significantly modify regional hydro-meteorology, which in turn can have a drastic and negative environmental and economic impact on societies over the globe (Barnett *et al.* 2005). River discharge is generally considered to be a proxy of hydrological processes and so an accurate reflector of climate changes in any given catchment (Sharif *et al.* 2013).

The impacts of prevailing climate change on hydrological regimes and water resources have been massively studied at all spatial scales, from regional to global (e.g. Jeelani *et al.* 2016; Maurer *et al.* 2016; Adnan *et al.* 2017; Armstrong *et al.* 2017; Bravo *et al.* 2017; Forsythe *et al.* 2017; Stigter *et al.* 2017; Shen *et al.* 2018; Valentin *et al.* 2018). There is substantial evidence available which shows that over the most recent decades the hydrological cycle of the earth is already responding to observed climatic warming (Mukhopadhyay *et al.* 2014; Azmat *et al.* 2018), which includes changes in precipitation patterns regionally and globally as well as increasing atmospheric water vapor content patterns (Owen *et al.* 2000).

The Upper Indus Basin (UIB) holds the major cryospheric reserves of Pakistan, which lies within the variable influence of the sub-Mediterranean westerly circulations, the summer monsoon, and the Tibetan anticyclone (Wake 1989). There are more than 6,000 glaciers in Pakistan which cover an area of around 13,000 km^2, and entire glacier cover areas in Pakistan lie in UIB (upstream Tarbela), Chitral, Swat and Jhelum Basin, respectively. Major river flows in Pakistan originate from the Hindukush-Karakoram-Himalaya (HKH) region, which is mostly covered with snow and ice throughout the year (Amin *et al.* 2018). Consequently, more than 70% of the upper Indus River flows are dependent on snow and ice melt water supplies (Archer 2003).

The excessive melting from snow and glaciers, changes in precipitation trends and their spatial distribution is significantly modifying the hydrological cycle and affecting water resources in terms of quality and quantity at both regional and global scales (Singh & Lars 2005; Lehnherr *et al.* 2018). To date, and to some extent, global climate change has also altered the availability of water resources in Pakistan, which is mainly dependent on Indus River water. The evaporation, precipitation, and discharge of Pakistani rivers and lakes have not yet been systematically quantified in order to identify changes owing to climate change (Khattak *et al.* 2011).

In this study, therefore, the main objective was to evaluate the relation between hydro-meteorological indicators in Hunza (Karakoram; glacier-fed) and Astore (western Himalaya; snow-fed) basins over the past few decades, in order to assess the impacts of climatic variability on Astore and Hunza river flows. This study would provide the basis for water management and adaptations to climate change, and would be helpful to plan and develop future strategies for better water resource management.

MATERIALS AND METHODS

Study area

The Upper Indus basin (UIB) is situated between 72°03′–77°44′E and 34°16′–37°06′N. It separates the Greater Himalaya from the central Karakoram (Bishop *et al.* 2010). The

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Upper Indus River commences from the Tibetan Plateau (TP) and flows towards northern Pakistan and subsequently diverges southward and supplies inflow to the Tarbela Dam. It is estimated that more than 12% of the area of this basin is covered by glaciers and perennial ice (Bolch *et al.* 2012). The UIB comprises six sub-basins, i.e. the Hunza, Gilgit, Astore, Shigar, Shingo and Shyok basins, which lie within the variable influence of the summer monsoon, Westerlies and the Tibetan anticyclone (Hewitt 1998; Asad *et al.* 2016). Two of the sub-basins of the UIB selected for this study were the Hunza (glacier-fed) and Astore (snow-fed) basins, which lie in the high-altitude Karakoram and western Himalayan regions, respectively (Figure 1).

Two-thirds of the annual precipitation in Astore basin falls in winter and spring, which is mainly fed by westerly circulations. However, the summer and autumn precipitation from monsoon and local jet streams accounts for only one-third of annual precipitation. The mean annual precipitation (MAP) at the valley-floor station of Astore basin is 500 mm, and it is 870 mm at the Burzil high-altitude station. In contrast, the Hunza basin's annual precipitation is evenly distributed in winter and summer, and depends mainly on westerly and summer monsoon systems, respectively. The three meteorological stations in the Hunza basin situated at Naltar, Ziarat and Khunjerab recorded MAP values of 720, 265 and 200 mm, respectively. Figure 2 shows mean monthly temperatures and precipitation values for all the stations in the Astore and Hunza basins.

