HYDROLOGIC ROLES OF SNOW AVALANCHES IN HIGH-MOUNTAIN ENVIRONMENTS: A REVIEW

by

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ABSTRACT

The hydrologic roles of snow avalanches in high-mountain environments are rarely addressed by the research community. Yet, as a component within the snow and ice subsystem of the hydrologic cascade, avalanches can provide a significant source of accumulation for glaciers; alter the nature and timing of seasonal snowmelt; disturb the winter runoff regime through damming of rivers and displacement of lake water; and increase the incidence of other mass movement processes by their disruption of slope sediments. The purpose of this paper is to review the current state of knowledge with respect to these roles, particularly as they affect downstream hydrologic processes.

INTRODUCTION

Snow avalanches are a ubiquitous feature of high-mountain environments possessing a seasonal or perennial snow cover. Research on the hazards they pose to human activity has represented one of the most active areas of applied glaciology in the last four decades (LaChapelle, 1977). The dominant concern has been with practical aspects of hazard management, as reflected in many of the texts on the subject (Perla and Martinelli, 1976; Armstrong and Williams, 1986; McClung and Schaerer, 1993). On the other hand, the hydrologic roles of snow avalanches have received little scientific attention, despite having been recognised for over 100 years (Heim, 1885). They are usually less noticeable than the hazard effects, and more difficult to measure when considered not only at appropriate spatial and temporal scales but as practical problems. Yet, on a global scale the hydrologic and geomorphic roles of snow avalanches may be more important than the latter (Alford, 1974). The purpose of this paper is to review the literature on hydrologic roles of snow avalanches, partly with the objective of demonstrating that while numerous authors have made reference to these roles, very few have carried out any substantive investigation of them. The term 'avalanche' is used synonymously with 'snow avalanche' throughout the paper; ice avalanches from glaciers are explicitly referred to as such.

HYDROLOGIC ROLES

The significance of avalanches in high-mountain hydrologic systems is acknowledged briefly in some reviews (Alford, 1974; Slaymaker, 1974), while others make no mention of them (Alford, 1985). Klemeš (1990) refers to avalanches as a non-linearity or threshold effect operating in the snowmelt component of such systems. In fact avalanches, representing the rapid downslope movement of snow, often over great vertical distances and involving large volumes of snow, can have four types of hydrologic roles (Fig. 1). These are: nourishment of mountain glaciers; acceleration or delay of seasonal snowmelt; disruption of the winter regime of runoff through damming of rivers or displacement of lake water; and, disruption of slope sediments with consequent effects on other hydrologic-geomorphic processes.

Nourishment of mountain glaciers

Under suitable topographic and climatic conditions avalanches can provide a significant source of accumulation for mountain glaciers, allowing them to exist below the climatic snowline (Fig. 2). Many authors have noted this form of glacier nourishment (Wiche, 1960; Kick, 1962; Lossev, 1967; Kotlyakov, 1973; Tushinsky, 1975; Vivian, 1975). However, glaciological texts usually make only passing reference to this role of avalanches (e.g. Paterson, 1994).

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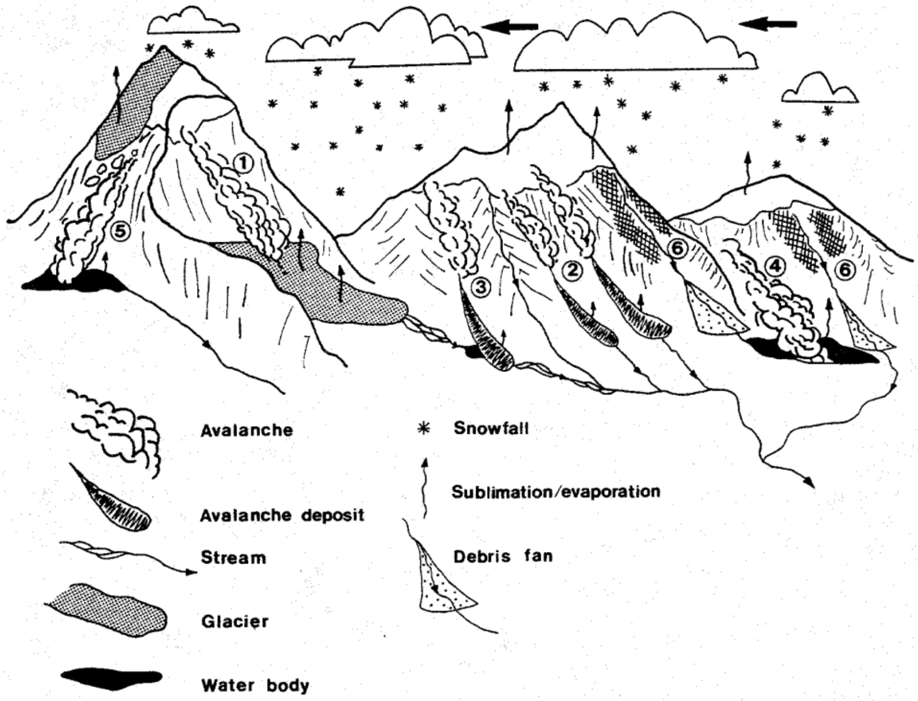

Figure 1 Roles of avalanches in high-mountain hydrologic systems. 1: glacier nourishment. 2: creation of snow deposits whose melting may differ from undisturbed snow cover. 3: damming of streams and rivers. 4: impacts on water bodies. 5: impacts on water bodies by ice avalanches from glaciers. 6: disruption of slope sediments which may affect other mass movements.

