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Hydro-meteorological trends in the upper Indus River basin in Pakistan

M. Shahzad Khattak[1], M. S. Babel[1,*], M. Sharif[3]

[1]Water Engineering and Management, Asian Institute of Technology, PO Box 4, Klong Luang, Pathumthani 12120, Thailand
[2]Department of Civil Engineering, Jamia Millia Islamia University, Jamia Nagar, New Delhi – 110025, India

ABSTRACT: We examined trends in several hydro-meteorological variables in the upper Indus River basin (UIRB) in Pakistan. To represent the diversity of hydro-meteorological conditions in the basin, mean monthly data from 20 meteorological and 8 hydrometric stations were analyzed for detection of trends using the non-parametric Mann-Kendall test in combination with the trend-free pre-whitening approach for correcting time series data sets for serial correlation. Sen's slope method, a non-parametric alternative for estimating a slope for a univariate time series, was used to determine the magnitude of trends. The meteorological variables we considered were: minimum temperature, maximum temperature, and precipitation, whereas the hydrological variable considered was streamflow. For several of the variables, many more trends were identified than can be expected to occur by chance. Analysis of winter maximum temperature revealed an increasing trend with the trend in slopes of 1.79, 1.66, and 1.20°C per 39 yr for the upper, middle, and lower regions, respectively. Precipitation trends were inconsistent and showed no definite pattern. Trends in streamflow were found to be related to increasing trends in mean maximum temperature, particularly in winter and spring seasons. Increased winter temperatures are likely to increase streamflow in winter and spring. During summer months streamflow will decrease and reduce the availability of water in the Tarbela Dam, thereby requiring changes in the reservoir operating policy towards more efficient management of available water.

KEY WORDS: Climate change · Trend analysis · Pakistan · Mann-Kendall test · Sen's slope test · Upper Indus River basin

1. INTRODUCTION

During the last few decades, the concentration of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere has increased considerably, mainly due to the burning of fossil fuels and biomass, rapid industrialization, and changing land-use patterns. Projected global changes in temperature are likely to intensify the hydrologic cycle and, hence, alter hydrologic systems. As a result, hydrological systems are anticipated to experience, not only changes in average availability of water, but also changes in extremes (Simonovic & Li 2003, Jiang et al. 2007). However, impacts of climate change on hydrological systems may vary from region to region.

Several studies have reported that warming has taken place over India (Arora et al. 2005, Singh et al. 2008), Bangladesh (Ahmad & Warrick 1996), and Nepal (Shrestha et al. 1999). Shrestha et al. (1999) reported increases of 0.61, 0.90, and 1.24°C decade^{-1} in winter maximum temperatures for Nepal, Himalayan, and trans-Himalayan climate stations, respectively. CICERO (2000) estimated a temperature rise of 0.9°C for Pakistan by 2020 and predicted that the temperature rise could double by 2050. Overall, an increasing temperature trend was reported for China, and a negative trend was detected in high-latitude regions during summer. Winter periods have shown a warming trend in the southwest Xinjiang and southwest Tibet regions (Gemmer et al. 2003). Fowler & Archer (2006) examined temperature data (1961–1999) of 7 climate stations in the Karakoram and Hindukush mountains using regression techniques, and detected a winter warming and a summer cooling trend.

*Corresponding author. Email: msbabel@ait.ac.th

Many precipitation trend studies have also been carried out in the South Asia region (e.g. Zhang et al. 2005, Huang et al. 2009). Gemmer et al. (2003) showed that there was an increasing precipitation trend 1951–2002 in southwestern Xinjiang, which is an area adjacent to the northern part of Pakistan, and in Jammu-Kashmir, which is southwest of Tibet. Archer & Fowler (2004) used linear regression to analyze precipitation data from various stations in the upper part of the Indus River basin with different record lengths. A significant increasing trend of precipitation in winter and summer during the period 1961–1999 was detected. On the contrary, Raziei et al. (2005) concluded that precipitation in Iran is decreasing. Kezer & Matsuyama (2006) investigated runoff trends for the Ili and East Rivers in Central Asia; no statistically significant change was observed except for runoff. Chen et al. (2007) investigated temporal (1951–2003) trends in annual and seasonal precipitation, temperature, and runoff in the Hanjiang basin in China using the Mann-Kendall test and linear regression. Results indicated that precipitation did not exhibit a significant trend, but a significant increasing trend for temperature was seen in most parts of the basin at the 5% level. Furthermore, a decreasing trend was seen in mean annual, spring, and winter runoffs in the Danjiangkou reservoir basin.

Results of several recent studies have confirmed that the South Asia region is indeed warming, and the trend of warming is broadly consistent with the global warming trend (Singh et al. 2008). As a consequence, many aspects of the natural environment, including water resources, are anticipated to experience potentially serious climatic impacts in the South Asia region. The recent Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2007a) clearly indicates the likelihood of considerable warming over subregions of South Asia, with greater warming in winter than in summer. Results of multimodel GCM (global climate model) runs under the Special Report on Emission Scenarios (SRES) B1 and A1F1 project an increase in average temperature over all of South Asia, with the greatest increase being projected for winter months. The projected rise in temperature for winter months exceeds the range of the global mean surface temperature rise (1.8 to 4°C) reported by the IPCC (2007b).

The impact of global climate change on hydrological systems has been extensively studied (Bates et al. 2008). Many recent works have focused on the assessment of the impacts of climate change in snow-dominated basins. Burn (1994) and Westmacott & Burn (1997) examined the impacts of climate change on the timings of spring runoff in West-Central Canada. Burn et al. (2004a,b) investigated trends and variability in hydrological variables for natural streamflow gauging stations for the Liard and Mackenzie River basins in northern Canada. Both basins exhibited an increase in winter flows and some increase in spring runoff. Abdul Aziz & Burn (2006) and Burn (2008) noted an earlier onset of the spring freshet over the Mackenzie River basin. Novotny & Stefan (2007) observed that the threat of flooding has increased due to rainfall events rather than snow melt in 5 major river basins of Minnesota, USA.

In developing countries like Pakistan, climate change could represent an additional stress on ecological and socioeconomic systems that are already facing tremendous pressure due to rapid urbanization, industrialization, and economic development. With its large and growing population and an economy that is closely tied to its natural resource base, Pakistan is highly vulnerable to the effects of climate change. According to the recent work of Vorosmarty et al. (2010), the South Asian region shows high incident threats to human water security or biodiversity. The Himalayan region has >12 000 glaciers (ICIMOD 2001), and the Indus River is replenished by melt-water from around 3300 glaciers (Thayyen & Gergan 2010). The water security of Pakistan is likely to be impacted due to changes in the temporal and spatial distribution of water. The erratic and uncertain pattern of water availability is likely to impact crop yields due to changes in the dynamics of the hydrological cycle. Therefore, the main focus of this research is to detect and analyze the trends in hydro-meteorological variables from several stations in the upper Indus River basin (UIRB).

Previous studies (Archer & Fowler 2004, Fowler & Archer 2006) in the UIRB applied a linear regression technique for the analysis of trends in temperature and precipitation variables. In the present study, the nonparametric Mann-Kendall test has been used for the trend analysis with the trend-free pre-whitening (TFPW) approach (Yue et al. 2002) for correcting time series for serial correlation. Apart from temperature and precipitation, the present study analyzes trends in streamflow as well. In previous work, meteorological stations covering only a more restricted upper part of the Indus River basin were considered, whereas the present work covers stations from the entire UIRB lying in Pakistan.

2. STUDY BASIN

The Indus River basin is one of the world's largest basins, covering an area of approximately 1.1×10^6 km^2, shared by Afghanistan (6.7%), China (10.7%), India (26.6%), and Pakistan (56%) (Wolf et al. 1999). The Indus River is the major river flowing through the basin. One of the world's longest rivers (3180 km), it originates from the Tibetan Plateau north of Lake Mansarovar at 5500 m above mean sea level. It flows through Jammu, Kashmir, and Pakistan before draining into the Arabian Sea (Negi 2004). The other main rivers that flow westwards into this basin are the Jhelum, Chenab, Ravi, Beas, and Sutlej, while the Kabul River originates at the base of the Unai Pass in Afghanistan and flows eastward towards Kabul city in Afghanistan and meets the Indus River at Attock in Pakistan.

The study area for this research is confined to the upper part of the Indus River basin that lies in Pakistan, and is referred to as the UIRB (Fig. 1). The UIRB lies between latitudes 32.48 and 37.07° N and longitudes 67.33 and 81.83° E, and covers an area of approximately 289 000 km^2. The basin is fed by a combination of seasonal snowmelt, permanent glacier melt, and direct runoff from rainfall during winter and summer monsoon seasons (Archer 2003). The Kabul River is the second major river in the basin. The Tarbela Reservoir (Fig. 1) is a major storage facility on the Indus River in Pakistan. It came into full operation in 1976. Owing to sedimentation, the gross storage capacity of the Tarbela Reservoir has been reduced from 14.3×10^9 to 10.3×10^9 m^3 (Haq & Abbas 2006). The main purpose of Tarbela Reservoir is to store water from the Indus River and to ensure a continued and improved supply of water for irrigated land in Pakistan, besides generating hydro-electric power (3500 MW) and controlling floods during the high flow period (summer season). Details on hydrometric locations, obtained from the Water and Power Development Authority (WAPDA) of Pakistan, are presented in Table 1. The mean monthly and mean annual runoff data for the major rivers in the UIRB are

