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Hydro-climatological variability in the Upper Indus Basin and implications for water resources

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Abstract The mountainous region of the Upper Indus Basin is a critical source of water for Pakistan. Most flow in the upper Indus is derived from melting snow and glaciers and summer runoff is strongly correlated to winter precipitation and summer temperature, though links may operate in opposing directions in glacier-fed and snow-fed hydrological regimes. From 1961 to 1999 there were significant increases in winter, summer and annual precipitation and significant warming occurred in winter whilst summer showed a cooling trend. These trends will impact upon water resource availability. Relationships between climatic variability and large-scale climatic processes may be used to increase forecasting lag time for water resources.

Key words climate variability; flow forecasting; teleconnections; Upper Indus Basin; water resources

INTRODUCTION

The Indus River and its tributaries, the Jhelum, Chenab, and Sutlej rivers originate in the Karakoram, Hindu Kush, and Himalayan mountain ranges, and the Upper Indus Basin (UIB) extends from the Tibetan Plateau to northeast Afghanistan. The mountains provide the main water source for the Indus Basin Irrigation System, one of the world's largest integrated irrigation networks. The Indus River itself (Fig. 1) contributes more than half the total flow and has a controlling storage at Tarbela Dam as the river emerges from the mountains. Tarbela was primarily designed for irrigation control but also has an installed hydropower capacity of 3700 Mw providing ~13% of Pakistan's annual power output. Inflow to Tarbela is measured at Besham, which has a mean annual flow of 2425 m^3 s^{-1} (1969–2001), varying annually from 80 to 130% of the mean. This represents considerable variation in the potential for irrigation and hydropower production.

An understanding of the governing factors of annual variability in volume and timing of flows, moisture and energy inputs is therefore vital for water management in the region. This then allows assessment of the impacts of trends or periodic variations in climatic controls arising from anthropogenic climatic change or from large-scale oceanic–atmospheric interactions.

In this paper the contrasting hydrological regimes of the UIB and the sometimes-opposing influences of climatic elements on runoff in different regimes are reviewed. Historic trends in annual and seasonal precipitation and temperature are then assessed and a preliminary investigation made of "teleconnections" to El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) index.

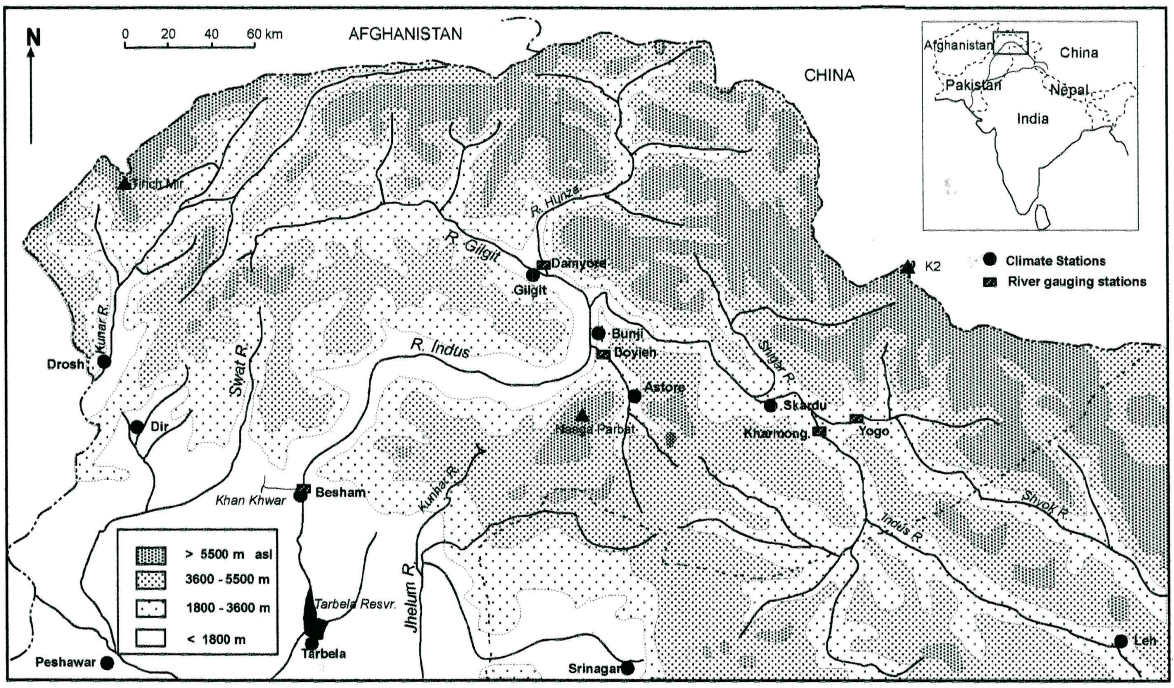

Fig. 1 The Upper Indus Basin showing climate and river flow gauging stations.