Hydro-climatological station data

Long-term meteorological data comprising daily mean, minimum and maximum temperature and precipitation records from the last few decades for low-altitude valley
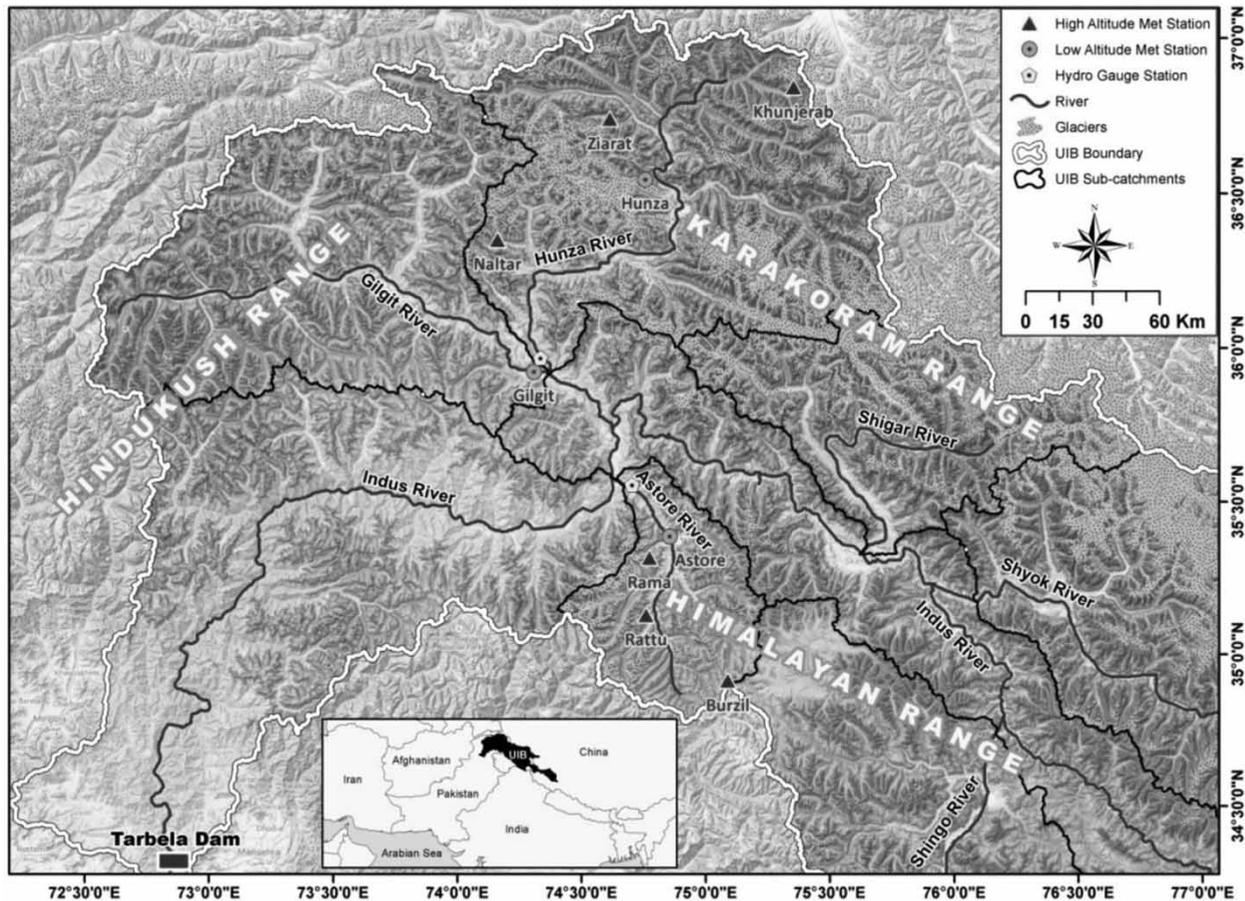

Figure 1 | Locations of meteorological and hydrographic stations in the study area.

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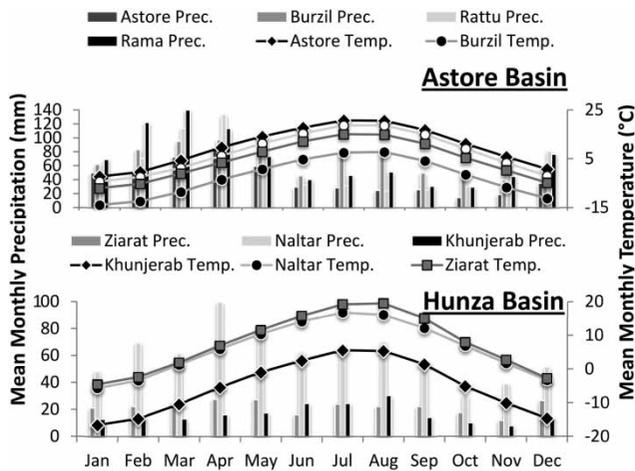
Figure 2 │ Mean monthly temperature and precipitation for the Astore and Hunza basins.

stations (for the Astore, Gilgit and Hunza basins) were acquired from Pakistan Meteorological Department (PMD). Furthermore, the daily data from the high-altitude Rattu, Rama and Burzil weather stations (Astore basin) and the Naltar, Khunjerab and Ziarat stations (Hunza basin) for the years 1995–2010 was provided by the Water and Power Development Authority of Pakistan (WAPDA). The network of discharge gauging stations is also maintained by WAPDA, and daily discharge records for both the Astore and Hunza basins from the 1970s onwards were

also made available for this study. There were no weather stations available in the Hunza basin prior to 1995; the nearest meteorological station was established at Gilgit city in the 1950s which is located on the southern perimeter of the Hunza basin. The daily correlation of Gilgit temperatures with Hunza basin temperatures during the common data period (1995–2010) were found to be very close, therefore Gilgit Station data have been used here as a proxy Hunza basin to aid the establishment of long-term trends. Figure 1 shows the locations of these stations. Table 1 gives details for hydro-climatological stations employed in this study.