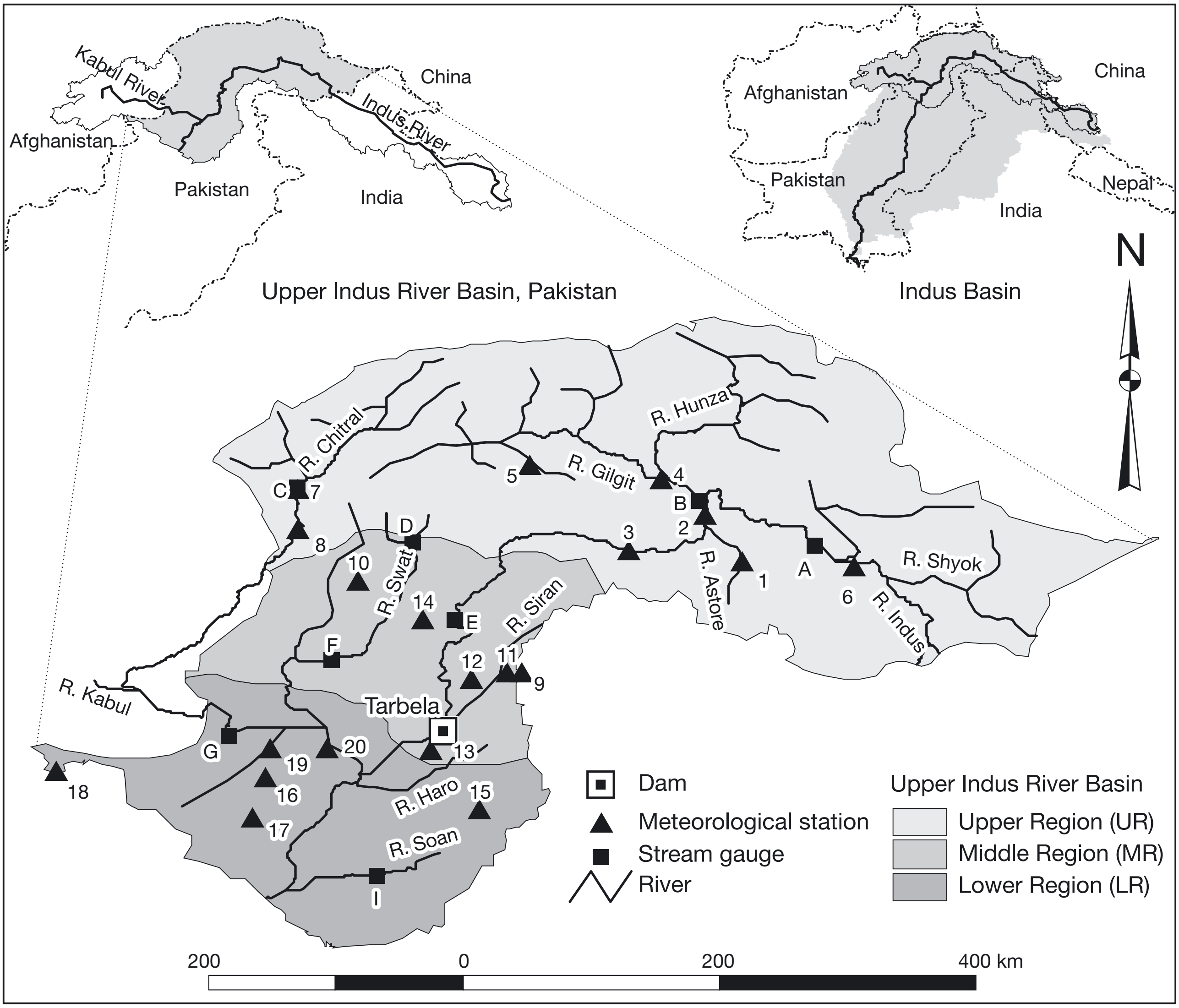

Fig. 1. Spatial distribution of climate and hydrometric stations in the upper Indus River basin (UIRB), Pakistan. Top right: full extent of the Indus River Basin (grey)

Table 1. Details of the hydrometric stations in the upper Indus River basin, Pakistan. Note: upstream basin areas with elevations >5000 m above sea level (a.s.l.) are considered permanent glaciers (Archer 2003). Data from WAPDA (2002)

ID	Hydrometric station	River name	Lat. (°N)	Long. (°E)	Catchment area (km^2)	Elevation (m a.s.l.)	Percent area >5000 m a.s.l.
A	Kachura	Indus	35.45	75.41	113 890	4789	45.7
B	Alam Bridge	Gilgit	35.76	74.60	28 039	4094	20.2
C	Chitral	Chitral	35.86	71.78	12 383	3794	16.8
D	Kalam	Swat	35.47	72.59	2025	3300	2.8
E	Besham	Indus	34.92	72.88	163 988	4505	35.6
F	Chakdara	Swat	34.64	72.02	5400	2499	1.1
G	Warsak	Kabul	34.10	71.30	68 217	2415	3.3
I	Dhok Pathan	Soan	33.12	72.34	6475	1240	0.0

Table 2. Mean monthly and annual runoff (mm) of major rivers (see Table 1 for further details) in the upper Indus River basin, during the period 1967–2005

	A Indus	B Gilgit	C Chitral	D Swat	E Indus	F Swat	G Kabul	I Soan
Jan	4.7	11.2	16.8	19.9	7.5	20.2	6.8	6.3
Feb	3.9	8.9	13.5	16.5	6.6	23.6	5.7	7.8
Mar	4.4	9.1	14.8	22.3	8.5	55.0	8.9	13.5
Apr	5.8	12.0	19.8	62.2	13.8	98.0	22.7	7.5
May	18.7	41.3	41.9	175.2	35.0	147.8	40.0	4.5
Jun	48.8	123.3	103.6	316.3	81.2	199.6	54.6	6.1
Jul	78.7	199.3	181.7	337.6	121.5	208.0	55.2	44.8
Aug	74.0	175.9	162.3	220.0	106.5	144.5	39.0	74.2
Sep	33.5	78.8	80.3	101.0	47.0	65.4	17.6	29.2
Oct	11.8	30.2	36.0	46.8	18.0	37.6	9.4	7.6
Nov	7.3	17.1	23.7	29.7	10.9	25.1	7.3	4.3
Dec	5.7	13.3	19.7	23.6	8.8	22.4	7.0	5.3
Annual	297.4	720.4	714.0	1371.1	465.2	1047.2	274.3	211.3

given in Table 2. The contribution of water from the UIRB is >60% of Pakistan's annual runoff. The water from the UIRB generates >80% of the total installed hydropower capacity of 6500 MW (WCD 2000, GoP 2005) and irrigates 9 Mha of land in Pakistan (Kahlown et al. 2005).

3. DATA USED

A hydro-meteorological monitoring network consisting of 20 climate stations and 8 hydrometric stations has been used in the present study. Owing to the wide variation in climate characteristics, the basin is divided into 3 distinct sub-regions, namely the upper region (UR), the middle region (MR), and the lower region (LR) (Ahmad 1951, Ali 1971). There are 8 climate and 3 hydrometric stations in the upper region, 6 climate and 3 hydrometric stations in the middle region, and 6 climate and 2 hydrometric stations in the lower region of the basin. Details of the climate and hydrometric stations are presented in Fig. 1 and Table 1, respectively. All the hydrometric stations considered in this research are unregulated and reasonably free from land-use changes. The dataset has been obtained from the Pakistan Meteorological Department (PMD) and WAPDA, Pakistan. Mean monthly minimum temperature (TMN) and maximum temperature (TMX), and precipitation (PPT) data were available from 17 climate stations in the basin, while the remaining 3 stations only had precipitation data. Daily streamflow data were available at all 8 hydrometric stations.

The details for the meteorological stations are provided in Table 3. Mean monthly streamflow data were derived using the daily discharge data available at the hydrometric stations and then converted into millimeters of water. The time series of TMN, TMX, PPT, and streamflow considered cover the period 1967–2005. For maximum coverage of the basin, and to ensure a uniform comparison period for all data types, an analysis period of 39 yr spanning 1967–2005 was chosen. A year is divided into 4 seasons of 3 months each, namely winter (December–February), spring (March–May), summer (June–August), and autumn (September–November).

4. METHODOLOGY

Many parametric and non-parametric methods have been applied for detection of trends (Kundzewicz & Robson 2004, Zhang et al. 2006). Parametric tests are more powerful than non-parametric tests, but the assumption that the data are normally distributed must be satisfied. Hydro-meteorological time series are often characterized by data that exhibit departures from normality, and, therefore, non-parametric tests are considered more robust compared to their parametric counterparts (Hess et al. 2001). One of the most widely used non-parametric tests for detecting a trend in the hydro-meteorological time series is the Mann-Kendall test (Mann 1945, Kendall 1975). A major advantage of the Mann-Kendall test is that it can tolerate outliers. Several researchers have employed the Mann-Kendall test to identify trends in the hydro-meteorological variables due to climate change (Burn

Table 3. Details of the meteorological stations in the upper Indus River basin. The data were provided by the Pakistan Meteorological Department, except as specifically indicated. UR: upper region; MR: middle region; LR: lower region

ID	Station name	Region	Lat. (°N)	Long. (°E)	Elevation (m a.s.l.)
1	Astore	UR	35.33	74.90	2394
2	Bunji	UR	35.66	74.63	1372
3	Chilas	UR	35.41	74.10	1250
4	Gilgit	UR	35.91	74.33	1460
5	Gupis	UR	36.01	73.40	2156
6	Skardu	UR	35.30	75.68	2210
7	Chitral	UR	35.85	71.78	1498
8	Drosh	UR	35.56	71.78	1465
9	Balakot	MR	34.55	73.35	980
10	Dir	MR	35.20	72.20	1375
11	Kakul	MR	34.55	73.25	1308
12	Oghi[a]	MR	34.50	73.00	1128
13	Tarbela[a]	MR	34.00	72.71	610
14	Shahpur[a]	MR	34.92	72.66	2012
15	Chaklala	LR	33.58	73.05	505
16	Cherat	LR	33.81	71.55	995
17	Kohat	LR	33.53	71.46	466
18	Parachinar	LR	33.86	70.08	1748
19	Peshawar	LR	34.01	71.58	359
20	Risalpur	LR	34.01	71.98	305

[a]Water and Power Development Authority, only precipitation data were available

1994, Douglas et al. 2000, Burn et al. 2004a,b, Chen et al. 2007, Burns et al. 2007, Singh et al. 2008). In the present study, 2 non-parametric statistical techniques have been used for the analysis of hydro-meteorological data: (1) the Mann-Kendall test in combination with the TFPW approach for trend detection and distribution of test statistics and (2) the Sen's (1968) slope method for quantification of trends during the analysis period.

