Hydrological implications of spatial and altitudinal variation in temperature in the upper Indus basin

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David Archer

JBA Consulting Engineers and Scientists, South Barn, Broughton Hall, Skipton, North Yorkshire BD23 3AE, UK.

E-mail: *davearcher@yahoo.co.uk*

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Abstract Runoff in the upper Indus in Pakistan is primarily fed by meltwater from snow and ice. Successful modelling of runoff thus depends on knowledge of the energy inputs for melt, and temperature provides a practical index. In this study, spatial and altitudinal variations in air temperature are investigated using correlation and regression analysis. The high levels of seasonal correlation between widely separated stations and with altitude suggest that conditions over a wide surrounding area and up to the freezing level may be inferred with reasonable reliability from climate stations at the valley level. Investigation of concurrent daily rainfall, temperature and runoff in extreme monsoon incursions shows that precipitation is accompanied by a sharp fall in temperature, reduced ablation and, most frequently, a decrease in river flow. Such temperature reductions have practical implications for short term flood forecasting and for design flood estimation.

Keywords Extreme events; melt runoff; spatial variation; temperature; upper Indus basin

Introduction

The Karakoram and neighbouring mountains of northern Pakistan provide the only areas of the country with substantial precipitation and an annual moisture surplus. The mountains supply the main sources of water via the upper Indus basin for irrigation and power for large populations living in the downstream plains of Punjab and Sindh. An understanding of the controls of the hydrological regime of the upper Indus basin is therefore critical for water resources planning and operation in Pakistan.

Runoff from the upper Indus basin is fed primarily by meltwater from seasonal and permanent snowfields and glaciers except on the southern slopes of the Himalayas where there is significant direct runoff from summer monsoon precipitation. Mountain valleys are predominantly arid but heavier precipitation falls as snow at higher altitudes, is stored during the winter months and released through melt at progressively higher elevations through spring and summer. Streamflow in the upper Indus thus depends jointly on the depth and extent of snow and ice and the energy available for ablation.

Generally in high mountain basins, as the area covered by ice increases, the ratio of summer to annual runoff increases, the timing of annual maximum monthly runoff is delayed and inter-annual variation in runoff is reduced (Collins and Taylor 1990; Wohl 2000). An analysis of the relationship between climatic parameters and streamflow in the upper Indus (Archer 2003) shows distinct differences between high elevation catchments such as the Hunza and Shyok (Figure 1), where summer streamflow is mainly controlled by energy input, whilst in lower and more southerly tributaries such as the Astore and Kunhar variations in summer runoff are primarily related to the preceding winter precipitation.

Energy input to snow and ice melt is thus a key requirement for modelling and forecasting runoff in the upper Indus basin. However, modelling is limited by the sparseness of the climatic network, the unrepresentative location of stations on valley floors and the limited number of variables in the snowmelt energy budget that are typically measured. One variable that has been consistently measured is temperature, usually as the daily maximum and

