THE CLIMATE AND FLOOD RISK POTENTIAL OF NORTHERN AREAS OF PAKISTAN

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ABSTRACT

The extreme floods in northern parts of Pakistan are caused by glacier lake out-bursts and Dam-Breaks following landslides, which block river valleys. Geographically glacier dams in mountain rivers and valleys have occurred from the east-western and west-western Karakuram ranges and in the lesser Karakuram range. Floods which arise from Karakuram region pose greater problem, as these floods are neither homogenous nor stationary. These floods arise from various generating mechanisms i.e. generated by melting of snow and glacier and those generated from the monsoon rainfall and dam-breaks following landslide into the river and out-burst of glacier lake. The estimation of present and future risk of flooding at sites in northern Pakistan requires an understanding, of the climate, which provides the generating mechanism of floods. Climates are extremely variable and depend op broad global circulation-patterns and local topographic influences.

The variables of the climate are studied using, available data, with emphasis on temperature and precipitation Spatial Co-relation in precipitation and temperature of various northern-area stations have been conducted to find Co-relation Co-efficient, using regression analysis. This is spread over intra-seasonal and inter-station comparisons. The time-series analysis of the climatic variables has been conducted to examine geographically and statistically the trend in their behaviour. This may be reflected in the hydrological regime of glaciers and rivers and it can cause non-linear flood-series through changes in any one of the flood-generating mechanisms.

The climate feed-back mechanism has been discussed, which are practically important because they assist m seasonal prediction of climate and flow in the Indus. Additionally, if climate warming is causing an upward Trend in winter and spring temperature and reduction in snowfall, the effect might be felt more widely over the region.

The non-linear changes with elevation and differences between windward and leeward sides indicate the complexity of the rainfall distribution m the region. The study gives monthly seasonal and annual total distribution of meteorological variables between various northern areas stations, while discussing each one with its impact and the co-relation with the other over a wider prospective.

THE CLIMATE OF NORTHERN PAKISTAN

The assessment of the present and future risk of flooding at sites in northern Pakistan requires an understanding of the climate, which provides the generating mechanisms of floods. Mountain climates are extremely varied and depend on both broad global circulation patterns and local topographic influences. In this study, the variability of climate is investigated using all available data, with special emphasis on temperature and precipitation. Since the measurement-network is of low density, studies have been carried out to assess the extent to which climate at ungauged sites can be inferred from available records, using correlation and regression analysis.

Mountain climates are influenced by the broad global circulation-patterns associated with latitude, position in the continental mass and proximity to the oceans. During the winter and spring, the Karakoram area is affected by broad-scale weather-systems, originating primarily from the Mediterranean or from the area of the Caspian Sea (Singh *et al,* 1995) from airmass convective storms in the pre-monsoon season, and from monsoon systems during the summer. Even in the summer, there are indications that at least some of the higher-level precipitation is also originating from westerly systems (Wake, 1987). However, in winter, under the prevailing influence of the Tibetan anticyclone, more local conditions prevail. Mountain climates are also influenced on the medium and local-scale by elevation, valley orientation, aspect and slope as well as the height and number of upwind barriers to the airflow.

Thus mountain climates are much more spatially variable than neighbouring plains and require a much greater density of measuring

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stations to define the climate and hydrological regime with the same level of accuracy as on neighbouring lowlands. However, for logistic reasons, the density of measuring stations in mountain-regions is typically much lower than in lowland areas and stations are generally concentrated at lower elevations in valleys and, thus, give a biased representation of the climate. This is certainly the case in the Karakoram. Nevertheless, inferences must be made from the available data.

Temperature

The principal influence on temperatures is that of elevation, but local factors, such as aspect and the duration of sunlight and shadow from neighbouring mountains and heat-reflection from bare hillsides, may produce strong local differences. Mean monthly and annual maximum, minimum and mean temperatures are shown in Table-1. Mean monthly temperatures are shown for the short period automatic weather-stations in Table-4.

