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Sediment transport from glacierized basins in the Karakoram mountains

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Abstract Detailed measurements of temporal variations of suspended sediment flux in meltwaters draining from Batura glacier, Hunza basin, Karakoram mountains throughout an ablation season indicate an annual sediment yield of 6086 t km^{-2} year^{-1}, or 10 144 t km^{-2} year^{-1} from the glacier sub-sole, assuming all the sediment is derived from glacial erosion. The seasonal pattern of sediment transport from Batura glacier results from the interaction of the sequence of hydrometeorologically-determined discharge events with the store of products of glacial abrasion beneath the ice. Glacier contributions to sediment flux downstream in the Indus basin are assessed in a framework of nested sub-basins. Sixty percent of the annual sediment yield of the Hunza (4770 t km^{-2} year^{-1}) and more than 40% of that of the Indus leaving the Karakoram (1228 t km^{-2} year^{-1}) are glacier-derived, in basins in which precipitation increases markedly with elevation above arid valley bottoms. Much sediment is deposited on the plain, reducing sediment delivery to the Arabian Sea to about 230 t km^{-2} year^{-1}, which masks high sediment fluxes in the small sub-basins within the Himalaya-Karakoram tectonic zone.

INTRODUCTION

According to Milliman & Syvitski (1992), a third of the estimated contemporary global flux of about 20 Gt year^{-1} of fluvial suspended sediment from the continents to the oceans is transported by the rivers of southern Asia. Of this total annual global flux, about 9% (1.73 Gt) is carried by five large rivers which originate in the Himalaya, the Brahmaputra, Ganga, Indus, Irrawaddy and Mekong. In general, the sediment fluxes of these rivers are substantially higher than those of rivers draining other mountainous regions of the world. If dams and barrages had not been constructed, the three principal rivers of the Indian sub-continent would annually deliver a combined 1.31 Gt (7% of the total global flux) to the coast (Milliman & Meade, 1983; Milliman & Syvitski, 1992). An earlier estimate by Meybeck (1976) suggested that the Brahmaputra, Ganga and Indus transported an aggregated pre-dam flux of 1.79 Gt year^{-1}. Average annual natural sediment yield from the three basins is thought to be around 600 t km^{-2} year^{-1}. Estimates of the actual masses transported are not well-constrained because the database of measurements of suspended sediment concentration on which such figures are founded is limited. Nonetheless, the sediment fluxes and yields from these large basins, on the lower flood plains of which much sediment is deposited before reaching the measurement sites at basin outlets (e.g. Milliman & Meade, 1983), point to exceptionally high sediment yields from smaller sub-basins upstream in the Himalayan ranges.

Large proportions of the runoff in the three great sub-continental rivers arise from mountain basins in the Himalayan region, over which levels of seasonal precipitation are increased orographically. Whilst denudation rates will in general be great in the montane basins along this belt, which has continuing tectonic activity, high relief, steep slopes, high runoff and, where rainfall occurs, intense precipitation, large differences in runoff and sediment yield are likely between basins in contrasting climatic environments on various lithologies throughout the Himalayan ranges. Processes of glacial erosion contribute much sediment to Himalayan rivers through meltwaters that drain from glaciers in the basins of headwater tributaries. In the principal sub-continental rivers, both quantity and quality characteristics change downstream with aggregation of flows arising from the smaller sub-basins in the various mountain climatic environments. Anthropocentrically-accelerated rates of sediment yield, for example resulting from deforestation in the Terai and Middle Hills of Nepal, may be enhancing contemporary sediment flux and causing aggradation in rivers downstream of some areas of the Himalaya, which are also experiencing enhanced flooding (e.g. Ives & Messerli, 1989).

