ASSESSING THE IMPORTANCE OF SNOWMELT WATER SUPPLY FROM 'HISTORICAL' RECORDS OF SNOW ACCUMULATION AND RUNOFF, JHELUM CATCHMENT, PAKISTAN HIMALAYA

by

Fes A. de Scally[1]

ABSTRACT

The importance of snowmelt water supply in the Jhelum River catchment is assessed by comparing 'historical' records of winter snow accumulation and runoff in Pakistani sub-basins. The snow accumulation records, although only five to eight years long, represent the only such data available for this region of the western Himalaya. Strong statistical correlations are found to exist between point measurements of the annual maximum of snowpack water equivalent or total winter precipitation, and total annual runoff. Point measurements of total winter Snowfall also show a generally significant correlation with annual runoff. Other evidence reinforces the conclusion that snowmelt is the dominant source of annual runoff, and indicates the potential value of such snow accumulation measurements for predicting seasonal and annual runoff, particularly since remotely sensed data have so far been difficult to obtain. However, such predictions may be complicated in this region by the effects of a continental-scale feedback mechanism between snow cover and the summer monsoon.

INTRODUCTION

The role of snowmelt water supply is poorly understood for rivers originating in the Himalaya, Karakoram and Hindu Kush mountains of northern Pakistan. Much of the past effort in runoff and particularly flood forecasting has focussed on monsoon rainfall which coincides in timing but is usually secondary in importance to snow and glacier melt. The perception that meltwater is generally not significant in the Upper Indus River Basin (UIB), at least after the arrival of the monsoon, persisted for some time (Kureishy, 1953; Gulati, 1973; World Meteorological Organization, 1977), even though its importance for some left-bank tributaries of the Indus was recognised back in the 1940s (Sain, 1946). Recently the importance of snow and glacier melt has been realised (Water and Power Development Authority, 1981a; 1981b), particularly its role in producing between two-thirds and nine-tenths of the annual water yield from the UIB in just six to ten weeks of the year (Hewitt, 1989). However, most research on the snow and ice cover of the UIB has been of an ad-hoc nature and directed at the glaciers of the higher ranges. Little scientific information exists on the seasonal snow cover as a result, and existing methods of forecasting meltwater inflows to major reservoirs such as Tarbela (Indus R.) and Mangla (Jhelum R.) are inadequate in terms of the economic value of the water for irrigation and power generation. On the Indus' main stem for example, 70% of the 1.431×10^{11} m^3 summer season flow, most of which is meltwater, is utilised primarily for irrigation (Nanuk Engineering, 1987).

Recently it has been demonstrated that satellite derived estimates of the snow-covered area can provide a relatively good basis for predicting seasonal totals of snowmelt water supply from sub-basins of the UIB and other basins in the region (Rango et al., 1977; Qureshi and Umar, 1978; Tarar, 1982; Dey et al., 1983; Ramamoorthi, 1983; 1987; Makhdoom and Solomon, 1986; Shashi Kumar, 1991). However, the necessary imagery may be difficult to obtain particularly for operational purposes (Tarar, 1982; Ramamoorthi, 1983). During the Snow and Ice Hydrology Project (SIHP), a collaborative research effort in the UIB between the Water and Power Development Authority (WAPDA) (Pakistan), International Development Research Centre (Canada) and Wilfrid Laurier University (Waterloo, Ontario), imagery suitable for runoff modelling was to have been provided to WAPDA by the Pakistan Space and Upper Atmosphere Research Commission. Over the five-year life span of the project (1985-89) this plan was however never realised (Snow and Ice Hydrology Project, 1990). For this reason, initial calibrations of a runoff model (University of British Columbia Watershed Model; Quick and Pipes, 1989) during the SIHP relied heavily on ground-based climate and snow accumulation data. Even with future availability of satellite imagery, developments in snowmelt runoff forecasting in the UIB will continue to rely to some degree on ground-based data (Mansell-Moullin, 1986; Nanuk Engineering, 1987; Snow and Ice Hydrology Project, 1990).

The purpose of this paper is to assess the importance of snowmelt water supply in the Jhelum catchment of the UIB using 'historical' records of snow accumulation which were discovered during the SIHP. These records, although only five to eight years long, represent the only such data available for the Pakistan Himalaya and are therefore more valuable then their length would suggest.

Presented at the 62nd Western Snow Conference, April 18-21, 1994, Sante Fe, New Mexico.

[1] Department of Geography, Okanagan University College, 3333 College Way, Kelowna, B.C. V1V 1V7

STUDY AREA AND DATA RECORDS

The Jhelum River originates in Indian Kashmir and flows across the United Nations cease-fire line into Pakistan (Figure 1). The only high-elevation (up to 5500 m a.s.l.) headwater tributaries in Pakistan are the Kunhar and Kishanganga (Neelum) Rivers, both on the south slope of the Punjab Himalaya and supplying on average 11% and 39% of the total annual discharge of the Jhelum respectively. Only the Kunhar basin (2500 km^2) is entirely on the Pakistan side of the cease-fire line. This makes it potentially extremely important for any ground-based data collection by WAPDA for purposes of snowmelt runoff forecasting, as was demonstrated by the UBC Watershed Model calibration for the Jhelum River (Snow and Ice Hydrology Project, 1990). The snowmelt contribution to the annual flow of the Jhelum is however poorly known. It has been estimated at anywhere between 20-40% (Gulati, 1973; Dreyer et al., 1982; Ferguson, 1985) and 65-75% (WAPDA, 1981a; Tarar, 1982; Hewitt, 1985; Nanuk Engineering, 1987). Glacial melt is a minor contributor to runoff since only one percent of the basin is glacierised.