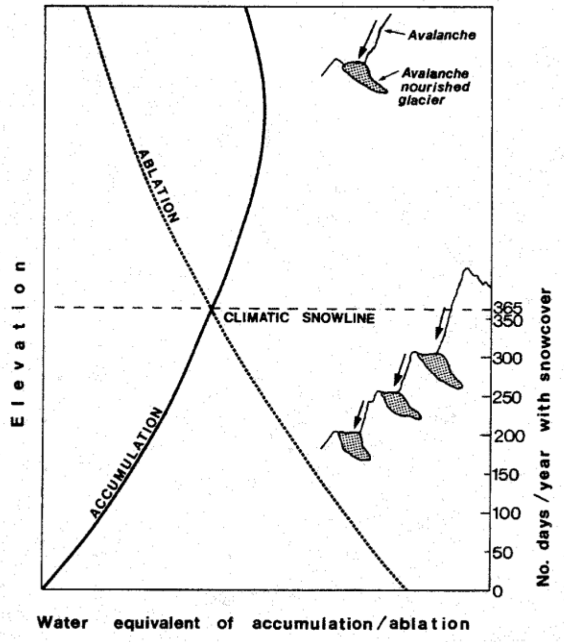

Figure 2 Lowering of glacier snowlines below the climatic snowline by avalanche nourishment (modified from Tushinsky, 1975).

Large glaciers which rely on avalanching rather than extensive firn fields for accumulation are so common in Central Asia that they are distinguished as 'Turkestan' (Klebelsberg, 1925; Bazhev et al., 1975) or 'Firnkessel' (Schlagintweit, 1856, cited in Kick, 1962) type glaciers. Glaciers of this type include the Chogolungma (330 km^2) in the Karakoram Mountains (Lossev, 1960) and Chungpar on Mt. Nanga Parbat, Punjab Himalaya (Kick, 1962). Much smaller glaciers supplied almost exclusively by ice avalanches from higher glaciers, and existing at very low elevations relative to the climatic snowline, are frequently referred to as 'rejuvenated' or 'regenerated' glaciers (Embleton and King, 1975; Tufnell, 1984; Hambrey and Alean, 1992). Between these two extremes, many other types of glaciers can be nourished by some combination of snow- and ice avalanches.

Most insights into avalanche nourishment of glaciers are the result of research carried out 20-30 years ago in the former Soviet Union. This research shows that individual avalanche snow deposits on glaciers can be enormous; Tushinsky (1975) for example reports a deposit with a volume of 14.5×10^6 m^3 on a small avalanche-fed glacier in the Caucasus Mountains. The total amount of glacial accumulation represented by such deposits is substantially more difficult to measure compared to snowfall accumulation on firn fields (Kick, 1962). Therefore, avalanche nourishment has usually been evaluated on the basis of estimates of the proportion of winter snow cover which avalanches, in both glacierised terrain (Kotlyakov, 1973; Tushinsky, 1975) and non-glacierised terrain (Lossev, 1967). A summary of the results is presented in Table 1, showing that the avalanche contribution can be as high as 19 and 57% of total accumulation on large and small glaciers, respectively. This can be sufficient to depress the glacier snowline as much as 1600 m below the climatic snowline, down to altitudes where snow cover would otherwise persist an average of only 200 days per year (Fig. 2 and Table 2) (Tushinsky, 1975). However, the importance of avalanche nourishment is highly dependent not only on the intensity of avalanching, but also on glacier morphology and the effect that has on concentrating snow onto the glacier surface (Table 1). The importance usually increases with a decreasing ratio of accumulation area size to ablation area size. Kotlyakov (1973) calculates ratios of 1.4- 1.5 for small cirque glaciers which receive most of their accumulation from a combination of avalanches and blowing snow. This importance should also increase with a decreasing ratio of glacier surface area to glacier basin area, as larger avalanche source areas are then provided above the glacier. The large and small glaciers in Table 1 have ratios of 0.50-0.95 and 0.15-0.65, respectively (Tsomaya, 1963, cited in Lossev, 1967). Some interesting attempts have been made to estimate mountain precipitation from glacier accumulation rates, taking into account the 'concentration' of accumulation by avalanches and wind (Krenke, 1975; Tareeva, 1988; Getker, 1988).

Glacier nourishment by avalanches is likely to be highly variable from one year to the next. As a result the accumulation, mass balance and flow velocity of glaciers dominated by avalanche inputs is probably more variable from year to year than glaciers nourished primarily by snowfall (Kick, 1962; Lossev, 1967; Kotlyakov, 1973). Establishing patterns of variations in these parameters may therefore require study of a greater number of glaciers over a longer time (Kick, 1962). A dendrochronological study by Turmanina (1970, cited in Tushinsky, 1975) shows that in the last 400 years glacial advances in the Caucasus Mountains have been preceded by intense avalanche activity lasting several winters. In order to shed further light on such relationships between avalanche nourishment, glacier mass balance and glacial movement, it is necessary to obtain further estimates of this nourishment relative to snowfall accumulation and glacier size and morphology (Kotlyakov, 1973). No estimates of this kind appear to have been made for North American glaciers.