Information concerning rates of production by sub-glacial erosion of finely-divided sediment, the freshly-abraded surfaces of which favour chemical reaction with meltwaters, sediment transfers in meltwaters draining from modern glaciers, and relative sediment yields from glacierized and ice-free basins in the Himalaya is needed if possible linkages between tectonics, climate and landscape development during the Cenozoic are to be evaluated. Uplift of the huge Himalaya-Tibetan plateau region may have cooled global climate by affecting atmospheric circulation (Ruddiman *et al.*, 1989) and, by greatly increasing monsoon precipitation (Schmitz, 1987), raised rates of physical and chemical weathering of susceptible rocks in the active tectonic area (Raymo *et al.*, 1988). The latter increase could have lowered the atmospheric concentration of CO_2 through increased consumption of the gas in mineral weathering, and hence have led to the onset of glaciation in the Northern Hemisphere. An alternative view is that as global climate cooled in the late Cenozoic relatively rapid glacial erosion unloaded buoyant crust, increasing elevation by isostatic rebound, and further perturbing climate (Molnar & England, 1990).

The aims of this paper are to provide an estimate of the sediment yield from a large glacier in the Karakoram mountains at the northwestern end of the Himalayan chain, to assess the contribution of glaciers to the sediment flux of rivers in larger less-glacierized basins downstream, and hence to evaluate the role of glaciers in overall natural contemporary sediment transfer from the Karakoram and Himalaya by confluents of the Indus.

RATIONALE

Measurements of annual sediment yield from nested basins on a uniform lithological substrate, in which both percentage cover by glacier ice and mean elevation decrease as basin size increases, are required in order to enable estimation of the contributions from glaciers and glacierized mountain sub-basins to sediment transfer from progressively larger basins. If measurements of yield are available from only one highly-glacierized sub-basin, then the sediment yields from other glacierized sub-basins, which, as basin size increases, become nested within larger basins, have to be inferred from that single database.

Considerable diurnal and day-to-day fluctuations in sediment concentration in meltwaters and diurnal and seasonal variations of discharge in glacier-fed streams necessitate frequent, preferably hourly, collection of samples of meltwater throughout an annual runoff cycle in order to allow accurate characterization of sediment yield from glacierized basins (e.g. Collins, 1991). Year-to-year changes in hydrometeorological conditions lead to inter-annual variations in runoff (of between −33% and +25% of the 20-year mean in the European Alps) and sub-glacial entrainment of sediment by meltwaters, resulting in deviations of between −27.5% and +36.8% from the 7-year mean of sediment flux from Gornergletscher, Switzerland, as estimated from hourly samples (Collins, 1991). Ideally, therefore, for the purpose of comparison of sediment fluxes close to glaciers with those at downstream locations, samples should be collected frequently, by the same technique, in the same year at all stations, and for estimation of annual sediment yield, sampling should additionally be undertaken throughout several years.

In this study, the suspended sediment yield from Batura glacier has been calculated from determinations of sediment content of samples collected predominantly at hourly intervals by pump sampler, with a fixed depth orifice close to the bank, during most of one ablation season, that of 1990. Sub-optimally, these data are used together with existing but less reliable estimates of sediment flux in the Hunza river, some 150 km downstream, obtained from infrequent mid-channel depth-integrated sampling and rating curves with discharge for the period 1966-1975. Other values of mean annual suspended sediment transport and discharge in rivers in the Indus basin, for various years preceding dam and barrage construction, have been taken from published sources.

STUDY AREA: THE INDUS BASIN

The basin containing Batura glacier is located at about 36°N in the Karakoram mountains (Fig. 1). Meltwaters in the sole river emanating from the portal of the 60 km-long valley glacier enter the Hunza River about 1 km from the glacier terminus. Flow in the Hunza is recorded at Danyore (Dainyor) Bridge, above the confluence with the Gilgit, a tributary of the upper Indus. The mountainous upper section of the Indus has been gauged at Partab Bridge and Besham, upstream of Tarbela reservoir, which was dammed in 1974. The valleys (and eastern plateau) of the upper Indus basin are arid (the 30-year mean annual precipitation at Gilgit, 1490 m a.s.l., was 132 mm and at Skardu, 2197 m, 202 mm (Whiteman, 1985); the May 1974-April 1975 total at Batura glacier terminus, 2563 m, was 97 mm). In the Karakoram and on Nanga Parbat, precipitation increases by an order of magnitude to about 2 m at *c.* 5000 m (Lanzhou Institute, 1980), nourishing the large glaciers which descend to the arid valleys. Snowfall produces the spring precipitation maximum (March-May) and a secondary peak in July-August reflects occasional penetration of summer monsoon precipitation to the Karakoram.