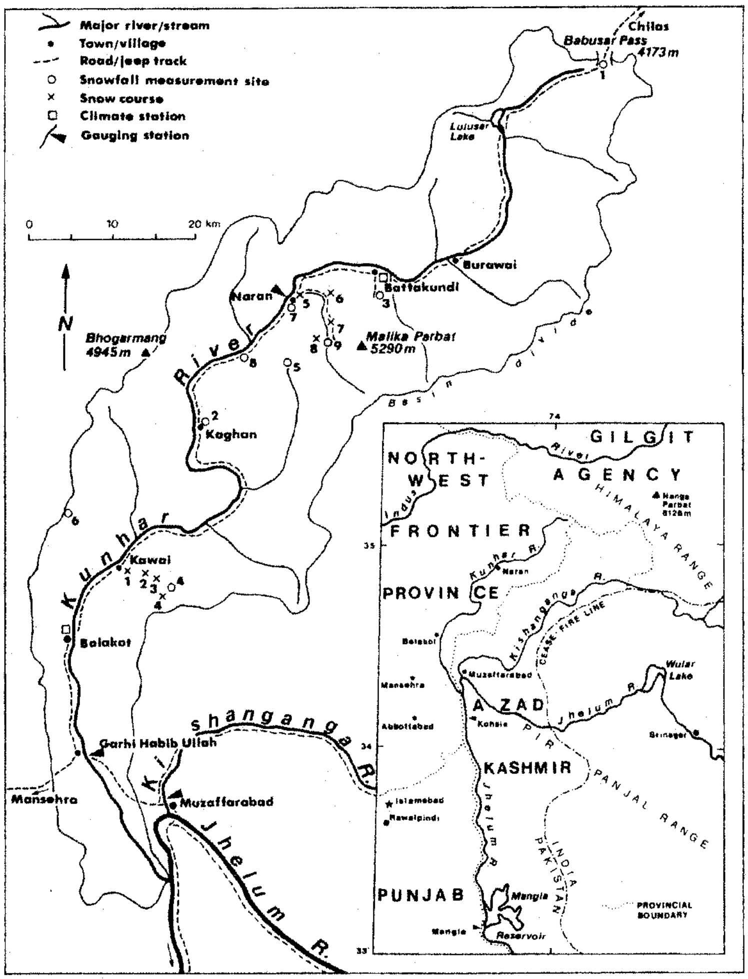


Figure 1. Jhelum catchment, Pakistan Himalaya, with detailed map of the Kunhar River basin showing measurement sites. See Table 1 for names of sites.

During field work in the Kunhar River basin from 1985 to 1987 we were informed that snow accumulation records existed for mountains of North-West Frontier Province in northern Pakistan. These records consist of:

(1) Snow accumulation records of the North-West Frontier Province Forest Department dating back to the 1920s. These include snowfall and end-of-month snow depth data from 47 sites in the Kunhar and Swat River basins and "The Galis" hills immediately northeast of the capital Islamabad (Figure 1). When these records were located in Abbottabad to be copied, it was discovered that the majority had disappeared and that for many stations the measurements were apparently continued for only one or two years.

(2) WAPDA snow survey records from eight snow courses in two areas of the Kunhar River basin for the period 1961 to 1968 (Figures 1 and 2). These measurements were

described at a Western Snow Conference meeting (Priest, 1962) but the programme was discontinued after only eight years because of financial problems and the conclusion at the time that the results were not significant for downstream reservoirs such as Mangla. Fortunately the snow survey data are preserved (WAPDA, 1969).

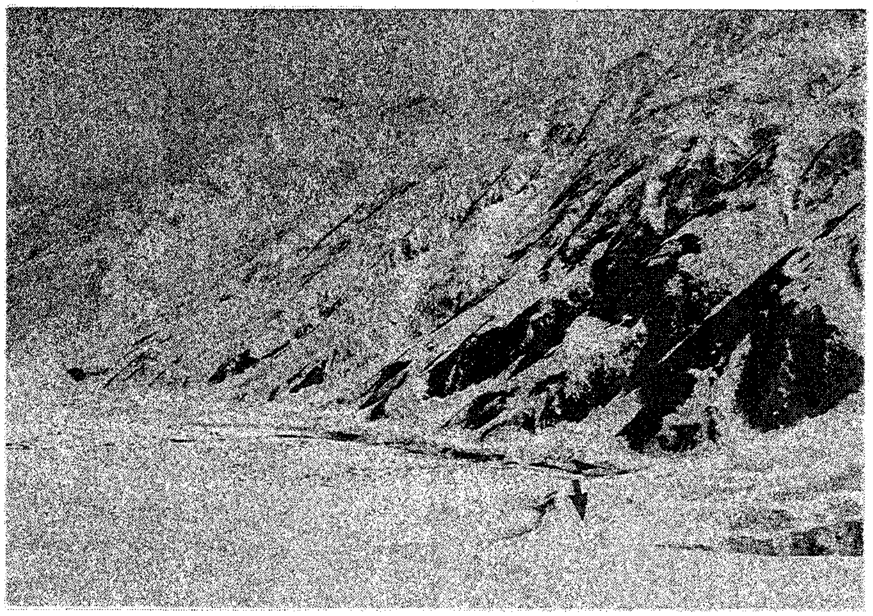


Figure 2. Saiful Maluk Lake snow course on 12 May 1987 (arrow). A stone bungalow beside the snow course is still completely buried by snow. This photo illustrates two common problems of high-elevation measurement sites in the Pakistan Himalaya; wind effects due to a complete lack of forest, and avalanches -- all of the slopes in the picture are extremely avalanche-prone as evidenced by snow deposits on the lake's ice cover.

(3) Winter precipitation records of the Seed Potato Research Programme from a climate station situated in the village of Battakundi, Kunhar River basin, for the period 1982 to 1989 (Figures 1 and 3). The record up to 1987 was copied in Battakundi and the rest forwarded to Canada at a later date.

