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Runoff and sediment transport from glacierized basins at the Himalayan scale

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Abstract Discharge and sediment content of meltwater from Batura glacier, upper Indus basin, Karakoram mountains, were obtained hourly, providing a detailed pattern of variations during an ablation season, against which measurements over shorter periods of less-frequent sampling at other glaciers in Himalayan basins of the Indus and Ganga rivers are compared. Total annual sediment flux from Batura glacier was 3.950 Mt, or 6.086 kt km^{-2} $year^{-1}$, considerably higher than in comparable periods for Chhota-Shigri and Dokriani glaciers. Glaciers contribute an estimated 60% of sediment loads of rivers in the Karakoram. Runoff from the glacierized upper Indus basin accounts for 35% of discharge at the mouth from 17% of the area. Monsoonal precipitation leads to considerable variation in seasonal runoff from glacierized areas along the Himalayan arc. In the central Himalaya, cloud cover reduces energy for melting ice, which component of runoff is not fully compensated by rainfall.

INTRODUCTION

Considerable quantities of water and sediment are discharged into the Bay of Bengal and the Arabian Sea, respectively, by the Ganga-Brahmaputra and Indus river systems. Meybeck (1976) estimates that 1.79 Gt $year^{-1}$ of suspended sediment (about 9% of the total annual load carried from the continents to the oceans worldwide) is transported in the three rivers by combined annual runoff of 1.19×10^3 km^3, 2.5% of the 47×10^3 km^3 from the continents estimated by Shiklomanov (1993). Large proportions of the runoff of these three rivers of the subcontinent, of which more than 75% occurs during May through October, originate from basins in the mountains of the Himalayan region, where levels of seasonal precipitation are relatively enhanced by comparison with adjacent lowlands. Continuing tectonic instability, high relief, steep slopes coupled with high rainfall and high specific discharge, together with runoff from glaciers in a heavily ice-covered area, suggest that much sediment also is derived from the Himalayan portions of the basins. Sediment is contributed to the headwaters of the major rivers by meltwater issuing from glaciers, by processes such as mass movement and mud flow, by debris torrents (e.g. His Majesty's Government of Nepal, 1987), and by channel erosion during catastrophic outburst floods from landslide-, moraine-, and glacier-dammed lakes. Although storage in the river bed and flood plain interacts with sediment transport, upper parts of a basin greatly influence water quality downstream.

This paper examines seasonal patterns of discharge and sediment transport from Himalayan glacierized basins with a view to identifying relations between hydrology and sediment delivery. Such relations should prove helpful in estimating (from few actual measurements of sediment content of meltwater) the contribution of glaciers to sediment transfer downstream in basins distributed from 28° to 38°N and 70° through 100°E. In this region, lithologic and climatic conditions, particularly amount and seasonality of precipitation, vary considerably. Information on sediment flux is of interest with respect to rates of denudation and hence reservoir infill, and as a backdrop to possible anthropologically-accelerated sediment yield from lower montane areas implicated in sedimentation in lowland rivers (e.g. Ives & Messerli, 1989).

MEASUREMENTS, DATA SOURCES, AND BASIN CHARACTERISTICS

Field measurements

Samples of meltwater were collected at 3-h intervals from 9 to 22 April and then hourly until 7 October 1990, at a site about 500 m downstream of the terminus of Batura glacier on the sole melt stream, Batura River, and at a similar distance upstream of the confluence with the Hunza River, a tributary of the Gilgit, the latter a confluent of the upper Indus River in the Karakoram (Fig. 1). Between 150 and 250 ml of meltwater were