The headwater tributaries of the rivers of the Punjab are predominantly fed by spring snowmelt and summer monsoon rains on the forested south flank of the Himalaya. Winter snowfall increases with both elevation and latitude, and westwards, whereas monsoon rain decreases to the northwest and behind mountain barriers reaching a maximum at about 2000 m a.s.l. (Barry, 1992). The 10-year mean annual precipitation is about 1400 mm at 2660 m in the Jhelum valley upstream of Mangla (de Scally, 1994). Meltwaters from glacierized Himalayan headwater basins are augmented by monsoon

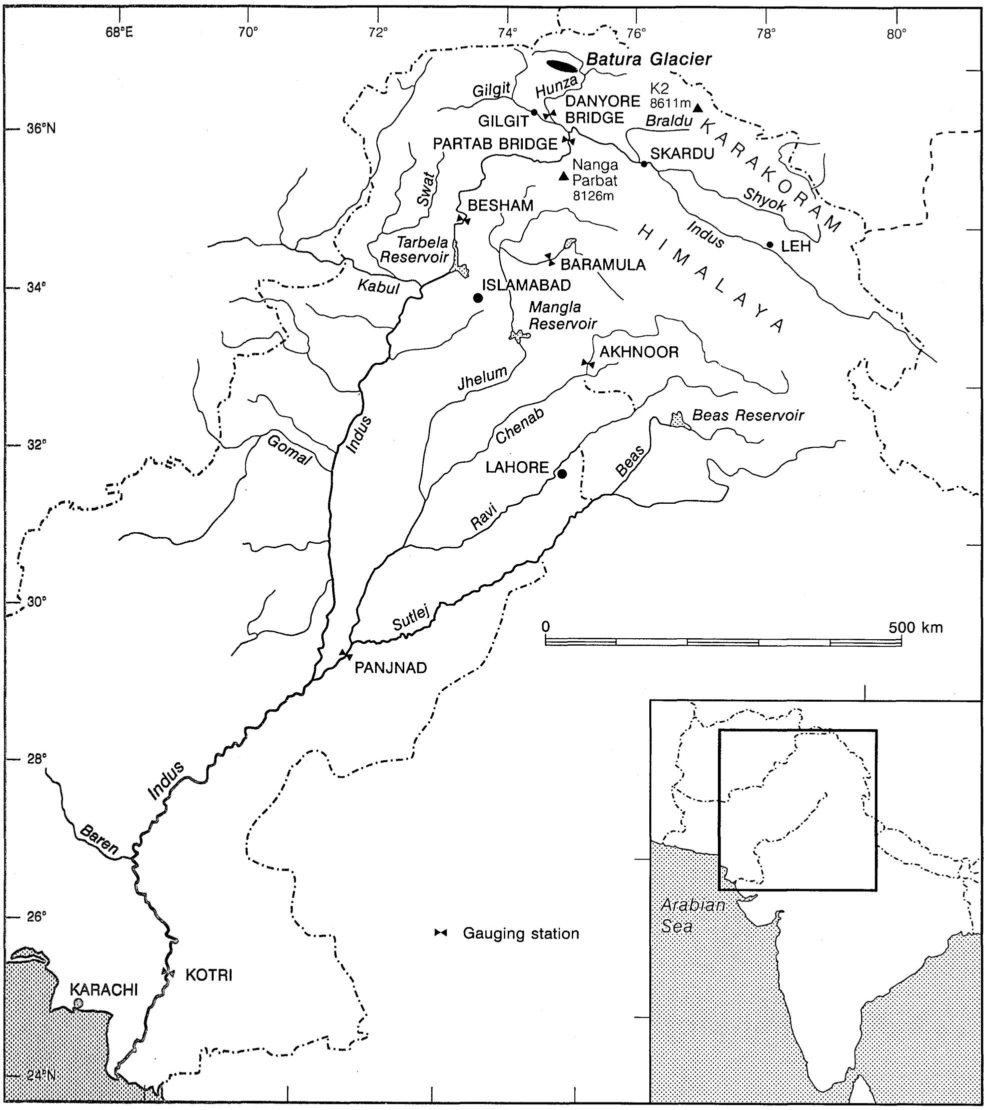

Fig. 1 Map of the Indus basin showing Batura glacier in the Karakoram mountains, and other gauging stations at which measurements have been obtained.