Avalanches can also influence the mass balance of glaciers through their effects on ablation. First, the concentrated nature of avalanche deposits on a glacier leaves a smaller surface area of snow exposed to energy exchanges and ablation is therefore slowed (see next section). This effect is enhanced if the avalanches are 'dirty' and a protective debris cover forms during initial melting of the snow. In Central Asia at least, such effects can complicate attempts to model glacial runoff (Young and Hewitt, 1990). Second, avalanching from the ablation zone, either as slush avalanches on low-gradient surfaces (Lossev, 1967) or avalanches from ice cliffs, can represent an important loss of glacier mass. At one time large avalanches were thought to have yet another effect on mass balance, by being at least partly responsible for triggering surging (e.g. Tarr and Martin, 1914). However, it is now generally agreed that surging results from the disruption of the normal subglacial drainage system, with climatic changes or avalanches playing little if any role (Paterson, 1994).

Table 1

Estimated contributions of avalanche snow to glacier accumulation; Caucasus, Tien Shan, Pamir-Alai and Polar Ural mountains.

PERCENTAGE OF SNOW COVER AVALANCHED[1]	SOURCE	PERCENTAGE OF TOTAL GLACIER ACCUMULATION SUPPLIED BY AVALANCHE SNOW[2]	
		Large valley glaciers	Small cirque-valley and valley glaciers
0.3	Lossev (1967)	<1	<1 - 2
1	Lossev (1967)	1 - 2	1 - 6
	Kotlyakov (1973)	<1	<1
10	Lossev (1967)	9 - 17	13 - 39
	Kotlyakov (1973)	< 1 - 7 (5)[3]	4 - 31 (17)[3]
20	Kotlyakov (1973)	< 1 - 14	8 - 47
25	Lossev (1967)	20 - 33	28 - 62
30	Lossev (1967)	23 - 38	33 - 67
	Kotlyakov (1973)	1 - 19	12 - 57

[1] Although not clearly explained, these percentages probably refer to individual avalanche paths/slopes, not the total slope area of the glacier basin.

[2] Total accumulation excludes wind-transported snow which for small glaciers may represent a substantial additional input.

[3] Figure in brackets is Kotlyakov's average contribution, based on both authors' average of 10% of the snow cover being avalanched. If the assumption in footnote (1) is correct, this 10% compares closely with averages from the Canadian Cordillera (Schaerer, 1988) and Punjab Himalaya, Pakistan (de Scally and Gardner, 1989).

Table 2

Depression of cirque and valley glacier snowlines below the climatic snowline as a result of avalanche nourishment.

MOUNTAIN RANGE	ELEVATION OF CLIMATIC SNOWLINE H_1 (m a.s.l.)	ELEVATION OF GLACIER SNOWLINE H_2 (m a.s.l.)	$H_1 - H_2$ (m)	DURATION OF SNOW COVER AT H_2[1] (Days yr^{-1})
Khibini Mtns.	1500	900	600	220
Urals	1700	1000	700	215
Suntar Khayata	2900	2300	600	290
Kodar				
- northern slope	3300	2300	1000	255
- southern slope	3300	2500	800	276
Kamchatka	3500	1850	1650	200
Katunsky Range	3600	2900	700	294
Zailiysky Alatau	4400	3800	600	315
Tien Shan				
- northern	4500	3200	1300	260
- southern	4500	3700	800	300
Caucasus	4300	3500	800	295
Pamir				
- southwest	5400	4000	1400	270
- east	5400	5000	400	320

Data from Tushinsky (1975)

[1] Average for a non-glacierised, level, unshadowed surface.

Acceleration or delay of seasonal snowmelt

The potential for changes in seasonal snowmelt following avalanching is probably the most important hydrologic role of avalanches in non-glacierised mountain basins. Much of the literature and research on this role have been presented at recent meetings of the Western Snow Conference (de Scally, 1993; 1995), so only a brief review is given here.

The most important change following avalanching is to the rate of meltwater production from an avalanche deposit compared to an equivalent volume of undisturbed snow cover (i.e. compared to if the snow had not avalanched and had therefore remained in the starting zone). Whether this rate is increased or decreased depends primarily on the counteracting effects of: faster ablation resulting from avalanching of the snow to a lower elevation and hence warmer environment, and reduced meltwater production due to concentration of the snow (i.e. reduction in the ratio of snow surface area to volume). Topographic shadowing of the avalanche deposit and a decrease in its albedo resulting from entrainment of debris, which would have counteracting effects on ablation, are also important considerations since solar radiation is frequently the dominant source of melt energy.

Martinec and de Quervain (1975) and Martinec (1976; 1985; 1989) show that meltwater production can be accelerated by avalanching, resulting in the snow disappearing earlier than in the case of normal snowmelt. However, their analysis involves only one unconfined avalanche deposit in the Swiss Alps. De Scally (1989; 1992; 1993) demonstrates that on several confined avalanche deposits in the Punjab Himalaya, Pakistan, a significant delay occurs in the disappearance of the snow. Similar observations have been made in mountains of the former Soviet Union (Lossev, 1960; Iveronova, 1966; Sosedov and Seversky, 1966; Zalikhanov, 1975). On deeply confined avalanche paths with a high 'concentration factor' (ratio of the surface area of snow cover prior to avalanching to surface area of the resulting avalanche deposit), the delay can be in the order of two to three months or more compared to undisturbed snow cover in the starting zone. Concentration factors on such paths can be as high as 18 (Zalikhanov, 1975) and 32 (de Scally, 1992; 1993). The disappearance of avalanche snow can also be delayed if the deposits are situated on steep north-facing slopes below high cliffs, and thus protected from solar radiation (de Scally, 1995; 1996). Many of the changes in actual ablation processes which occur following avalanching are in fact the result of the avalanched snow lingering into the warm summer months (de Scally and Gardner, 1990).