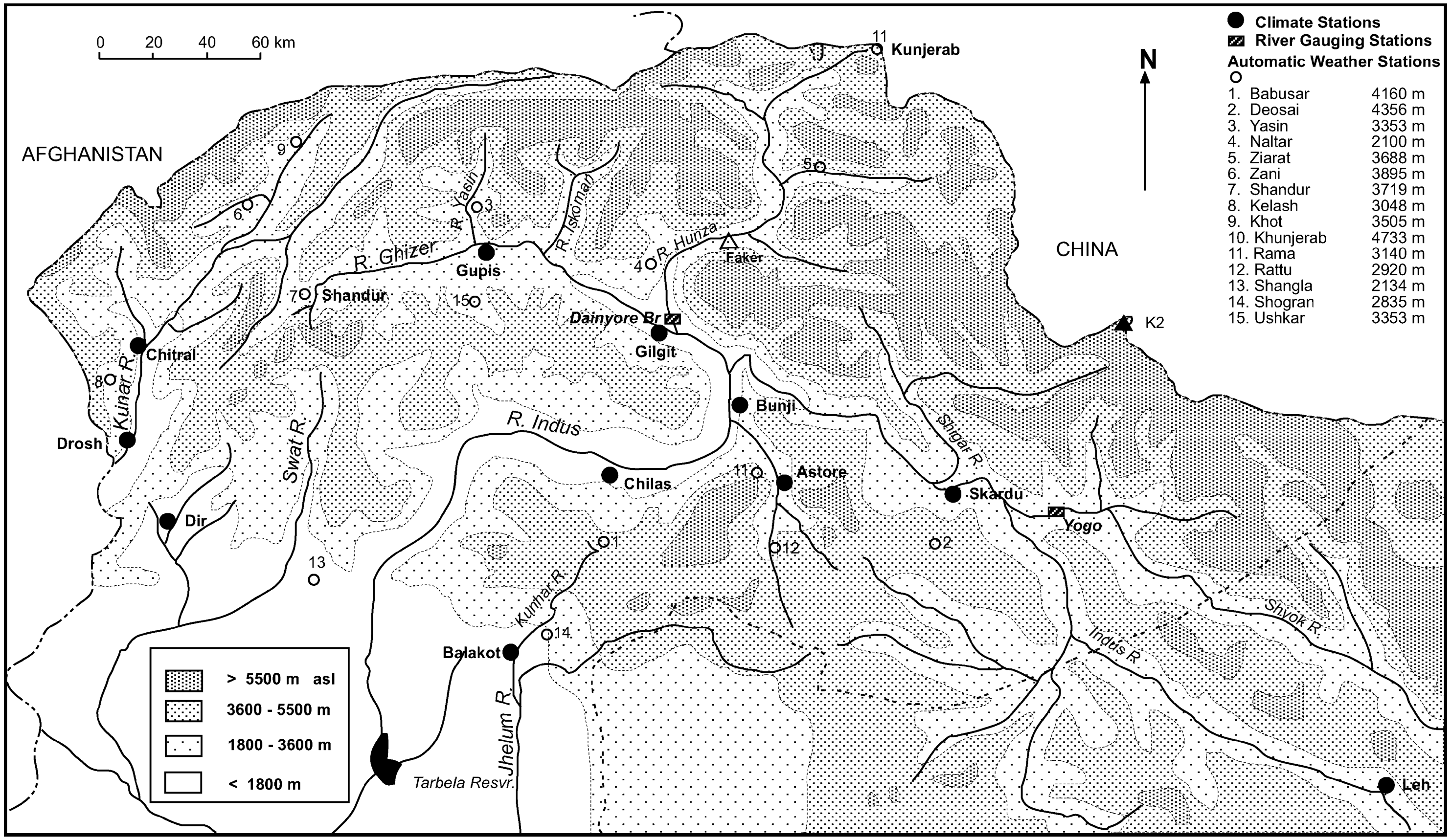

Figure 1 Northern Pakistan showing relief, rivers and climate stations

minimum. Air temperature is an imperfect indicator of the heat budget at the snow and ice surface, especially where melt is primarily due to radiant heat under cloudfree conditions. However, in practice temperature has been found to perform as well in modelling streamflow as using the full set of variables for the energy budget (WMO 1986; Bergström *et al.* 1992).

Temperature has the distinct advantage of being spatially conservative. However, it is unclear to what extent widely spaced measurements at valley sites can be used to estimate energy inputs at higher elevations and at a distance from the observation. In this paper, spatial and altitudinal variations in temperature in the upper Indus basin are investigated. Spatial variation of seasonal mean temperature is investigated using regression analysis between stations, and seasonal lapse rates are studied using regression between elevation and mean temperatures.

In addition, there is a specific practical need for an understanding of the behaviour of temperature during extreme rainfall events and the joint impact of precipitation and temperature changes on runoff.

Data

Several data sources have been used for this analysis:

(1) The Pakistan Meteorological Department (PMD) maintains standard meteorological stations at sites shown in Figure 1 and listed in Table 1. The stations range in elevation from 980 m asl at Balakot to 2394 m at Skardu. Daily records were available for Gilgit and Skardu whilst monthly records were available at the remainder. Several stations have records in excess of 40 years.

(2) For the pre-partition period, daily weather statistics for the whole Indian sub-continent were published by the India Meteorological Department in books each covering a six month period. The longest records for the Northern Areas were those for Gilgit and Skardu and these were selected for digitisation. Records for Skardu commenced in 1900 and for Gilgit in 1903. The record is essentially complete from 1905 to 1935 and thereafter is intermittent until June 1947. When concatenated with the post-partition PMD data, the total daily record length for these two stations was 80 years.

(3) A historic monthly temperature record for Leh on the upper Indus in Ladakh for the period from 1882 to 1968 was obtained from the Climate Research Unit at University of East Anglia, England. The record is intermittent over the decade before closure.

(4) The International Development Research Centre (IDRC), in conjunction with the Canadian International Development Agency (CIDA), set up a programme of snow and ice measurement in northern Pakistan consisting of a network of automatic

Table 1 Principal climatological stations used in the analysis

Station	Period of record	Years of record	Elevation (m)
Astore	1954–97	44	2394
Bunji	1953–97	45	1372
Drosh	1950–97	48	1465
Dir	1968–97	31	1425
Gilgit	1903–99	80	1460
Skardu	1900–99	80	2210
Gupis	1961–90	30	2156
Balakot	1961–90	30	980
Chilas	1961–90	30	1251
Leh	1882–68	87	3506

climatological stations. The first of the network of automatic stations commenced in 1991 but for this study records were available for most stations for a period of five years from mid-1994 to 1998 and Kunjerab and Shandur to November 2000. The stations are at higher altitude than the standard network and range from 2100 m to 4733 m. The quality and completeness of these records is variable but with the greatest operational problems at stations at high altitudes. Station locations and elevations are shown in Figure 1.