rains in summer, which also add to the flows of the Jhelum (dammed in 1967), Chenab, Ravi and Sutlej rivers across the northern plains. The extent of glacierization is much less than in the Karakoram. The broad arid Indus plain extends over 1000 km to the sea, the lowest gauging station (Kotri) being 250 km from the coast.

Batura glacier lies on Gujhal dolomite, Passu slates and biotite-granodiorite. The Hunza and Indus initially flow over metamorphic shales and limestones, and granodiorite of the Eurasian plate, before crossing Kohistan sedimentary and volcanic rocks (Searle, 1991). East of Nanga Parbat and south of Besham, Indian Plate Precambrian gneisses, granites, limestones and slates underlie the Himalaya.

MEASUREMENTS AND DATA SOURCES

Measurements at Batura glacier

Samples of meltwater were collected at 3 h intervals between 9 and 22 April 1990 and then hourly until 7 October 1990, about 500 m downstream of the terminus of Batura glacier. Between 150 and 250 ml of meltwater were collected using an EPIC 1011 automatic liquid sampler. Samples were filtered through individually pre-weighed Whatman No. 1 filter circles, which were then dried at 105°C and the sediment content obtained gravimetrically. Stage was continuously recorded with a pressure transmitter, and discharge estimated, with some inaccuracy at high flows, from rating curves based on occasional measurements of discharge obtained using a current meter suspended from the bridge over the Batura river about 150 m above the confluence with the Hunza. Hourly sediment flux was calculated as the product of average discharge and instantaneous sediment concentration. Air temperature and precipitation were recorded at about 2700 m a.s.l. near the terminus of Passu glacier, 10 km down the Hunza valley. Air temperatures at higher elevations were estimated assuming a constant lapse rate of 0.6°C 100 m^{-1}.

Table 1 Measured totals and mean annual values of runoff and sediment transport from partially-glacierized basins in the Indus catchment area.

Basin/gauging station	Area	Discharge: total in period or annual mean		Period	Glacierization	Suspended sediment flux: total in period or annual mean		Source
	($\times 10^3$ km^2)	(km^3)	(m)		(%)	(Mt)	(t km^{-2} $year^{-1}$)	
Indus	950	211	0.222			475	500	Meybeck (1976)
				1902-25		436	460	Holeman (1968)
Indus/Kotri	832							UNESCO (1985)
	970	105	0.126	1931-47		270	232	Milliman *et al.* (1984), after WAPDA
Indus/Besham	162	74.2	0.457	1969-75				WAPDA data
Indus/Partab Bridge	143	54.2	0.380	Q 1969-75				WAPDA data
				S 1963-75		160	1120	Ferguson (1984) after WAPDA
Hunza/Danyore Bridge	13.2	12.0	0.911	Q 1969-75	28.5			WAPDA data
				S 1966-75				Ferguson (1984) after WAPDA
		11.9	0.902	1971-1981		63	4770	Haserodt (1984) after WAPDA
Batura/Batura Bridge	0.687	0.93	1.349	V/1974-IV/1975	60.0			Lanzhou Institute (1980)
	0.649	0.79	1.150	V-X/1974	56.3	3.95	6086	
		1.25	1.928	IV-X/1990				
Chenab/Panjnad	280	98.60	0.352	1973-75				UNESCO (1979)
Chenab/Akhnoor	22.7	25.63	1.130	1971-74, 1976-79				UNESCO (1979, 1985)
Jhelum/Baramula	12.5	6.73	0.390	1971-74, 1976-79				UNESCO (1979, 1985)

Data sources

The Water & Power Development Authority, Pakistan (WAPDA) has maintained a programme of measurements of sediment flux and discharge in partially-glacierized sub-basins in the Karakoram, and far downstream at Kotri. Occasional determinations of sediment concentration are used with 9 hourly daytime measurements and rating curves to produce estimates of annual sediment flux (Ferguson, 1984; Milliman *et al.*, 1984). Characteristics of the basins are given in Table 1.