THE REGIONAL SETTING

The UIB is a high mountain region and contains the greatest area of perennial glacial ice outside the polar regions (22 000 km^2); the area of winter snow cover is an order of magnitude greater (Hewitt, 2001). The mountains limit the intrusion of the monsoon whose influence weakens northwestward. Except on the south-facing foothills, climatic controls in the UIB are therefore quite different from the eastern Himalayas. Over the UIB, most of the annual precipitation falls in winter and spring and originates from the west. Monsoonal incursions bring occasional rain to trans-Himalayan areas but, even during summer months, not all precipitation derives from monsoon sources (Wake, 1987).

Climatic variables are strongly influenced by altitude. Northern valley floors are arid with annual precipitation from 100 to 200 mm. Totals increase to 600 mm at 4400 m, and glaciological studies suggest accumulation rates of 1500 to 2000 mm at 5500 m (Wake, 1989). Winter precipitation (October to March) is highly spatially correlated across the UIB, north and south of the Himalayan divide (Archer & Fowler, 2004). In contrast, during the period from April to September, although there is significant correlation between neighbouring northern stations, a consistent weak but occasionally significant negative correlation occurs between stations north and south of the divide.

Meteorological and hydrological stations (Fig. 1) cover a distance east to west of approx. 300 km and north to south of over 200 km and are all within Pakistan, with the exception of the longest record at Srinagar in Indian-controlled Kashmir.

Climate records are thought to be consistent with respect to measurement practice. Standard meteorological measurement practice was established by the Indian Meteorological Department in 1891 and the same standards have been adopted for rainfall by the Pakistan Meteorological Department (PMD) and the Water and Power Development Authority (WAPDA).

CLIMATIC CONTROL OF HYDROLOGICAL REGIMES

Analysis of relationships between seasonal climate and runoff (Archer, 2003) suggested that the UIB could be divided into three distinct hydrological regimes. These are:

(a) High altitude catchments with large glacierized proportion (e.g. Rivers Hunza and Shyok) with summer runoff that is strongly dependent on concurrent energy input represented by temperature.

(b) Mainly middle altitude catchments south of the Karakoram (e.g. Rivers Astore and Kunhar) that have summer flow predominantly defined by preceding winter precipitation. However the main Upper Indus catchment at Kharmong also shows the same winter precipitation control.

(c) Foothill catchments (e.g. Khan Khwar) that have a runoff regime controlled mainly by current liquid precipitation, predominantly in winter but also during the monsoon.

Rivers in the three hydrological regimes may differ significantly in their runoff response to changes in the driving variables of temperature and precipitation as shown by linear regression analysis (Archer, 2003). For example, whilst the foothill catchments show significant correlation between monthly and seasonal precipitation and runoff, the high and middle altitude catchments show a negative correlation between summer precipitation and runoff. This negative response is the result of cloudiness and lowered temperatures associated with precipitation (Archer, 2004).

Summer runoff on the high altitude glacier-fed catchments shows significant positive correlation with summer temperatures. Figure 2(a) suggests a 17% increase in summer runoff for the River Shyok for 1°C temperature rise. However, temperature and runoff are negatively correlated on middle altitude (snow-fed) catchments. Here, increased temperature results in increased evaporative loss and (since snow cover volume is limiting) reduced runoff, with an estimated reduction of ~18% for a 2°C rise in temperature (Singh & Bengtsson, 2005).

Winter precipitation is strongly correlated with summer runoff on the snow-fed catchments (r = 0.88). Significant correlation is achieved as early as March, providing a useful lead time for forecasting, as demonstrated in Fig. 2(b) for the upper Indus at Kharmong. The relationships suggest an increase in runoff of 5% at Astore and 3% at Kharmong for a 10% increase in mean winter precipitation. In contrast, no significant correlation was found for the predominantly glacier-fed catchments. On the foothill catchments, significant correlation was found with spring (April to June) but not with summer runoff.