The prevailing influence of elevation can be seen in these statistics, with the highest mean annual temperature recorded at the lowest station, Balakot. However the influence of elevation is not uniform and Gupis, which is at a similar elevation to Skardu, is consistently more than 1^{o} C hotter throughout the year. Temperatures at Balakot and Dir are suppressed by greater cloudiness and rainfall, especially during the summer months.

Gilgit has the highest average range of temperatures of the stations investigated, and Karimabad, Gupis and Astore the lowest range in the valley, whilst the high-level stations at Kunjerab and Shandur have significantly lower ranges. This is likely to be a local effect, dependent on shading or reflection from surrounding hills and duration of sunshine and the persistence of snow at high levels.

Valley floors and levels below 3000 meters receive little precipitation (generally less than 200 mm) and therefore contribute little to runoff. There is considerable orographic enhancement of precipitation and at 4000 meters annual precipitation of greater than 600 mm may be expected. The zone of intermittent melt reaches this level from late March to mid November and continuous melt of any remaining snow can be expected to occur from late May to late September.

SOME CONCLUSIONS

Major summer storms are accompanied by a drop of 12-15^{o}C in daily mean temperature. Daily maximum temperatures are more affected and may fall by as much as 20^{o}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 reductions in temperature have practical implications, both for short-term flood-forecasting and also for design flood estimation, where based on 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 contribution proportion of the catchment below this level.

Table-1: Maximum, Minimum and Mean Temperatures (For The Main Stations)

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
(a) Maximum Temperature													
Astore	2.4	4	8.4	14.6	19.2	24.5	27.1	27	23.5	17.2	11.1	5	15.3
Bunji	9.6	12.5	17.9	24	28	33.7	36.2	35.7	32.5	25.7	18.5	11.8	23.9
Drosh	8.8	11	15.9	22.5	28.6	35.6	36.8	35.9	33	26.6	18.9	11.8	23.8
Dir	11.3	12.3	16	22.1	27.3	32.5	31.4	30.3	29	24.8	20.1	13.9	22.6
Gilgit	9.2	12.3	17.7	23.7	28	33.9	36.1	35.4	31.9	25.3	18	11.2	23.6
Skardu	2.6	5.4	11.7	18.3	22.5	28.2	31.5	31.2	27.2	20	12.7	6	18.2
Gupis	4.1	6.6	12.2	18.5	23	29	32.1	30.9	26.4	19.9	13.6	5.8	18.5
Balakot	14	15.4	19.5	25.3	31	35.3	32.3	31.3	30.9	27.5	21.9	16	25
Chilas	12.3	14.5	20.1	26.1	31.1	37.6	39.6	38.6	35.1	28.4	20.9	13.7	26.5
Karim-abad	2.1	4.3	9	16.1	20.2	25.8	28.5	29.4	23.8	18.1	10.7	4.3	16
Misgar	-1.1	1.7	7.2	12.3	16.3	21.2	24.6	25.2	20.8	14	6.9	0.5	12.5
Kunjerab	-13.4	-10.9	-6.8	-0.2	3.6	6.9	11.8	11	6.6	-0.6	-6	-10.5	-0.7
Shandur	-8.9	-6.5	-1.4	5.7	10.6	14.7	19.8	19.2	14.8	7.4	0.5	-5.3	5.9