DISCHARGE AND SEDIMENT FLUX FROM BATURA GLACIER

Seasonal variations

Variations of water and sediment discharge from Batura glacier through the ablation season of 1990 have characteristics which resemble those measured in glacierized basins in other mountain massifs (e.g. Collins, 1989). Discharge only started to rise in early May, although daily mean air temperature at the terminus had reached 10°C by mid-April (Fig. 2). Most of the glacier remained covered with high-albedo snow so that much of the increasing radiation through May and early June was not utilized in melting. Once snow cover is removed, the lower albedo of underlying ice leads to greatly increased specific yield of meltwater for the same energy input. The first steep rise in flow on 13 May accompanied a rapid temperature increase, taking the 0°C isotherm above 5700 m a.s.l. to include 84% of the basin area. Further steep rises in discharge between 18 and 26 June, 29 June and 9 July, and 25 July and 13 August resulted from rapid increases in ice area as the transient snow line ascended. At other times, discharge tracked energy input. Falling radiation inputs from August, no longer offset by increasing areal exposure of ice by transient snow line rises, resulted in a generally downward trend in runoff.

Principal precipitation events on 21-22 July, 14-15 and 30 August were associated with lower temperatures. On each occasion, discharge remained subdued for several days before recovery, although energy input recovered more rapidly. Precipitation fell as snow above about 4000 m raising albedo and reducing ablation of ice, the effect being greatest in mid-August when the ice area was largest and energy inputs remained high.

Rises and falls in sediment flux mimic those of discharge in that when discharge was relatively high so also qualitatively was sediment flux (Fig. 2). The actual increases in sediment flux above values on surrounding days depend on the timing and position of events in the series. Sudden increases in suspended sediment transport from a glacier, termed sub-glacial hydrological events by Collins (1989), result from the interaction of meltwaters with sediment, produced by glacial erosion, that has accumulated at the sub-sole. During minimal winter runoff, products of erosion accumulate across the glacier sub-sole. As discharge rises, meltwater progressively integrates parts of the sub-sole that have remained isolated from flow since the previous summer, flushing stored sediment on the first wetting each season. An initial sediment flux event occurred under Batura glacier between 11 and 18 May, followed by further events on each time discharge exceeded levels last reached in 1989. Doubling of discharge between 18 and 26 June induced a massive sediment transport event, with 71 000 t of suspended material being