These varied responses to changes in the driving variables mean that caution must be exercised in the prediction of runoff response to climate change, especially in complex catchments with a mix of hydrological regimes.

RECENT CLIMATIC TRENDS

Analyses by Archer & Fowler (2004) and Fowler & Archer (2005) have assessed trends in precipitation and temperature data respectively over the past 100 years. The main results are summarized here.

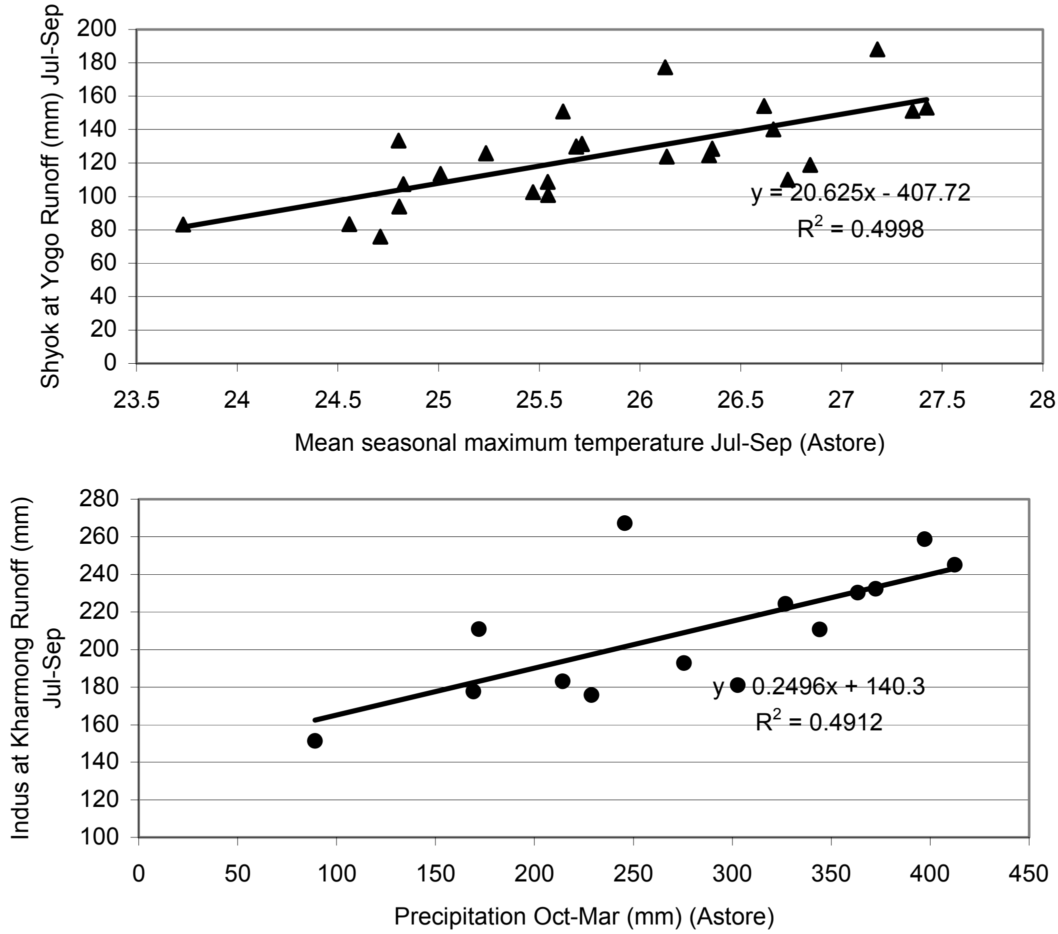

Fig. 2 Relationships between seasonal climate and summer runoff: (a) between mean maximum temperature at Astore and Shyok runoff at Yugo, and (b) between preceding winter rainfall (October–March) at Astore and Upper Indus runoff at Kharmong.

Based on three long-term (1894–1999) records at Gilgit, Skardu and Srinagar, there is no statistically significant trend in annual or seasonal precipitation over the last century. However, analysis of these and other records shows evidence of an upward trend in winter precipitation across the region since 1961, which is statistically significant ($P < 0.05$) at Skardu and Dir, with increases of 18 and 16% per decade, respectively.