At the basin scale the importance of the meltwater contribution from avalanche deposits, regardless of whether accelerated or delayed compared to normal snowmelt, would be expected to decrease with increasing basin size or stream order. However, Table 3 shows that in at least one large basin in the Punjab Himalaya the estimated contribution is exceptionally large as a result of large-scale avalanching (de Scally and Gardner, 1989; 1994; de Scally, 1992). Estimates from a small basin in the Cascade Mountains, B.C. (Table 3) may be more representative overall of North American mountains. The proportion of streamflow contributed by avalanche deposits may be expected to increase following winters with widespread avalanching. However, if such winters are accompanied by greater snow accumulation, any increase in a summer (i.e. delayed) contribution of avalanche snowmelt may be obscured by the larger and possibly later peak in normal snowmelt (Fig. 3a). On the other hand, the maximum contribution from delayed avalanche snow melting would be achieved if despite widespread avalanching, the snowpack at the end of the winter is relatively shallow and the period following the diminished snowmelt peak experiences little rain (Fig. 3b). The greatest challenge in understanding this role of avalanching is the difficulty of estimating the temporal distribution of the avalanche snowmelt contribution to streamflow from the whole basin (de Scally, 1992). Such estimates would in part require an assessment of the extent to which delayed melting on some avalanche paths is compensated for by accelerated melting on others. Last, avalanche activity may also produce a small increase in total snowmelt runoff, since sublimation/evaporation and infiltration/percolation losses would be sharply reduced (Iveronova, 1966; Sosedov and Seversky, 1966; Martinec, 1985; de Scally and Gardner, 1990).

Disruption of the winter runoff regime

Disruption of the winter runoff regime by avalanches can occur either as a result of damming of streams and rivers by avalanche snow, or from the impact of avalanches striking a water body.

Table 3

Proportion of basin streamflow derived from avalanche snow.

SOURCE	MOUNTAIN RANGE	BASIN SIZE (km^2)	NO. YEARS DATA	PERCENTAGE OF RUNOFF DERIVED FROM MELTING OF AVALANCHE-TRANSPORTED SNOW (MEAN VALUE IN PARENTHESES)	
				Annual runoff	Snowmelt runoff
Schultz (1956)	Tien Shan (West)	?	?	≤50	?
Sosedov and Seversky (1966)	Tien Shan (North)	1.2 [1]	2 [2]	3-21 (11.2)	10-31 (22.1)
de Scally (1992;1993)	Punjab Himalaya	2500	8	1-2 (1.4)[3]	2-3 (2.2)[3]
		2500	8	3-6 (4.8)[4]	5-10 (7.6)[4]
de Scally (1995;1996)	Cascades, B.C.	5.0	3 [5]	?	10-24 (15.7)[6]

[1] Average of three small basins.

[2] One winter of below-average, one of above-average avalanche activity.

[3] Following a winter of "normal" avalanche activity.

[4] Following a winter of "severe" avalanche activity.

[5] All winters characterised by low snow accumulation and corresponding avalanche activity.

[6] Over a 11 - 13 wk summer period following the disappearance of all undisturbed snow cover.

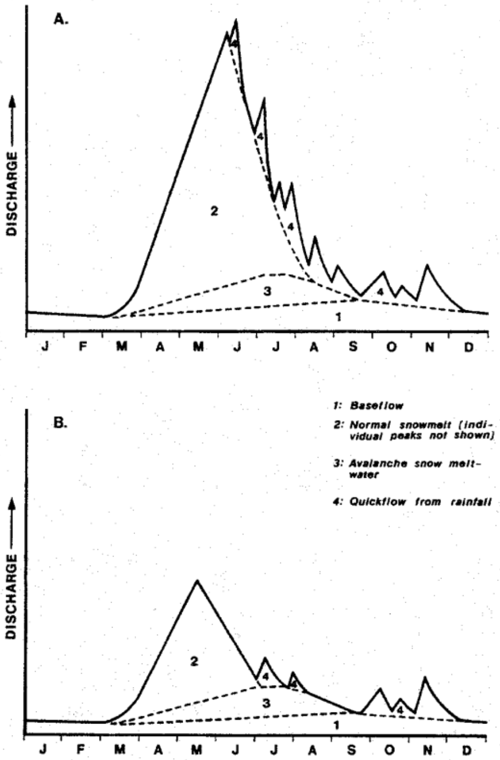

Figure 3 Hypothesised contributions of delayed avalanche snow melting to summer streamflow from high-elevation basins. The timing and total volume of runoff generated by melting avalanche snow is identical in both cases. A: relatively small proportion of total summer streamflow contributed by avalanche snow. B: relatively large proportion of total summer streamflow contributed by avalanche snow.

The ability of avalanche snow deposits to dam streams and rivers has been noted in many parts of the world (Allix, 1924; King, 1934; Peattie, 1936; Rapp, 1960; Tricart et al., 1961; Iveronova, 1966; Ayzenberg et al., 1971; Mokievsky-Zubok, 1975; Martinec, 1985; 1989; Ackroyd, 1987; Campbell, 1988; Butler, 1989; de Scally and Gardner, 1994). However, few detailed studies of this phenomenon have been made; the only substantive North American research on avalanche snow dams has been carried out by Butler (1989).