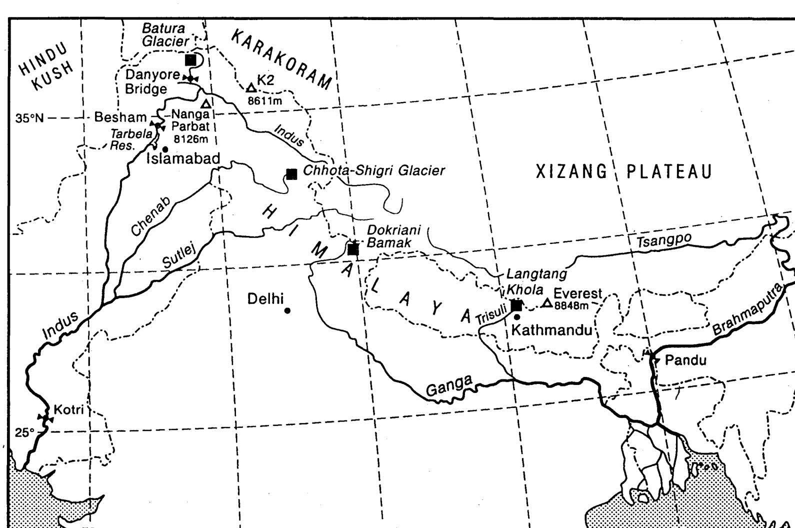

Fig. 1 Map of the Himalayan region between 28° and 38°N showing gauging stations on principal rivers and locations of the glacierized basins in which measurements have been undertaken.

collected using an Epic 1011 automatic liquid sampler; the sediment content was determined gravimetrically following filtration. A tipping-bucket raingauge was installed 10 km down the Hunza valley at the terminus of Passu glacier.

Similar techniques were used to collect three daily samples from 18 July through 11 August 1987, 1.5 km downstream of Chhota-Shigri glacier, on a tributary of the Chandra River, itself tributary to the Chenab, a confluent of the Indus River (Hasnain *et al.*, 1989). Samples were collected from 27 August through 21 September 1992, every 2 h in daylight from the Din Gad, 600 m downstream of Dokriani Bamak (glacier) in the upper Ganga basin of the Garhwal Himalaya (Fig. 1). Stage was continuously recorded at the stations and rating curves were obtained using current meters. By the velocity-area method, discharge was estimated for unstable cross-sections with some inaccuracy at high flows.

Data sources

Temporal patterns of sediment flux and discharge downstream of the glacierized areas were obtained from a variety of sources. WAPDA (Water & Power Development Authority, Pakistan) has measured discharge and sediment concentration using depth-integrating samplers at main-stem stations and on tributaries of the Indus River above Tarbela Dam since 1963, including Dainyor (Danyore) Bridge on the Hunza (Ferguson, 1984). Sediment samples were taken every 1-4 h through three 24-h periods from Langtang Khola, a tributary of the Trisuli and ultimately the Ganga River by Ohta *et al.* (1987). Annual data for the pre-dammed Indus River at Kotri, 1902-1925, and information, without explanation, for the Brahmaputra River at Pandu and the Ganga River in the delta are given by Holeman (1968) and Meybeck (1976) (Fig. 1).

Basin characteristics

Drainage basin areas, mean annual discharges, estimated mean annual sediment yields, and percent glacierization, where determined, are given in Table 1. Although area of permanent ice is greater in the Himalaya (33 150 km^2) than in the Karakoram (15 670 km^2), percent glacier cover is greater in the latter range.

SEASONAL PATTERNS OF DISCHARGE AND SEDIMENT FLUX FROM GLACIERS

Typical ablation-season variations of water and sediment discharge from glacierized basins are illustrated by hourly sampling at Batura glacier (Fig. 2). Discharge rose in early May, accompanied by an initial increase in sediment flux, with further small sediment peaks on each occasion that discharge rose above levels not previously reached since the October recession. In late June, rise of the transient snow line led to discharge doubling with massive sediment transport. The relation between sediment transport and discharge to the end of July was compatible with the concept of Collins (1989) for alpine glaciers that additional flow, created by ablation over an area enlarging up-glacier as ice

Table 1 Mean annual runoff and sediment transport from partially glacierized basins in the Brahmaputra, Ganga and Indus catchments.