There are contrasting trends in annual mean temperature in the UIB. Long-term stations at Skardu and Srinagar show a warming trend whilst Gilgit shows a cooling trend. These trends have intensified since 1961, as exemplified for Srinagar in Table 1.

Trends differ between seasons and between mean daily maximum and minimum temperatures. The greatest warming rates are found in winter, with warming since 1961 resulting primarily from the increase in winter maximum temperature. This increase is large and statistically significant ($P < 0.05$) at Gilgit, Skardu and Dir, with increases of 0.27, 0.55 and 0.51°C per decade, respectively.

Significant summer cooling has occurred since 1961, with negative trends in both minimum and maximum temperature. Reductions in summer minimum temperatures are statistically significant ($P < 0.05$); ranging from −0.4 to −1.11°C per decade.

Table 1 Trend in mean temperature from 1961–2000 for annual and by 3- and 6-month periods, showing change in °C per decade. Change in mean temperature from 1894 to 2000 and 1894 to 1960 is given for Srinagar as a comparison.

Station	Annual	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter half-year (O–M)	Summer half-year (A–S)
Astore	−0.08	−0.07	−0.06	***−0.30***	+0.01	0.00	−0.14
Bunji	**−0.52**	−0.03	**−0.32**	**−0.99**	**−0.66**	**−0.35**	**−0.72**
Drosh	+0.01	+0.19	+0.02	−0.04	−0.03	−0.09	+0.10
Dir	**−0.26**	−0.03	***−0.41***	**−0.35**	−0.19	−0.22	**−0.28**
Gilgit	−0.13	***+0.17***	−0.08	**−0.38**	−0.15	−0.02	−0.18
Skardu	**+0.21**	**+0.38**	***+0.24***	−0.05	**+0.26**	**+0.34**	+0.11
Srinagar	**+0.19**	**+0.51**	+0.07	−0.05	+0.08	**+0.25**	+0.10
Srinagar (1894–1999)	**+0.07**	**+0.12**	***+0.06***	+0.02	**+0.06**	**+0.10**	**+0.04**
Srinagar (1894–1960)	**+0.11**	**+0.10**	***+0.06***	+0.10	**+0.13**	**+0.09**	**+0.11**

Note: Bold—$P < 0.05$; Bold Italic—$P < 0.10$.

However, the cooling of maximum temperature is less significant. This response is shared with the neighbouring region of northwest India where Hingane *et al.* (1985) found a negative trend of –0.05°C per decade since 1901.

PREDICTING WATER RESOURCE AVAILABILITY USING "TELECONNECTIONS"

Whilst observed trends in temperature and precipitation may be attributed to global warming due to increasing concentration of greenhouse gases (IPCC, 2001), annual variability may be attributed to large scale ocean–atmosphere interactions. Since the climate of the UIB is influenced both by monsoonal and westerly flows, links both to El Niño Southern Oscillation (ENSO) and to the North Atlantic Oscillation (NAO) have been investigated.

ENSO is the most important coupled ocean–atmosphere phenomenon causing global climate variability on interannual time scales. Statistical prediction methods for Indian summer monsoon rainfall have relied heavily on relationships with ENSO indices since the early 20th century (Krishna Kumar *et al.*, 1995). Although the analysis above indicates that winter precipitation is more critical for flow in the UIB, links between ENSO and winter precipitation has received less attention. Here we use a combined index, the Multivariate ENSO Index (MEI), which uses six observed variables over the tropical Pacific and is computed seasonally (Wolter & Timlin, 1993). Average seasonal temperature and precipitation for stations in the UIB are compared for maximum El Niño and La Niña years, computed for summer MEI (May–September). El Niño years are 1965, 1972, 1982, 1987, 1991, 1993, 1994 and 1997, and La Niña years are 1950, 1955, 1956, 1964, 1971, 1974, 1988 and 1999. Results are shown in Table 2.

With respect to precipitation, the most consistent contrast is between enhanced winter precipitation in El Niño years and reduced early winter precipitation in La Niña years. No consistent pattern of anomalies is found in UIB summer precipitation. However, summer temperatures are lowered in El Niño years and increased in La Niña

Table 2 Comparison of long-term averages to averages in maximum El Niño and La Niña years: (a) ratio of seasonal precipitation long-term average, (b) difference (°C) in seasonal temperature between El Niño and La Niña years and long-term average.