The stations within Pakistan cover a distance east to west of approximately 300 km and north to south of over 200 km. Leh is a further 200 km to the east.

Spatial correlation in temperature

With the wide spacing between climate stations, it is necessary to establish whether inter-annual variations in temperature in one part of the area are reflected in another. Correlation and regression analysis was carried out on annual, seasonal and monthly mean temperatures for seven long period records and two shorter records at high level stations at Shandur and Kunjerab. Early records at Leh have also been compared with Gilgit and Skardu only. The Gilgit and Skardu records were subdivided between pre- and post-partition periods.

Mean annual temperatures

Results of regression analysis for annual temperature are shown in Table 2. Positive correlation coefficients occur between all stations and generally the closer the distance the better the correlation. However, Astore appears to have good correlation with all stations and surprisingly better correlation with the more distant stations of Drosh (240 km) and Dir in the Chitral valley than with its closest neighbours at Skardu (64 km) and Bunji (34 km). The annual correlation between Gilgit and Skardu is better for the later period from 1954 to 1999 than the earlier period from 1905 to 1935 (0.61 and 0.43). The high correlations between the high level stations at Kunjerab and Skardu are based on five years of data only.

Mean seasonal temperatures

Seasonal correlations for six-month periods are shown in Table 3. Good correlation during the spring and summer months is of particular importance for modelling as these are the seasons of melt at progressively higher elevations. Separate correlation has been carried out for two component three-month periods (April to June and July to September) and shown in Table 4.

With reference to Tables 3 and 4, correlation during the spring and summer is much higher than during the winter months. During the summer the area is affected by broad scale

Table 2 Correlation coefficient (*r*) between annual mean temperature at stations in Northern Pakistan

Station	Astore	Bunji	Drosh	Dir	Gilgit	Skardu
Astore						
Bunji	**0.65**					
Drosh	**0.71**	**0.41**				
Dir	**0.74**	**0.54**	**0.57**			
Gilgit	**0.84**	**0.64**	**0.57**	**0.58**		
Gilgit 05-35						*0.43*
Skardu	**0.66**	*0.32*	**0.42**	0.11	**0.61**	
Kunjerab					*0.86*	*0.94*
Shandur					0.81	*0.91*
Leh					**0.49**	**0.60**

Bold figures: significance 0.01. Italic: significance 0.05.

Table 3 Correlation coefficient (*r*). (a) Winter temperatures (October to March) – upper triangle. (b) Spring and summer mean temperature (April to September) – lower triangle

Station	**Astore**	**Bunji**	**Drosh**	**Dir**	**Gilgit**	**Gilgit 05-35**	**Skardu**	**Kunjerab**	**Shandur**	**Leh**
Astore		**0.55**	**0.53**	**0.56**	**0.62**		**0.76**			
Bunji	**0.76**		0.18	**0.44**	*0.31*		0.29			
Drosh	**0.71**	**0.38**		*0.38*	*0.34*		0.28			
Dir	**0.80**	**0.53**	**0.50**		**0.48**		0.24			
Gilgit	**0.92**	**0.76**	**0.61**	**0.72**			**0.69**	*0.91*	0.68	**0.74**
Gigit 05-35							**0.79**			
Skardu	**0.76**	**0.49**	**0.58**	**0.46**	**0.75**	**0.65**		−0.50	− *0.88*	**0.68**
Kunjerab					0.45		**1.00**			
Shandur					0.25		0.58			
Leh					**0.61**		**0.79**			

Bold figures: significance 0.01. Italic: significance 0.05.

weather systems (although receiving only sporadic monsoon rainfall in the northern part of the area). In winter under the prevailing influence of the Tibetan anticyclone, more local conditions prevail and temperature correlation between valley stations is affected by local temperature inversions. Other features to note in these tables are:

(1) On average the station with the best seasonal correlation with other stations is again Astore, where over the spring and summer months the correlation coefficient is greater than 0.7 with all stations except Drosh.
(2) Correlation coefficients between Gilgit and Skardu are usually similar for the early record (1905–1935) and the later 1965–1999 record.
(3) In spite of the separating distance, there are significant correlations between Leh on the upper Indus and Gilgit and Skardu.
(4) Because the differences from year to year between seasonal and annual temperature are quite small, data errors could potentially lead to sharp reductions in correlation coefficients.
(5) Correlations for individual months (not shown) are generally better than their seasonal three- or six-month combinations.