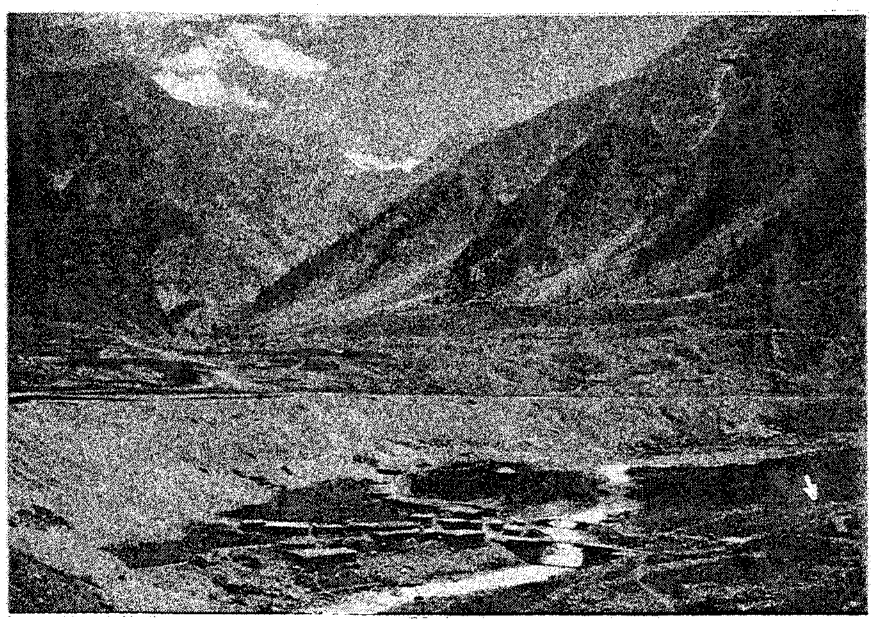


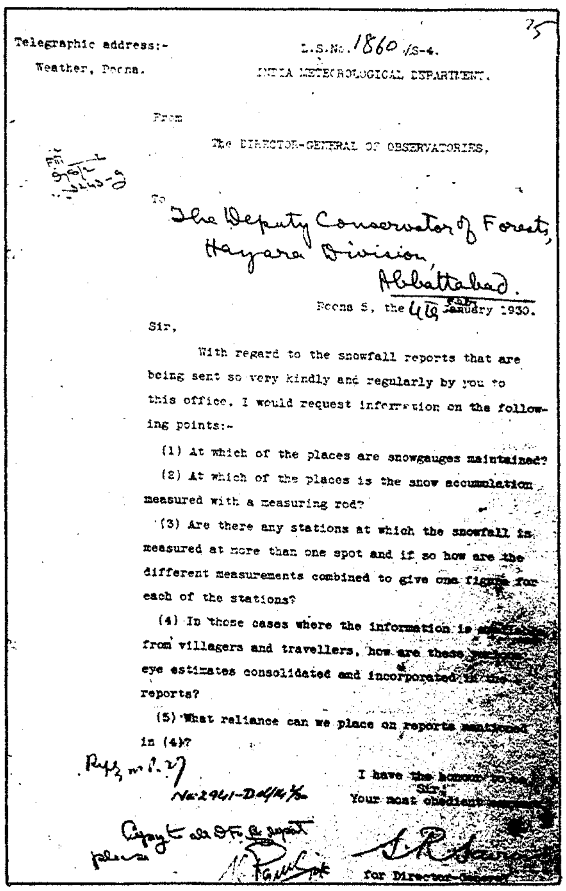
Figure 3. Battakundi climate station in August 1985 (arrow). Visible to the left is the village bazaar, where some inhabitants remain over the winter despite the jeep track being closed by snow. This station has proven extremely useful for flow forecasting but would benefit from a telemetry system.

Table 1. Data availability and correlation coefficients for snow accumulation and annual discharge. The numbers of the measurement sites correspond to Figure 1.

		Correlation Coefficient for Annual Discharge:					
Snow Accumulation Measurement Site and Elevation (m a.s.l.)	Period of Record	Kunhar R. at Naran	Kunhar R. at Garhi Habib Ullah	Jhelum R. at Kohala	Jhelum R. at Mangla	Kishanganga R. at Muzaffarabad	Mean
<u>Total winter snowfall</u>:							
1-Babusar Pass (4170)	1963-65;72-76	+0.412	+0.534	+0.805		+0.589	+0.585
2-Kaghan village (2060)	1963-65;72-76	+0.269	+0.392	+0.803		+0.527	+0.498
3-Lalazar village (3050)	1963-65;72-76	+0.367	+0.480	+0.773		+0.558	+0.544
4-Makra Peak (3430)	1963-65;72-76	+0.165	+0.240	+0.482		+0.109	+0.249
5-Manur Gali (3890)	1963-65;72-73	+0.558	+0.523	Insuff.data		+0.241	+0.441
6-Musa-ka-Musalla (4050)	1963-65;72-76	+0.151	+0.138	+0.235		+0.069	+0.148
7-Naran village (2440)	1963-65;72-76	+0.489	+0.581	+0.844		+0.594	+0.627
8-Paludran village (2290)	1963-65;72-74	+0.297	+0.465	+0.837		+0.476	+0.519
9-Saiful Maluk Lake (3220)	1963-65;72-76	+0.371	+0.484	+0.809		+0.571	+0.559
Mean		+0.342	+0.426	+0.698		+0.415	
<u>Max. annual snowpack w.e.</u>:							
Shogran area:							
1-Shogran Rest House (2360)	1961-68	+0.454	+0.395(+0.414)[1]		+0.580		+0.461
2-Malakand Meadow (2650)	1961-68	+0.643	+0.711(+0.708)[1]		+0.879		+0.735
3-Sari Kabai (2800)	1961-68	+0.769	+0.914(+0.907)[1]		+0.950		+0.885
4-Paya Makra Saddle (3050)	1961-68	+0.794	+0.841(+0.877)[1]		+0.870		+0.846
Naran area:							
5-Nursery (2440)	1961-68	+0.716	+0.928(+0.862)[1]		+0.940		+0.862
6-Shelf/Katha village (2680)	1961-66;68	+0.682	+0.892(+0.893)[1]		+0.967		+0.858
7-Grove (3020)	1961-68	+0.550	+0.451(+0.594)[1]		+0.940		+0.634
8-Saiful Maluk Lake (3220)	1961-68	+0.637	+0.565(+0.690)[1]		+0.969		+0.715
Mean		+0.656	+0.712(+0.743)[1]		+0.887		
<u>Total winter precipitation</u>:							
Battakundi village (2660)	1982-87;89		+0.886				

[1] Correlation coefficient for estimated total snowmelt discharge shown in brackets.