Dams usually result from wet-snow avalanches which not only consist of high-density snow but can attain a considerable size (Butler, 1989; de Scally and Gardner, 1994). Erosion by the impounded water will generally breach a dam relatively quickly; estimates of damming duration range from as little as one hour to several days (Allix, 1924; Mokievsky-Zubok, 1975; Martinec, 1985; 1989; de Scally and Gardner, 1994). Timber contained in the snow can help to stabilise the dam and prolong its existence, and can also act as battering rams in the ensuing flood (Butler, 1989). The flooding may be only minor if the damming occurs in midwinter when streamflow is low, although even in these situations the disruption in flow is usually noticeable at downstream gauging stations (Martinec, 1985; 1989) (Fig. 4). Thaw triggered avalanching in spring has the potential to block streams which are swollen by snowmelt (Campbell, 1988). In this way outburst floods exceeding the historic peak snowmelt discharge may occur (Butler, 1989). The downstream damage in such cases can range from relatively minor in sparsely populated areas (Butler, 1989) to catastrophic in densely populated valleys (King, 1934; Peattie, 1936; Tricart et al., 1961). In the Punjab Himalaya, valley-bottom villages immediately upstream of avalanche dams also can be flooded by the impounded water (de Scally and Gardner, 1994).

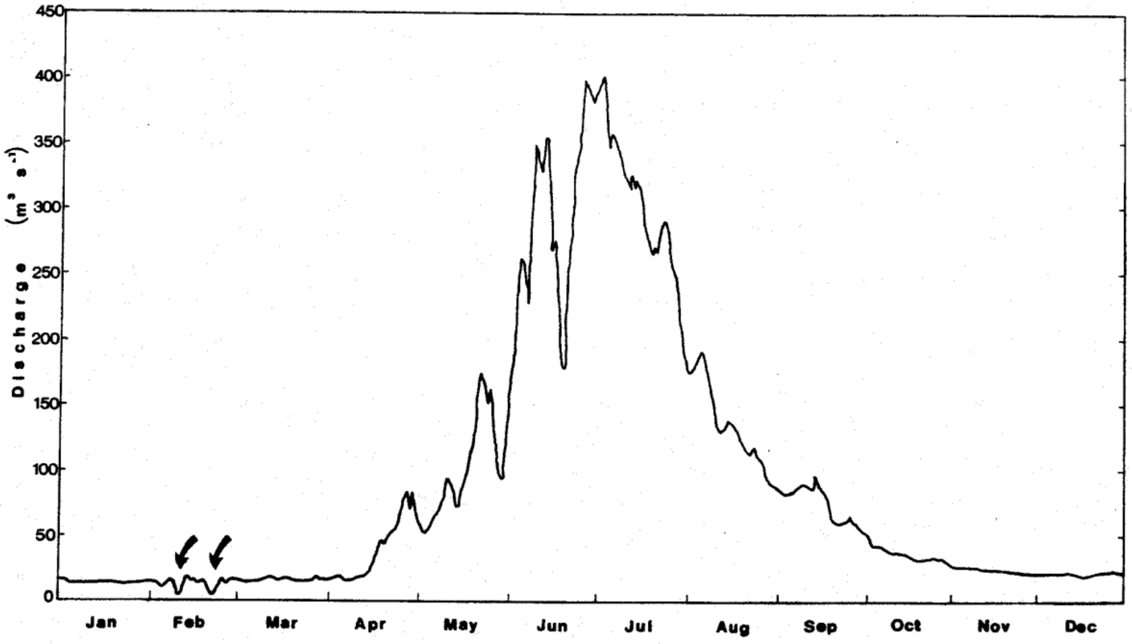

Figure 4 1967 hydrograph for Kunhar River at Khanian (1500 km^2), a snowmelt-dominated river on the south slopes of the Punjab Himalaya, Pakistan. The arrows indicate disruptions to flow by avalanche snow dams far upstream.

Avalanche dams can have other downstream effects in addition to the flood hazard. For example dams of longer duration, by temporarily lowering the water level downstream and causing river ice to lose support and break up, may produce a drop in water temperature and enhance the formation of frazil ice (Iveronova, 1966). The sudden release of water from behind the dam has been observed to have significant geomorphic effects downstream (Mokievsky-Zubok, 1975; Ackroyd, 1987).

The effect of a large avalanche falling into a water body such as a lake or fjord depends largely on whether that body is ice-covered or not. With no ice cover dangerous waves can be generated, since approximately 50% of the kinetic energy of the avalanche can be converted into wave energy (McClung and Schaerer, 1993). The large impact forces generated by this kinetic energy are clearly manifested in the avalanche landform known as an 'avalanche tarn' or 'impact pool' (Corner, 1980; Fitzharris and Owens, 1984; de Scally and Gardner, 1994; Matthews and McCarroll, 1994; Smith et al., 1994). Even larger waves can be generated by ice avalanches descending from glaciers above the water body. These are capable of breaching morainal dams or overtopping man-made dams to cause catastrophic downstream flooding (Lliboutry et al., 1977; Tufnell, 1984; Vuichard and Zimmermann, 1986; 1987; Hambrey and Alean, 1992).