The Mann-Kendall test is a ranked based approach that compares each value of the time series with the remaining values in a sequential order (Hirsch et al. 1982). The test statistic S is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} Sgn(x_j - x_k) \quad (1)$$

where

$$Sgn(x_j - x_k) = \begin{bmatrix} 1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{bmatrix} \quad (2)$$

and x_j and x_k are the sequential data values, and n is the length of the dataset. A positive value of S indicates an upward trend, and a negative value indicates a downward trend. For samples >10, the test is conducted using the normal distribution (Helsel & Hirsch 1992), with the expectation (E) and variance (Var) as follows:

$$E[S] = 0 \quad (3)$$

$$\text{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \quad (4)$$

where t_p is the number of data points in the pth tied group and q is the number of tied groups in the dataset. The standardized test statistic (Z_{mk}) is calculated as:

$$Z_{mk} = \begin{bmatrix} \dfrac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ \dfrac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \\ 0 & \text{if } S = 0 \end{bmatrix} \quad (5)$$

where the value of Z_{mk} is the Mann-Kendall test statistic that follows a standard normal distribution with mean 0 and variance 1. The Z_{mk} value can be related to a p-value of a specific trend. A p-value is a measure of evidence against the null hypothesis of no change. The smaller the p-value, the greater the strength of evidence against the null hypothesis. In a 2-sided test for trend, the null hypothesis of no trend H_o is accepted if $-Z_{1-\alpha/2} \leq Z_{\text{mk}} \leq Z_{1-\alpha/2}$, where α is the significance level that indicates the trend strength. In the present study, the trends are categorized as very strong (VS), strong (S), weak (W), little (L) and very little (VL) according to p-values as follows: $0.0 < p \leq 0.01$ (VS), $0.01 < p \leq 0.05$ (S), $0.05 < p \leq 0.10$ (W), $0.10 < p \leq 0.50$ (L), and $0.50 < p \leq 1.0$ (VL)

The Mann-Kendall test requires the data to be serially independent, as the existence of serial correlation in a time series can either overestimate or underestimate the significance level of trends depending upon whether the serial correlation is positive or negative (Yue et al. 2002). To remove the effect of serial correlation, the techniques suggested by Yue et al. (2002) and used by Abdul Aziz & Burn (2006), Novotny & Stefan (2007), Burn (2008), Zhang & Lu (2009), and Kumar et al. (2009) were adopted in the present study. The binomial test and quantile-quantile plots were also applied to Mann-Kendall statistics to test the null hypothesis of no trend.

Burn & Elnur (2002), Partal & Kahya (2006), Burns et al. (2007), Pasquini & Depetris (2007), Burn (2008), and Zhang & Lu (2009), among others, have estimated the slope of an existing trend in hydro-meteorological data using the Sen's slope method. The method involves computing slopes for all the pairs of ordinal time points and then using the median of these slopes as an estimate of the overall slope. The Sen's slope method is insensitive to outliers and can be effectively used to quantify a trend in the data. The estimate of the trend slope β is given by:

$$\beta = \text{median}\left(\frac{x_j - x_k}{j - k}\right) \qquad \forall k < j \qquad (6)$$

where x_j is the data value at time j, x_k is the data value at time k, and j is time after k ($j > k$). The Sen's estimator β provides the rate of change in any variable, which enables determination of the total change during the analysis period. Further details on the methodology used can be found in Brauner (1997) and Timo et al. (2002). There is large variation in the seasonal and annual runoff of the upper Indus River and its tributaries, as can be seen from Table 2. Therefore, for the ease of comparison of the Sen's slope of streamflow for different rivers, the trends are expressed in percentage terms (Yue et al. 2002) in addition to millimeters. All Sen's slopes are expressed as rate of change per 39 yr (1967–2005).

5. RESULTS

The basic climate information of the basin was used to derive the mean monthly data. The mean seasonal and annual series of all the variables for each station were then derived using the mean monthly data. Analysis for trends was carried out for both the seasonal and regional data. A p-value of ≤0.10 (critical value of Z_{mk} = ±1.64) was used to indicate the statistical significance of trend results.

5.1. Climate of the UIRB

The climate conditions of the part of the UIRB located in Pakistan were extremely diverse in terms of temperature and precipitation. The spatial variability of mean annual TMN, TMX, and PPT is illustrated in Fig. 2. The mean annual TMN was between 4 and 17°C, and the mean TMX was between 15 and 30°C. Peshawar, in the lower region, had a long-term mean TMX of >40°C in the month of June, while the mean monthly TMN was –8°C in the upper region of Skardu. The spatial and temporal distribution of precipitation was highly variable in the region. The mean annual PPT ranged from 137 to 1595 mm. In mountainous regions such as Balakot, the mean annual PPT exceeded 1500 mm, while it was only 137 mm in Gilgit, an arid upper area. In the upper region, the mean monthly TMX and mean monthly TMN ranged from 34.4°C in June to –2.8°C in January. More than 1600 mm annual PPT was reported at an altitude of 5000 m in the form of snow (Winiger et al. 2005). Of this total amount, the mean annual PPT in the form of rain was estimated at around 300 mm at altitudes <3000 m. The middle region includes mountainous areas and the intervening valley. The mean monthly TMX was 33.2°C in the month of June, and the mean monthly TMN was 0.4°C in January. Monsoon rain is the main source of water in the region. The mean annual rainfall was around 1300 mm, of which 40% fell during summer, 25% during spring, and 20% during winter. In the lower region, the mean monthly TMX was 37.4°C during June, and the mean monthly TMN was 2.4°C in January. Mean annual rainfall was about 700 mm. The seasonal contribution of PPT in this region was almost the same as in the middle region.

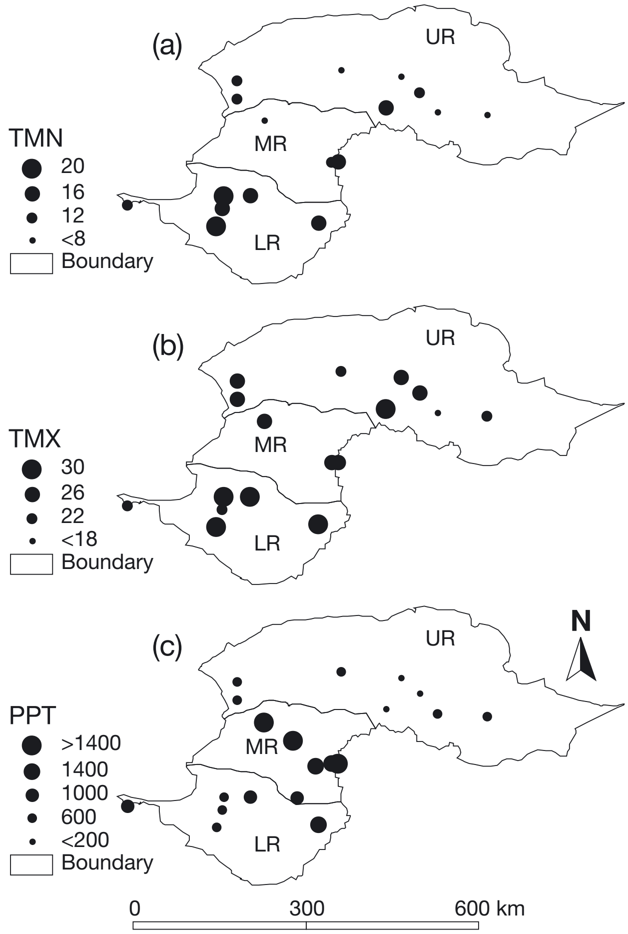

Fig. 2. Spatial variability of mean annual (a) minimum (TMN) and (b) maximum (TMX) temperatures (°C), and (c) precipitation (PPT, mm) in the upper Indus River basin

5.2. Seasonal trends

Summaries of the results from the trend analysis of seasonal temperature data from 17 stations and seasonal precipitation data from 20 stations are presented in Fig. 3. Results from the trend analysis of streamflow data from 8 hydrometric stations are also presented (see Table 8 and Fig. 5). Each figure shows increasing or decreasing trends with the corresponding significance.

5.2.1. Mean monthly TMN

Fig. 3 shows the spatial distribution of trends in mean monthly TMN for different seasons and on an annual scale. Fig. 3 also shows a large number of increasing and decreasing trends, although decreasing trends dominate. Decreasing trends for the spring season were exhibited by 35% of the stations (6 stations), with $p < 0.10$ (Fig. 3b, TMN). Of these 6 stations, 3 showed very strong ($p \leq 0.01$) and 2 showed strong trends ($0.01 < p \leq 0.05$). A majority of stations (76%, 13 stations) showed a decreasing trend ($p < 0.10$) for the summer (June–August) season. Fig. 3c (TMN) indicates that there is a predominance of decreasing trends, particularly for the summer season. On an annual scale, 47% of the stations (8 stations) exhibited a decreasing trend in the mean monthly values of TMN (Fig. 3e, TMN). Of these 8 stations, 7 exhibited very strong trends and 1 exhibited strong trends.

5.2.2. Mean monthly TMX

Trend characteristics of TMX for the various seasons are presented in Fig. 3. Analysis of winter TMX is important, as it is during this period that the precipitation is stored in the form of snow. Any change in winter TMX is likely to produce significant changes in the runoff during winter and subsequent seasons. Results clearly indicated that there were increasing trends, implying that warming of the region was indeed taking place. The highest warming trend was observed for the winter months (December–February), with 71% of the stations (12 stations) showing an increasing trend, with $p < 0.10$ (Fig. 3a, TMX). Of these 12 stations, very strong and strong trends were observed at 7 and 3 stations, respectively. No station exhibited significant decreasing trends for the winter and spring seasons. For the spring season, only 18% of the stations (3 stations) were found to exhibit increasing trends with $p < 0.10$. However, for the autumn (September–November) season, 12% of the stations exhibited very strong and 18% of the stations exhibited strong increasing trends (Fig. 3d, TMX). On an annual scale, 41% of the stations (7 stations) exhibited a warming trend, with $p < 0.10$ (Fig. 3e, TMX). The trend analysis results reported herein are consistent with the results of multimodel GCM runs under SRES scenarios B1 and A1F1 for South Asia, which project the largest increase for the winter months (IPCC 2007a). The impact of winter warming on the inflows to the Tarbela Reservoir is discussed in subsequent sections.

5.2.3. Mean monthly PPT

Fig. 3 presents the seasonal and annual spatial trends in PPT in the UIRB. No decreasing trends were evident with $p < 0.10$, except for the summer season, where 3 stations (15%) showed a decreasing trend with $p < 0.10$ (Fig. 3c, PPT). For the autumn season, none of the stations showed very strong trends, but a strong positive trend was shown by 1 station (Fig. 3d, PPT). The majority of stations (>76%) in all seasons did not show either increasing or decreasing trends with $p < 0.10$. The results of the trend analysis were contradictory, perhaps due to the fact that the physical processes underlying the phenomenon of precipitation are highly complex. Further, the spatial and temporal distributions of precipitation were highly non-uniform compared to temperature. For many regions of the world, the trend analyses for PPT have indicated contrasting trends (Dore 2005).