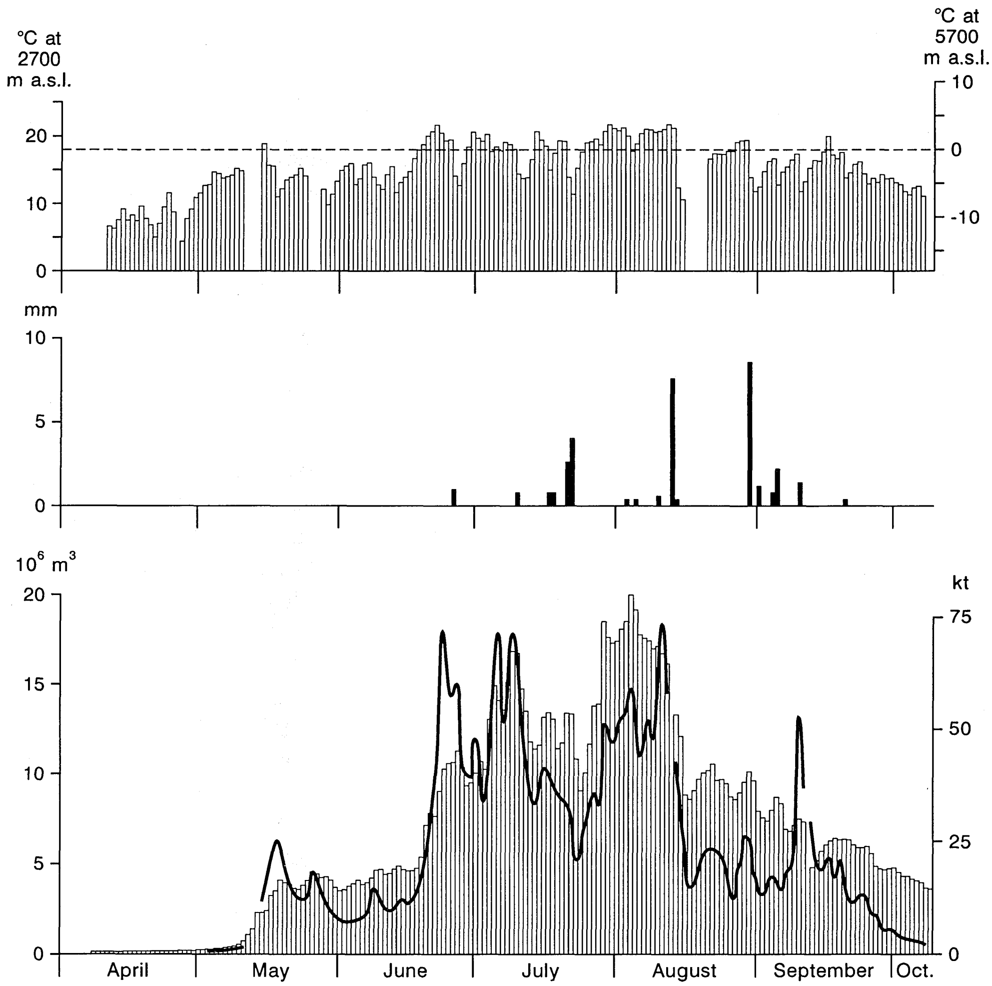

Fig. 2 Seasonal variations of daily mean air temperature recorded at 2700 m a.s.l. (upper), daily total precipitation (centre), and daily total discharge (columns) and measured daily total suspended sediment transport (curve) (lower) from Batura glacier between April and early October 1990. The zero degree level at 5700 m is equivalent to a temperature of 18°C at 2700 m.

transferred on 23 June. Sediment flux event magnitudes through July and early August appeared to depend on the marginal increase in wetted area flushed of sediment by progressively higher discharge (see Collins, 1996). Thereafter, sediment flux would have been expected to decline with generally falling flow and shrinkage of the basal drainage network. However, two unusually large flux events occurred subsequently on 10 August and 9-10 September, evacuating 72 000 t and a total of 88 000 t of sediment respectively. 0.6 mm of rain fell on 10 August, and 1.4 mm on 10 September, much less precipitation than on days with rain and no sub-glacial events. The configuration of the basal channel pattern was probably dislocated suddenly on both occasions.

Annual fluxes

About 85% of the total annual flow from Batura glacier is discharged between May and September (Lanzhou Institute, 1980). Total flow measured in 1990 was 1.25 km^3, equivalent to a January-December discharge of 1.47 km^3 (2.265 m), considerably higher than the 0.93 km^3 (1.354 m) estimated for 1974. Total sediment flux from Batura glacier, calculated by the method of Collins (1991) to take into account missing data in the mid-ablation season, was 3.950 Mt or 6 086 t km^{-2} $year^{-1}$ (Table 1). These detailed data provide a reliable indication of annual flux, as sediment transport is negligible during late October and in winter. Annual sediment yield from Batura glacier is much greater than the comparably-measured mean of 1 207 t km^{-2} $year^{-1}$ from Gornergletscher, which occupies an 84% glacierized 82 km^2 basin in the European Alps (Collins, 1991). If it is assumed, not unreasonably in the near absence of rain on ice-free slopes, that the sediment is derived entirely and uniformly from beneath the glacier-covered area, specific suspended sediment yield from the sub-sole of Batura glacier would be 10 144 t km^{-2} $year^{-1}$.

CONTRIBUTION OF GLACIERS TO DOWNSTREAM DISCHARGE AND SEDIMENT FLUX

Hunza River basin

The runoff regime of the Hunza River at Danyore Bridge reflects the pattern of discharge from the large glaciers in the basin, peaking in July or August. Taking the means

Table 2 Percentages of annual totals of discharge and sediment yield contributed by nested sub-basins to basins within the Indus catchment area.