Basin/gauging station	Area (x 10^3 km^2)	Mean annual discharge (km^3)	Mean annual discharge (m)	Period	Glacierization (%)	Mean annual sediment transport (Mt)	Mean annual sediment transport (t km^{-2} $year^{-1}$)	Source
Brahmaputra/Pandu	580	600	1.048			794.6	1 370	Meybeck (1976)
Ganga (delta)	975	366	0.375			523.6	540	Meybeck (1976)
Din Gad/Dokriani	0.023	-	-	part 1992	45.0	-	-	-
Langtang Khola/S1	0.333	0.45	1.357	1985-86	38.0	0.08	243	Fukushima et al. (1987) Ohta et al. (1987)
Indus/Kotri	950	211	0.222	 1902-25		475 436	500 460	Meybeck (1976) Holeman (1968)
Indus/Besham	162	74.2	0.457	1969-75		-	-	WAPDA data
Hunza/Danyore Bridge	13.2	12.0	0.911	Q 1969-75 S 1966-75	28.5	 63	 4 770	WAPDA data Ferguson (1984) after WAPDA
Batura/Batura Bridge	0.649	0.93 1.25	1.432 1.928	V/1974-IX/1975 IV - X/1990	60.0	 3.95	 6 086	Lanzhou Institute (1980) -
Chhota-Shigri/glacier	0.040	0.1	3.0	part 1987	25.0	-	-	Hasnain et al. (1989)

is progressively revealed by removal of snow, flushes those parts of the bed reached by flowing water for the first time since the previous summer. From the end of July sediment flux mimicked discharge, in a subdued manner, on account of sediment exhaustion, and failed to rise to earlier levels despite high flows in early August. An unusually large event subsequently evacuated 72 kt on 10 August with another in early September. These were probably subglacial events in which the basal channel pattern was suddenly dislocated (Collins, 1989); the second one, however, was associated also with 1.4 mm of rain that fell on 10 September in the usually arid valley bottom, presumably with considerably more at high elevations. Rain also caused an initially enhanced discharge and sediment pulse on 30 August that was followed by marked recession of both fluxes, the result of snowfall higher in the basin that raised albedo and reduced melt.

In the larger Hunza basin, WAPDA data (fewer than 20 samples at Danyore in April through September) reveal that, for a particular discharge level, sediment content of meltwater was highest on the first occasion in the ablation season that the level was reached. Sediment flux reached a maximum in July, falling generally thereafter, although imitating the pattern of discharge fluctuations.

In the short 1987 period at Chhota-Shigri glacier, two subglacial sediment-releasing events were observed (Fig. 3). The headwater valley bottoms of the upper Chenab are arid, and water and sediment fluxes were not influenced by precipitation. Dokriani glacier is influenced by monsoonal precipitation and rain was recorded on all but one

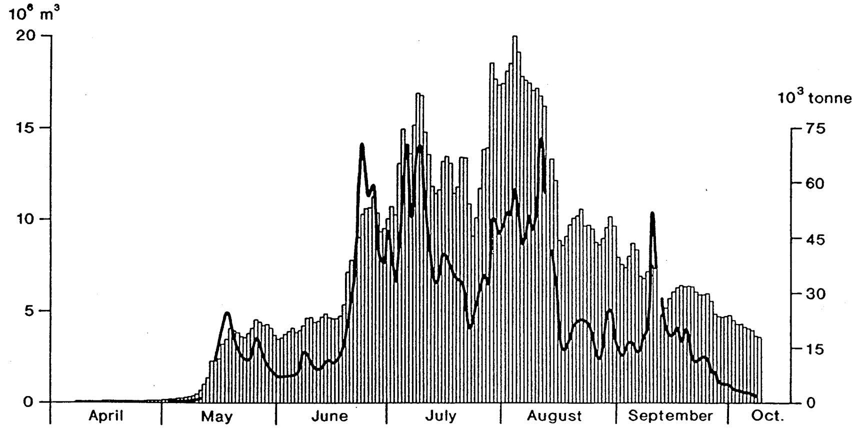

Fig. 2 Seasonal variation of daily total discharge (columns) and measured daily total suspended-sediment transport (curve) of Batura glacier from April through October 1990.

day during field observations in 1992 (Fig. 3). Suspended sediment transport, however, declined as discharge receded during September. There was no suggestion of precipitation influence so late in summer, presumably following earlier flushing of sediment. Overall, sediment flux in meltwater draining these Himalayan glaciers appears to follow a similar pattern. Limited impact of monsoonal rainfall on sediment flux from Dokriani glacier in September does not preclude such influence having occurred earlier in the year.