Large avalanches can also have significant hydrologic effects on an ice-covered water body, especially if it is a lake with a relatively small volume. An ice cover 4 m thick is reported to have been shattered and pushed onto the distal shore by avalanche-generated waves (Peev, 1966). Even if the ice cover remains intact, the dynamic forces can depress it sufficiently to generate a large pulse of water at the lake's outlet. For example in the Sierra Nevada, California, one large avalanche depressed a 1.7 m thick ice cover on a small lake sufficiently to generate a floodwave which drained 70% of the unfrozen water in that lake (Williams and Clow, 1990). Such flood events can have major negative impacts on the short-term success of fish spawning in small lakes, yet in the long term play a role in maintaining the gravel spawning beds (Williams and Clow, 1990). A large static load can also be exerted on the ice cover of a water body by an avalanche deposit, particularly when the deposit attains a mass of 10^5-10^6 t (de Scally and Gardner, 1989). Depression of the ice cover below the hydrostatic level would generate further outflow as well as promote the formation of 'white ice' (Williams and Clow, 1990). In addition, substantial amounts of organic material (e.g. trees) and rock debris entrained by the avalanche will eventually be deposited in the water body. Peev (1966) reports a large avalanche deposit in the Pirin Mountains, Bulgaria which during melting deposited enough sediment in a lake to decrease the water depth from 14 to 6 m.

Disruption of slope sediments

At many sites avalanches occur in a symbiotic relationship with other hydrologic and geomorphic processes such as rockfall, debris flow, mudflow and fluvial activity. The complex interactions between them have been recognised both from the theoretical perspective of landform evolution (e.g. Rapp, 1960; Luckman, 1978; 1992) and the practical perspective of identification and evaluation of mountain hazards (e.g. Aulitzky, 1974; Desloges and Gardner, 1984; Gardner and de Scally, 1993; de Scally and Gardner, 1994).

Some observations have been made of hydrologic conditions under which the efficiency of sediment erosion from unvegetated slopes by full-depth avalanches is maximised (Rapp, 1960; Gardner, 1983). However, the hydrologic linkages through which the disturbance of slope sediments by avalanches might in turn affect other processes remain very poorly understood. The impact of wet snow avalanches can be sufficient to directly trigger debris flows in steep channels if sufficient runoff and unconsolidated sediment are present (Church and Miles, 1987). However, the most important hydrologic effect of midwinter avalanching in this respect might be to promote freezing in wet soil or sediments following the thinning or removal of the snow cover (Sosedov and Seversky, 1966). Subsequently during rapid snowmelt or heavy rain in spring, infiltration would be reduced and Hortonian overland flow increased, thereby increasing the likelihood or size of debris flows, mudflows or streamflow (Sosedov and Seversky, 1966; Iveronova, 1966). Personal observations of heavily eroded, unvegetated avalanche slopes in the Punjab Himalaya support this hypothesised link between avalanches and other mass movements. However, erosion by full-depth avalanches directly as well as overgrazing by livestock appear to be contributing factors there. Ackroyd (1987) documents in detail some of the changes in erosional processes and geomorphic stability which occur in a stream channel following the impact of an avalanche, but comparable research on slopes higher on the avalanche path has not been carried out.

CONCLUSIONS

The purpose of this paper has been to review the literature on hydrologic roles of snow avalanches, and to demonstrate that while we have a basic understanding of these roles, little information exists by which to judge their extent, importance and detailed mechanisms. Unlike the topics of avalanche hazard and avalanche geomorphology, the hydrologic roles have been largely neglected by researchers since the 1970s. Since these roles can potentially benefit humans as well as create or exacerbate hazards, their further investigation may be justified.

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REFERENCES

Ackroyd, P., 1987. "Erosion by Snow Avalanche and Implications for Geomorphic Stability, Torlesse Range, New Zealand", Arctic and Alpine Research, 19: 65-70.

Alford, D., 1974. "Snow", in Arctic and Alpine Environments, J.D. Ives and R.G. Barry, eds., Methuen, London, 85-110.

Alford, D., 1985. "Mountain Hydrologic Systems", Mountain Research and Development, 5: 349-363.

Allix, A., 1924. "Avalanches", Geographical Review, xiv: 519-560.

Armstrong, B.R. and Williams, K., 1986. The Avalanche Book, Fulcrum, Golden.

Aulitzky, H., 1974. Endangered Alpine Regions and Disaster Prevention Measures, Nature and Environment Series 6, Council of Europe, Strasbourg.

Ayzenberg, M.M., Vol'ftsum, M.L. et al., 1971. "Effect of Snow Avalanches on Flash Flood Formation in the Carpathians" (abstract), Soviet Hydrology Selected Papers, 5: 502.

Bazhev, A.B., Kotlyakov, V.M., Rototayeva, O.V. and Varnakova, G.M., 1975. "The Problems of Present-Day Glaciation of the Pamir-Alai", in International Association of Hydrological Sciences, Publication 104, 11-21.

Butler, D.R., 1989. "Snow Avalanche-Dams and Resultant Hazards in Glacier National Park, Montana", Northwest Science, 63: 109-115.

Campbell, P.A., 1988. "Debris Torrents in the Robson Valley, East Central B.C., Canada" (abstract), Zeitschrift für Geomorphologie N.F., 67: 77.

Church, M. and Miles, M.J., 1987. "Meteorological Antecedents to Debris Flow in Southwestern British Columbia; Some Case Studies", in Reviews in Engineering Geology, Vol. VII, Geological Society of America, 63-79.