Table-1 (contd.) Maximum, Minimum And Mean Temperatures

(b) Minimum Temperature												
Astore	-7.5	-5.7	-1.1	3.5	7.1	11	14.5	14.6	10.5	4.4	-0.7	-4.5	3.8
Bunji	0.1	2.7	7.6	12.1	15.2	19.6	23.4	22.8	18.1	11.3	5.2	1.4	11.6
Drosh	-0.1	1.2	5	10.1	14.9	20.7	23.2	22.5	18.4	11.8	6.2	2.2	11.4
Dir	-2.5	-1.1	3	7.8	11.4	15.6	19.3	18.7	13.8	7.5	2.5	-0.7	7.9
Gilgit	-2.5	0.6	5.7	9.4	11.9	15	18.5	17.9	13	6.8	0.8	-1.9	7.9
Skardu	-8.2	-5	1.5	6.5	9.6	13.5	16.6	16.2	12	4.7	-1.6	-5.4	5
Gupis	-4.9	-2.8	2.2	7.6	11.3	16	18.8	18	13.5	7.2	1.6	-3.1	7.1
Balakot	2	3.9	7.6	12.6	17.2	21	21.3	20.6	17.1	11.5	6.2	2.9	12
Chilas	0.9	3.4	8.4	13.8	18.4	24.3	27.3	26.8	22.5	14.6	7.1	2.1	14.1
Karim-abad	-4	-2.6	2.4	7.2	10.6	13.9	16.4	17.2	11.5	7.7	2.6	-1.8	6.8
Misgar	-13.2	-9.7	-5.4	-0.2	3.4	8	11.1	11.6	6.6	-0.1	-5.8	-10.6	-0.4
Kunjerab	-22.1	-20.2	-16	-10.4	-6.9	-2.8	0.8	0.4	-3.4	-10.8	-15.4	-19.4	-10.5
Shandur	-16.2	-15	-11.8	-5.8	-0.5	4.6	9.4	8.9	4.4	-2.7	-8.7	-13.5	-3.9
(c) Mean Temperature													
Astore	-2.5	-0.8	3.6	9	13.1	17.7	20.8	20.8	17	10.8	5.2	0.2	9.6
Bunji	4.9	7.6	12.7	18	21.6	26.7	29.8	29.2	25.1	18.3	11.7	6.5	17.6
Drosh	4.4	6.1	10.4	16.3	21.8	28.1	30	29.2	25.7	19.2	12.6	6.9	17.6
Dir	4.4	5.6	9.5	14.9	19.4	24	25.4	24.5	21.4	16.2	11.3	6.6	15.3
Gilgit	3.3	6.4	11.7	16.6	20	24.4	27.3	26.6	22.5	16	9.4	4.7	15.7
Skardu	-2.8	0.2	6.6	12.4	16.1	20.8	24.1	23.7	19.6	12.3	5.5	0.3	11.6
Gupis	-0.5	1.9	7.2	13	17.1	22.5	25.4	24.4	20	13.6	7.6	1.4	12.8
Balakot	8.1	9.6	13.5	19	24.1	28.2	26.8	25.9	24	19.4	14	9.4	18.5
Chilas	6.6	9	14.2	20	24.8	31	33.5	32.6	28.8	21.5	14	7.9	20.3
Karim-abad	-1	0.8	5.7	11.6	15.4	19.8	22.4	23.3	17.6	12.9	6.6	1.2	11.4
Misgar	-7.2	-4	0.9	6	9.8	14.6	17.8	18.4	13.7	7	0.6	-5	6
Kunjerab	-17.6	-15.8	-11.6	-5.4	-1.4	2.1	6.3	5.6	1.5	-5.5	-10.7	-14.9	-5.6
Shandur	-12.5	-11.1	-6.8	0	5.3	9.7	14.6	14.1	9.5	2.4	-4.1	-9.2	1.2
Leh	-7.7	-5.8	0.2	5.8	9.9	14.2	17.4	17.1	13.1	6.8	0.8	-4.7	5.6
(d) Mean Temperature Range Between Minimum And Maximum													
Astore	10	9.8	9.5	11.1	12.1	13.5	12.7	12.4	13	12.8	11.8	9.6	11.9
Bunji	9.5	9.8	10.3	11.9	12.8	14.1	12.8	12.9	14.4	14.4	13.3	10.4	12.3
Drosh	8.9	9.7	10.9	12.4	13.6	14.9	13.6	13.5	14.7	14.9	12.7	9.6	12.6
Dir	13.8	13.5	13	14.3	15.9	16.9	12.1	11.6	15.2	17.3	17.5	14.7	14.6
Gilgit	11.7	11.7	12	14.3	16.2	18.9	17.6	17.5	18.9	18.4	17.1	13.1	15.6
Skardu	10.8	10.3	10.2	11.8	12.9	14.8	14.9	14.9	15.2	15.3	14.4	11.4	13.1
Gupis	9	9.3	10	10.8	11.7	13	13.3	13	12.9	12.7	12	8.9	11.4
Balakot	12.2	11.4	11.8	12.9	13.8	14.4	11.1	10.6	13.8	16	15.7	13.2	13.1
Chilas	11.4	11.2	11.7	12.3	12.7	13.3	12.3	11.9	12.5	13.8	13.9	11.6	12.4
Karim-abad	6.1	6.9	6.6	8.9	9.6	11.9	12.1	12.2	12.3	10.4	8.1	6.1	9.3
Misgar	12.1	11.4	12.6	12.5	12.9	13.2	13.5	13.6	14.2	13.9	12.7	10.1	12.7
Kunjerab	8.4	9.9	9.6	10.4	10.1	9.6	11.1	10.8	10.3	9.9	9.4	8.8	9.8
Shandur	7.1	9.2	10.7	11.5	10.5	10	10.5	10.4	10.6	9.9	9.2	8.5	9.9