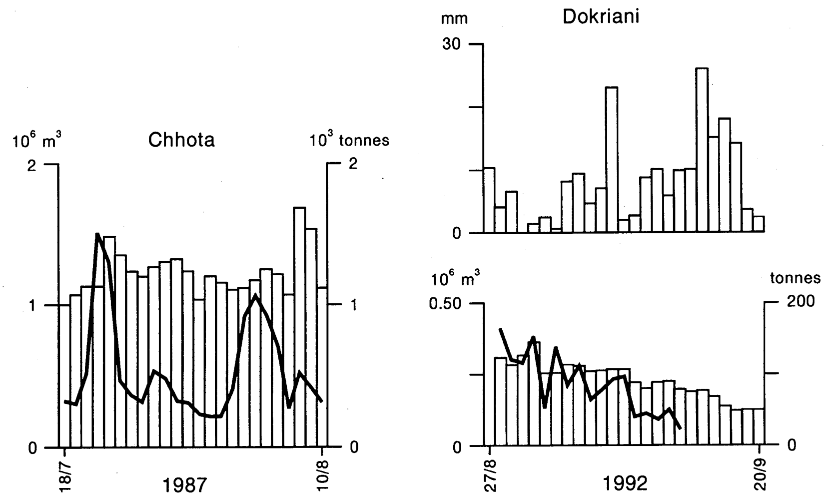

Fig. 3 Daily total discharge (columns) and daily total suspended sediment transport (curves) from Chhota-Shigri glacier in July and August 1987 (left), and from Dokriani Bamak in September 1992, with daily total monsoon precipitation (right).

ANNUAL SEDIMENT AND WATER YIELDS

Highly-glacierized basins

Estimates of total annual sediment loads are often unreliable because of infrequent sampling, random coincidence of timing of samples with seasonal variation or pulses in sediment flux providing over- or under-estimation, and uncertainties inherent in calculating load from flow-duration and sediment-concentration relations. Comparison of suspended sediment load estimates among rivers is problematic because of use of different sampling techniques and designs. Comparisons using data from different years, or one year only, suffer from annual variations in load as a result of differing hydrometeorological sequences. Considerable year-to-year variations in glacier runoff and suspended-sediment transport occur in the European Alps (−33.0% to +25.3% of a 20-year mean for discharge and −27.5% to +36.8% of a 7-year mean for sediment in hourly sampling at Gornergletscher, Switzerland (Collins, 1991)). The data for Batura glacier provide a reliable indication of total sediment flux in 1990; 3.950 Mt, or 6.086 kt km^{-2} $year^{-1}$ (Table 1), was calculated by Collins (1991). Estimates for the Hunza River at Danyore Bridge, with a mean of 4.770 kt km^{-2} $year^{-1}$, in a range of −55.5% to 60.3% in 1966 through 1975 (Ferguson, 1984), are less accurate. Assuming that sediment is derived uniformly from beneath the ice-covered area only, the specific yield from Batura glacier is 10.144 kt km^{-2} $year^{-1}$. Behaving uniformly, the glaciers of the Hunza basin would deliver 38.162 Mt at Danyore Bridge, which, if measurements are assumed typical, accounts for 60% of the mean annual load as estimated from infrequent sampling. By comparison with equivalent periods in the 1990 Batura record, specific sediment yields from Chhota-Shigri in 1987 and Dokriani in 1992 are about 20% and 10%, respectively, of those from Batura glacier, perhaps reflecting lithological differences.