Satellite remote sensing data

Daily snow cover data from MOD10A1 (Terra) was combined with MYD10A1 (Aqua) onboard MODIS (500 m spatial resolution) data provided by http://nsidc.org/data/ to estimate the spatio-temporal snow cover extent over both the basins. Terra and Aqua data has previously been combined in various studies to counter the effect of cloud cover (Parajka & Blöschl 2008; Wang *et al.* 2009). The MODIS-Terra instrument began data acquisition in 2000, whereas the MODIS-Aqua data were first collected in July 2002. As a consequence, a total of 3,090 common-period image

Table 1 │ Hydro-climatological station characteristics for the Hunza and Astore basins

Meteorological stations

Sr.	Stations	Basin	Data period	Elevation (m.a.s.l)	X coordinate	Y coordinate	Data source
1	Burzil	Hunza	1995–2010	4,030	75.089167	34.912821	WAPDA
2	Khunjerab	Hunza	1995–2010	4,730	75.354394	36.842341	WAPDA
3	Naltar	Hunza	1995–2010	2,810	74.162443	36.351177	WAPDA
4	Hunza	Hunza	2007–2010	2,374	74.757266	36.544034	PMD
5	Rama	Astore	1995–2010	3,140	74.809563	35.355483	WAPDA
6	Rattu	Astore	1995–2010	2,920	74.784495	35.147805	WAPDA
7	Ziarat	Astore	1995–2010	3,669	74.614251	36.740438	WAPDA
8	Astore	Astore	1974–2010	2,168	74.861020	35.355980	PMD
9	Gilgit	Gilgit	1966–2010	1,459	74.308615	35.922112	PMD

Hydrological stations

Sr.	Stations	Basin	Data period	Catchment area (km^2)	X coordinate	Y coordinate	Data source
1	Daniyor Bridge	Hunza	1966–2010	13,717	74.335346	35.967721	WAPDA
2	Doyian	Astore	1974–2010	3,995	74.704429	35.554481	

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pairs of Terra and Aqua data from 4 July 2002 to 31 December 2010 were used in this study. Only 13 days (i.e. eight from 2003, three from 2008, and one each from 2004 and 2006) were missing from the whole dataset.

Trend analysis

The impact of climate change on the hydro-climatology of the region can be statistically analyzed using parametric and/or non-parametric tests. Since the time-series of the hydro-climatological datasets for this region are asynchronous, non-parametric tests are more appropriate to use than parametric tests (Hess *et al.* 2001). The non-parametric Mann–Kendall test has been commonly used to test for randomness in hydro-climatological time-series trends. According to this test, the null hypothesis H_o represents the time-series data $(x_1, \ldots, x_n)$ as a sample of n independent and identically-distributed random variables (Yu *et al.* 1993). The alternative hypothesis H_1 of a two-sided test is such that the distribution of x_k and x_j is not identical for all k and $j \leq n$ with $k \neq j$. The test static S is calculated using Equations (1) and (2) which employ the mean zero and variance of S, computed by $Var(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right]/18$, and which are asymptotically normal, where t represents the extent of any given ties and $\sum_t$ denotes the summation of all ties. For cases where $n > 10$, Equation (3) computes the standard normal variate z (Douglas *et al.* 2000). In a two-sided test for trends, H_0 should be accepted if $|z| \leq z_{\alpha/2}$ at α level of significance; a positive value of S indicates an upward trend, whereas a negative value indicates a downward trend.

$$S = \sum\nolimits_{k=1}^{n-1} \sum\nolimits_{j=k+1}^{n} sgn(x_j - x_k) \tag{1}$$

$$sgn(x_j - x_k) = \begin{cases} +1 & if \quad (x_j - x_k) > 0 \\ 0 & if \quad (x_j - x_k) = 0 \\ -1 & if \quad (x_j - x_k) < 0 \end{cases} \tag{2}$$

$$z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \tag{3}$$

RESULTS AND DISCUSSION

Hydrological and cryospheric dynamics of the basins

The area of snow cover (snow cover area – SCA) for both the basins was estimated using MODIS products acquired during 2003–2010. The average SCA varies from 85% in March to 14% in late August or early September in the Astore basin, whereas in the Hunza basin SCA mean maximum reaches only 58% of the basin area in March–April, although the minimum SCA is considerably higher than that of Astore basin, i.e. 24% in August–September (Figure 3(a)). The snow accumulation period in both the basins starts in September at higher altitudes and continues until March–April. However, in late March or early April the snow-melt period starts, and almost all the snow is melted by July or early August at the latest (Figure 3(b)). After this date, most of the river flow depends on glacier-melt and/or summer precipitation. Since the minimum SCA occurs in August, when it diminishes to ca. 13–14% in the Astore and 24–25% in the Hunza basin, we can interpret this as being the residual exposed ice area of glaciers. Indeed, the Randolph Glacier Inventory estimate also indicates similar glacier coverage in both the basins.

