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Can Avalanche Activity Alter the Pattern of Snowmelt Runoff from High-Mountain Basins?

F.A. DE SCALLY
Department of Geography
Okanagan University College
3333 College Way
Kelowna, British Columbia V1V 1V7 Canada

ABSTRACT

Avalanche activity can affect the subsequent generation of snowmelt runoff as a result of two main changes occurring during avalanching: concentration of the snow mass, and an ambient temperature increase resulting from the avalanches' fall to a lower elevation. The balance between these changes largely determines whether the rate of meltwater production from individual avalanche deposits is decreased or increased in comparison to undisturbed snow. Any noticeable effect on the temporal pattern of snowmelt runoff at the basin scale depends first on the proportion of the total basin snow cover which has been disturbed by avalanching, and second on the balance between delayed and accelerated meltwater production from all avalanche deposits in the basin. This paper discusses the effect of avalanche activity on runoff from a large (2500 km^2) basin in the Punjab Himalaya, Pakistan and ongoing research from small high-elevation basins in the Cascade Mountains, British Columbia.

INTRODUCTION

The vast majority of research on snow avalanches has been motivated by the hazard they create for winter-time activities in the mountains. Little attention has been paid to their role as a transfer mechanism within a high-mountain hydrological system. Yet, avalanche activity can have a number of different effects on such a system including providing a source of snow accumulation for glaciers, short-term damming of rivers, disruption of slope materials with a resulting increase in mudflow and debris flow activity, and creation of snow deposits in which the processes of density increase, ablation and runoff generation can differ markedly from an undisturbed snow cover (Kick, 1962; Iveronova, 1966; Sosedov and Seversky, 1966; Kotlyakov, 1973; Tushinsky, 1975; Zalikhanov, 1975; Martinec, 1985; de Scally and Gardner, 1990). The last effect is significant in terms of potential impacts on the temporal pattern of snowmelt runoff from non-glacierised basins (Figure 1).

Differences in the generation of meltwater from avalanche snow deposits as compared to the undisturbed snow cover are the result of three changes which occur during avalanching:

(1) An increase in ambient air temperature owing to transport of the snow from a higher to a lower elevation.
(2) A reshaping and/or concentration of the snow mass, increasing the density and reducing the surface area that is exposed to atmospheric energy exchanges. This is complicated by differences in the sky dome, and hence radiation exchanges, between the starting and runout zones of the avalanche path.
(3) A reduction in the snow surface albedo resulting primarily from the entrainment of debris, which increases the energy gain from shortwave radiation. The albedo usually decreases throughout the ablation season as debris is melted out of the avalanche deposit, dropping as low as 15% for a completely debris-covered snow surface (de Scally, 1989). The debris cover rarely gets thick enough to inhibit sensible heat transfer from the surface to the snow underneath.

Whether the generation of meltwater is delayed or accelerated by avalanching depends on which of the three changes outlined above is dominant. While (2) will result in delays to meltwater production, (1) and (3) will accelerate it. Assuming that air temperature represents the total available melt energy, the counteracting effects of the two most significant changes (1) and (2) are equal when

$$a \cdot T \cdot A_{(SZ)} = a \cdot (T + h \cdot \gamma) \cdot A_{(RZ)} \tag{1}$$

where a is the melt factor or amount of snowmelt per degree of positive mean daily air temperature, T is the air temperature at the mean elevation of the avalanche path's starting zone, $A_{(SZ)}$ and $A_{(RZ)}$ are the surface area of the starting and runout zones respectively, h is the difference in elevation between $A_{(SZ)}$ and $A_{(RZ)}$, and γ is the temperature lapse rate with elevation (Martinec, 1976). Thus, the rate of meltwater production (relative to undisturbed snow) is accelerated on avalanche paths where avalanched snow falls a large vertical distance and/or is spread out in the runout zone, and is delayed on paths where the snow falls a shorter distance and/or is highly concentrated in the track or runout zone.