Indus River basin

Runoff from the 17.1% of the Indus River basin over the Karakoram Mountains, gauged at Besham, is 35.2% of total flow at the mouth. This difference emphasizes the importance of snow- and ice-melt runoff, as summer monsoon precipitation infrequently penetrates behind the front ranges of the Himalaya in this region. The left-bank tributaries, Jhelum, Chenab, Ravi and Sutlej, provide most of the remainder of the discharge of the Indus, with considerable snowmelt and monsoon rainfall contributions from the southern flanks of the Himalaya. Disproportionate contributions from small mountain sub-basins to discharge of larger basins in the Indus catchment are indicated in Table 2.

Were the Indus River not dammed, and assuming steady sediment exchange with in-channel storage, the Hunza would deliver 13.8% of the sediment at the mouth (Table 2); hence, glaciers in that basin (1.4% of the area of the Indus) might be expected to contribute about 8% of the Indus River load. From the upper Indus basin above Besham, with a glacierized area of 8%, glaciers in the Karakoram contribute up to 30% (131 Mt) of the total load at the mouth.

Table 2 Percentages of discharge and sediment yield provided by sub-basins nested within the Indus catchment area.

Basin	Sub-basin	Discharge %	Sediment yield %	Area %
Hunza	Batura	9.0	6.2	4.9
Indus/Besham	Batura	1.5	-	0.4
	Hunza	16.2	-	8.1
Indus/Kotri	Batura	0.5	0.87	0.07
	Hunza	5.7	13.8	1.4
	Indus/Besham	35.2	-	17.1

Ganga and Brahmaputra river basins

Mean annual specific discharge through the delta of the Ganga-Brahmaputra rivers is higher than that at the mouth of the Indus, reflecting monsoon precipitation over the plains and southern flanks of the Himalaya. Estimates of annual sediment flux in the Ganga are in the same range as for the Indus, but those for the Brahmaputra are higher (Table 1). Sediment transport from Langtang Khola appears limited (Ohta *et al.*, 1987). These data, however, include only one 24-h period fairly late in the ablation season (11 to 12 August 1985), when subglacial events are small and infrequent; hence, the true annual sediment flux may be underestimated. Runoff is also low for an area of the Nepal Himalaya influenced by the monsoon. Seventy-eight percent of the 1.225-m annual precipitation is in June through October, but Langtang is orographically-shielded behind the main ridge of the Himalaya. It would be ambitious, therefore, with only these limited measurements from Dokriani Bamak and Langtang, to estimate the sediment-transport contribution of glaciers in the monsoon-dominated central part of the Himalaya.

REGIONAL CLIMATIC INFLUENCES ON RUNOFF

Although subglacial hydrologic events deliver pulses that punctuate the seasonal pattern of sediment flux from glaciers, climatic conditions have substantial influence on sediment evacuation. Subglacial events initially accompany rises in flow to levels above those previously experienced in the ablation season until sediment storage is exhausted. Events result occasionally from rainfall that may entrain sediment from ice-free slopes in partially-glacierized basins.

Climatic conditions that influence energy for melting and rainfall and have an impact on the temporal pattern and quantity of runoff, affect patterns, timing and amounts of sediment delivery from basins distributed along the arc of the Himalayan ranges. Length of monsoon season and quantity of precipitation generally decrease from southeast to northwest. High-intensity summer rainstorms occur, although snow falls at higher elevations. Snow also occurs in winter, in smaller quantities, from disturbances in the westerlies. Thick winter snow, summer cloud cover and summer snowfall reduce energy for melting, although the effect on runoff may be offset by rain.