Corner, G.D., 1980. "Avalanche Impact Landforms in Troms, North Norway", Geografiska Annaler, 62A: 1-10.

de Scally, F.A., 1989. "The Role of Avalanche Snow Transport in Seasonal Snowmelt, Himalaya Mountains, Pakistan", Unpub. Ph.D. Thesis, University of Waterloo.

de Scally, F.A., 1992. "Influence of Avalanche Snow Transport on Snowmelt Runoff", Journal of Hydrology, 137: 73-97.

de Scally, F.A., 1993. "Can Avalanche Activity Alter the Pattern of Snowmelt Runoff from High-Mountain Basins?", in Proceedings, 61st Western Snow Conference, Quebec City, Quebec, 213-221.

de Scally, F.A., 1995. "Delaying Seasonal Snowmelt With Avalanche Activity: Some Results from the Cascade Mountains, Southern British Columbia", in Proceedings, 63rd Western Snow Conference, Sparks, Nevada, 38-48.

de Scally, F.A., 1996. "Avalanche Snow Melting and Summer Streamflow Differences Between High-Elevation Basins, Cascade Mountains, British Columbia, Canada", Arctic and Alpine Research, 28: 25-34.

de Scally, F.A. and Gardner, J.S., 1989. "Evaluation of Avalanche-Mass Determination Approaches: An Example from the Himalaya, Pakistan", Journal of Glaciology, 35: 248-252.

de Scally, F.A. and Gardner, J.S., 1990. "Ablation of Avalanched and Undisturbed Snow, Himalaya Mountains, Pakistan", Water Resources Research, 26: 2757-2767.

de Scally, F.A. and Gardner, J.S., 1994. "Characteristics and Mitigation of the Snow Avalanche Hazard in Kaghan Valley, Pakistan Himalaya", Natural Hazards, 9: 197-213.

Desloges, J.R. and Gardner, J.S., 1984. "Process and Discharge Estimation in Ephemeral Channels, Canadian Rocky Mountains", Canadian Journal of Earth Sciences, 21: 1050-1060.

Embleton, C. and King, C.A.M., 1975. Glacial Geomorphology, Arnold, London.

Fitzharris, B.B. and Owens, I.F., 1984. "Avalanche Tarns", Journal of Glaciology, 30: 308-312.

Gardner, J.S., 1983. "Observations on Erosion by Wet Snow Avalanches, Mount Rae Area, Alberta, Canada", Arctic and Alpine Research, 15: 271-274.

Gardner, J.S. and de Scally, F.A., 1993. "Geomorphology Applied to Hazard Site Identification in Mountain Areas: Examples from Kaghan Valley, Pakistan", in Applied Geomorphology in the Tropics, P.R. Sharma, ed., Rishi Publishers, Varanasi, 60-72.

Getker, M.I., 1988. "Method of Calculating Maximum Snow Reserves in Mountain Glacier Regions to Compile Maps for the World Atlas of Snow and Ice Resources", in Data of Glaciological Studies (Transl.), G.A. Avsyuk, ed., Oxonian Press, New Delhi, 213-228.

Hambrey, M. and Alean, J., 1992. Glaciers, Cambridge University Press, Cambridge.

Heim, A., 1885. Handbuch der Gletscherkunde, Verlag von J. Engelnhern, Stuttgart.

Iveronova, M.I., 1966. "The Hydrological Role of Avalanches", in International Association of Scientific Hydrology, Publication 69, 73-77.

Kick, W., 1962. "Variations of Some Central Asiatic Glaciers", in International Association of Scientific Hydrology, Publication 58, 223-229.

King, W.D.V.O., 1934. "The Mendoza River Flood of 10-11 January 1934 - Argentina", Geographical Journal, 84: 321-326.

Klebelsberg, R., 1925. "Der Turkestanische Gletschertypus", Zeitschrift für Gletscherkunde, xiv.

Klemeš, V., 1990. "The Modelling of Mountain Hydrology: The Ultimate Challenge", in International Association of Hydrological Sciences, Publication 190, 29-43.

Kotlyakov, V.M., 1973. "Snow Accumulation on Mountain Glaciers", in International Association of Hydrological Sciences, Publication 107(1), 394-400.

Krenke, A.N., 1975. "Climatic Conditions of Present-Day Glaciation in Soviet Central Asia", in International Association of Hydrological Sciences, Publication 104, 30-41.

LaChapelle, E.R., 1977. "Snow Avalanches: A Review of Current Research and Applications", Journal of Glaciology, 19: 313-323.

Lliboutry, L., Morales, A.B., Pautre, A. and Schneider, B., 1977. "Glaciological Problems Set by the Control of Dangerous Lakes in Cordillera Blanca, Peru", Journal of Glaciology, 18: 239-290.

Lossev, K.S., 1960. "Avalanches as the Hydrological Factor", Meteorology and Hydrology, 5.

Lossev, K.S., 1967. "The Role of Avalanches in Mass Budget of Glaciers", in Physics of Snow and Ice, Proceedings of the International Conference on Low Temperature Science, Sapporo, August 1966, v. 1, pt. 2. Institute of Low Temperature Science, Hokkaido University, 385-388.

Luckman, B.H., 1978. "Geomorphic Work of Snow Avalanches in the Canadian Rocky Mountains", Arctic and Alpine Research, 10: 261-276.