5.3. Regional trends

The Mann-Kendall trend statistics and the magnitudes of trends in seasonal and annual TMN, TMX, and PPT in various regions of the UIRB are presented in Tables 4–6, respectively. Table 7 lists the linear correlations between streamflow, temperature, and precipitation, while Table 8 provides the results of the Mann-Kendall test, with p-values, and the magnitude of trend slopes for streamflow in various regions of the UIRB.

5.3.1. Mean monthly TMN

The trend statistics and Sen's slopes were computed for the TMN data for the different regions of the basin and are presented in Table 4. It can be seen that for the winter season all regions, except the upper, showed decreasing trends with $p = 0.12$ (L) and $p = 0.01$ (VS) for the middle and lower regions, respectively. For all other seasons, decreasing trends were observed. However, decreasing trends with $p < 0.10$ were seen during summer (June–August) and autumn (September–November) seasons in all regions of the basin. The same significant trend could be seen even on an annual scale in all regions. The summer minimum temperature for the upper, middle, and lower regions decreased by 2.08, 1.05, and 2.11°C per 39 yr, respectively, which indicates that Sen's slopes were greatest for the lower region of the basin.

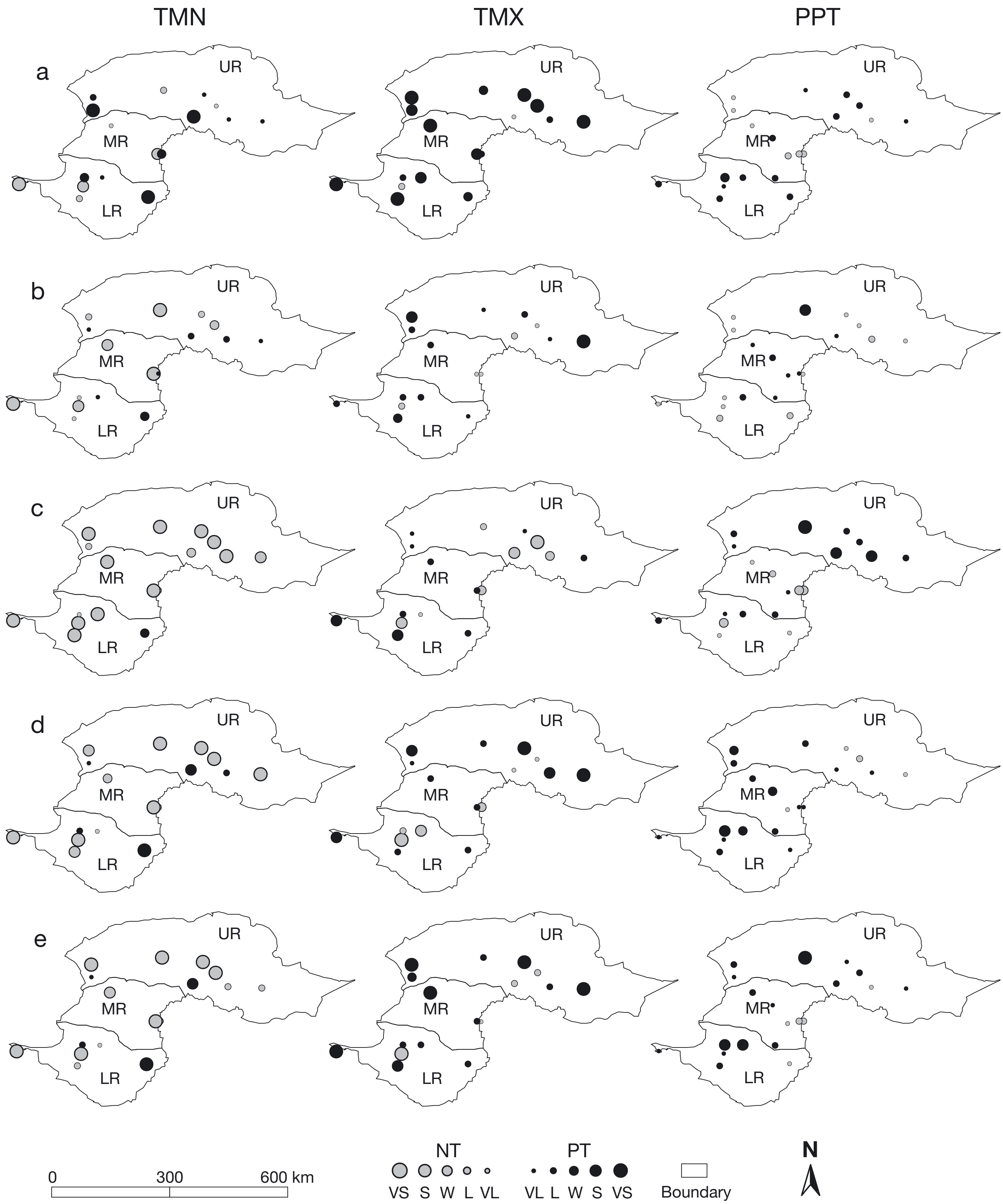

Fig. 3. Spatial distribution of Mann-Kendall changing trends of minimum (TMN) and maximum (TMX) temperatures and precipitation (PPT) in: (a) winter, (b) spring, (c) summer, (d) autumn, and (e) annual over the period 1967–2005. In the key— VS: very strong ($0.0 < p \leq 0.01$); S: strong ($0.01 < p \leq 0.05$); W: weak ($0.05 < p \leq 0.10$); L: little ($0.10 < p \leq 0.50$); VL: very little ($0.50 < p \leq 1.0$) show trend significance, while PT indicates a positive trend and NT indicates a negative trend

5.3.2. Mean monthly TMX

Mann-Kendall test results and Sen's slopes of trends in TMX are presented in Table 5; the greatest trends with $p < 0.10$ were observed for the winter season in all regions. For the winter (December–February) season, Sen's slopes for the upper, middle, and lower regions were 1.79, 1.66, and 1.20°C per 39 yr, respectively. The magnitudes of Sen's slopes clearly indicated that all 3 regions were experiencing a strong warming trend, particularly for the winter season. All 3 regions exhibited an increasing trend for the spring (March–May) season, although none of these trends were found to be statistically significant ($p > 0.10$). For the summer and autumn seasons, mixed trends were detected. In the autumn season, the upper region showed an increasing trend with $p < 0.05$ (S) and a trend slope of 0.87°C per 39 yr. On an annual scale, increasing trends were observed in the 3 regions; however, the p-values for the trends in the middle and lower regions were found to be 0.42 (L) and 0.12 (L), respectively. For the upper region, the p-value of the trend was found to be 0.10 (W).

5.3.3. Mean monthly PPT

Trend test results of precipitation are shown in Table 6. For the winter and spring seasons, there were 2 increasing and 1 decreasing trend, and none of them were statistically significant as p-values were >0.10. For the summer (June–August) season, a statistically significant ($p = 0.01$, VS) increase in precipitation at the rate of 23.9 mm per 39 yr was observed in the upper region. The middle region showed a decreasing trend, with $p = 0.33$ (52.1 mm per 39 yr), while the lower region showed an increasing trend, but the trends were not statistically significant ($p = 0.64$, VL). All regions exhibited an increasing trend in autumn precipitation, which could be categorized as 'little' ($0.10 < p < 0.50$). On an annual scale, an increasing trend in precipitation was noted in the upper and lower regions of the UIRB and a decreasing trend could be seen in the middle region. In both cases, the trends could be categorized as 'little'. As discussed earlier, the processes leading to precipitation were highly complex, and this was probably the reason why no conclusive trends were observed in the precipitation data. Overall, the number of increasing trends in seasonal precipitation was greater than the number of decreasing trends.

5.3.4. Regional hydro-meteorological time series and correlation

For graphic illustration, the series of seasonal and annual temporal changes of TMN, TMX, and PPT during the period 1967–2005 (Fig. 4) for the upper, middle, and lower regions of the UIRB have been plotted. The sea-

Table 4. Mann-Kendall test statistics (Z_{mk}), p-values and Sen's slopes of trends in seasonal minimum temperatures for the upper, middle, and lower regions of the upper Indus River basin. W_i: winter; S_p: spring; S_u: summer; A_u: autumn; A_n: annual; T_t: Sen's slope (trends are expressed as rate of change per 39 yr in degrees Celsius); **bold** normal print: $0.0 < p \le 0.01$ (VS, very strong); ***bold italic*** print: $0.01 < p \le 0.05$ (S, strong); **bold underlined** print: $0.05 < p \le 0.10$ (W, weak); normal print: $0.10 < p \le 0.50$ (L, little); *normal italic* print: $0.50 < p \le 1.0$ (VL, very little)

Season	Upper			Middle			Lower		
	Z_{mk}	p	T_t	Z_{mk}	p	T_t	Z_{mk}	p	T_t
W_i	1.56	0.12	0.62	−1.56	0.12	−0.53	−2.46	**0.01**	−0.95
S_p	−0.23	*0.82*	−0.09	−1.78	**0.08**	−1.05	−1.44	0.15	−0.89
S_u	−3.82	**<0.001**	−2.08	−2.33	***0.02***	−1.05	−5.41	**<0.001**	−2.11
A_u	−3.40	**<0.001**	−1.00	−2.70	**0.01**	−1.24	−2.63	**0.01**	−0.85
A_n	−2.32	***0.02***	−0.62	−2.65	**0.01**	−0.96	−4.05	**<0.001**	−1.35

Table 5. Mann-Kendall test statistics (Z_{mk}), p-values, and Sen's slopes of trends in seasonal maximum temperature for upper, middle, and lower regions of the upper Indus River basin. See Table 4 for further details

Season	Upper			Middle			Lower		
	Z_{mk}	p	T_t	Z_{mk}	p	T_t	Z_{mk}	p	T_t
W_i	2.60	**0.01**	1.79	2.52	**0.01**	1.66	1.96	***0.05***	1.20
S_p	0.99	0.32	0.72	0.47	*0.64*	0.46	0.65	*0.51*	0.70
S_u	−1.31	0.19	−0.88	−0.08	*0.93*	−0.05	0.67	*0.51*	0.33
A_u	1.97	***0.05***	0.87	0.24	*0.81*	0.09	−0.22	*0.83*	−0.11
A_n	1.64	**0.10**	0.84	0.81	0.42	0.40	1.57	0.12	0.54

Table 6. Mann-Kendall test statistics (Z_{mk}), p-values and Sen's slopes of trends in seasonal precipitation for upper, middle, and lower regions of the upper Indus River basin. See Table 4 for details, except T_t (trends are expressed as rate of change per 39 yr in mm)