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.

PRECIPITATION

Precipitation is the basic-input to the hydrological cycle, making a direct contribution through rainfall or a delayed contribution as snow. Precipitation is also a factor in the occurrence of mass-movement, though freeze-thaw action and mechanical weathering, as a medium for conveyance of debris-flows, etc., and as a lubricating agent for mass-movement with slipping and sliding mechanisms.

Studies of precipitation-distribution in Northern Pakistan and neighbouring mountains have been more limited due to the limited availability of data, especially at higher elevations. An early study by Hill (1881) suggested that rainfall in the northwest Himalayas increases with elevation, up to about 1200 m, and decrease, thereafter. Dhar and Rakhecha (1981) found that maximum rainfall occurred in the foothills of the Nepal Himalayas at an elevation of 2000 to 2400 m.

Singh *et al* (1995) studied the distribution of precipitation in the Western Himalayas of the neighbouring upper Chenab basin. Data from 31 stations for a common period of 17 years was used. The stations ranged in elevation from 305 m to 4325 m. Separate analysis was made for windward and leeward sides, and for the outer, middle and greater Himalayas. Separate analysis was also carried out for rainfall and snowfall, but it is difficult to draw conclusions concerning total precipitation. The windward side is assumed to be the south for both winter and monsoon rainfall.

For the Greater Himalayas, snowfall (total snow/water equivalent) increased linearly through the range of altitude from 2000 m to 4325 m, reaching a maximum of 650 mm. At higher elevations the number of snowy days increases, but the intensity of snowfall decreases. Annual rainfall decreases with elevation as the proportion of snow to rain increases. Total precipitation is of the order of 700 to 850 mm from 3000 m to 4325 m.

Whilst the upper Chenab and Jhelum basins are influenced to a much greater extent by monsoon airflow than the Karakorams, the above conclusions have some bearing on the precipitation regime of the Karakorams. Firstly, the non-linear changes with elevation and the differences between windward and leeward sides illustrate the complexity of spatial rainfall-distribution in the region and this can be expected to be repeated in the Karakorams. Secondly, since the Karakorams are further sheltered from the monsoon airflow by mountain barriers, the monsoon precipitation is likely to be less than that for the Upper Chenab and Jhelum basins at the same altitude. Thirdly, the Karakorams are affected to a much greater extent by the winter and spring westerly weather-systems for which the windward side is the west and the leeward the east.

CONCLUSIONS

a. At an elevation of about 3000 m, solid and liquid precipitation are about equal over a year.
b. Seasonal proportion of rainfall differs from Outer to Greater Himalayas, with 60% during the monsoon season on the windward outer Himalayas and 35% on the Greater Himalayas (windward)
c. For the outer Himalayas, more rainfall is received on the leeward side, except during the Monsoon season, while on the windward side the precipitation decreases at elevations over 600 m.
d. In the middle Himalayas, rainfall on the windward side increases with elevation up to a certain altitude (varying from 1600m to 2200 m depending on season) and then decreases. Rainfall on the leeward side is lower and has a maximum at about the same elevation range as the windward side. Snowfall increases linearly with elevation on the windward side to a maximum of 950 mm at 2500 m, but on the leeward side it first increases and then decreases. Total precipitation is significantly less on the leeward side.
e. Monthly, seasonal and annual totals and seasonal distribution at Gilgit, Gupis and Bunji are very similar.
f. These stations also receive amounts very similar to Skardu and Chilas during the period from April to September, but Skardu and Chilas receive significantly greater rainfall during the winter months.