Luckman, B.H., 1992. "Debris Flows and Snow Avalanche Landforms in the Lairig Ghru, Cairngorm Mountains, Scotland", Geografiska Annaler, 74A: 109-121.

Martinec, J., 1976. "Snow and Ice", in Facets of Hydrology, J.C. Rodda, ed., Wiley, Bristol, 85-118.

Martinec, J., 1985. "Time in Hydrology", in Facets of Hydrology II, J.C. Rodda, ed., Wiley, Chichester, 249-290.

Martinec, J., 1989. "Hydrological Consequences of Snow Avalanches", in Hydrology of Disasters, Ö. Starosölszky and O.M. Melder, eds., James and James, London, 284-293.

Martinec, J. and de Quervain, M.R., 1975. "The Effect of Snow Displacement by Avalanches on Snowmelt and Runoff", in International Association of Hydrological Sciences, Publication 104, 364-377.

Matthews, J.A. and McCarroll, D., 1994. "Snow-Avalanche Impact Landforms in Breheimen, Southern Norway: Origin, Age, and Paleoclimatic Implications", Arctic and Alpine Research, 26: 103-115.

McClung, D. and Schaerer, P., 1993. The Avalanche Handbook, The Mountaineers, Seattle.

Mokievsky-Zubok, O., 1975. "Sudden Flood and Sorted Debris Over the Winter Snowpack Within Sentinel Glacier Basin, British Columbia", Canadian Journal of Earth Sciences, 12: 873-879.

Paterson, W.S.B., 1994. The Physics of Glaciers (3rd ed.), Pergamon/Elsevier, Kidlington (UK).

Peattie, R., 1936. Mountain Geography, Harvard University Press, Cambridge.

Peev, C.D., 1966. "Geomorphic Activity of Snow Avalanches", in International Association of Scientific Hydrology, Publication 69, 357-368.

Perla, R.I. and Martinelli, M., Jr., 1976. "Avalanche Handbook", Agriculture Handbook 489, U.S. Department of Agriculture, Forest Service, Fort Collins.

Rapp, A., 1960. "Recent Development of Mountain Slopes in Kärkevagge and Surroundings, Northern Scandinavia", Geografiska Annaler, 42: 71-200.

Schaerer, P.A., 1988. "The Yield of Avalanche Snow at Rogers Pass, British Columbia, Canada", Journal of Glaciology, 34: 188-193.

Schultz, V.L., 1956. Snow-Field Thawing in the Mountains of Central Asia, Publishing House of Academy of Sciences of the Uzbek S.S.R.

Slaymaker, H.O., 1974. "Alpine Hydrology", in Arctic and Alpine Environments, J.D. Ives and R.G. Barry, eds., Methuen, London, 133-158.

Smith, D.J., McCarthy, D.P. and Luckman, B.H., 1994. "Snow-Avalanche Impact Pools in the Canadian Rocky Mountains", Arctic and Alpine Research, 26: 116-127.

Sosedov, I.S. and Seversky, I.V., 1966. "On Hydrological Role of Snow Avalanches in the Northern Slope of the Zailiysky Alatau", in International Association of Scientific Hydrology, Publication 69, 78-85.

Tareeva, A.M., 1988. "Amount of Solid Precipitation on Caucasus Glaciers", in Data of Glaciological Studies (Transl.), G.A. Avsyuk, ed., Oxonian Press, New Delhi, 204-212.

Tarr, R.S. and Martin, L., 1914. Alaskan Glacier Studies, Washington.

Tricart, J., Rimbert, S., Marbach, J., Obermuller, R., Hirsch, A.R. and LeBourdiec, F., 1961. "Mécanismes Normaux et Phénomènes Catastrophiques dans l'Evolution des Versants du Bassin du Guil (Htes.-Alpes, France)", Zeitschrift für Geomorphologie, 5: 277-301.

Tufnell, L., 1984. Glacier Hazards, Longman, London.

Tushinsky, G.K., 1975. "The Part Avalanches Play in the Formation and Dynamics of Mountain Glaciers and Snow Patches in the Territory of the USSR", in International Association of Hydrological Sciences, Publication 104, 381-389.

Vivian, R., 1975. Les Glaciers des Alpes Occidentales, Allier, Grenoble.

Vuichard, D. and Zimmermann, M., 1986. "The Langmoche Flash-flood, Khumbu Himal, Nepal", Mountain Research and Development, 6: 90-94.

Vuichard, D. and Zimmermann, M., 1987. "The Catastrophic Drainage of a Moraine-Dammed Lake, Khumbu Himal, Nepal: Cause and Consequences", Mountain Research and Development, 7: 91-110.

Wiche, K., 1960. "Klimamorphologische Untersuchungen im Westlichen Karakorum", Verhandl. Deutschen Geographentag, 32.

Williams, M.W. and Clow, D.W., 1990. "Hydrologic and Biologic Consequences of an Avalanche Striking an Ice-Covered Lake", in Proceedings, 58th Western Snow Conference, Sacramento, California, 51-60.

Young, G.J. and Hewitt, K., 1990. "Hydrology Research in the Upper Indus Basin, Karakoram Himalaya, Pakistan", in International Association of Hydrological Sciences, Publication 190, 139-152.

Zalikhanov, M.Ch., 1975. "Hydrological Role of Avalanches in the Caucasus", in International Association of Hydrological Sciences, Publication 104, 390-394.