Season	Upper			Middle			Lower		
	Z_{mk}	p	T_t	Z_{mk}	p	T_t	Z_{mk}	p	T_t
W_i	0.35	*0.73*	6.25	−0.18	*0.86*	−11.23	0.96	0.34	41.45
S_p	0.45	*0.65*	16.79	0.54	*0.59*	32.37	−0.13	*0.89*	−6.37
S_u	2.67	**0.01**	23.90	−0.98	0.33	−52.10	0.47	*0.64*	17.72
A_u	1.32	0.19	12.98	0.91	0.36	34.20	1.61	0.11	27.20
A_n	1.42	0.16	71.07	−0.11	*0.91*	−11.35	1.03	0.30	86.28

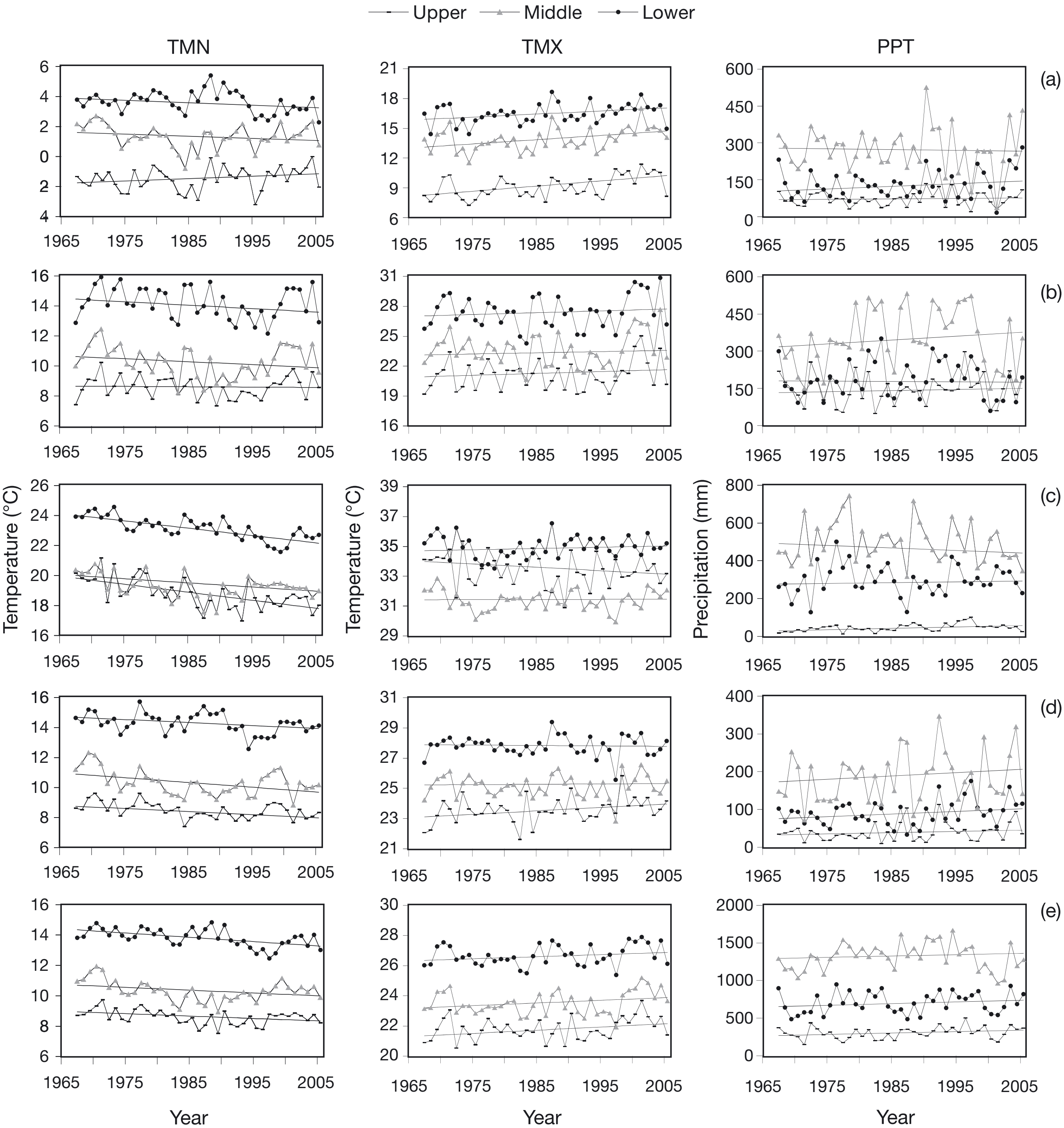

Fig. 4. Minimum (TMN) and maximum (TMX) temperature and precipitation (PPT) series of the upper, middle, and lower regions in the upper Indus River basin during the: (a) winter, (b) spring, (c) summer, and (d) autumn seasons, and (e) on an annual basis over the period 1967–2005

sonal and annual variations of trends estimated by the Sen's slope method are also given in the figure. The observed seasonal temperatures in the upper, middle, and lower regions indicated an increasing trend, particularly after 1997 (Fig. 4, TMN & TMX). The highest mean annual TMX was seen in 2001, in all regions of the UIRB (Fig. 4e, TMX). The observed precipitation (Fig. 4e, PPT) in the same period (after 1997) indicated a decreasing trend in contrast to that of temperature. The lowest annual precipitation occurred in 2001 in the middle region.

During winter and spring seasons, precipitation occurred mostly in the form of snow in the mountain ranges of the study area; therefore, temperature had a major impact on the formation and transformation of water and on the flow regime. The annual runoff contribution of snow and glacier melt to Tarbela Dam was >75% (TAMS & Wallingford 1998). For investigating the regional strength of linkages between streamflow, temperature, and precipitation, 3 hydrometric stations, 1 in each region, were considered. The Gilgit-Hunza River at Alam Bridge derived a significant portion of flow from snow and glacier melt from a high runoff catchment in the upper region. The Swat River at Chakdara represented a mixed runoff catchment in the middle region. The Soan River at Dhok Pathan in the lower region represented catchment influenced directly by seasonal rainfall. Regression analysis was performed between seasonal and annual streamflow and temperature, seasonal, and annual streamflow and precipitation (Rawlins et al. 2009) for each station. The correlation coefficients (r) between seasonal and annual streamflow, and temperature and precipitation are given in Table 7a,b, respectively. The results showed a marked difference between the correlation characteristics of the 3 stations. In the Gilgit-Hunza River, all seasonal flows were significantly correlated with TMX, the highest correlation being 0.61. For the Swat River, a weak positive correlation existed between streamflow and summer temperature. The Soan River had a significant negative correlation in all seasons, and the maximum correlation was seen in the spring season (r = –0.68).

In the Gilgit-Hunza River, the correlation coefficient of runoff with summer precipitation was –0.39, p = 0.02. One reason for such a negative correlation, as explained by Archer (2003), was that summer precipitation and the associated cloudiness at high elevations reduced energy input for ablation and, subsequently, increased albedo from new snow. A significant ($p < 0.01$) positive correlation (r = 0.49) was found between streamflow and precipitation for the Swat River in the winter season, while the highest correlation (r = 0.79) in the Soan River was found in the spring season. This suggests that, in the upper region catchments, temperature may exert a much greater impact on runoff than precipitation, while a mixed (temperature and precipitation) response in MR catchments can be seen. The correlation between runoff and precipitation (Table 7b) revealed that seasonal precipitation could be considered the direct main source of water availability in the middle and lower regions. Thus, the changing trend of precipitation may have serious implications for runoff, particularly in these 2 regions.

Table 7. Seasonal and annual correlation coefficients (r) between streamflow and (a) temperature or (b) precipitation in the upper, middle, and lower region catchments. **Bold** normal print: $0.0 < p \leq 0.01$ (VS, very strong); ***bold italic*** print: $0.01 < p \leq 0.05$ (S, strong); **<u>bold underlined</u>** print: $0.05 < p \leq 0.10$ (W, weak); normal print: $0.10 < p \leq 0.50$ (L, Little); *normal italic* print: $0.50 < p \leq 1.0$ (VL, very little)

Hydrometric station	Winter	Spring	Summer	Autumn	Annual
(a) Maximum temperature					
Alam Bridge	**<u>0.30</u>**	**0.61**	**0.56**	**<u>0.31</u>**	0.10
Chakdara	–0.19	**<u>–0.27</u>**	0.11	–0.11	**<u>–0.27</u>**
Dhok Pathan	–0.11	**–0.68**	***–0.47***	**<u>–0.28</u>**	***–0.49***
(b) Precipitation					
Alam Bridge	*0.07*	–0.22	***–0.39***	0.11	0.11
Chakdara	**0.49**	***0.38***	–0.11	**0.46**	**0.41**
Dhok Pathan	**0.55**	**0.79**	**0.63**	***0.34***	**0.59**

5.3.5. Mean monthly streamflow

Trend statistics and Sen's slopes of monthly streamflow for different seasons and on an annual scale are presented in Table 8. All 8 hydrometric stations exhibited an increasing trend (winter season), with Sen's slopes that ranged from 7.2% (1.9 mm) per 39 yr at Chitral to 35.6% (4.9 mm) per 39 yr at Besham. Of the 8 hydrometric stations, 4 showed significant increasing trends ($p < 0.10$). The highest trend ($p < 0.001$), with a Sen's slope of >35% per 39 yr was observed at Besham, which is located just upstream of Tarbela Reservoir, as shown in Fig. 1. The spring streamflow at 4 of the 8 sites showed increasing trends with $p < 0.10$ (Fig. 5b). Of these 4 stations, 1 showed very strong (p = 0.01) and 3 showed strong trends ($0.01 < p \leq 0.05$). Of the 8 sites, Warsak showed a weak decreasing trend (p = 0.30). The summer streamflow appeared to be depicting a contrasting trend with 6 out of 8 stations showing decreasing trends (Fig. 5c). Data from 3 of the 8 stations exhibited significant trends ($p < 0.10$).

Kachura is the only hydrometric station that showed a consistently increasing significant trend during all 4 seasons. It may, however, be concluded that stations exhibiting increasing trends for winter and spring outnumber those exhibiting decreasing trends. The increasing trends in streamflow during winter and spring may be attributed to warming that causes early melting of snow particularly in the upper region (Fig. 6a) of the UIRB, as no significant increasing or decreasing precipitation trends can be seen in the basin (Fig. 6b).