With respect to the high level stations at Kunjerab and Shandur the correlation coefficients by season are variable and, in some cases, poor. However, there are generally higher

Table 4 Correlation coefficient (*r*). (a) Spring mean temperature (April to June) – upper triangle. (b) Summer mean temperature (July to September) – lower triangle

Station	**Astore**	**Bunji**	**Drosh**	**Dir**	**Gilgit**	**Gilgit 05-35**	**Skardu**	**Kunjerab**	**Shandur**	**Leh**
Astore		**0.77**	**0.82**	**0.77**	**0.93**		**0.80**			
Bunji	**0.79**		**0.48**	**0.50**	**0.84**		**0.57**			
Drosh	**0.59**	*0.36*		**0.76**	**0.78**		**0.63**			
Dir	**0.79**	**0.59**	**0.58**		**0.60**		*0.40*			
Gilgit	**0.91**	**0.82**	**0.54**	**0.74**			**0.80**	*0.95*	−0.27	**0.68**
Gilgit 05–35							**0.78**			
Skardu	**0.78**	**0.58**	**0.46**	**0.46**	**0.73**	**0.46**		0.21	−0.28	**0.81**
Kunjerab					0.81		**0.98**			
Shandur					0.25		0.58			
Leh					**0.47**		**0.76**			

Bold figures: significance 0.01. Italic: significance 0.05.

correlation coefficients by month, and regression with Gilgit and Skardu yields on average eight months with correlation coefficients greater than 0.8.

High correlations between stations separated by considerable horizontal distances and intervening mountain barriers strongly imply that these correlations will be reflected over much shorter vertical distances.

Temperature lapse rates

Lapse rates have been investigated as a further basis for interpolation and extrapolation from valley sites to higher altitudes. Regression analysis (Table 5) has been carried out between mean seasonal and annual temperatures and station elevation as follows:

(1) For nine long period stations.
(2) For the long period stations excluding the most southerly stations at Balakot and Dir but including the two high elevation automatic weather stations at Kunjerab and Shandur.
(3) Including all northern automatic weather stations (Figure 2).

The high level of correlation between station temperature and elevation is shown in Table 5 by the correlation coefficient *r* being greater than 0.90 for annual and seasonal temperatures, with the exception of the summer months. Correlation is much improved if southern stations at Balakot and Dir are removed from the data set, since temperatures at these stations are influenced by the effects of cloudiness and precipitation, especially during the summer months. Their omission especially improves the summer correlation (July to September).

The inclusion of the high elevation stations at Kunjerab and Shandur further improves the correlation (Table 5) and all *r* values now exceed 0.98. Correlation coefficients remain high when all the additional short period automatic weather stations outside the monsoon's influence are included and the regression relationships are little changed. The short period of the overlapping record of long-period and automatic weather stations did not permit a common period to be used for analysis.

Using elevation rather than temperature as the dependent variable yields values of slope and intercept which have useful physical meanings. (The reversal of dependent and

Table 5 Mean seasonal temperature statistics and regression with elevation

Station	Annual mean	JFM	AMJ	JAS	OND	Oct–Mar	Apr–Sep
Regression analysis (9 long period stations)							
Correl	**−0.93**	**−0.98**	**−0.93**	**−0.75**	**−0.96**	**−0.98**	**−0.86**
Slope	−130.7	−131.0	−119.6	−101.9	−137.0	−136.1	−116.2
Intercept	3653.4	2417.7	4031.0	4218.8	3069.5	2752.2	4273.1
°C/100 m	0.77	0.76	0.84	0.98	0.73	0.73	0.86
Including Kunjerab and Shandur, omitting Balakot and Dir							
Correl	**−0.99**	**−1.00**	**−0.99**	**−0.99**	**−0.99**	**−1.00**	**−0.99**
Slope	−140.2	−138.3	−134.5	−137.5	−152.8	−142.5	−136.3
Intercept	3878.4	2489.2	4405.8	5302.2	3274.8	2837.6	4856.6
°C/100 m	0.71	0.72	0.74	0.73	0.65	0.70	0.73
Including northern automatic weather stations							
Correl	**−0.99**	**−0.99**	**−0.99**	**−0.98**	**−0.99**	**−0.99**	**−0.99**
Slope	−142.3	−143.1	−133.5	−139.4	−151.1	−145.0	−136.3
Intercept	3936.4	2562.1	4388.4	5387.4	3275.9	2890.4	4864.2
°C/100 m	0.70	0.70	0.75	0.72	0.66	0.69	0.73

Bold figures: significance 0.001.