In fact, the winter-season rainfall seems to arrive earlier at Skardu than at any of the other stations, with significant amounts and percentages in December, January and February. This is surprising, as one would anticipate that, with winter-rainfall arriving predominantly on westerly airflow, stations further to the west would benefit first.

g. Astore is similar to Chilas, Bunji and Gilgit, in receiving only small amounts of summer precipitation (amounts are greater than at Gilgit but summer percentage is lower). Astore's location further south does not appear to add greatly to the risk of monsoon incursions. Seasonal distributions at Chilas and Astore are similar.
h. Rainfall at Leh on the Upper Indus is the lowest for any station and its seasonal distribution is quite different from its nearest neighbour, Skardu. The seasonal distributions at Leh and Balakot are similar, with high percentages during the monsoon period, but with very different actual rainfall.
i. Snowfall, which is measured using a standard raingauge, is notoriously difficult to measure accurately, mainly because of the effect of windspeed on gauge-catch (Archer, 1998). However, in the prevailing low windspeed in the valleys, this is likely to be less of a problem than in high latitudes or at higher elevations. For the high-level stations at Kunjerab and Shandur as well as several other automatic weather-stations, the automatic measurement of snowfall has been unsatisfactory and not sufficiently reliable to assess annual and seasonal totals.

Precipitation Correlation

The seasonal and annual correlation-coefficients for precipitation between valley-stations in Northern Pakistan, often separated by major topographic barriers, are believed to be sufficiently high, so that the valley-stations can give a reasonable representation of the year-to-year changes in precipitation over the region as a whole; this confirms Whiteman's (1985) suggestion that low-level stations can give a good indication of precipitation-variations in the upper part of catchments. This will be investigated further, with respect to relationships between seasonal precipitation and runoff.

The following conclusions are drawn from the Tables:

a. With the exception of Leh, all correlations are positive.
b. Proximity appears to be the best basis for correlated precipitation, with high correlation- coefficients, for example between Gilgit, Astore and Bunji and between Skardu, Astore and Bunji.
c. The westerly stations at Drosh and Dir in the Kabul River basin correlate reasonably with each other, but poorly with other stations.
d. Leh exhibits no correlation with Gilgit and Skardu on a monthly, seasonal or annual basis. In conjunction with the quite different seasonal distribution of rainfall from its nearest neighbour Skardu, the lack of correlation suggests a distinct climatic boundary between the two stations.
e. Correlation-coefficients for six-monthly seasonal totals from April to September are marginally higher than for October to March, while April to June provides the best r values of the three month series.

TEMPERATURE TREND

Time series of seasonal and annual temperature are investigated graphically and statistically for evidence of trend.

Table-2: Correlation Coefficient (r) Between A. Precipitation (Jan-Mar) – Lower Triangle – and B. Spring Rainfall April to June – Upper Triangle, at Stations in the Northern Pakistan

Station	Astore	Bunji	Drosh	Dir	Gilgit	Gilgit (05-35)	Skardu	Leh
Astore		0.75	0.46	0.24	0.78		0.81	
Bunji	0.57		0.17	0.17	0.79		0.65	
Drosh	0.55	0.11		0.64	0.32		0.27	
Dir	0.52	0.15	0.77		0.28		0.02	
Gilgit	0.68	0.63	0.16	0.17			0.59	-0.14
Gigit 05-35							0.72	
Skardu	0.62	0.29	0.29	0.19	0.41	0.28		0
Leh					-0.16		0.02	

Other aspects of trend are sought, in first and last frost dates and in the annual extreme maximum and minimum temperature.

The 100-year change in each of the measures for Skardu and Gilgit is shown in Table-3. The Gilgit record has been broken into two blocks - from 1903 to 1964 and from 1965 to 1999. The sum of the changes is then calculated and the step between the end of the first series and the beginning of the second series is shown in the final column to indicate the effect of the change in location. The level of variance explained by the regression (r^2) of temperature with year is low, with the highest value of r^2 of 0.34 (r=0.58) for Skardu for annual maximum temperature.