The estimated basin mean annual discharge (water depth equivalent) reaches 1,183 mm in the Astore basin and 762 mm in the Hunza basin. More than 90% of the annual volume of the Hunza and Astore basins flows during April–October. The cumulative flows from April–June contributed to 18–22 and 36–40% of the total annual volume for the Hunza and Astore basins, respectively, generated from seasonal snow-melt at elevations $\leq$ 4,500 m.a.s.l. July on its own contributes 26–30% of the Hunza basin, and 22–26% of the Astore basin's annual volume, this being a mixture of winter and spring seasonal snow-melt from high altitudes $\geq$4,500 m.a.s.l. in addition to glacier-melt. From August to October, the summer monsoon makes little contribution; flows are mostly dependent upon glacier-melt, accounting for 42–46% of the Hunza basin, and 26–30% of the Astore basin's annual volume. These statistics suggest that >70% of the annual volume of the Hunza basin is generated from July to October, when glacier melt-water is the principal contributor; conversely, more
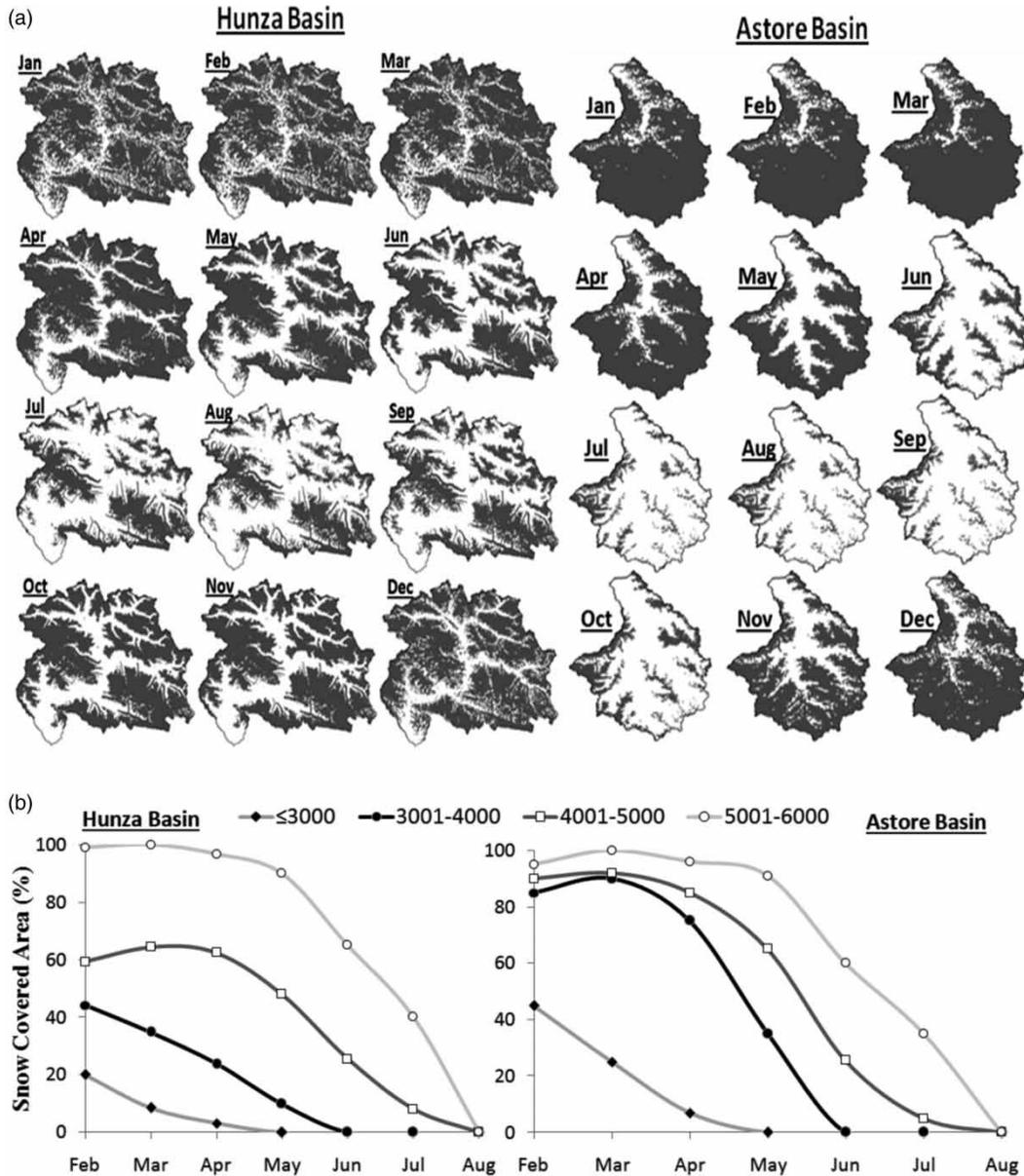
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Figure 3 │ (a) Extent of mean monthly basin snow cover; (b) Mean monthly snow cover recession curves.