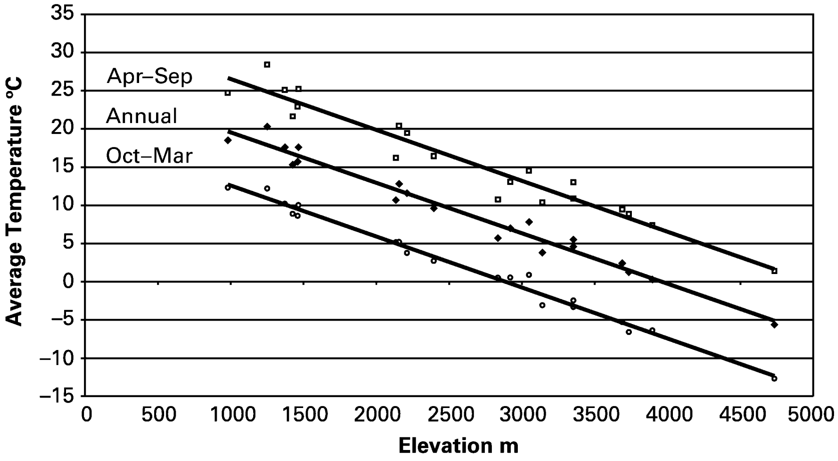

Figure 2 Karakoram lapse rates – annual and 6-month periods

independent variables has little effect on the regression equation with correlation coefficients as high as those shown.) The slope of the relationship shows the elevation increment for 1°C change in mean temperature. The inverse of this is also shown as the change in mean temperature for 100 m change in elevation. When considering only the lower elevation stations, the change appears to be greater during the summer months and less during the winter. However, where Kunjerab and Shandur are included the difference between summer and winter lapse rates diminishes. The value of the intercept shows by extrapolation or interpolation the elevation at which the mean temperature becomes zero on average for the season.

The analysis has been repeated on a monthly basis for mean, maximum and minimum temperatures and the equivalent freezing level calculated for each month. The resulting freezing level estimates are shown in Figure 3 for mean monthly maximum and minimum temperatures. This is a quantitative form of the general diagram shown by Hewitt (1968, 1989). From a hydrological point of view the upper zone is one of continuous frost, where

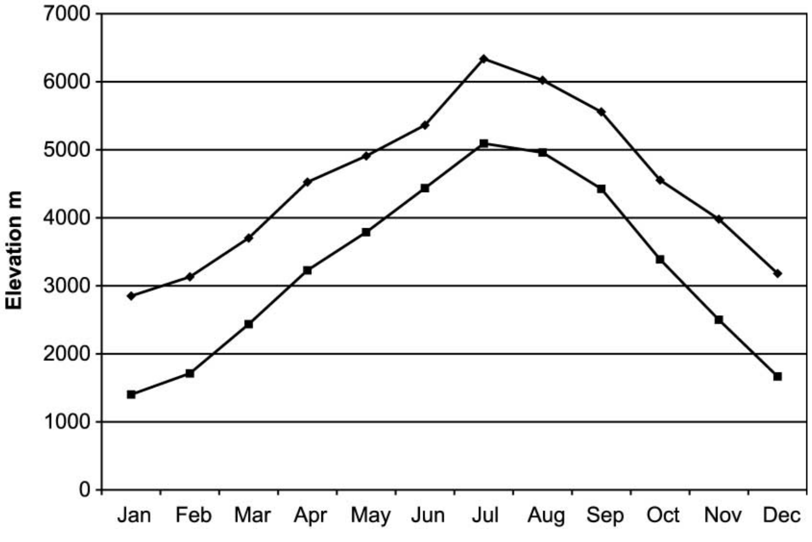

Figure 3 Elevation of the freezing level for monthly maximum and minimum temperatures

precipitation falls as snow and where there is virtually no contribution to river runoff. However, it provides nourishment to lower zones through snow avalanching and glacier flow. The middle zone is one with frequent freeze–thaw cycles, where precipitation may fall as rain or snow, melt of lying snow occurs during daylight hours and refreezing occurs at night. In the lower zone with continuous above-freezing temperatures, precipitation is expected to fall as rain and melt is continuous, though enhanced during daylight hours.

Valley floors and levels below 3000 m receive little precipitation (generally less than 200 mm per annum) and therefore contribute little to runoff. There is considerable orographic enhancement of precipitation; at 4000 m annual precipitation of greater than 600 mm may be expected (Cramer 1997) whilst Wake (1989) has suggested annual snow accumulation rates of 1500–2000 mm at 5500 m elevation. The zone of intermittent melt reaches 4000 m from late March to mid-November, and continuous melt of any remaining snow at this level can be expected to occur from late May to late September.