It is noted that there are both distinct similarities and differences in the trends of temperature at the two stations. At Skardu, all measures of seasonal and annual temperature show an upward trend over the twentieth century, but with rates that differ significantly between seasons. Annual temperature during the century has risen by 1.4°C, whilst the mean daily maximum has risen significantly more than the mean daily minimum. The bulk of the change has occurred during the winter-months, with the period January to March being the highest 3-month period, with an increase of nearly 3°C. This represents an elevational shift of approximately 400 m in the frost- line, which would mainly influence whether precipitation occurs as rain or snow and the amount of accumulation of snow available for melt during the spring and summer. In contrast, the increase in spring and summer-temperatures has been quite modest. The change of 0.77°C from April to September, which is the season of snow and glacier-melt, represents an upward shift in elevation of only about 100 meters of the freeze- thaw boundary.

The greater backward movement of the last spring-frost than forward movement of the first winter-frost is consistent with the greatest temperature-changes occurring in the first three months of the year. In addition, the change in frost-free days with elevation is consistent with the difference between average frost-free days at Gilgit and Skardu. The two stations are separated by 750 m of elevation and have a mean difference of 30 frost-free days.

At Gilgit, in contrast, there is a mixture of positive and negative changes, even with the effects of change in station-location taken into account. The mean annual temperature has declined by 0.4°C; annual maximum temperature shows an increase, whilst annual minimum shows a decrease of over 2° C.

Table-3: 100-Year change in Temperature Measures at Skardu and Gilgit

Temperature measure	Change 1900-99	Change 1900-64	Change 1965-99 °C	Change 1900-99 °C	Step change 1964-65
	°C	°C			
	Skardu	**Gilgit**	**Gilgit**	**Gilgit**	**Gilgit**
Mean annual temperature	1.37	-0.54	0.13	-0.41	-0.81
Mean annual daily maximum	2.35	0.44	0.9	1.34	0.31
Mean annual daily minimum	0.54	-1.52	-0.65	-2.17	-1.92
Annual absolute maximum	2.01	0.01	0.73	0.79	1.43
Annual absolute minimum	2.85	-3.36	0.24	-3.12	0
Jan - Mar mean	2.92	0.51	0.31	0.82	-0.19
Apr - Jun mean	0.99	-1.66	-0.28	-1.94	0.09
Jul - Sep mean	0.72	-0.71	-0.32	-1.03	-0.6
Oct - Dec mean	0.93	-0.56	0.8	0.24	-1.29
Oct - Mar mean	2.11	0.1	0.43	0.53	-1.28
Apr - Sep mean	0.77	-1.31	-0.3	-1.61	-0.17
Last spring frost	-10.8 days	+2.59 d	-3.6 d	-1.0 d	+17.7 d
First winter frost	+3.5 days	-2.16 d	-4.7 d	-6.8 d	-20.7 d
Frost free days	+12.0 days	-4.10 d	-0.4 d	-4.5 d	-37.2 d

Seasonally, winter mean-temperatures show an increase, whilst spring and summer temperatures show a decrease. Although the overall trend is different from Skardu, the rank-order of changes amongst the seasons is about the same. This suggests that the observed changes are real systematic changes and not simply a function of the random variability of the two series.

The effects of change in location of the station at Gilgit is shown by the figures in Table-3. There was a sharp downward step in minimum temperature in 1965, as also in winter temperatures and particularly in the number of frost free days. In contrast, maximum temperature shows a small rise. For most measures, there was greater change during the first period and very little change from 1965 onward.

Periodicity in Temperature

Periodicity in the time-series may be investigated by inspecting the time series histograms. A 5-year moving average has been added to the histograms for Skardu, and periods with temperatures above and below the trend line are illustrated. However, spurious peaks and troughs occur during the significant period of intermittent data from 1936 to 1954.

Some of the lowest seasonal and annual temperatures occur right at the beginning of the record from 1900 to 1907, and these may have a significant influence on the regression relationships and derived temperature-changes. It is tempting to remove these, as subject to greater uncertainty of measurement due to a greater number of missing days. However, as this was a period of greater frequency of occurrence of GLOFS, the temperature-depression may be glaciologically and hydrologically significant.