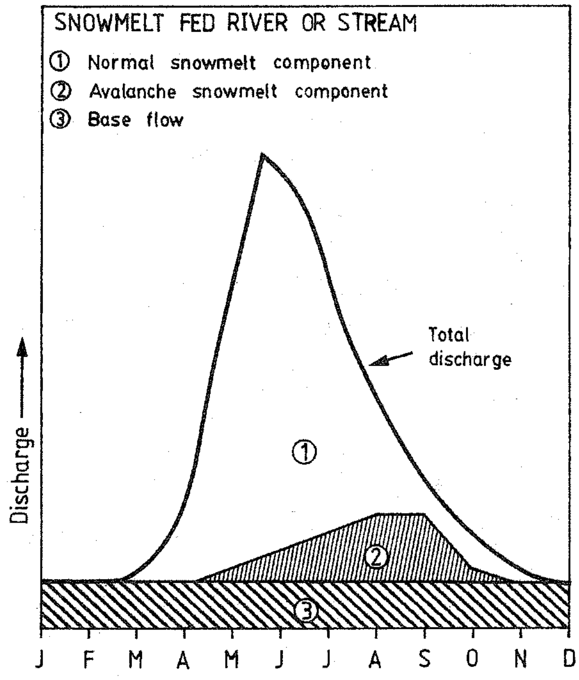

Figure 1: Hypothetical avalanche effect on seasonal snowmelt runoff, in this case showing a delay relative to melting of the undisturbed snow cover.

Two factors determine whether changes in rates of meltwater production on individual avalanche paths, as described above, can affect the temporal pattern of snowmelt runoff from higher-order basins. First is the proportion of the basin's snow cover, and hence subsequent snowmelt runoff, which is avalanched in any given winter. In very small high-elevation basins it may be possible to survey the total volume of avalanche-transported snow at the beginning of the ablation season. In larger basins the total volume of such snow can be estimated by

$$V_A = A_A \cdot W_U \cdot f \tag{2}$$

where V_A is the total water-equivalent volume of avalanche snow in the basin, A_A is the total area of the basin affected by avalanches, W_U is the basin-averaged precipitation that winter (snow and rain), and f is the average 'yield coefficient' or fraction of W_U which is transported on avalanche paths. The estimation of A_A can be accomplished from aerial photographs, other remotely sensed imagery and even ground mapping (de Scally, 1992) but is variable from year to year. The large variability of f, from both path to path and year to year, is discussed by de Scally and Gardner (1989). Winter precipitation W_U has to be adjusted for elevational gradients of precipitation and the hypsometry of the basin.

The second factor that determines any basin-scale effect on runoff is the proportion of avalanche paths which, by virtue of their morphology, delay meltwater production to those which accelerate it. For example, Figure 1 illustrates a hypothetical annual hydrograph where the former type of avalanche path is dominant. In larger basins this balance is difficult to estimate even with the aid of detailed avalanche maps, since it requires a consideration of the factors in equation (1) for each path.

The objectives of this paper are twofold. The first objective is to report on results of a study on the effect of avalanche snow transport on snowmelt at both the avalanche path and basin scales in the Pakistan Himalaya. The second objective is to describe an ongoing study on this effect in small, high elevation basins in the Cascade Mountains, British Columbia, Canada.

STUDY AREAS AND METHODOLOGY

The Himalayan study was carried out in the Kunhar River basin (2500 km^2), a major tributary of the Jhelum River in the Punjab Himalaya of North-West Frontier Province, Pakistan (Figure 2). Total annual flow at Garhi Habib Ullah near the mouth of the basin is on average 3.330 x 10^9 m^3. Heavy winter snowfall, extremely steep terrain, extensive unvegetated slopes, and a runoff regime dominated by snowmelt (60-70% of the total annual discharge) make the Kunhar basin ideal for this type of study.