The data which could be extracted from these records for the purposes of assessing the importance of snowmelt water supply are shown in Table 1. Considerable effort had to be spent in checking the data for accuracy and consistency. This was particularly problematic with the NWFP Forest Department data, as can be seen by examples of correspondence appended to the records (Figure 4). Uncertainties about the reliability of the records, particularly later ones, and their truncation in many cases resulted in only snowfall data from nine sites in the Kunhar River basin being usable. The best data appear to be the WAPDA snow survey records in (2) above.



Telegraphic address:- Weather, Poona.

I.S.No. 1860/S-4.

INDIA METEOROLOGICAL DEPARTMENT.

From

The DIRECTOR-GENERAL OF OBSERVATORIES,

To

The Deputy Conservator of Forest, Hazara Division, Abbottabad.

Poona 5, the 4th Feb. 1930.

Sir,

With regard to the snowfall reports that are being sent so very kindly and regularly by you to this office, I would request information on the following points:-

(1) At which of the places are snowgauges maintained?

(2) At which of the places is the snow accumulation measured with a measuring rod?

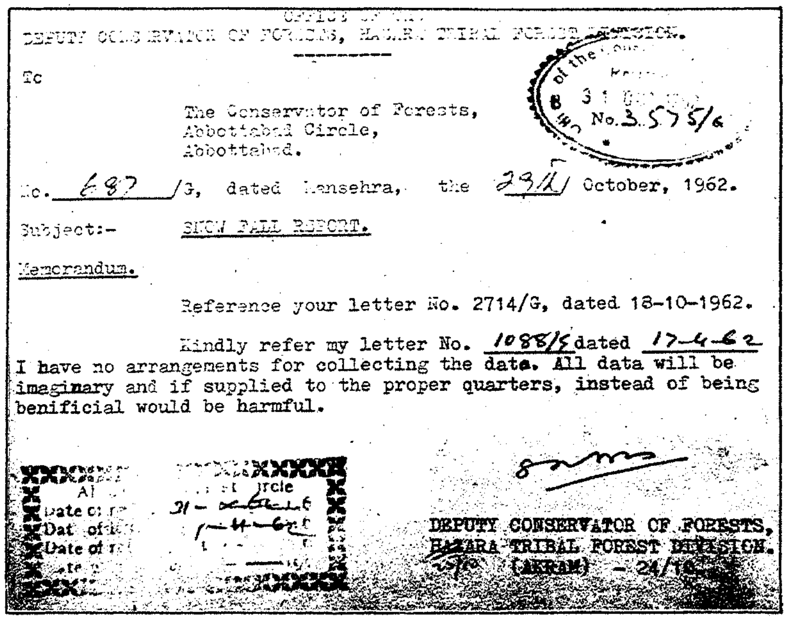
(3) Are there any stations at which the snowfall is measured at more than one spot and if so how are the different measurements combined to give one figure for each of the stations?

(4) In those cases where the information is obtained from villagers and travellers, how are these eye estimates consolidated and incorporated in the reports?

(5) What reliance can we place on reports mentioned in (4)?

I have the honour to be, Sir, Your most obedient servant,

for Director-General



OFFICE OF THE DEPUTY CONSERVATOR OF FORESTS, HAZARA TRIBAL FOREST DIVISION.

To

The Conservator of Forests, Abbottabad Circle, Abbottabad.

No. 687/G, dated Mansehra, the 23rd October, 1962.

Subject:- SNOW FALL REPORT.

Memorandum.

Reference your letter No. 2714/G, dated 18-10-1962.

Kindly refer my letter No. 1088/S dated 17-4-62 I have no arrangements for collecting the data. All data will be imaginary and if supplied to the proper quarters, instead of being benificial would be harmful.

DEPUTY CONSERVATOR OF FORESTS, HAZARA TRIBAL FOREST DIVISION.

Figure 4: Two photos of correspondence appended to the NWFP Forest Department snow records. The 1930 correspondence (left) is a query about data collection methods and reliability, while the 1962 correspondence (right) is a complaint about the lack of resources for data collection. Such ancillary information is valuable for assessing the quality of available records.

Total winter snowfall is obtained from the first data set. The totals are from December to May at sites below 2700 m a.s.l. and November to June at sites above this elevation, assuming that winter snow accumulation begins during the first month with a mean air temperature below 0°C. Snowfall depths were measured with a ruler and have not been converted to water equivalent. The annual maximum of snowpack water equivalent is extracted from the approximately weekly snow surveys in the second data set. This maximum occurs anytime between mid-February and mid-May depending on the elevation of the snow course (Figure 5) and the snow conditions that year. Total winter (November-April) precipitation is obtained from the third data set. It includes the total of new snow converted to precipitation equivalent using an assumed density of 100 kg m^{-3}, and rainfall as measured with an unshielded, manually read rain gauge.

Originally it was intended that the records of snow accumulation be used to calculate total basin snow storage which could then be compared against total annual runoff. However, this proved impossible given the significant horizontal and altitudinal variability of snow accumulation in this region. Simple correlation techniques are therefore used to test the strength of snow accumulation-runoff relationships. The available discharge data are shown in Table 1. All but the Naran gauging station are located roughly at the point where the rivers emerge from the mountains onto the foothills and plains. For 1961-68 the total snowmelt discharge also is estimated, using the annual hydrographs in WAPDA (1969).