Station	Apr–Jun	Jul–Sep	Oct–Dec	Jan–Mar	Apr–Jun	Apr–Jun	Jul–Sep	Oct–Dec	Jan–Mar	Apr–Jun
(a) Precipitation El Niño						Precipitation La Niña				
Gilgit	0.73	1.10	1.83	1.51	0.82	0.76	1.02	0.79	1.17	1.06
Skardu	0.94	0.80	1.77	1.51	0.92	1.27	0.96	0.66	1.19	1.45
Astore	0.83	0.99	1.42	1.34	0.77	0.96	0.90	0.63	1.07	1.29
Drosh	1.23	1.00	1.14	1.27	0.87	0.94	1.11	0.75	1.28	1.38
Tarbela	1.40	0.93	1.18	1.18	1.12	0.93	0.92	0.66	0.85	1.08
Srinagar	1.08	0.82	1.43	1.40	0.96	0.85	1.19	0.48	1.07	1.15
Peshawar	0.94	0.93	0.79	1.44	0.91	0.47	1.80	0.34	0.99	0.83
(b) Temperature El Niño						Temperature La Niña				
Gilgit	–0.4	–0.6	–0.2	–0.4	0.1	0.4	0.1	0.2	–0.5	–0.8
Skardu	0.1	–0.3	0.2	–0.8	0.2	0.1	–0.2	0.0	–0.2	–0.7
Astore	–0.2	–0.4	0.0	–0.4	0.1	0.4	0.1	0.5	–0.5	–0.8
Drosh	–0.5	–0.2	–0.1	–0.2	0.3	0.4	0.1	0.8	–0.6	–0.7
Srinagar	–0.4	–0.5	0.1	0.5	0.2	0.3	0.2	0.5	–0.5	0.0

Precipitation: Dark grey highlight—Ratio > 1.10; Light grey highlight—Ratio < 0.90.

Temperature: Dark grey highlight—Index year higher by >0.2°C; Light grey highlight—Index year lower by >0.2°C.

years. These preliminary results are indicative only, but appear to justify further study as a basis for forecasting.

Since the late 1970s the strong relationship between ENSO and the Indian monsoon has weakened. Chang *et al*. (2001) suggest that this breakdown has been caused by the strengthening and poleward shift of the jet stream over the North Atlantic, which has led to a significant correlation between wintertime western European surface air temperatures and the ensuing monsoon rainfall. A measure of North Atlantic influences is the North Atlantic Oscillation (NAO) index, which is usually defined by the December–March average of normalized sea-level pressure difference over the Azores and Iceland (e.g. Jones *et al.*, 1997), but can also be derived on a monthly basis.

Archer & Fowler (2004) obtained statistically significant correlation between winter precipitation and a monthly index of the NAO, particularly during the months from November to January. In addition, significant negative correlation was found between NAO and summer rainfall at several stations, suggesting that in summer there is interplay of weather between monsoonal and westerly sources. Whilst this preliminary analysis has identified significant links to ENSO and NAO indices, a more comprehensive analysis of links to a range of global climatic variables is required to make a practical contribution to water resource management of the River Indus.

DISCUSSION AND CONCLUSIONS

Linkages have been established between seasonal precipitation, energy budget (represented by temperature) and summer runoff. However, complex catchments with multiple regimes such as the main Indus require separate assessment of the impact of changes in controlling variables in the contributing regimes.

Analysis of time series shows regional trends in precipitation and temperature since 1961, notably upward trends in precipitation and winter temperature, but a reduction in summer temperature. The increase in winter temperature is significant and widespread; resulting in a changed proportion of precipitation falling as rain near the freezing level, although this may have little effect at higher elevations where greatest accumulation occurs. Therefore, runoff from foothill and snow-fed catchments may be significantly affected but there may be limited impact on runoff on glacier-fed catchments.

Derived climate–runoff relationships suggest that the observed decreasing trend in summer temperature will result in a seasonal decrease in runoff on predominantly glacier-fed catchments such as the River Hunza, but may increase runoff volume on snow-fed catchments due to decreased evaporative loss.

Preliminary analysis of teleconnections indicates links both to ENSO and the North Atlantic Oscillation and suggests that the Upper Indus occupies a pivotal position between tropical and temperate weather systems. Further analysis of such links may provide a basis for seasonal forecasting and improved management of water resources, including operation of the Tarbela Reservoir.

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