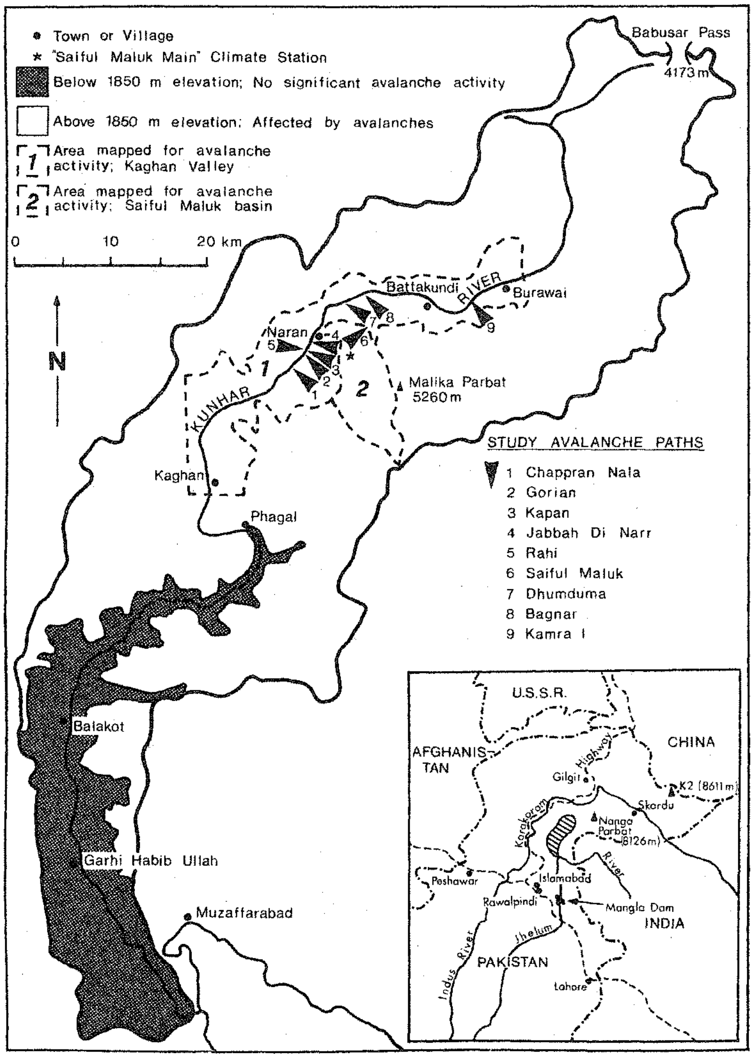

Figure 2: Kunhar River basin in North-West Frontier Province, Pakistan, showing the location of the study area.

Individual avalanche paths in the Kunhar basin were studied during two ablation seasons in order to determine whether avalanching on them resulted in an acceleration or delay of snowmelt runoff (Figure 2). The paths were chosen on the basis of their representativeness with respect to size, aspect, morphology and snow transport characteristics. Total vertical falls on the paths range from 317 to 1715 m and starting zone areas from 39,200 to 5,236,570 m^2. Avalanche deposit volumes estimated with cross-section surveys in 1986 and 1987, after two moderate to severe avalanche winters, approach and in one case exceed 10^6 m^3 water equivalent on the larger paths. Using collected data on the paths' morphology, avalanche deposit surface areas and volumes, ablation rates, winter precipitation and air temperatures and temperature lapse rates during the ablation season, the mean monthly rate of meltwater production and date of snow disappearance in 1986 and 1987 is calculated for each avalanche path. The calculations are performed for three scenarios: no avalanche activity (i.e. all snow on the avalanche path remains undisturbed); the entire snow cover in the starting zone is transported into the runout zone by avalanching; and, the surveyed volume of avalanche snow is transported into the runout zone. The equations for calculating the rates of meltwater production and dates of snow disappearance are described by de Scally (1992). The avalanche paths and measurements required for the calculations are described by de Scally (1989) and de Scally and Gardner (1989; 1990).