Temperature runoff linkages – an example

On the basis of analysis of spatial and altitudinal correlations in temperature, it was postulated that time series of temperature at valley stations might be used to represent the energy budget of the snowpack and glaciers at higher elevation. Statistical analysis was carried out for 15 gauged catchments in the upper Indus Basin (Archer 2003) and linkages between summer runoff and preceding and current precipitation and temperature. It was shown that middle altitude catchments south of the Karakoram have a summer flow predominantly defined by the preceding winter precipitation, whilst high altitude Karakoram catchments with high glacierised proportion have summer and annual runoff strongly dependent on concurrent energy input represented by seasonal temperatures. The high altitude catchments include the River Hunza at Dainyore Bridge (13,925 km^2) and the River Shyok at Yogo (65,025 km^2) (Figure 1).

As a further illustration of this linkage, correlation coefficients between monthly runoff and monthly temperature are shown for the two high elevation catchments in Table 6(a). For the River Hunza the nearest concurrent temperature record is at Gilgit, just outside the catchment boundary with a station elevation of 1460 m compared with a mean catchment elevation for the Hunza of 4472 m. In the case of the River Shyok, the best correlation was achieved using the temperature record at Astore, with a station elevation of 2394 m compared with the catchment mean elevation of 4900 m. Astore is at a distance of more than 100 km outside the Shyok catchment boundary. Despite the differences in elevation and distance from the runoff sources, significant monthly correlation of runoff with the current month mean temperature is achieved throughout the melt season from April to September for both catchments.

Whilst such relationships indicate the potential to generate monthly runoff from historic temperatures or to assess the impact of climatic change, they do not provide a basis for flow forecasting in the current season. However, preliminary analysis shows that there is a weak correlation during summer between runoff in one month and temperature in the previous month (Table 6(b)) which appears to be partly related to serial correlation in monthly temperature (Table 6(c)) and partly to lag in catchment response. Such analysis indicates a limited scope on these catchments for monthly flow forecasting. Furthermore, flow forecasting is also influenced by the occurrence of episodic monsoon incursions with associated cloud and rain into the upper Indus Basin and their impact on temperature and melt rates, as illustrated in the following.

Table 6 Correlation between monthly runoff for the River Hunza at Dainyore Bridge and monthly mean temperature at Gilgit, and between runoff on the River Shyok at Yogo and temperature at Astore

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr
(a) Current month temperature													
Hunza	0.44	−0.26	0.00	**0.66**	**0.83**	*0.55*	**0.77**	**0.81**	*0.50*	0.02	−0.11	0.38	**0.64**
Shyok	0.33	−0.01	0.08	**0.56**	**0.72**	**0.75**	**0.67**	**0.76**	**0.62**	0.10	0.44	0.06	**0.54**
(b) Previous month temperature													
Hunza	0.33	0.30	−0.08	−0.23	−0.04	0.41	0.42	*0.50*	0.07	0.19	−0.08	−0.15	−0.09
Shyok	0.17	0.25	0.05	0.14	−0.06	0.13	**0.65**	0.35	*0.42*	*0.42*	−0.11	0.33	0.10
(c) Serial monthly temperature correlation (lag 1)													
Gilgit	*0.33*	0.03	−0.14	0.00	0.25	0.30	**0.49**	*0.32*	0.25	0.21	*0.42*	0.28	
Astore	0.30	**0.50**	*0.36*	0.14	0.19	*0.34*	**0.42**	0.29	0.10	0.14	0.24	*0.36*	

Bold figures: significance 0.01. Italic: significance 0.05.

Temperatures during monsoon rainfall

In addition to spatial variations and seasonal variations with altitude, there is a specific need for an understanding of the behaviour of temperature during extreme rainfall events and the impact on runoff. It has been observed that on those occasions, where widespread rainfall occurs at valley locations such as Gilgit and Skardu, there is rarely any increase in Karakoram river flow. Four events, selected both for their severity and widespread spatial extent, have been examined in more detail to establish typical magnitudes of temperature change during rainfall.

The daily rainfall of 9 September 1992 was the Rank 2 event in 100 years of records at Skardu and the Rank 5 event in the same period at Gilgit. The October 1987 rainfall was the third highest total in the period at both stations. The other two events were selected as high and widespread rainfalls occurring in mid-summer. Two-day rainfall amounts for the events are shown in Table 7.

It is observed that the two-day rainfall total increases southward but the return period of the rainfall shows less dramatic spatial variation. In the following descriptions, reference is mainly made to temperature changes in the valley stations at Gilgit and Skardu.