than 60% of Astore basin flow is generated from April to July, when seasonal snow-melt is the main factor.

Historic hydro-meteorological variability at low-altitude stations

The trends estimated by the Mann–Kendall test are summarized in Figure 4. The lack of high-altitude weather stations prior to 1995 in the UIB restricts the user to low-altitude meteorological station data when investigating historic climate trends. As a result, we have used records from just two stations, i.e. the Astore and Gilgit (for Hunza) stations. Although the meteorological data from these two stations has been available since the 1950s, the time series for the basic hydrological data from the 1950s are not consistent with those for the meteorological data. As we needed to use synchronous time series for any complete comparison of the relevant factors, we conducted trend tests which
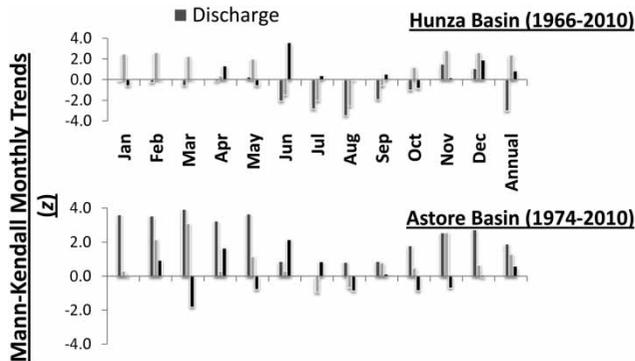
Figure 4 | Temperature, precipitation and discharge trends for the Astore and Hunza basins; values ≥ 1.96 and ≤ -1.96 represents a trend significance level $\alpha < 0.01$.

employed overlapping time series, i.e. 1966–2010 for the Hunza, and 1974–2010 for the Astore, basins. Although we employed only low-altitude station data to investigate historic climate trends, we found a highly correlative relation between temperature records for the stations in the Hunza basin, i.e. Ziarat, Naltar and Khunjerab and those in the Astore basin, i.e. Rama, Rattu and Burzil for the period 1995–2010, with a significance level $\alpha < 0.01$. Low-altitude weather stations can thus be taken as representative of the whole basin, at least for the investigation of historic climate trends.

The general trends of mean monthly Hunza basin (1966–2010) and Astore basin (1974–2010) temperatures reveal significant warming in winter and the early spring months (October–March), and only slight warming during April–May. Conversely, there is slight cooling in the Astore basin during July and August and significant cooling in the Hunza basin's summer temperatures during June–September. The cooling rate in the Hunza basin during the latter period was –0.08 °C per decade, whereas the observed warming for the other relevant months was +0.11 °C per decade. Although in the Astore basin there was an almost similar rate of cooling of –0.07 °C per decade from July to August, during the other months (September–June) the warming rate was slightly higher than in the Hunza basin, i.e. +0.14 °C per decade. The mean annual temperature (MAT) in the Astore basin thus reflects a strong warming trend, with a decadal rate of +0.1 °C; this trend was slight in the Hunza basin, with a rate of +0.04 °C per decade. These increases in annual and winter temperatures appear to be in line with the overall increase in global temperatures. Fowler & Archer (2006) observed similar strong warming

trends in the UIB's annual and winter temperatures in valley stations data; their work was supported by Immerzeel *et al.* (2009), who used coarse-resolution global data and found relatively similar trends. Nonetheless, the observed propensities are not homogenous for the whole year, i.e. in summer, the cooling temperatures are in stark contrast to global summer temperature trends as well as climate modelling results for the TP grid box (UIB is a part of that grid), both of which reveal substantial warming trends in every season. Similar summer cooling trends in the UIB were also observed by Hussain *et al.* (2005) and Sheikh *et al.* (2009), though Immerzeel *et al.* (2009) found weaker warming trends in UIB summer temperatures.

No significant trends in precipitation were identified, except from June to November for the Hunza basin, when rapidly increasing trends were observed. Conversely, there were significant increases in spring and summer, and significant decreases during March in the Astore basin, with only slight decreases in late summer months. Consequently, there was a slight increase in the aggregated annual precipitation in the Astore basin of 0.8% per decade, and a relatively higher decadal increase of 2.2% for the Hunza basin over the same period.