The proportion of the Kunhar basin's snow cover and hence snowmelt runoff which is affected by avalanching is analysed using equation (2). The equation is applied to the years 1961 to 1968, the only period for which data on both winter snowfall and for comparison discharge of the Kunhar River are available (Water and Power Development Authority, 1969; 1975). Estimates of A_A are based on 1986 and 1987 ground mapping in representative below-treeline and above-treeline areas of the basin, covering 14% of the total area prone to avalanche activity (Figure 2). The mapping procedures are described in detail by de Scally (1992) and de Scally and Gardner (1993). A mean value of 0.099 for f is obtained from measurements on the study avalanche paths (de Scally and Gardner, 1989). The mean winter precipitation W_U in each year is taken as the total November to April precipitation or maximum snowpack water equivalent, whichever is greater, at measurement sites in the vicinity of Naran village (Figure 2).

In non-glacierised mountains of North America any measurable effect of avalanche activity on snowmelt runoff is probably limited to much smaller alpine or subalpine basins, since the intensity and magnitude of avalanche activity usually does not equal that found in many Himalayan basins. Therefore the aim of the ongoing study in the Cascade Mountains, Manning Provincial Park, is to compare the temporal pattern of snowmelt runoff from a small avalanche-prone basin (Frosty Creek; 56% of the 5 km^2 total area is affected by active or potential avalanche activity) and an adjacent avalanche-free 'control' basin (12 km^2; 7% is affected by avalanche activity) (Figure 3). By measuring streamflow from both basins during and after the ablation period the net effect of all avalanche snow in the Frosty basin can be assessed, a task which was impossible to accomplish in the much larger Kunhar basin. The main difficulty will be to separate the avalanche effect from other factors affecting snowmelt such as differences in forest cover, aspect and hypsometry between the two basins. This study will therefore attempt to understand the effect of these differences in addition to collection of data on the transport and ablation of avalanche snow.