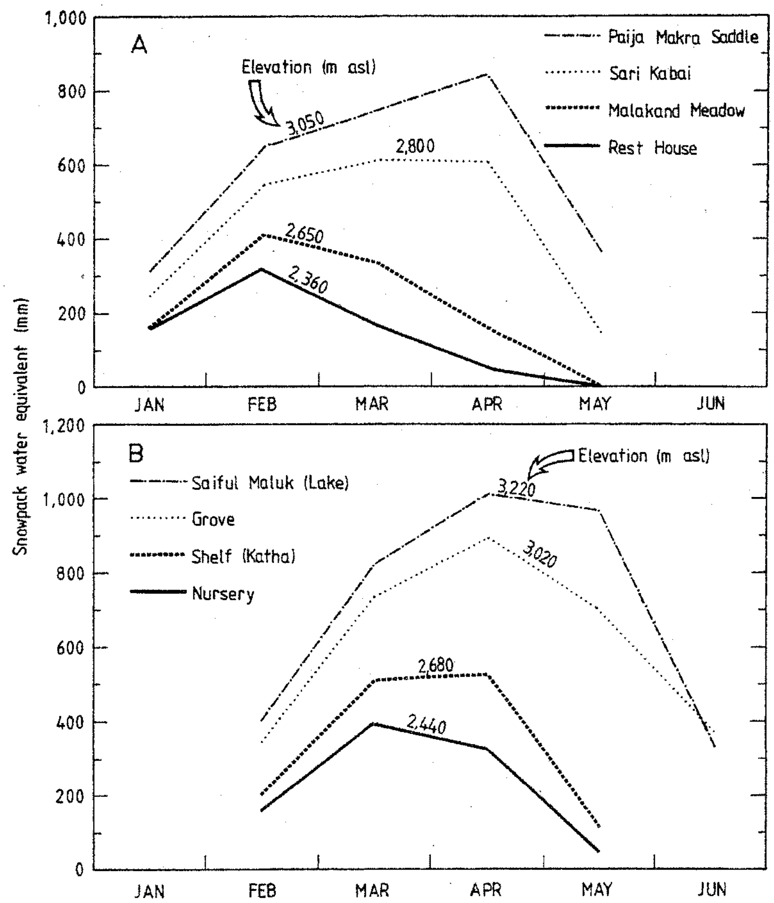


Figure 5: Mean monthly snowpack water equivalent, Kunhar River basin 1961-68. A: Shogran area snow courses. B: Naran area snow courses.

RESULTS AND DISCUSSION

Total winter snowfall

The correlation coefficients for total winter snowfall and annual discharge are shown in Table 1. Averaged for each snowfall measurement site, the coefficients range from +0.148 (Musa-ka-Musalla) to +0.627 (Naran village), while the average for each gauging station ranges from +0.342 (Kunhar River at Naran) to +0.698 (Jhelum River at Kohala). When snowfall data from two or three sites are correlated with discharge a significant improvement is obtained (Table 2). The highest coefficients are again obtained for the Jhelum River at Kohala, including +1.000 for two combinations of sites (five years of record).

The correlation between winter snowfall and annual discharge is surprisingly strong in many cases given the limitations of such simple snowfall measurements. These limitations are sometimes exacerbated by inaccurate or rounded-off measurements, for example the depth of large snowfalls is frequently only given to the nearest foot. The correlations strengthen with snowfall data from further upstream in the Kunhar basin. This, and the fact that most of the snowfall data from lower in the basin correlates weakly with Kunhar River discharge at Naran (Tables 1 and 2), supports the idea that snowfall data from more southerly locations is a poor index of the greater snow accumulation near the Himalayan crestline (Figure 6). Despite the steep altitudinal gradients of snowfall (Figure 7) the effect of site elevation on the correlations is unclear. The strongest correlations with discharge are in fact produced by snowfall data collected in the bottom of a deep, narrow valley where rain can make up a significant percentage of the winter precipitation (Naran village; Table 1).

The strong correlations between snowfall in the Kunhar basin and annual discharge of the Jhelum River (Tables 1 and 2) are encouraging with respect to forecasting seasonal inflows to Mangla Reservoir, since most of the rest of the Jhelum headwaters are inaccessible to WAPDA. The correlations between Kunhar basin snowfall and discharge of the Kishanganga are much weaker despite the proximity of the two basins (Figure 1) and their similar snow conditions (Priest, 1962).

Table 2. Summary of multiple correlation coefficients for snow accumulation and annual discharge.

	Range and Mean (in brackets) of Multiple Correlation Coefficients for Annual Discharge:					
Number of Snow Accumulation Measurement Sites	Kunhar R. at Naran	Kunhar R. at Garhi Habib Ullah	Jhelum R. at Kohala	Jhelum R. at Mangla	Kishanganga R. at Muzaffarabad	Mean
Total winter snowfall[1]:						
2	+0.600 ↓ +0.698 (+0.649)	+0.664 ↓ +0.701 (+0.682)	+0.854 ↓ +0.887 (+0.870)		+0.597 ↓ +0.640 (+0.618)	+0.706
3	+0.561 ↓ +0.747 (+0.679)	+0.702 ↓ +0.765 (+0.731)	+0.999 ↓ +1.000 (+1.000)		+0.669 ↓ +0.692 (+0.679)	+0.772
Max. annual snowpack w.e.:						
2	+0.665 ↓ +0.795 (+0.728)	+0.636 ↓ +0.941 (+0.850) +0.722[2] ↓ +0.923[2] (+0.857)[2]		+0.973 ↓ +0.998 (+0.986)		+0.855
3[3]	+0.900	+0.975 +0.989[2]		+0.999		+0.966
4	+0.780 ↓ +0.910 (+0.841)	+0.935 ↓ +0.992 (+0.961) +0.927[2] ↓ +0.995[2] (+0.960)[2]		+1.000 ↓ +1.000 (+1.000)		+0.940

[1] Using sites with the highest individual correlation coefficients.
[2] Estimated total snowmelt discharge.
[3] Only one combination of three sites.

Annual maximum of snowpack water equivalent

The correlation coefficients for the annual maximum of snowpack equivalent and annual as well as snowmelt discharge are shown in Table 1. Averaged for each snow course, the coefficients range from +0.461 (Shogran Rest House) to +0.885 (Sari Kabai), while the average for each gauging station ranges from +0.656 (Kunhar River at Naran) to +0.887 (Jhelum River at Mangla). A significant improvement in the correlations occurs when data from two, three or four snow courses are used (Table 2). The highest coefficients are again obtained for the Jhelum River, including +1.000 for four combinations of snow courses. This again points to the potential value of the Kunhar basin for providing an index of snow accumulation in the Jhelum system.