Because the Tarbela Dam is one of the largest earth and rockfill dams in the world (WCD 2000), it was important to investigate whether any changes in the hydrological regime were occurring that could lead to changes in reservoir operation. Interpretation of

Table 8. Mann-Kendall test results and Sen's slopes of trends in seasonal streamflow at various hydrometric stations in the upper Indus River basin over the period 1967–2005. Sen's slope (trends are expressed as rate of change per 39 yr in mm) and P_c (percentage changes per 39 yr) are also shown. A negative sign of the Sen's slope value indicates a decreasing trend, and a positive sign indicates an increasing trend. Kachura station data were available only for the period 1970–2005. Other abbreviations and designations, see Table 4

Season	Kachura			Alam Bridge			Chitral			Kalam			Besham			Chakdara			Warsak			Dhok Pathan		
	p	P_c	T_t	p	P_c	T_t	p	P_c	T_t	p	P_c	T_t	p	P_c	T_t	p	P_c	T_t	p	P_c	T_t	p	P_c	T_t
W_i	**0.01**	32.6	2.2	0.14	14.7	2.6	0.36	7.2	1.9	***0.05***	20.4	5.4	**<0.001**	35.6	4.9	0.27	15.9	7.6	0.52	12.9	1.4	**0.08**	32.2	8.3
S_p	***0.05***	25.2	7.2	0.49	10.4	4.8	0.33	11.2	8.5	***0.04***	22.3	57.7	**0.01**	18.7	10.7	***0.05***	24.6	73.9	0.30	−19.2	−13.7	*0.93*	3.1	0.5
S_u	**0.003**	33.6	67.5	***0.03***	−21.8	−108.4	0.12	7.5	44.7	0.42	−9.0	−78.5	0.46	−8.3	−25.6	0.20	−23.0	−84.3	***0.02***	−34.0	−50.7	**0.004**	−82.5	−102.3
A_u	**0.01**	33.6	17.8	0.46	7.4	9.4	**0.01**	18.0	25.3	*0.95*	1.1	1.2	0.20	9.5	7.2	*0.74*	5.5	5.0	*0.64*	−6.0	−2.1	*0.82*	14.1	3.8
A_n	**0.004**	32.9	97.1	0.18	−11.1	−79.4	***0.04***	8.0	72.1	*0.97*	−0.5	−4.7	*0.86*	1.0	4.8	*0.99*	0.1	0.6	**0.07**	−26.0	−71.4	**0.10**	−44.0	−92.1

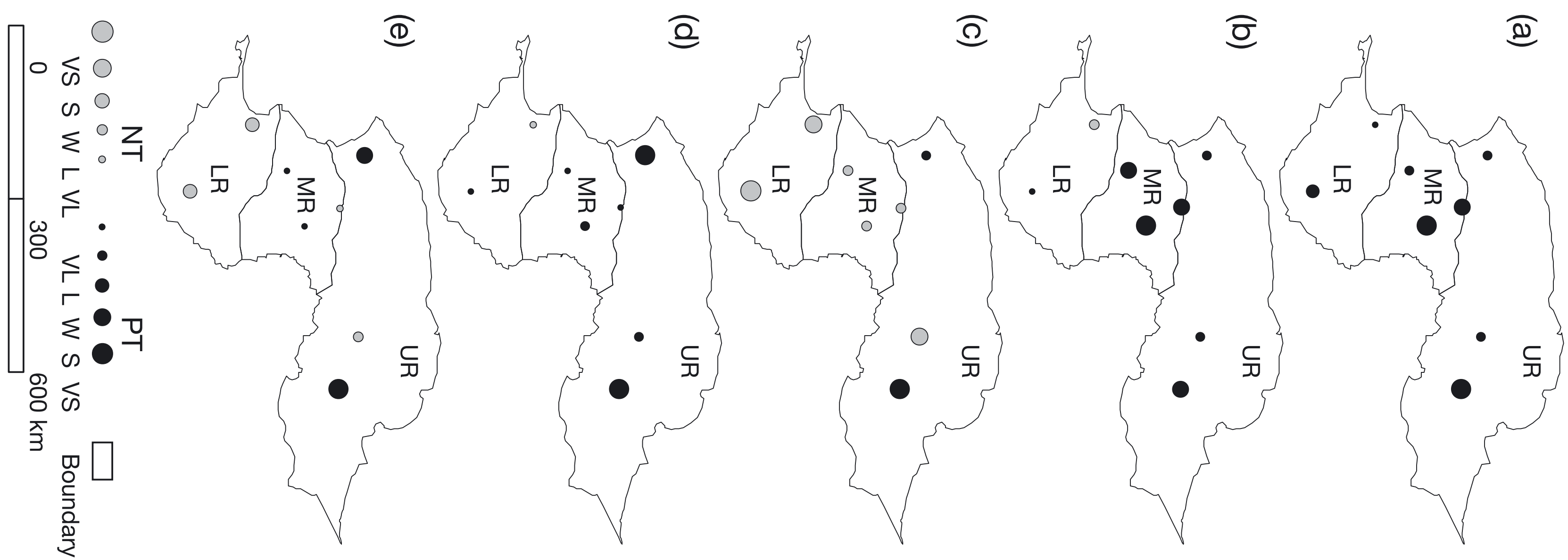

Fig. 5. Same as in Fig. 3, but for runoff

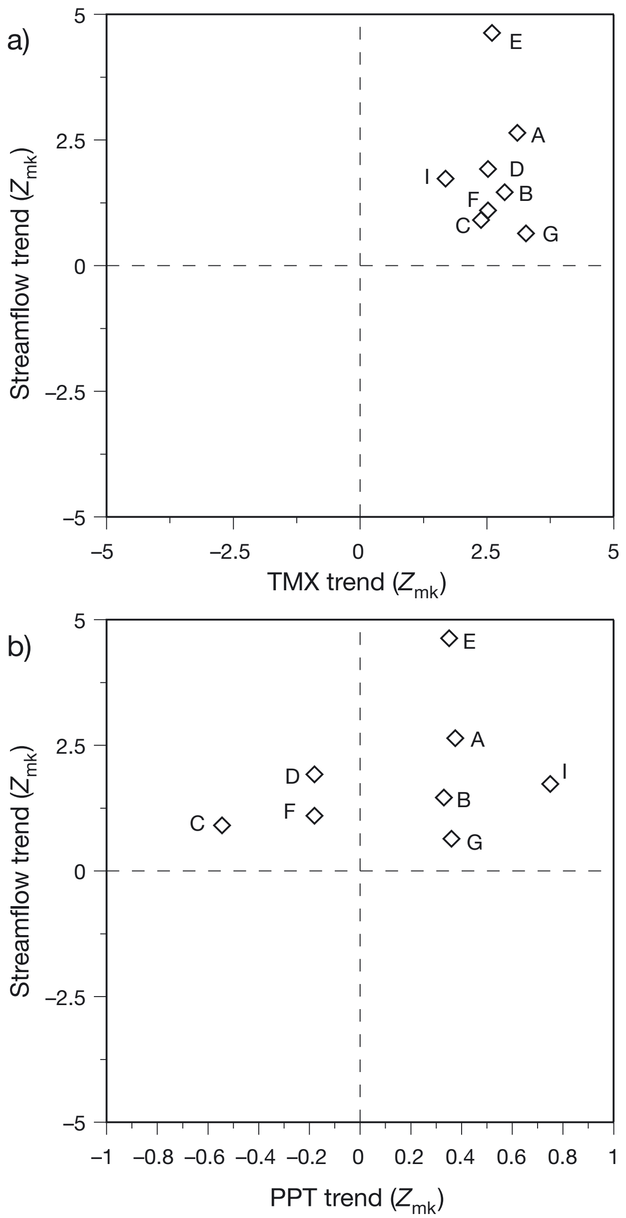

Fig. 6. Trend in winter streamflow versus (a) winter maximum temperature (TMX) and (b) winter precipitation (PPT) for various hydrometric stations (A–I, see Fig. 1) of the upper Indus River basin

streamflow trends at Besham, a hydrometric station upstream of Tarbela, therefore assumes greater significance, as it gives an indication of scenarios of likely water availability at Tarbela in the near future. Furthermore, detection of any possible streamflow trends at Besham is likely to contribute towards more efficient and integrated management of available water at Tarbela. It can be seen from Table 8 that winter (December–February) mean streamflow at Besham had a very strong increasing trend ($p < 0.001$). The magnitude of the trend slope for winter was also quite high (35.6% per 39 yr). An increasing streamflow trend ($p = 0.01$) was also observed for the spring (March–May) season (18.7% per 39 yr). For graphic illustration the time series plots for various seasons at Besham are given in Fig. 7. It is interesting to note that increasing streamflow trends for the winter and spring seasons were accompanied by increasing trends in TMX for these seasons (Astore, Bunji, Gilgit, Gupis, and Skardu climate station trends in Fig. 3a, b). If this current temperature trend continues, more water is likely to be available during winter and spring in the future, due to the early melting of snow and falling of precipitation in the form of rain instead of snow. Thus, less snow would be available and therefore the amount of summer season flow would be reduced. The decreasing trend of summer runoff in the UIRB can be attributed partly to winter warming and partly to the decreasing trend of summer precipitation (Fig. 3c) in the middle and lower regions.

5.4. Binomial test

In order to evaluate the regional trends in TMN, TMX, PPT, and runoff for the whole UIRB in all seasons, as well as on an annual basis, the binomial distribution was fitted to the signs of local time trends (Nasri & Modarres 2009). The null hypothesis was the lack of positive (negative) field trends. This hypothesis would imply a probability of local positive (negative) time trends of $p = 0.5$ ($Q = 0.5$). The results showed that the null hypothesis of no apparent trend in regional scale could be rejected for TMN during the summer season ($p < 0.001$) and on an annual basis ($p = 0.05$). Similarly, for TMX during the winter season, and on an annual basis, the p-values were <0.001 (VS) and 0.05 (S), respectively. However, the spring season exhibited a weak trend ($p = 0.14$).