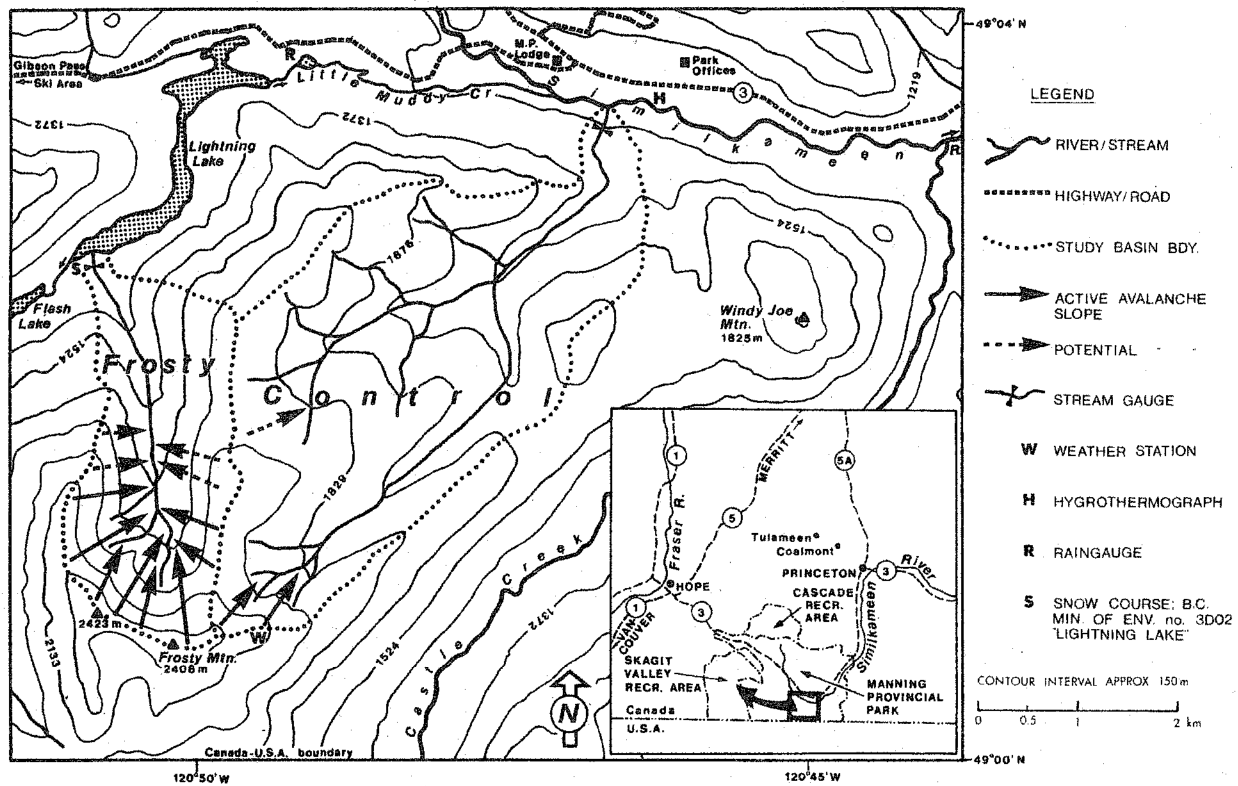

Figure 3: Frosty Creek and 'control' study basins in Manning Provincial Park, British Columbia, Canada.

RESULTS AND DISCUSSION

Table 1 shows the concentration factor and ambient temperature increase for snow following avalanching on each of the Kunhar basin paths. The calculations of meltwater production indicate that the former is dominant on all of the paths, as illustrated by two representative paths in Figure 4. As a result, very high rates of surficial melting on low-elevation avalanche snow (see de Scally and Gardner, 1990) are outweighed by the small surface area of the deposits, significantly decreasing the rate of meltwater production compared to the undisturbed snow cover in the paths' starting zones (Figure 4). Meltwater production from the undisturbed snow in each path's starting zone ($Q_{U(SZ)}$) is delayed until the temperature climbs above 0°C. However when ablation there does begin, the rate of meltwater production increases rapidly owing to the large surface area of the snow cover (i.e. $A_{(SZ)}$ in equation (1)). Ablation begins earlier in the runout zones ($Q_{A(RZ)}$) because of their lower elevation, but the rate of meltwater production remains low owing to the small surface area (i.e. $A_{(RZ)}$ in equation (1)). Further calculations described in de Scally (1992) show that just prior to the time of disappearance of the undisturbed snow cover from the avalanche paths' starting zones (assuming that the snow cover thins uniformly over the whole starting zone and then disappears at once), the ratio of meltwater production there to meltwater production from avalanche snow in the runout zones ranges from 4 to 18. In other words, the undisturbed snow cover is capable of generating as much as 18 times more meltwater daily than the snow avalanched into the runout zone. Whether the avalanche deposit actually persists longer than the undisturbed snow cover in the starting zone also depends on the total volume of the deposit. The high 'concentration factors' ($A_{(SZ)}/A_{(RZ)}$) responsible for this reduction in the rate of meltwater production are a function of the avalanche path morphology; most moderate-sizedto large paths in the Kunhar basin are deeply confined. The mean concentration factor in Table 1 (15.9) agrees closely with the range of values (10-18) reported by Zalikhanov (1975). The factors in Table 1 might be slightly overestimated; the surface area of the avalanche deposits is substituted for the runout zone area $A_{(RZ)}$ due to the difficulty of surveying the runouts in their entirety. However on six of the nine study paths almost all of the track and runout was covered by avalanche snow in 1986 and 1987, making the deposits' surface area virtually the same as $A_{(RZ)}$.

Table 2 shows the change in the time of snow disappearance following avalanching on each of the study paths. The calculations are based on a number of simplifying assumptions which are

Table 1. Concentration of the snow and ambient temperature increase with avalanching on the study avalanche paths, Kunhar River basin.

Path	*Snow concentration factor*[1]		*Ambient temperature increase* [2] *(°C)*
	1986	*1987*	
Chappran Nala	10.0	7.2	4.0
Gorian	19.9	21.9	7.7
Kapan	25.3	21.6	6.7
Jabbah Di Narr	—[3]	—[3]	1.9
Rahi	—[3]	—[3]	5.3
Saiful Maluk	5.7	7.6	4.2
Dhumduma	25.8	31.7	7.4
Bagnar	7.4	8.9	7.4
Kamra I	—[3]	14.2?	4.2

[1] $A_{(SZ)}/A_{(RZ)}$ (see equation 1); the surface area of the avalanche deposit in each year is substituted for $A_{(RZ)}$ because the runouts could not be surveyed in their entirety.