The generally strong correlations between the annual maximum of snowpack water equivalent and discharge provide the best evidence that snowmelt is the dominant water supply in the major Pakistani tributaries of the Jhelum River. Unlike the snowfall data there appears to be no clear relation between either the location or elevation of the snow courses and the strength of the correlations, despite steep elevational gradients of snowpack water equivalent (Figure 7). Overall, snow courses in the Naran area performed slightly better than those in the Shogran area. Those in the Saiful Maluk valley (e.g. Figure 2) were used in 1988 for calibrating the UBC Watershed Model on the Jhelum River (Snow and Ice Hydrology Project, 1990) and are recommended as sites for future measurements (Mansell-Moullin, 1986).

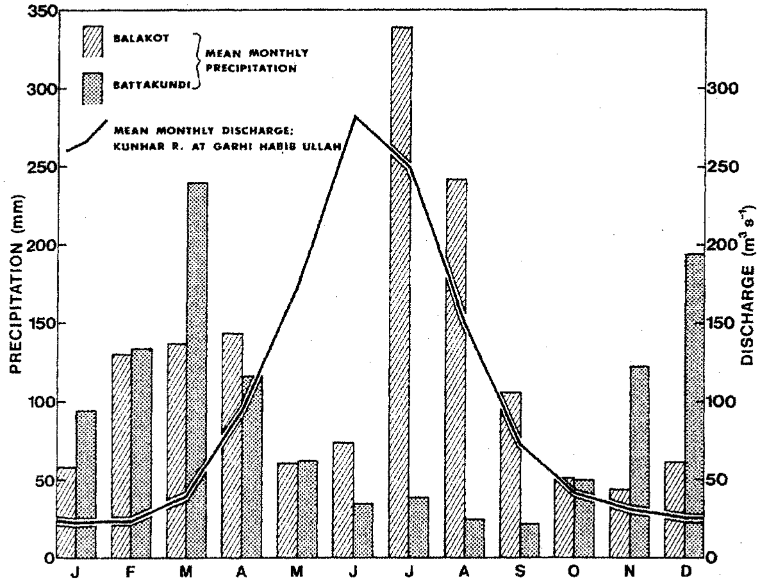


Figure 6: Mean monthly precipitation at Balakot (1961-68) and Battakundi (1981-90) and mean monthly discharge, Kunhar River at Garhi Habib Ullah (1961-68; 1976-89).

Total winter precipitation

Total winter precipitation at Battakundi (Figure 3) correlates strongly with discharge of the Kunhar River although not as strongly as snowpack water equivalent (Table 1). The lower coefficient is produced by one anomalous year which appears to result from error in precipitation measurement. The Battakundi station appears to be ideally situated for measuring winter precipitation since it receives significantly greater amounts than areas lower in the Kunhar basin (Figure 6). Initial attempts at seasonal and short-term runoff forecasting for the Jhelum River (UBC Watershed Model) have relied heavily on precipitation and temperature data from this station (Snow and Ice Hydrology Project, 1990).

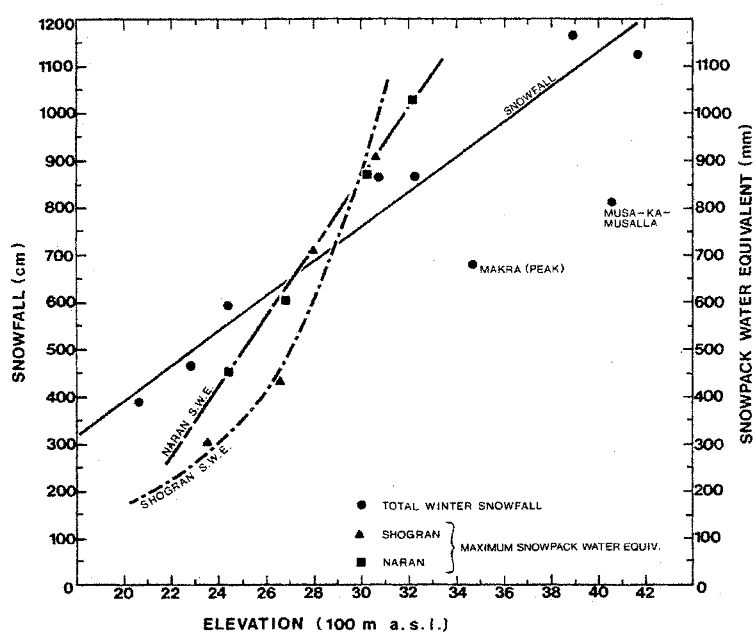


Figure 7: Total winter snowfall and annual maximum of snowpack water equivalent as a function of elevation, Kunhar River basin. Best-fit lines are estimated. The two named snowfall outliers are the result of their significant distance southwest of the Himalayan crestline.

The above results provide compelling evidence that snowmelt water supply is important in the annual flow of the Jhelum and its Pakistani headwaters. The high-elevation areas near the Himalayan crestline appear most important in this respect because of the horizontal and altitudinal patterns of winter precipitation (Figures 6 and 7). Summer monsoon rainfall on the other hand decreases toward the crestline (Figure 6) and as a result appears to be of secondary importance as a source of runoff in the headwaters. The correlation coefficients for summer (May to October) precipitation at Battakundi and Balakot, and annual discharge of the Kunhar River at Garhi Habib Ullah are only +0.193 and +0.206 respectively (8-year records). Summer precipitation at Balakot displays a strong negative correlation with Jhelum River discharge at Mangla ($r = -0.822$) although this is based on only five years of record. Monsoon rainfall does appear to be important in years of low snowmelt water supply, and in producing short-lived but extremely damaging floods such as those in the fall of 1992. In addition, more southerly as well as easterly (Indian) tributaries of the Jhelum are considerably more exposed to the monsoon's influence. North of the Himalayan crestline the importance of snow and ice melt increases considerably (Hewitt, 1985), although monsoon generated snowfall in the highest ranges (e.g. Nanga Parbat massif) can still be significant.