The null hypothesis of no trend could not be rejected during winter, spring, or summer seasons in the case of precipitation, as the test p-value was >0.10. For the autumn season and for the annual scale, the p-values were 0.01 (VS) and 0.04 (S), respectively. The null hypothesis could be rejected in the case of runoff during winter ($p < 0.001$), spring ($p = 0.07$), and autumn seasons ($p = 0.07$). The quantile-quantile plots (qq plot) of the estimated Z_{mk} values are presented for the hydro-meteorological parameters in Fig. 8. The null hypothesis of no trend should be rejected when departure from the uniform distribution takes place (Small et al. 2006, Nasri & Modarres 2009). As discussed above, for all seasons in each parameter where the null hypothesis of no trend was rejected when the binomial test was used, the deviation from linearity of those parameters for such seasons can also be seen in Fig. 8. For instance, clear departure during summer TMN (Fig. 8c), winter TMX (Fig. 8a), annual PPT (Fig. 8e),

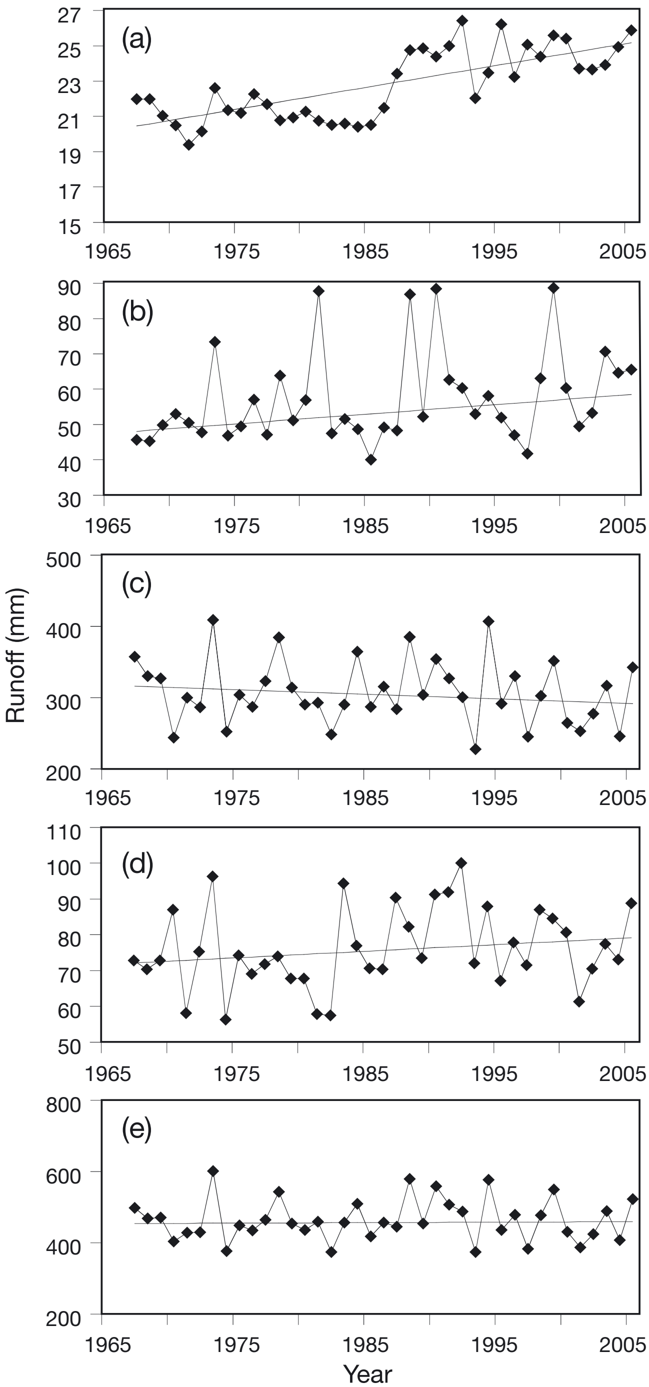

Fig. 7. Runoff series for the Indus River at the Besham hydrometric station in: (a) winter, (b) spring, (c) summer, and (d) autumn, and (e) on an annual basis over the period 1967–2005

and winter and spring runoff (Fig. 8a,b) can be observed. Further it can be inferred from the binomial test results and qq plots that the increasing trend of TMX in winter and spring and the increasing trend of precipitation in autumn resulted in an increasing trend of runoff in the basin in these seasons.

6. DISCUSSION

The analysis conducted here has revealed that changes are occurring in the hydrological regime of the upper Indus River, part of which may be attributed to warming in the basin, which is evident from the analysis of temperature trends. Significant trends ($p < 0.10$) in the TMX and streamflow data, both on a seasonal and regional basis, were detected. There has been a consistent warming trend in the basin, particularly in the winter, as well as in the spring seasons (Table 5). The impact of these warming trends is reflected in the trends in streamflow presented in Table 8 and Fig. 5. It can be seen from Table 8 that increasing trends in TMX during winter (December–February) and spring (March–May) seasons are accompanied by increasing trends in streamflow in winter and spring seasons. The likely reasons for these increasing trends in streamflow are the occurrence of precipitation in the form of rain and the increased contribution of snowmelt to the runoff in the basin. Besham, a hydrometric station upstream of Tarbela Reservoir, has shown an increasing trend in streamflow during winter and spring seasons, and it has shown a decreasing trend in the summer (June–August) season. The presence of such a trend implies that the temporal availability of water at Tarbela is likely to be impacted, leading to significant implications for water resources in the basin.

7. CONCLUSIONS

In the present study, the trend detection framework based on the non-parametric Mann-Kendall test is applied to the dataset of several hydro-meteorological variables pertaining to the UIRB in Pakistan. The TFPW approach has been used for correcting the time series for autocorrelation. Trend analysis of hydrometeorological data from 17 climate stations and 8 hydrometric stations has resulted in identification of more significant trends than would be expected to occur by chance. Results clearly indicate that changes are occurring in the temperature and streamflow characteristics of the study basin. The TMX and streamflow have been found to have particularly strong trends. Analysis of winter (December–February) TMX has revealed a significantly increasing trend ($p < 0.10$), with Sen's slopes of 1.79, 1.66, and 1.20°C per 39 yr for upper, middle, and lower regions, respectively (Table 5), which is a sufficient indicator that warming is indeed taking place in the basin. A major implication of increased winter temperatures is on the runoff patterns, which, in turn, will impact the temporal availability of water in the basin and, particularly, at the

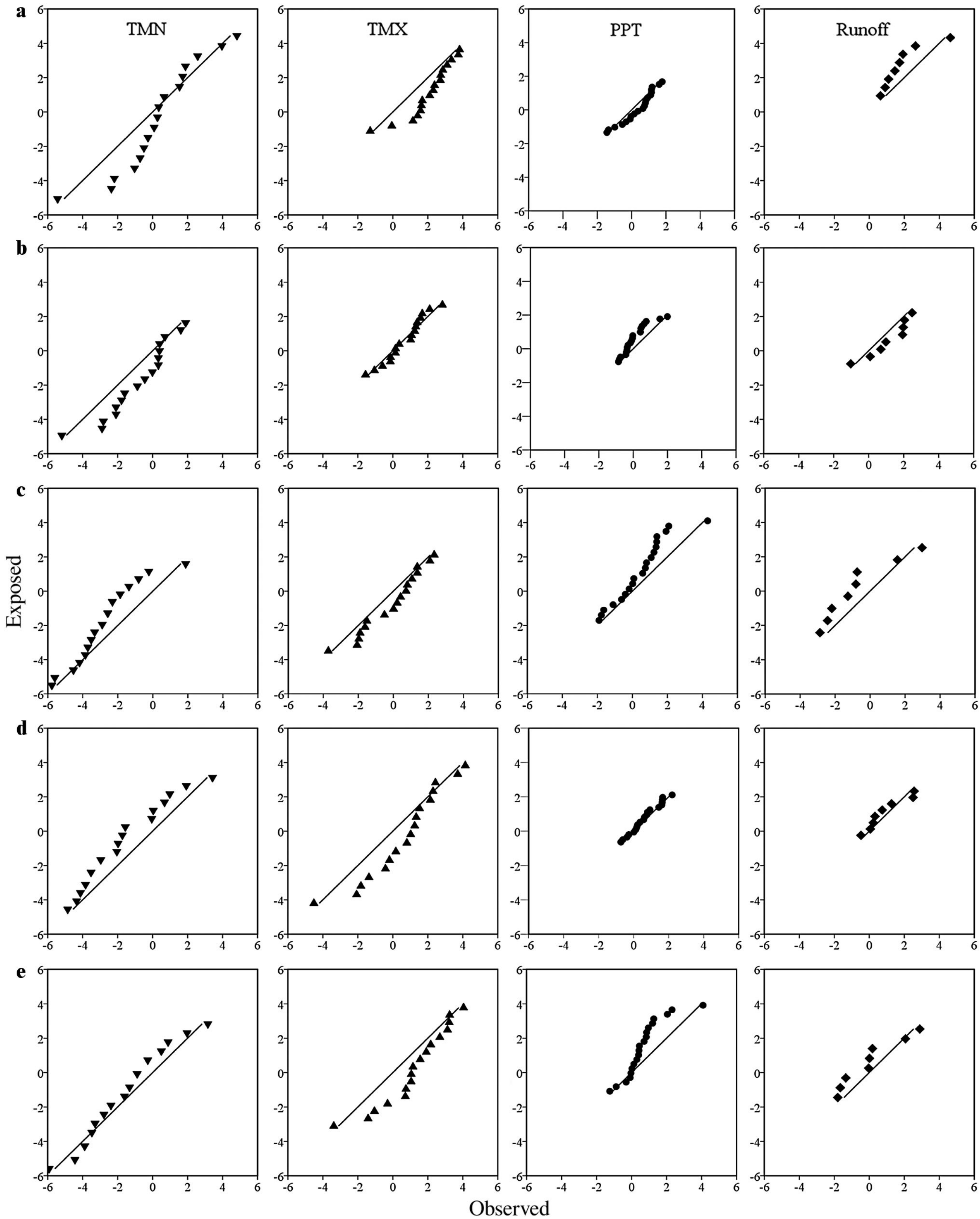

Fig. 8. Quantile-quantile plot of uniform distribution for the trend test of minimum (TMN) and maximum (TMX) temperatures, precipitation (PPT), and runoff for: (a) winter, (b) spring, (c) summer, and (d) autumn, and (e) an annual time series for the upper Indus River basin

Tarbela Reservoir, thus necessitating revision of current reservoir operating policy. Furthermore, the similarities in the trend patterns of meteorological and hydrological variables imply that the trends in hydrologic variables are, to some extent, related to trends in meteorological variables. In particular, trend patterns of winter TMX (upper region climate stations, including Astore, Bunji, Gilgit, Gupis, and Skardu as shown in Fig. 3a) are likely related to the trend patterns of streamflow at Besham, as is evident from Table 8 and Fig. 5a. Results also indicate that the precipitation trends are inconsistent, with no definite pattern, either increasing or decreasing. Further, no correlation appears to exist between the temperature and precipitation trends, as changes in the processes causing precipitation are complex and difficult to determine.