[2] $h \cdot \gamma$ (see equation 1); h is measured from the mid-elevation of the starting zone to the top of the runout zone in order to represent the 'average' avalanche travel distance, γ is taken as 0.0073 °C m^{-1} on the basis of temperature records from several elevations during the ablation season.

[3] Surface area of the avalanche deposit is too small to represent $A_{(RZ)}$.

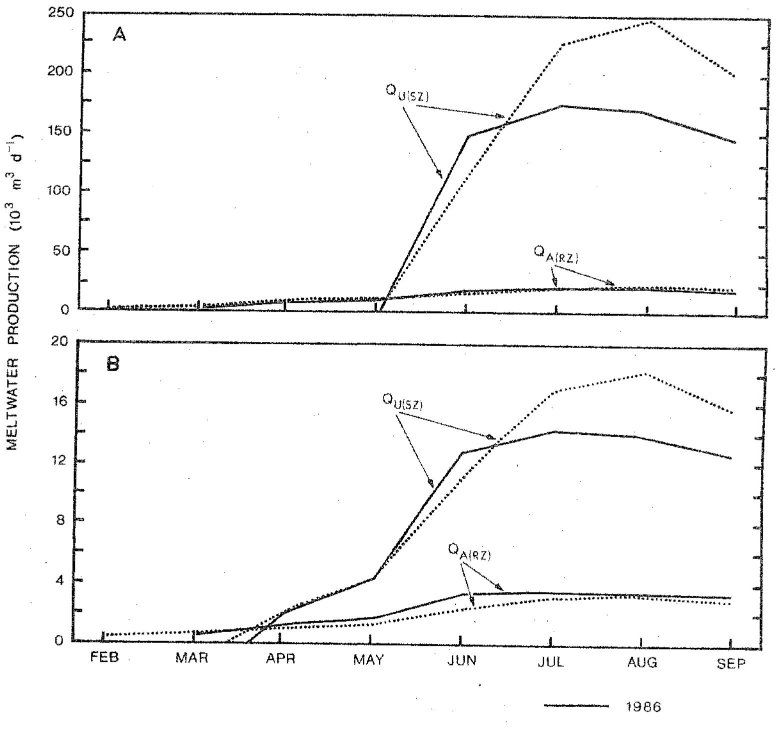

Figure 4: Calculated mean monthly rates of meltwater production from avalanche snow in the runout zone ($Q_{A(RZ)}$) and undisturbed snow in the starting zone ($Q_{U(SZ)}$) for two representative paths. $Q_{A(RZ)}$ is based on the surveyed surface area of the avalanche deposits. A: 'Gorian' path; B: 'Saiful Maluk' path.

discussed by de Scally (1992). Significant delays in the disappearance of snow are produced if it is assumed that all of the snow from the starting zones ($A_{(SZ)}$) is avalanched into the runout zones ($A_{(RZ)}$). However, while these delays do support the results of the above calculations of rates of meltwater production (Figure 4), they are overestimated because 1) rarely does all of the snowpack in a starting zone avalanche, and 2) $A_{(RZ)}$ is based on the surface area of the avalanche deposits surveyed in 1986 and 1987, and not the whole runout area (de Scally, 1992). The result in the equation is an avalanche deposit that is too deep and hence takes too long to melt.