Event of 2 August 1976

Prior to the storm rainfall, mean daily temperatures were very high, approaching the annual maximum and weather was generally dry. The melt of high altitude snow and glaciers had produced daily discharges above the mean annual flood level at several Karakoram stations in the two-week period preceding the rainfall and a slow recession had begun. Similar recessions were in progress in rivers further south (Rivers Astore, Kunhar and upper Swat) but from peak levels which were not so exceptional.

A sharp drop in daily mean temperature occurred on the day preceding the main rainfall and there was a further fall on the day of heavy rainfall. The total temperature drop was 14.5°C at Gilgit and 14.0°C at Skardu. This implies a fall in the freezing level of nearly 2500 m and the occurrence of snow rather than rain above an elevation of about 4200 m.

As a consequence, flow measurement stations in the Karakorams showed an almost unbroken recession through the period of rainfall. Further south on the upper reaches of the

Table 7 Two-day rainfall (mm) for four severe storm events at rainfall stations in Northern Pakistan

Station	2 Aug 1976	11 Oct 1987	9 Sep 1992	26 Jul 1995
Gilgit	48.3	57.0	59.2	18.5
Skardu	44.9	68.1	75.2	34.4
Astore	74.3	52.2	145.8	11.1
Doyien	29.5	73.7	83.8	40.9
Chitral	0.0	45.2	M	M
Dir	26.8	82.0	M	M
Drosh	3.3	47.4	M	M
Besham	64.2	107.7	119.9	90.2
Shahpur	86.4	137.4	83.1	150.6
Shinkiari	104.6	152.4	252.0	71.4
Balakot	132.0	164.5	M	M
Muzafferabad	114.8	158.7	M	M
Puran	90.2	172.7	64.3	139.7
Oghi	132.8	216.4	229.6	68.5

M = Missing.

Astore, Kunhar and Swat, small breaks in the recession occurred but in the lower parts of these rivers, significant floods were generated, in some cases above the mean annual flood.

Event of 11 October 1987

This storm was one of the most widespread and severe over the entire area of northern Pakistan. It was the third highest rainfall in 100 years at both Gilgit and Skardu and totals increased southward, reaching two-day totals of over 150 mm in the Jhelum catchment. High rainfall also extended to the Chitral area. River flows were already well into recession from the summer maximum. The period preceding the heavy rainfall was characterised by partly cloudy conditions and rain on some days, and temperatures were declining sharply, as is characteristic of October.

Precipitation occurred from 10–13 October but with the heaviest falls on 11 October, accompanied by a drop in the mean daily temperature of 12°C. Observed valley temperatures and a saturated adiabatic lapse rate implied a freezing level of about 3000 m with precipitation occurring as snow over the greater part of the northern basins. River flows were unaffected except on foothill basins with areas predominantly below 3000 m where precipitation fell as rain and significant floods were generated.

Event of 9 September 1992

Rainfall of exceptional magnitude occurred throughout northern Pakistan and caused flooding and disastrous loss of life in the Jhelum basin. Rainfall totals in excess of 200 mm were experienced in parts of the Jhelum and over 100 mm in foothill tributary basins of the Indus. It was the second highest rainfall on record at Skardu, and at Gilgit the rainfall was only marginally less extreme. It was described as a 100-year flood by Bohle and Pilardeaux (1993).

The period preceding the storm was predominantly dry but with some light to moderate rainfall on 3 September. Rainfall commenced on 8 September but the main storm in the north occurred on 10 September. It was accompanied by a fall in mean daily temperature of about 13°C and the implied freezing level based on temperatures at Gilgit and Skardu and the saturated adiabatic lapse rate was about 3800 m. However, Hansen (1997) reports that, during the night of 9 September, precipitation fell as snow down to 2000 m in the Astore valley.

River flows at the onset of the event were generally well below the summer maximum and in sharp recession. Unlike the events described above there was a break in the flow recession at all stations but the flow augmentation due to rain was less than the initial flow and much below the annual maximum in Karakoram basins. Even on the Astore and upper Kunhar and Swat there were limited increases in flow due to rainfall but major floods occurred on the lower Kunhar and Swat.

Event of 26 July 1995

The monsoon storm of 26 July 1995 also brought widespread precipitation but with the greatest intensity over the foothill tributaries of the Indus. Rainfall totals in the north were severe but not extreme. The event was again accompanied by a fall in mean daily temperature of about 13.5°C at Gilgit and Skardu. For this event several automatic weather stations were in operation. These showed a smaller temperature depression than at Gilgit and Skardu but it is not clear whether this is because of the different measurement methods or because the depression is lower at higher altitudes. The average depression in mean daily temperature for automatic stations over 3000 m was 9.3°C.