The results of correlation analysis showed that the runoff in the upper region catchments depends on temperature, while for the middle region it depends upon both temperature and precipitation. As expected, the runoff in the lower region catchments is dependent on seasonal rainfall only. Based on results of the binomial test and qq plots, the null hypothesis of no trend can be rejected for summer TMN, winter TMX, spring TMX, and autumn precipitation. The null hypothesis of no trend must also be rejected in the case of runoff in winter, spring, and autumn seasons. Thus, it can be concluded that the increasing trend of TMX in winter and spring seasons and the increasing trend of precipitation in the autumn have caused an increasing trend of runoff in the basin.

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LITERATURE CITED

Abdul Aziz OI, Burn DH (2006) Trends and variability in the hydrological regime of the Mackenzie River basin. J Hydrol (Amst) 319:282–294

Ahmad KS (1951) Climate regions of West Pakistan. Pa Geogr 6:1–35

Ahmad QK, Warrick RA (1996) The implications of climate and sea level change for Bangladesh. Kluwer Acedemic Publisher, Dordrecht

Archer DR (2003) Contrasting hydrological regimes in the Upper Indus basin. J Hydrol (Amst) 274:198–210

Archer DR, Fowler HJ (2004) Spatial and temporal variations in precipitation in the Upper Indus basin, global teleconnections and hydrological implications. Hydrol Earth Syst Sci 8:47–61

Arora M, Goel NK, Singh R (2005) Evaluation of temperature trends over India. Hydrol Sci J 50:1–93

Ali MA (1971) Climate and hydrology in west Pakistan: a summary. Pak Soils Bull 3:23–25, Soil Survey of Pakistan, Lahore

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva

Brauner JS (1997) Non-parametric estimation of slope: Sen's method in environmental pollution. Available at: www.cee.vt.edu/ewr/environmental/teach/smprimer/sen/sen.html. (accessed 15 November 2009)

Burn DH (1994) Hydrological effects of climatic change in west-central Canada. J Hydrol (Amst) 160:53–70

Burn DH (2008) Climatic influences on streamflow timing in the headwaters of the Mackenzie River basin. J Hydrol (Amst) 352:225–238

Burn DH, Elnur MAH (2002) Detection of hydrologic trend and variability. J Hydrol (Amst) 255:107–122

Burn DH, Cunderlik JM, Pietroniro A (2004a) Hydrological trends and variability in the Liard River basin. Hydrol Sci J 49:53–67

Burn DH, Abdul Aziz OI, Pietroniro A (2004b) A comparison of trends in hydrological variables for two watersheds in the Mackenzie River basin. Can Water Resour J 29:283–298

Burns DA, Klaus J, Mchale MR (2007) Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. J Hydrol (Amst) 336:155–170

Chen H, Guo S, Chong-yu X, Singh VP (2007) Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. J Hydrol (Amst) 344: 171–184

CICERO (Center for International Climate and Environmental Research-Oslo) (2000) Developing strategies for climate change: the UNEP country studies on climate change impacts and adaptations assessment. Report 2000, Vol 2, CICERO, Oslo

Dore MHI (2005) Climate change and changes in global precipitation patterns: What do we know? Environ Int 31: 1167–1181

Douglas EM, Vogel RM, Knoll CN (2000) Trends in flood and low flows in the United States: impact of spatial correlation. J Hydrol (Amst) 240:90–105

Fowler HJ, Archer DR (2006) Conflicting signals of climate change in the Upper Indus basin. J Clim 19:4276–4293

Gemmer M, Becker S, Jiang T (2003) Detection and visualization of climate trends in China, No. 15. Nanjing Institute of Geography and Limnology, Chinese Academy of Science (CAS), Nanjing http://geb.uni-giessen.de/geb/volltexte/2004/1374/pdf/ZeuDiscPap15.pdf (accessed on 12 March 2008)

GoP (Government of Pakistan) (2005) Pakistan energy yearbook. Hydrocarbon Development Institute of Pakistan, PO Box 1308, Islamabad

Haq IU, Abbas T (2006) Sedimentation of Tarbela and Mangla Reservoirs. (paper presented at the 70th annual session of the Pakistan Engineering Congress, Lahore, Pakistan, December 2–4, 2006)

Helsel DR, Hirsch RM (1992) Statistical methods in water resources. Elsevier, New York

Hess A, Lyer H, Malm W (2001) Linear trend analysis: a comparison of methods. Atmos Environ 35:5211–5222

Hirsch RM, Slack JR, Smith RA (1982) Techniques of trend analysis for monthly water quality data. Water Resour Res 18:107–121

Huang Y, Cai J, Yin H, Cai M (2009) Correlation of precipitation to temperature variation in the Huanghe River (Yellow

River) basin during 1957–2006. J Hydrol (Amst) 372:1–8

ICIMOD (International Centre for Integrated Mountain Development) (2001) Inventory of glaciers, glacial lakes and glacial lake outburst floods, monitoring and early warning system in the Hindu Kush–Himalayan region, Nepal. (UNEP/RC-AP)/ICIMOD, Kathmandu

IPCC (Intergovernmental Panel on Climate Change) (2007a) Impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Asia climate change 2007. Cambridge University Press, Cambridge, p 469–506

IPCC (Intergovernmental Panel on Climate Change) (2007b) Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Cambridge University Press, Cambridge, p 13–14

Jiang T, Chen YD, Xu CY, Chen X, Singh VP (2007) Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang basin, south China. J Hydrol (Amst) 336:316–333

Kahlown MA, Khan AD, Azam M (2005) The World's largest contiguous irrigation system: developments, successes and challenges of the Indus irrigation system in Pakistan. History of Water 1:1–35

Kendall MG (1975) Rank correlation measures. Charles Griffin, London

Kezer K, Matsuyama H (2006) Decrease of river runoff in the Lake Balkhash basin in Central Asia. Hydrol Process 20: 1407–1423

Kumar S, Merwade V, Kam J, Thurner K (2009) Streamflow trends in Indiana: effects of long term persistence, precipitation and subsurface drains. J Hydrol (Amst) 374:171–183

Kundzewicz ZW, Robson AJ (2004) Change detection in hydrological records — a review of the methodology. Hydrol Sci J 49:7–19

Mann HB (1945) Non-parametric tests against trend. Econometrica 13:245–259

Nasri M, Modarres R (2009) Dry spell trend analysis of Isfahan Province, Iran. Int J Climatol 29:1430–1438

Negi SS (2004) Himalayan Rivers, lakes and glaciers. Indus Publishing Company, New Delhi

Novotny EV, Stefan HG (2007) Stream flow in Minnesota: indicator of climate change. J Hydrol (Amst) 334:319–333

Partal T, Kahya E (2006) Trend analysis in Turkish precipitation data. Hydrol Process 20:2011–2026

Pasquini AI, Depetris PJ (2007) Discharge trends and flow dynamics of South American rivers draining the southern Atlantic seaboard: an overview. J Hydrol (Amst) 333: 385–399

Rawlins MA, Ye H, Yang D, Shiklomanov A, McDonald KD (2009) Divergence in seasonal hydrology across northern Eurasia: emerging trends and water cycle linkages. J Geophys Res 114:D18119 doi:10.1029/2009JD011747

Raziei T, Arasteh PD, Saghfian B (2005) Annual rainfall trend in arid and semi-arid regions of Iran. (paper given at the ICID 21st European Regional Conference, Frankfurt-Oder, Germany, and Slubice, Poland, May 15–19, 2005)

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63:1379–1389

Shrestha AB, Wake C, Mayewski PA, Dibb JE (1999) Maximum temperature trends in the Himalaya and its vicinity. An analysis based on temperature records from Nepal for the period 1971–1994. J Clim 12:2775–2786

Simonovic SP, Li L (2003) Methodology for assessment of climate change impacts on large-scale flood protection system. J Water Resour Plan Manage 129:361–372

Singh P, Kumar V, Thomas T, Arora M (2008) Basin-wide assessment of temperature trends in northwest and central India. Hydrol Sci J 53:421–433

Small D, Islam S, Vogel RM (2006) Trend in precipitation and streamflow in the eastern U.S.: Paradox or perception? Geophys Res Lett 33:1–4

TAMS, Wallingford HR (1998) Tarbela dam sediment management study. WAPDA, Lahore

Thayyen RJ, Gergan JT (2010) Role of glaciers in watershed hydrology: a preliminary study of a 'Himalayan catchment'. The Cryosphere 4:115–128 (www.the-cryosphere.net/4/115/2010/tc-4-115-2010.html)

Timo S, Maatta A, Anttila P, Airola TR, Amnell T (2002) Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates. Finnish Meteorological Institute/Library, Helsinki

Vorosmarty CJ, McIntyre PB, Gessner MO, Dudgeon D and others (2010) Global threats to human water security and river biodiversity. Nature 467:555–561

WAPDA (Water and Power Development Authority) (2002) River discharge, sediment and water quality data. Surface Water Hydrology Project, Vol 1(62), Lahore, p 13–173

WCD (World Commission on Dams) (2000) Tarbela dam and related aspects of the Indus River basin Pakistan. Vlaeberg, Cape Town

Westmacott JR, Burn DH (1997) Climate change effects on the hydrological regime within the Churchill-Nelson River basin. J Hydrol (Amst) 202:263–279

Winiger M, Gumpert M, Yamout H (2005) Karakorum–Hindukush–western Himalaya: assessing high altitude water resources. Hydrol Process 19:2329–2338

Wolf AT, Natharus JA, Danialson JJ, Ward BS, Pender JK (1999) International basins of the world. Int J Water Resour Dev 15:387–427

Yue S, Pilon P, Phinney B, Cavadias G (2002) The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol Process 16:1807–1829

Zhang S, Lu XX (2009) Hydrological responses to precipitation variation and diverse human activities in a mountainous tributary of the lower Xijiang, China. Catena 77:130–142

Zhang Q, Jiang T, Gemmer M, Becker S (2005) Precipitation, temperature and runoff analysis from 1950 to 2002 in the Yangtze basin, China. Hydrol Sci J 50:1–80

Zhang Q, Liu C, Xu CY, Xu YP, Jiang T (2006) Observed trends of water level and streamflow during past 100 years in the Yangtze River basin, China. J Hydrol (Amst) 324:255–265

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