None of the above results provide any estimate of the percentage of annual runoff provided by snowmelt water supply. However, by comparing the estimated total snowmelt discharge with the total annual discharge of the Kunhar River at Garhi Habib Ullah (Table 3) an average value of 66% is obtained. This compares closely with estimates for the Jhelum quoted earlier (WAPDA, 1981a; Tarar 1982; Hewitt, 1985), and is significantly higher than the estimates by Gulati (1973), Dreyer et al. (1982) and Ferguson (1985).

Table 3. Percentage of Kunhar River discharge at Garhi Habib Ullah derived from snowmelt, 1961-68.

Year	Total Annual Discharge (10^9 m^3)	Total Snowmelt Discharge[1] (10^9 m^3)	Percentage of Total Annual Discharge Contributed by Snowmelt
1961	2.886	1.776	62
1962	2.726	1.517	56
1963	2.232	1.986	89
1964	3.626	2.307	64
1965	4.046	2.714	67
1966	3.552	2.282	64
1967	3.737	2.270	61
1968	3.158	1.949	62
Mean			66

[1] Estimated from annual hydrographs.

The results of this basic analysis of snow accumulation-discharge relations indicate that ground-based measures of snow accumulation may have significant potential for providing an estimate of annual and seasonal flows in the Pakistan Himalaya, if remotely sensed data are unavailable. Snow surveys are particularly attractive since data from accessible, low-elevation snow courses in the Kunhar basin appear to be as useful as data from more remote high-elevation sites. Some high-elevation sites can also be relatively easily accessed at the time of the maximum snowpack water equivalent because lower elevations are by then mostly bare of snow (Figure 5). Tributary valleys are especially useful in this regard since they generally gain elevation much more quickly than the trunk valleys. In the Kunhar basin for example, the 800 m elevation gain from Naran village to the Saiful Maluk Lake snow course (Figure 2) is accomplished over a distance of only eight kilometres whereas in the main valley this gain takes 60 km to accomplish (to Lulusar Lake in Figure 1). Furthermore, the snow surveys would be very inexpensive to operate; Mansell-Moullin (1986) estimates a seasonal cost of US $100 per snow course not including the initial capital outlay. However, careful siting is extremely important given the significant effects of wind and particularly avalanching (Figure 2). For this reason, as well as to lengthen the currently truncated records it is recommended that any snow surveys be continued at existing snow courses.

The estimation of seasonal totals of snowmelt water supply, both on the basis of point measurements of snow accumulation on the ground and snow-covered area from satellite imagery, may be complicated in the Pakistan Himalaya by the operation of a negative feedback mechanism between winter snow cover and subsequent monsoon rainfall. Delay in the onset of the monsoon and total monsoon rainfall in India show significant positive and negative correlations, respectively, with Eurasian and Himalayan snow-covered area in spring (Hahn and Shukla, 1976; Dey and Bhanu Kumar, 1982; 1983; Bhanu Kumar, 1987). Variations in the snow-covered area appear to produce variations in the degree of heating of the upper troposphere and hence in the strength of the monsoon circulation (Dey and Bhanu Kumar, 1982; Bhanu Kumar, 1987; Parthasarathy et al., 1990). The strong negative correlation (-0.822) between summer precipitation at Balakot and annual discharge of the Jhelum River at Mangla, as well as individual years where winter snow accumulation and summer precipitation show a clear inverse relationship, are an indication that this feedback mechanism may be felt in the Pakistan Himalaya. However, it is not clear how snow accumulation at specific points is related to the snow-covered area which apparently affects tropospheric heating. If the mechanism is in fact felt in this region, winters with above-average snow accumulation or springs with delayed snowmelt should be followed by less monsoon rainfall and vice versa, with consequent compensating effects on seasonal runoff. This hypothesis is supported by the much lower year to year variability of annual discharge for rivers in this study (mean *c.v.* = 17%) compared to the variability of snow accumulation (mean *c.v.* = 33-38%). However, further research is required to understand the effects of this continental-scale feedback mechanism on smaller scale precipitation and runoff patterns in a region situated near the limit of the monsoon influence.

CONCLUSION

The objective of this paper is to demonstrate the importance of snowmelt water supply in headwater tributaries of the Pakistan Himalaya which supply the Jhelum River and Mangla Reservoir, using available records of winter snow accumulation and annual runoff. The paper proposes that ground-based point measurements of snow accumulation can be useful for forecasting annual and seasonal runoff, given that satellite imagery for estimating the snow-covered area has in the past been difficult to obtain and that the ground measurements can be accomplished inexpensively by trained inhabitants of the high valleys. Another objective of this paper is to demonstrate how little is known about snowmelt water supply in some mountainous developing countries, and how even simple estimates of its contribution to runoff are difficult because of the paucity of data. In the Pakistan Himalaya this difficulty may compounded by the effect on seasonal runoff of a continental-scale feedback mechanism between winter snow cover and the summer monsoon.

ACKNOWLEDGEMENTS

The data for this paper were collected during the Snow and Ice Hydrology Project, funded by the International Development Research Centre (Canada), Water and Power Development Authority (Pakistan) and Wilfrid Laurier University (Waterloo, Ontario). Additional funding was provided by the Natural Sciences and Engineering Research Council of Canada. The assistance and cooperation of G. Veale, M. Mansell-Moullin, WAPDA (Lahore), Seed Potato Research Programme (Abbottabad) and North-West Frontier Province Forest Department (Abbottabad) in the data collection are gratefully acknowledged.

REFERENCES

Bhanu Kumar, O.S.R.U. (1987) Seasonal variation of Eurasian snowcover and its impact on the Indian summer monsoon. In: *Large Scale Effects of Seasonal Snow Cover* (Proc. Vancouver Symp., July 1987), 51-60. IAHS Publ. no. 166.

Dey, B. and Bhanu Kumar, O.S.R.U. (1982) An apparent relationship between Eurasian spring snow cover and the advance of the Indian summer monsoon. *J. Appl. Met.* **21**, 1929-1932.