Salient features of regional climatic influences on runoff from glaciers in the Himalaya are shown by contrasting regimes at Passu/Batura (38°N, 75°E) and Langtang Khola (28°N, 86°E) (Fig. 4). Incoming radiation, with a stronger seasonality at 38° N, is intercepted by cloud cover to give periodic depressions in the curve of irradiance of the ground at Passu, but leads to sustained reduction from late June to early August during the monsoon in Nepal. At Batura, these reductions result in periods with lower runoff than would be expected from adjacent values. In Langtang, summer cloud cover reduces energy for melting and leads to precipitation. Flows are generally lower in July and August than in June, suggesting that monsoon runoff and melt of summer snow in the lower basin far from compensate runoff lost when new snow prevents melting of ice throughout the elevation range. Summer runoff is more evenly distributed, after the initial rise of the transient snow line, reflecting limits to areal extent over which ice ablation can occur due to summer snows. The difference between regimes of runoff from the drier west and monsoonal central Himalayan glacierized basins probably leads to contrasting patterns of sediment flux. Climatic variations along the Himalayan arc also affect mass balance of glaciers and the distribution of permanent snow and ice, which in turn affect river regime at local and larger scales.

CONCLUSIONS

Regional climatic trends, from the Bay of Bengal northwest and in a trans-Himalayan direction due to elevation and orographic effects, influence seasonal distribution and annual amounts of runoff in the three large rivers and determine the contributions of

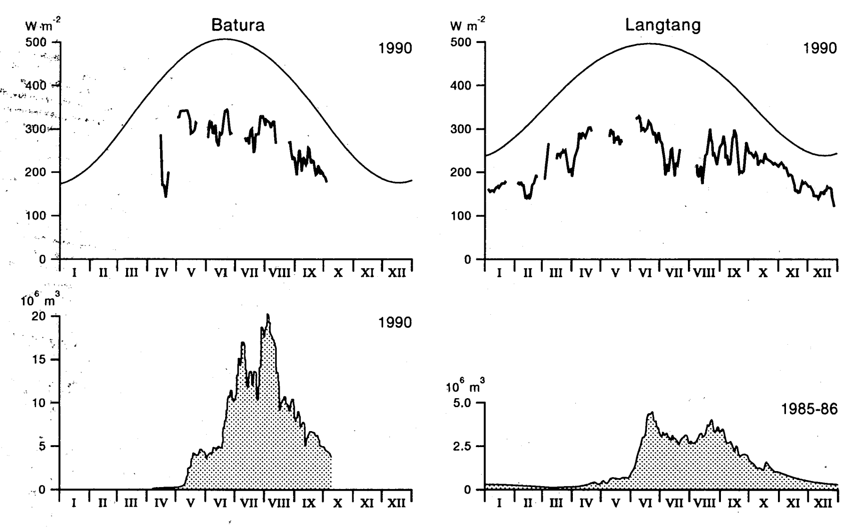

Fig. 4 Calculated radiation at the top of the atmosphere (thin) and 7-day moving average measured irradiation (thick) at Passu, Hunza basin, Karakoram, at 38°N (left upper) and at Langtang in the Nepal Himalaya at 28°N (right upper) in 1990. Daily total discharge from Batura glacier in 1990 (left lower) and in Langtang Khola, July to December 1986, composite with January through June 1985 (after Fukushima *et al.*, 1987).

glaciers to flow. Disproportionately large contributions are from Himalayan basins to all three rivers, markedly so from the upper Indus basin with a short monsoon season and low precipitation southwest of the mountains. Prevailing conditions provide high energy availability for melting ice, but at the larger scale, limited rainfall to compensate loss of icemelt in poor weather. Across the central Himalaya, icemelt is subdued during the longer monsoon but substituted to an extent by rain contributing to runoff in areas close to glaciers and downstream.

Frequent collection of meltwater samples through the ablation season is necessary to characterize accurately sediment transport from glacierized Himalayan basins. There are few such measurements available for subcontinental rivers. The pattern of measured sediment flux from Batura glacier is a useful model against which infrequent and short-term observations elsewhere can be assessed. Very high suspended-sediment yields are indicated for basins in the Karakoram, but true yields from glaciers are probably large elsewhere in the Himalaya, and glacierized mountain basins provide disproportionate specific yields. Measurements of sediment transport throughout the ablation season monsoon are now required to assess rates of denudation in glacierized basins strongly influenced by monsoon precipitation.

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