For both Gilgit and Skardu, there is a steady rise in mean temperature from the beginning of the century up to a peak around 1915 to 1917, then a sharp decline over the following 5 years to a generally lower level, which is maintained through the 1920s at Gilgit, but at Skardu gradually builds up again to the mid 1930s after which the data become intermittent. Although the pattern of temporal changes is displayed in each season, it is more pronounced during the spring and summer seasons (Apr-Sept).

During the second half of the century, the pattern of changes has been less distinct, with no long runs of above or below-average temperature. At Gilgit, there is the suggestion of below-average temperatures during the 1960s and above-average temperatures during the 1970s, most of which is accounted for by changes during the winter months. At Skardu, the same pattern exists, but is less distinct.

Periodicities and trends are further investigated below, in relation to the occurrence and frequency of glacier-lake outburst floods.

CLIMATIC TREND, PERIODICITY AND STATIONARITY OF FLOW AND FLOOD SERIES

It is concluded that there have been systematic changes, both in temperature and precipitation, during the twentieth century in the Karakoram and that these have a potential significance for the generation of floods in the rivers of the Upper Indus Basin. They are also relevant to water- resources management and to the design and operation of flood-defence and flood-forecasting systems.

Changes in precipitation have been particularly marked and the following are noted.

a. An overall increase in precipitation; if repeated at higher altitudes (and it is not clear if this is the case) would lead to greater nourishment and vigour of glaciers
b. An increase in summer rainfall could lead to an increased potential for summer flooding from intense summer-storms
c. There has been a marked increase over the twentieth century in the annual 1-Day Maximum rainfall, from 10 to 28 mm at Gilgit and from 12 to 30 mm at Skardu.
d. There appears to be a strong association between rainfall and the occurrence of mass- movement, especially landslides and debris-flows, which could lead to an increased frequency and severity of river blockage and subsequent landslides.

HISTORICAL INFORMATION ON GLOF FLOODS

- 1999 (6 Aug) A debris-flow occurred from a right bank between Khalti Lake and Gupis. There is reported to be a small glacier

(Charti Glacier)at the head of this valley and also 2 glacial lakes below the glacier-terminus. The debris-flow crossed the Gupis to Shandur Road and blocked the Ghizer River, creating a lake about 1.5 km in length, now known as Khankhui Lake. The duration of blockage is not known, but the flow over the debris lobe is still constricted to a 5- metre channel, with rapids downstream over a distance of 150 m. This event also occurred without accompanying rainfall.

- 2000 (27 Jul) A GLOF and debis-flow occurred at Kande from a tributary of the Hushe River (tributary of the Shyok). Villagers referred to a supraglacial lake on the glacier before the flood occurred. A previous flood had occurred from the same source on 25 July 1997, but was much less severe than the one in 2000. Kande village was virtually destroyed in the flood, including 124 houses and a primary school. The event happened in the middle of the day, during a period of exceptionally hot weather and without rain. Villagers heard a roar in the hills about 10 minutes before the arrival of the flood and fled to higher ground and so there were no fatalities. The initial flood/debris wave did most of the damage, but sporadic bursts of water occurred for a further 8 days.

- 2000 (10 June) A lake formed again in the Shimshal valley, as described above. Water began to flow over the top of the ice-dam on 28 May and breached on 10 June. The level in the Hunza was reported as increasing by 10 feet at Passu, but only 2 feet at Hunza. No serious damage resulted, as the breach occurred early in the year when the lake size was small (Focus Humanitarian Assistance, 2000).

CLIMATIC TIME - SERIES AND LANDSLIDE/DAM-BREAK FLOODS

A significant number of floods, resulting from landslide or debris flow dambreaks, have occurred over the last three decades, but examples from earlier dates are restricted to events of extreme magnitude. Table-4 provides a summary list of such events, drawn from a variety of sources.