Discharge trends show a significant decrease in the summer months (June–September) for the Hunza basin, but there is not much obvious variation in winter and spring (January–May). On the other hand, there is a significant increase in discharge in October–November and a substantial decrease in December. This is in stark contrast to discharge in the Astore basin, where a significant increase from October–May is followed by only a slight increase during the summer months (June–September). Looking at monthly trends, the mean annual discharge of both basins evinces contrasting trends, i.e. a rising trend in Astore and a declining one in Hunza (Figure 5(a)). These findings are in accordance with those of Khattak *et al.* (2011) and Sharif *et al.* (2013).

A comparative assessment of daily runoff volumes between asynchronous periods is highly inappropriate due to the stop-go nature of daily flow volumes. To counter this, a time-series based on a pentad (five-year) daily mean runoff volume was established. Figure 5(b) shows the deviation from the base period (1966–1970 for the Hunza and 1976–1980 for the Astore basin) for the pentad series, which reveals significant seasonal fluctuations and shifts in
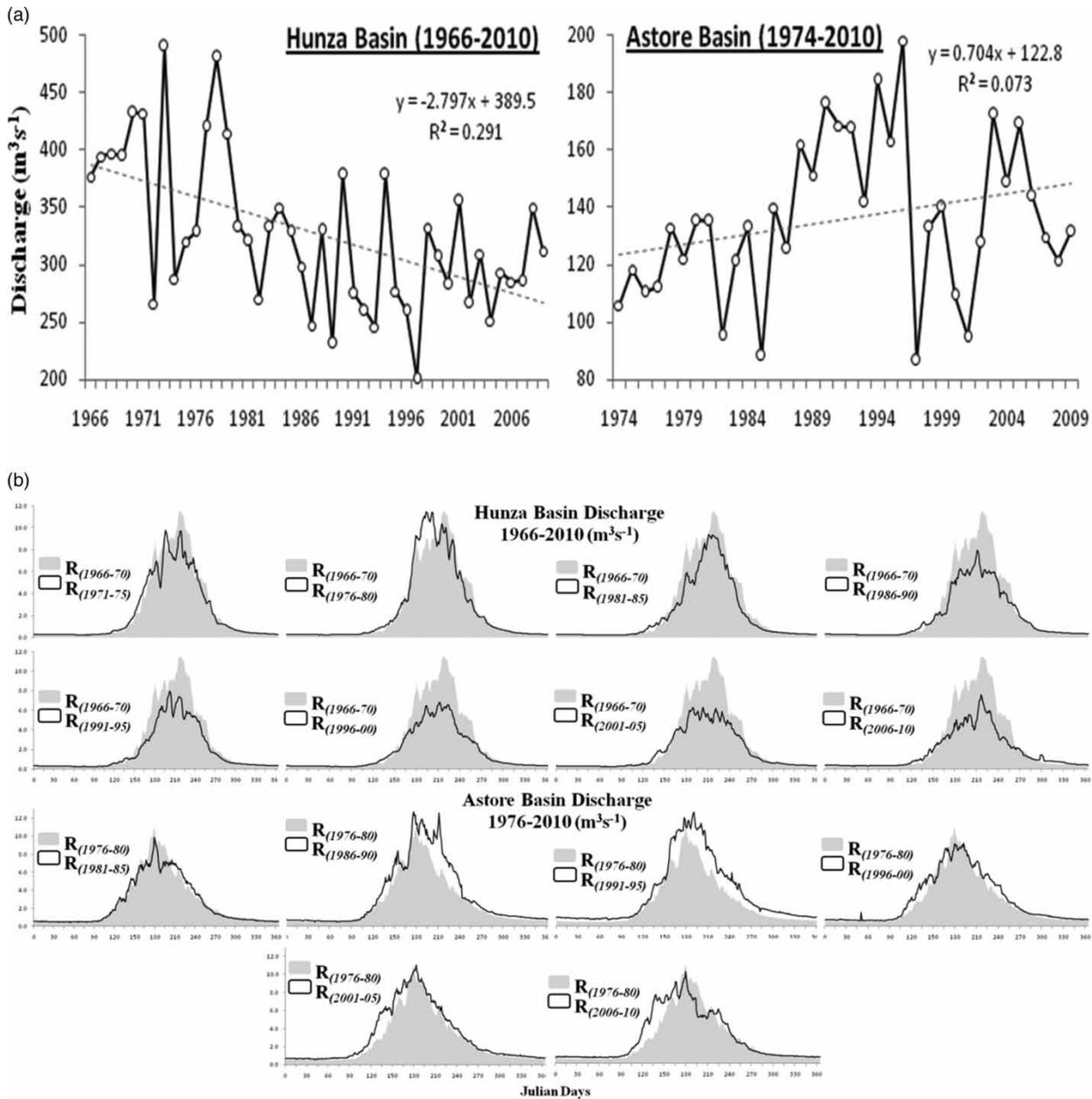
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Figure 5 | (a) Annual discharge trends; and (b) Pentad five-year daily mean discharge fluctuations from the base period for the Hunza and Astore basins.

daily flows. Hunza runoff exhibits a significant decline in all the seasons/days except winter, when it shows a slight increase during 1966–2010. On the other hand, Astore runoff in the spring season portrays a significant increase despite little mean variation in summer flows during 1976–2010, although summer runoff does show a significant increase until 1995 (Figure 5(b)).