Dey, B. and Bhanu Kumar, O.S.R.U. (1983) Himalayan winter snow cover area and summer monsoon rainfall over India. *J. Geophys. Res.* **88**, 5471-5474.

Dey, B., Goswami, D.C. and Rango, A. (1983) Utilization of satellite snowcover observations for seasonal streamflow estimates in the western Himalayas. *Nordic Hydrol.* **14**, 257-266.

Dreyer, N.N., Nikolayeva, G.M. and Tsigelnaya, I.D. (1982) Maps of streamflow resources of some high-mountain areas in Asia and North America. In: *Hydrological Aspects of Alpine and High-Mountain Areas* (Proc. Exeter Symp., July 1982), 11-20. IAHS Publ. no. 138.

Ferguson, R.I. (1985) Runoff from glacierized basins: a model for annual variation and its forecasting. *Wat. Resour. Res.* **21**, 702-708.

Gulati, T.D. (1973) Role of snow and ice hydrology in India. In: *The Role of Snow and Ice in Hydrology* (Proc. Banff Symp., September 1972), 610-623. IAHS Publ. no. 107(1).

Hahn, D.G. and Shukla, J. (1976) An apparent relationship between Eurasian snow cover and Indian monsoon rainfall. *J. Atmos. Sci.* **33**, 2461-2462.

Hewitt, K. (1985) Snow and Ice Hydrology in Remote, High Mountain Regions: the Himalayan Sources of the River Indus. Snow and Ice Hydrology Project, Working Pap. no. 1, Wilfrid Laurier University, Waterloo, Ontario.

Hewitt, K. (1989) Hazards to water resources development in high mountain regions. The Himalayan sources of the Indus. In: *Hydrology of Disasters* ed. Ö. Starosölszky and O.M. Melder, 294-312. James and James, London.

Kureishy, K.U. (1953) Hydrographic control of Kashmir on Pakistan. *Pak. Geogr. Rev.* **VIII**, 78-93.

Makhdoom, M.T.A. and Solomon, S.I. (1986) Attempting flow forecasts of the Indus River, Pakistan using remotely sensed snow cover data. *Nordic Hydrol.* **17**, 171-184.

Mansell-Moullin, M. (1986) Mission Report: Improvement of the River Forecasting and Flood Warning System for the Indus River Basin in Pakistan -- Phase II (PAK/84/003/A/01/16). World Meteorological Organization, Geneva (unpublished).

Nanuk Engineering (1987) Upper Indus Basin, Snow and Ice Runoff Monitoring and Forecasting Project: Draft of Project Identification Report to the Canadian International Development Agency. Nanuk Engineering, Calgary, Alberta (unpublished).

Parthasarathy, B., Rupa Kumar, K. and Sontakke, N.A. (1990) Surface and upper air temperatures over India in relation to monsoon rainfall. *Theor. Appl. Climatol.* **42**, 93-110.

Priest, J.E. (1962) Snow surveys in West Pakistan water resources development. In: *Proc. Western Snow Conference* (30th Annual Meeting, Cheyenne, Wyoming), 40.

Quick, M.C. and Pipes, A. 1989. Manual - U.B.C. Watershed Model (Unpub.). Department of Civil Engineering, University of British Columbia, Vancouver.

Qureshi, A.A. and Umar, Ch.M. (1978) *Water Resources Investigation in Pakistan with the Help of ERTS Imagery - Snow Surveys 1975-76*. Hydrology and Investigation Organization, Water and Power Development Authority, Lahore.

Ramamoorthi, A.S. (1983) Snow-melt run-off studies using remote sensing data. *Proc. Indian Acad. Sci. (Engg. Sci.)* **6**, 279-286.

Ramamoorthi, A.S. (1987) Snow cover area (SCA) is the main factor in forecasting snowmelt runoff from major river basins. In: *Large Scale Effects of Seasonal Snow Cover* (Proc. Vancouver Symp., August 1987), 187-198. IAHS Publ. no. 166.

Rango, A., Salomonson, V.V. and Foster, J.L. (1977) Seasonal streamflow estimation in the Himalayan region employing meteorological satellite snow cover observations. *Wat. Resour. Res.* **13**, 109-112.

Sain, K. (1946) *The Role of Glaciers and Snow on Hydrology of Punjab Rivers*. Central Board of Irrigation (India), Publ. no. 36, Simla.

Shashi Kumar, V., Haefner, H. and Seidel, K. (1991) Satellite snow cover mapping and snowmelt runoff modelling in Beas basin. In: *Snow, Hydrology and Forests in High Alpine Areas* (Proc. Vienna Symp., August 1991), 101-109. IAHS Publ. no. 205.

Snow and Ice Hydrology Project (1990) *Snow and Ice Hydrology Project Overall Report* (Canadian Centre). Wildrid Laurier University, Waterloo, Ontario.

Tarar, R.N. (1982) Water resources investigation in Pakistan with the help of Landsat imagery -- snow surveys 1975-1978. In: *Hydrological Aspects of Alpine and High-Mountain Areas*. (Proc. Exeter Symp., July 1982), 177-190. IAHS Publ. no. 138.

Water and Power Development Authority (1969) *Snow Surveys of West Pakistan, 1961-1968*. Surface Water Hydrology, WAPDA, Lahore.

Water and Power Development Authority (1981a) *Brief Regarding WAPDA's Activities on Ice and Snow Hydrology*. Hydrology and Investigation Directorate/Hydrology and System Analysis Organization, Planning Division, WAPDA, Lahore.

Water and Power Development Authority (1981b) *Rabi Flow Forecasting for Western Rivers of Indus Basin*. Hydrology and Investigation Directorate, Rep. no. 6, WAPDA, Lahore.

World Meteorological Organization (1977) *Flood Forecasting and Warning System for the Indus River Basin, Pakistan. A Plan for Improving Flood Forecasting Networks in Pakistan*. United Nations Development Programme/WMO Tech. Rep. no. 1 (PAK/74/027), Geneva.