Information on Landslide/Dam-break Floods:

1972/3 A mudflow blocked the Hunza River at Batura, following 10.3 mm rainfall in 2 days – date given as 1972 (Miller, 1984). Shi Yafeng (1980) in the introduction to the glaciological study of the Batura glacier refers to the 1973 flood, which damaged the highway and bridge over the Batura channel. The team of Chinese glaciologists was sent to Batura Glacier, in response to this event and to consider reconstruction, and work was done during 1974 and 1975. The report gives no further English description of the event.

Table-4: Floods Generated By Landslide And Debris Flow Dam Breaks

Year	Date	Location	River/Basin	Source
1841	June	Lichar Ghar	Indus	Drew, Hewitt
1858	Aug	Phungurh	Hunza	Belcher, Goudie et al
1937	Jul	Faker/ Hakuchar	Hunza	Said
1974	11-Apr	Baltbar near Batura	Hunza	Cai Xiangxing *et al*
1974	14-Aug	Batura	Hunza	Cai Xiangxing *et al*
1977/78		Darkot	Yasin/Gilgit	Raschid (1995) Whiteman (1985)
1970s		Yashpur, Henzel	Gilgit	
1999	Jul?	Juj Bargo	Ghizer/Gilgit	

- April 11. A mudflow, with a front 20 to 30 m high, occurred from Baltbar Nallah, a left bank tributary 18 km south of Batura. A fan was formed 300 to 400 m wide, over 150 m long and 80 to 100 m high, blocking the Hunza River and submerging the Friendship Bridge constructed in 1970 and creating a lake 12 km long (Xiangxing *et al*, 1980). Mr Ali Madad, owner and manager of the Kisar Inn, Altit, was an eye-witness to the debris flood. He recalls that he and his uncle had reached the Nallah near Gulmit when they stopped their jeep and his uncle went forward to inspect the bridge, there having been some previous rains. Suddenly, he heard a roaring sound and saw a smoke-like mist upstream. A wave-front of stones and mud rushed down the valley, overwhelmed the bridge and killed his uncle instantly, along with some villagers working in nearby fields. He fled and narrowly escaped.

- 1974 A debris flow from a left-bank gully followed heavy rainfall and blocked the Hunza River, which then had a flow of 250 m^3/sec. The mudflow had a front 5 m high; the stage rose rapidly and submerged the bridge over the Hunza. One hour later, the river cut through the fan deposits

- Raschid (1995) quotes a resident of Darkot on the Upper Yasin River as saying “In 1977 a flood of rocks and mud all but obliterated the village and destroyed every inch of farmland”. Whiteman (1985) refers to this event as occurring in 1978.

- 31 Jul/August A debris-flow from a small steep left-bank nallah at Juj Bargo produced a debris lobe across the river against the rock-face on the right bank. A lake was formed upstream and destroyed the small village of Juj Bargo and still (in 2001) extends about 1 km in length upstream from the remaining barrier. The site is a short distance upstream from Gakuch and the Ishkoman confluence.

SUMMARY OF CONCLUSIONS ON FLOOD STATIONARITY

Changes in the climate have had, or may have had, an influence on the magnitude and frequency of flooding in rivers in northern Pakistan.

With respect to snow and glacier melt, the magnitude of temperature-changes during the spring and summer are insufficient to have caused a major change in the flood-potential of catchments. However, changes in winter-temperatures are sufficient to have influenced the amount and altitudinal distribution of snow available for melt in the subsequent season and this may influence the magnitude of the summer peak.

Changes in precipitation may be more significant in flood-generation. Not only have the seasonal and monthly totals shown a significant upward trend, but also the maximum annual daily amount. It would thus be inappropriate to include the full 100 year data set in the assessment of rainfall-frequency at Gilgit and Skardu, but to restrict the analysis to the last few decades.

Changes in amount and intensity of precipitation may also play a role in the frequency of landslides, which create river-dams and subsequent flood-waves. It is possible that the greater reported number over the last few decades is a reflection of more frequent occurrence, due to increased rainfall, but it may also be due to the presence of scientific observers to record the events. However, it is clear that there are sufficient occurrences of landslide and debris-flow blockages of many rivers, that the possibility must be considered in any design-estimation. A previous occurrence implies that there is a risk of future recurrence.

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