Recent climatic trends at high-altitude stations, 1995–2010

Most of the glacier-cover in the UIB lies at high altitudes. To understand climate behavior at high altitudes therefore seems essential. Accordingly, high-altitude station data from 1995–2010 was employed to investigate climate trends at

these elevations. The Mann–Kendall trend test was applied to all seven meteorological stations in both basins (found at different altitudes) over the whole period. The outcomes show a consistently significant correlation between all the stations in their respective basins, and for almost all the climate indicators.

Temperature trends were relatively similar to those found at the low-altitude stations, e.g. a significant cooling in summer and a warming in winter and spring months in both basins during 1995–2010 (Figure 6). Moreover, there was a significant decrease in precipitation during the spring and summer months in the Astore basin, and a marked increase during the winter. On the other hand, no general precipitation trend was observed in the Hunza basin: some stations evinced falls in precipitation, and others increases, for the same months. An interesting turn-around was observed in the Hunza basin's discharge trends during 1995–2010, as almost all the monthly trends were markedly inversed from those analyzed for the 1966–2010 period (Figure 6). For example, the winter discharge (November–December) declined significantly, whereas

during the other months it rose, albeit slightly. A similarly inverted pattern was also noted in the Astore basin, where significant declines in discharge were observed during July–February (excluding August, which showed a slight increase). Conversely, marked increases were observed during March–June (Figure 6). Spring and early summer stream-flow is mainly dependent upon snow-melt runoff yields: due to the increase in spring temperatures and the redistribution of monthly snow-melt yields, the spring and early summer stream-flows also increased, particularly in the Astore basin.

The overall results from the high- and low-altitude stations revealed consistent summer cooling, and warming in winter and spring seasons in both the Karakoram and western Himalayan basins of the Hunza and Astore. This summer cooling trend is well-supported by the findings of Fowler & Archer (2006) and Farhan *et al.* (2015). The intensity of these changes was not found identical in both basins, i.e. the Hunza basin depicts slightly higher summer cooling rates and slightly lower annual, winter and spring warming rates as compared to Astore Basin. The slight increase
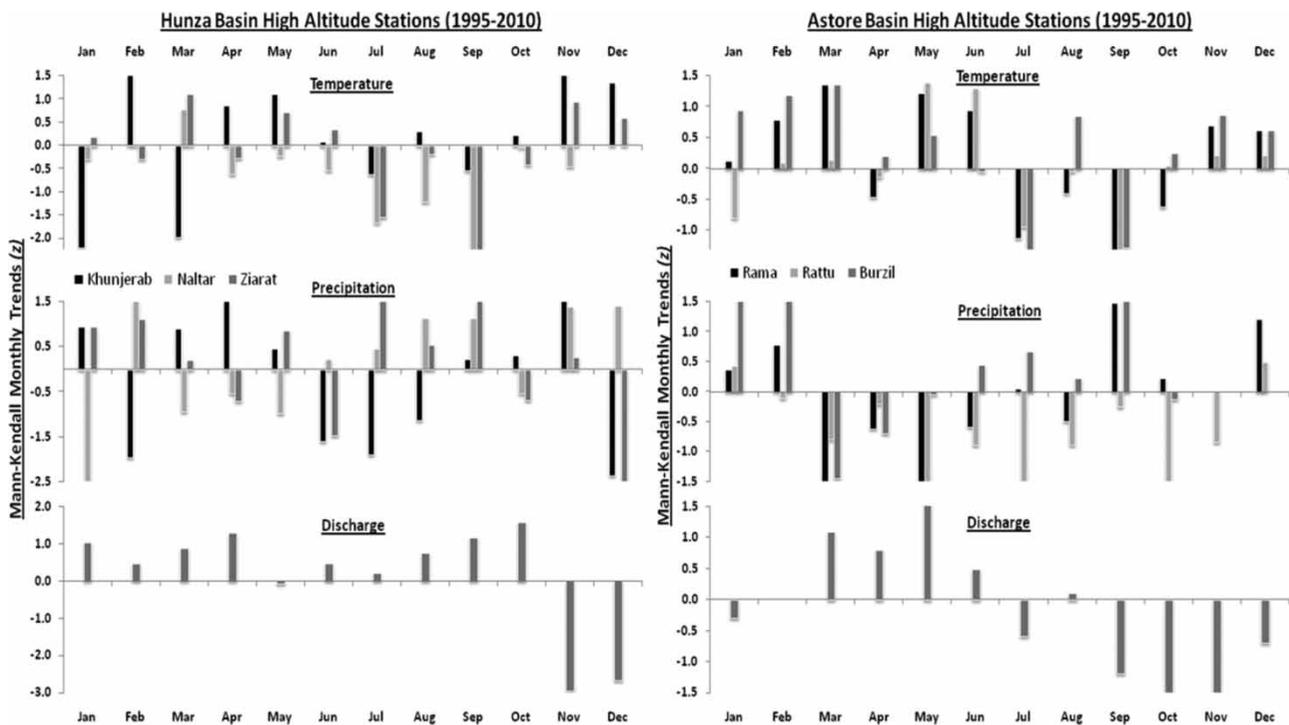