When the real volumes of avalanche snow on the study paths are considered, Table 2 shows the disappearance of snow to be accelerated by avalanching. This is because the equation assumes the avalanche deposit to be evenly distributed in the runout zone (i.e. of uniform depth throughout). In fact, neither of the equations used to calculate the values in Table 2 can model the observed situation very well, in which the thin, spread-out portions of the avalanche deposits disappear relatively rapidly, but avalanche snow concentrated in gullies and other terrain concavities melts very slowly because of its small surface area. Deposits in deeply gullied track zones, which are very common in the Kunhar basin, are especially significant in this regard and are mainly responsible for the two to three month delay in the disappearance of snow observed on large avalanche paths following avalanche activity. Avalanche snow in the track zone accounts on average for 51% of the total deposit on the study paths in both years, and 74% on those paths with deeply gullied tracks ('Chappran Nala', 'Gorian', 'Kapan' and 'Dhumduma'). This percentage appears to increase in years of less severe avalanche activity because less snow is transported all the way into the runout zone, stopping in the track instead. In some years in the Kunhar basin, portions of avalanche deposits have been observed to linger well into the autumn or even into the following winter on large paths. A number of Soviet studies report a similar decrease in spring runoff and alimentation of flows during the summer and autumn on large avalanche paths (Iveronova, 1966; Sosedov and Seversky, 1966; Zalikhanov, 1975).

Martinec and de Quervain (1975) have demonstrated that on a less confined avalanche path,

Table 2. Change in the time of snow disappearance following avalanche activity. The delay or acceleration is relative to a "no-avalanche" situation (i.e. all of the undisturbed snow cover remains in the starting zone).

Path	*Case 1*[1] *(days)*[3]		*Case 2*[2] *(days)*[3]	
	1986	*1987*	*1986*	*1987*
Chappran Nala	+119	+94	-22	-30
Gorian	+170	+226	-86	-77
Kapan	+243	+244	-53	-61
Jabbah Di Narr	—	—	+47	—
Rahi	—	—	-73	-73
Saiful Maluk	+62	+111	-29	-24
Dhumduma	+231	+326	-84	-73
Bagnar	+21	+62	-111	-110
Kamra I	—	+209	-38	-75
Mean	+163		-57	

[1] All of the snow cover in $A_{(SZ)}$ is avalanched into $A_{(RZ)}$, and the resulting deposit is assumed to be of uniform depth.

[2] The surveyed volume of avalanche snow in $A_{(RZ)}$, assumed to be of uniform depth.

[3] + = Delay; - = acceleration in the time of snow disappearance.

avalanching will accelerate meltwater production and the disappearance of the snow. In the Kunhar basin this is observed on some smaller unconfined paths where the snow is not concentrated to any great degree during avalanching. It is not known exactly how these compensate at the basin scale for delayed melting on the large confined paths, but it appears reasonably certain that the latter are dominant due to the numerous large, concentrated avalanche deposits that are present at the beginning of the ablation period each year.

The results of calculations of the proportion of the Kunhar discharge stored as avalanche snow are shown in Table 3. Since the actual extent of avalanche activity in the winters 1961 to 1968 is unknown, the calculations using equation (2) are based on assumed 'intense' and 'normal' avalanching. 'Intense' avalanche activity assumes that all avalanche paths are active. In this case the average proportion of slope area potentially affected by avalanching (65%) as estimated from ground mapping (Figure 2), combined with the area of the basin high enough to experience avalanche activity (2110 km^2; Figure 2) yields a total avalanche-affected area of 1372 km^2. For a 'normal' avalanche winter a conservative density of one avalanche per 2.5 km^2 is assumed (LaChapelle, 1968). For comparison this density appears to have been about two to three times higher in 1985-86 and 1986-87, two moderate to bad avalanche winters according to local sources. If the 2110 km^2 area is combined with this assumed density of avalanches and the average mapped path size (0.48 km^2), the result is 389 km^2 of total avalanche-affected area in a 'normal' winter. The total volume of avalanche-transported snow in the basin (V_A) using equation (2) then averages 1.62 x 10^8 and 0.46 x 10^8 m^3 water equivalent following 'intense' and 'normal' avalanching respectively. Table 3 shows that with 'intense' avalanching, on average 7.6% of the snowmelt runoff and 4.8% of the annual runoff of the Kunhar River are supplied by avalanche snow. Following a 'normal' winter, avalanche snow supplies on average 2.2% of the snowmelt runoff and 1.4% of the annual runoff. These can be compared to percentages reported for small (mean area = 1.2 km^2) avalanche basins by Sosedov and Seversky (1966); 10-34% of snowmelt runoff and 3-11% of annual runoff derived from avalanche-transported snow. Considering the much larger size of the Kunhar River basin (2500 km^2) the percentages from there appear to be exceptionally high, reflecting the intense winter-time avalanche activity.