In the preceding period, river flows due to snow and glacier melt had reached a summer peak on the northern tributaries, in some cases with discharges well above the mean annual flood, but a slow recession had commenced at the onset of rainfall. The streamflow response to this event appears more varied. On the Hunza, Shigar and Shyok, there was a sharp intensification of the recession (more rapid reduction in flow) but an increase in flow on the River Gilgit. The direct runoff from rainfall contributed to a high annual maximum on the Astore (although the melt runoff contributed a higher proportion of the total). The greatest impact was on the lower Swat where, with locally more intense rainfall, the highest flood in its 37-year record was experienced.

Conclusions on temperature change during monsoon rainfall

Evidence from the largest monsoon and post-monsoon rainfalls in the records suggests that the direct contribution of rainfall to river flow is small in northern catchments whereas it may result in the most devastating floods in foothill basins. In most instances the reduction in melt runoff in high altitude basins, due to reduced temperature and energy inputs, more than compensates for direct runoff from rainfall, and the occurrence of rainfall is often accompanied by a sharp reduction in flow.

Major summer storms are accompanied by a drop in daily mean temperature of 12–15°C. Daily maximum temperatures are more affected and may fall by as much as 20°C. This results in a drop in the freezing level of more than 2000 m and the occurrence of snow rather than rain over much of the high Karakoram basins.

Such temperature reductions have practical implications both for short term flood forecasting and also for design flood estimation, for example for spillway design, where based on the analysis of storm rainfall. The assessment of effective storm rainfall over a basin for design purposes must take into account the freezing level and the contributing proportion of the catchment below this level (Archer 2001). The assumption of average seasonal temperatures in association with extreme rainfall is likely to lead to an overestimate of the contributing area and a very conservative estimate of discharge.

It is worth noting, however, that whilst rainfall rarely results directly in the most extreme floods in the upper Indus tributaries, very severe floods may be caused indirectly by landslides triggered by extreme rainfall or influenced by preceding seasonal rainfall or snowmelt. It may not be coincidence that in early summer 1937 the largest landslide dambreak flood in the last 100 years on the River Hunza followed shortly after the highest daily rainfall at Gilgit since 1895. A massive landslide destroyed the village of Faker (Figure 1), killed 60 inhabitants and blocked the River Hunza for a period variously estimated as between six and twenty days (Said 1998). The ensuing dambreak was said to be sudden, causing serious flood damage downstream.

Discussion and conclusions

Altitudinal gradients of temperature have previously been investigated locally by Cramer (1997) and Jacobsen (1997) in the Yasin and Bagrot tributaries, respectively, of the Gilgit River. This is the first study on a regional scale of spatial and altitudinal variations in temperature in the upper Indus Basin, and it is at this scale that results are most relevant to hydrological modelling as a basis for flow prediction. In the context of the large, high altitude tributaries of the Upper Indus, such as the Hunza and Shyok, where the annual hydrograph is highly damped by reasons of catchment size and the predominance of snow and glacial melt, the modelling of monthly and seasonal flows is of more practical significance for water resources management than daily flows.

The significance of the correlation between summer runoff for these two high elevation Karakoram catchments and temperature measured at valley sites beyond the catchment boundary demonstrates the viability of extending the flow record back on the basis of historical climatic records. For Gilgit and Skardu such records commence early in the 20th century. The analysis also suggests a basis for assessing the impact of trend in summer temperature arising from climate change on seasonal runoff. Such relationships could be expected to apply only in the short to medium term as ultimately an increase in temperature would affect runoff in the opposite direction through a reduction in the area of perennial snow and ice.

The underlying basis for the correlation of summer runoff with distant climate stations is the spatial conservatism of temperature, demonstrated by the significant correlation in spring and summer temperature between climate stations separated by distance, by mountain barriers and over a wide range of altitude. Analysis of lapse rates suggests that seasonal temperature may be inferred with reasonable reliability from valley stations to elevations in excess of 4000 m.

Archer (2003) has shown that, in more southerly, middle-altitude tributaries of the Indus, summer flow is more dependent on preceding winter precipitation than on summer temperature. In these tributaries, such as the Rivers Astore and Kunhar (Figure 1), practical forecasting with a lead time of several months is possible, using winter precipitation measurements at valley stations. Forecasting is more problematic in the high altitude Karakoram tributaries, but monthly correlation of runoff with the previous month's temperature provides a limited basis for forecasting.

The effect of infrequent monsoon incursions also adds complexity to flow forecasting. Joint inspection of precipitation, temperature and streamflow during severe monsoon incursions into the Karakoram shows that high and widespread rainfall is generally accompanied by a sharp drop in temperature. This in turn causes a lowering in the freezing level and the elevation at which precipitation falls as snow. The reduction in the energy input and increase in albedo associated with new snow generally more than compensate for direct runoff from rainfall. Thus, flow in the main rivers frequently diminishes after the occurrence of precipitation at valley stations.

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