Figure 6 │ Monthly temperature, precipitation and discharge trends during 1995–2010 for the Hunza and Astore basin high altitude stations; values ≥1.96 and ≤ − 1.96 represent a trend significance level $\alpha < 0.01$.

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in overall aggregated annual precipitation of the Astore Basin was not found to be identical with Hunza basin's precipitation, since the Hunza basin precipitation shows a relatively higher increasing trend, which is also in accordance with the findings of Fowler & Archer (2006), Treydte *et al.* (2006) and Yao *et al.* (2012). Similar temperature trends were observed at both high and low altitude stations; however on the contrary, the precipitation shows a different pattern of behavior, i.e. significantly increased winter precipitation at high-altitude Astore stations was in contrast to the precipitation recorded by low-altitude stations.

We found increasing precipitation trends in Hunza Basin (Karakoram region), however, on the other hand, the summer River runoff/discharge was found to be declining. It may be explained here that the reduced summer temperatures *vis-à-vis* the 'anomalous cooling', as suggested by Fowler & Archer (2006) and recently explained as 'Karakoram vortex' by Forsythe *et al.* (2017), also reduced the rate of melting which resulted in the decrease of melt-water from glacier storage and, consequently, may lead to glacier growth, as has been reported for many other Karakoram glaciers for some periods in recent decades, since most of the runoff of Hunza River is dependent on the melting of glaciers in the summer season. This glacier stability, consequent upon cooling summer temperatures, increased precipitation and is found to be in line with the observed stability/growth of Karakoram glaciers *vis-à-vis* 'Karakoram Anomaly' (Hewitt 2005), however, it is contrary to the widespread decay and retreat in the eastern Himalayas, and undergoes a different response to global warming compared to glaciers in most other parts of the globe. Since no in-situ glacier observations and mass balance data are yet available for this basin, uncertainties remain and should not be ignored because the behavior of some glaciers in the basin may differ as a result of the basin's local dynamics and so may not be clearly identified using only satellite remote sensing data.

CONCLUSIONS AND RECOMMENDATIONS

Climate change has a drastic effect on thermal and hydrologic regimes of snow- and glacier-fed rivers, having a direct impact on freshwater availability, ecosystems and domestic water use. River discharge is generally considered to be a proxy of hydrological processes and so an accurate reflector of climate changes in any given catchment. Therefore, in this study we evaluated the impact of climatic variability on Astore and Hunza river flows and assessed their historical trends. The conclusions drawn from this study are mainly inferred from long-term in-situ hydro-meteorological data. The study suggested that climate change is significantly influencing and altering the characteristics and hydrological resources of this region. The high- and low-altitude stations are experiencing consistent summer cooling, and warming in winter and spring seasons in both Hunza and Astore Basins, although the intensity of these changes was not found to be identical in both basins. The slight increase in overall aggregated annual precipitation of the Astore Basin was also found to be incomparable with Hunza basin's precipitation, which shows a relatively high increasing trend of precipitation in the Hunza basin.

Furthermore, the comparable temperature trends were observed at both high and low altitude stations, however on the contrary the precipitation shows a different pattern of behavior, i.e. significantly increased winter precipitation at high-altitude Astore stations was in contrast to the precipitation recorded by low-altitude stations. The significant decline in stream-flow during the glacier-melt season, particularly in the Hunza basin, was found to be mainly associated with summer cooling, less glacial ablation and, ultimately, a significant decrease in Hunza River discharge. The same was not true for the Astore basin; during the glacier-melt season there was a slight increase in discharge but a decrease in temperature. This negative correlation between temperature and discharge in snow-fed catchments, ignoring the lack of any in-situ observations of evaporative losses, makes it difficult to evaluate the impact of climate change on glacier-melt regimes using hydrological feedback. Comprehensive studies to identify the impact of ongoing climate change on the local hydrological cycles in snow- and glacier-fed basins are thus to be recommended. Overall, this study provides the basis for water management and adaptations to climate change, and would be helpful in planning future strategies of water management and adaptations strategies. It is also recommended that future studies should take into account the other critical factors influencing river runoff, particularly land use and

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precipitation spatial pattern changes, in order to obtain a more comprehensive assessment and to improve adaptation strategies.

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