Preliminary results of streamflow measurements in the Cascade Mountains study show that there are marked differences in the pattern of snowmelt runoff from the avalanche-prone and avalanche-free basin, even following a winter with a shallow snowpack and little avalanche activity (1991-92). The total volume of avalanche snow estimated in the Frosty Creek basin using cross-section surveys, probing and measurements of deposit surface areas in early July 1992 was approximately 74,000 m^3 water equivalent. To what

Table 3. Proportion of Kunhar River discharge stored as avalanche snow, 1961-1968.

Year	Proportion of discharge (%)[1]			
	Intense[2]		Normal[2]	
	Snowmelt[3]	Annual[4]	Snowmelt[3]	Annual[4]
1961	6.9	4.2	2.0	1.2
1962	5.3	3.0	2.5	0.8
1963	10.5	6.5	3.0	1.8
1964	6.6	4.2	1.9	1.2
1965	8.0	5.3	2.3	1.5
1966	8.6	5.5	2.4	1.6
1967	8.2	5.0	2.3	1.4
1968	6.9	4.3	2.0	1.2
Mean	7.6	4.8	2.2	1.4

[1] Calculations are based on winter precipitation/snowpack water storage (W_U in equation (2)) and discharge data from the Water and Power Development Authority (1969; 1975).

[2] Intense = 1372 km^2; Normal = 389 km^2 affected by avalanching (A_A in equation (2)).

[3] Total snowmelt discharge at Garhi Habib Ullah.

[4] Total annual discharge at Garhi Habib Ullah.

extent the differences in the runoff pattern are attributable to the effect of avalanche snow transport has not yet been determined.

Several implications arise out of this research. First, the results from the Kunhar basin demonstrate that if the total volume of avalanche-transported snow is sufficiently great, it can represent a measurable proportion of the seasonal runoff from even large mountainous basins. However, Himalayan basins may be unique in this regard because the combination of their winter climate, steep terrain and extensive deforestation is conducive to very intense avalanche activity. Regardless, contributions from avalanche deposit melting would be most significant in a summer of low rainfall preceded by a winter of intense avalanche activity but only modest snowpack depths. The results also show that avalanche snow which is concentrated in terrain concavities is protected from melting and therefore continues to produce meltwater through the summer and even into the autumn. In many Himalayan basins, large avalanche paths are frequently deeply confined because of the intensity of other erosional processes on them including streams and debris flows. However, avalanche snow transport on unconfined paths with a large vertical fall can accelerate the disappearance of snow. Therefore, any evaluation of the net basin effect must take into account all avalanche paths which transport significant quantities of snow during the winter.

This research may eventually provide insight into the practicality of artificially triggering avalanches in uninhabited high-elevation basins in order to ameliorate spring-time snowmelt floods and increase summer water yields. The latter may prove to have the most practical significance, given that some general circulation models predict earlier and less snowmelt runoff and decreased summer soil moisture levels in North America from increasing CO$_2$ levels in the atmosphere (e.g. Wetherald, 1991; Barry, 1992).

CONCLUSION

Research in the Punjab Himalaya of Pakistan shows that intense avalanche activity can alter the timing of the melting of large quantities of snow by up to three months, primarily as a result of the morphological characteristics of the avalanche paths. In the relatively large stream basin studied, avalanche snow can represent up to 8 and 5 percent of the total snowmelt and total annual runoffs respectively, and appears to delay the former to an unknown extent. Further work in the Cascade Mountains of southern British Columbia is investigating this effect in small high-elevation stream basins.

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