Basin	Sub-basin	Discharge (%)	Sediment yield (%)	Area (%)
Hunza/Danyore	Batura	10.0	6.2	4.9
Indus/Partab	Batura	2.3	2.5	0.45
	Hunza	22.1	39.4	9.2
Indus/Besham	Batura	1.6	–	0.40
	Hunza	16.2	–	8.1
	Indus/Partab	73.0	–	88.3
Chenab/Panjnad	Chenab/Aknoor	26.0	–	12.3
	Jhelum/Baramula	6.8	–	4.5
Indus "mountain headwaters"	Batura	0.7	–	0.2
	Hunza	6.9	–	3.0
	Indus/Partab	31.4	–	32.4
	Indus/Besham	43.1	–	36.7
	Chenab/Aknoor	14.8	–	5.1
	Jhelum/Baramula	3.9	–	2.8
	Chenab/Panjnad	57.1	–	63.3

of 1974 and 1990, and the 1969-1981 annual runoff from Batura glacier and the Hunza respectively, 10% of the flow in the latter is derived from the 4.9% of the basin forming the Batura sub-basin (Table 2). Given minimal precipitation at lower elevations, that 10% is probably derived from the 2.76% of the Hunza basin occupied by Batura glacier itself. This indicates that glaciers are responsible for all the runoff in the Hunza River.

Patterns of sediment flux in the Hunza River are derived from WAPDA data consisting of fewer than 20 samples collected at Danyore between April and September each year. For a particular discharge level, the sediment content of meltwaters was highest on the first occasion in an ablation season that the level was reached. Sediment flux reached a maximum in July, generally falling thereafter, although imitating the pattern of discharge fluctuations, as at Batura. Estimated mean annual sediment yield for the Hunza at Danyore Bridge is 4770 t km^{-2} year^{-1}, with a range from −55.5% to +60.3% between 1966 and 1975 (Ferguson, 1984).

Behaving uniformly, the 3762 km^2 glacierized area of the Hunza basin might be expected to deliver 38.162 Mt of suspended sediment at Danyore Bridge, which, if the one year with measurements at Batura is taken as average, would account for about 60% of the mean annual load indicated by the infrequent sampling.

Of course, some sediment will be deposited on, and some mobilized, from the valley train between glacier termini and Danyore Bridge. These amounts are unlikely to be balanced. During and since the period of measurement by WAPDA, sedimentation has occurred in a 12 km long lake accumulated behind a debris flow that dammed the Hunza in 1974 at Shiskat about 20 km downstream of the confluence with the Batura outflow. That lake is now aggraded with sediment.

Upper Indus basin

Disproportionate runoff from the glacierized sub-basins of the Hunza is accentuated by the low yield of the Indus above the Braldu confluence, which reduces runoff from 911 mm at Danyore Bridge to 380 mm in the Indus at Partab Bridge. Runoff from the glaciers on Nanga Parbat and from rain and snowmelt on the Himalaya however increases flow in the Indus again, contributing 27% of the 457 mm of runoff at Besham from 11.7% of the area. The Hunza contributes 16.2% from 8.1% of the basin area.

The proportions of the total annual suspended sediment load of the Indus at Partab Bridge contributed by Batura glacier and the Hunza basin are shown in Table 2. Glaciers in the Hunza basin probably contribute about 24% of the load at Partab Bridge. Percentage glacierization of the rest of the upper Indus basin has yet to be established. *Pro rata*, if the valley glaciers on the northern slopes of Nanga Parbat cover 20% of the basin area added between Partab Bridge and Besham, and all sediment is glacier-produced, 38 540 t of sediment will be contributed to the Indus, giving a total flux at Besham of 199 Mt year^{-1} (1228 t km^{-2} year^{-1}). Of this, the Hunza and Nanga Parbat glaciers contribute about 79 000 t or 40% of the suspended load transported by the Indus from the Karakoram and Himalaya. Extensive glacierization of the Braldu basin will also influence the total load at Partab Bridge, so that probably more than 40% of the sediment load leaving the mountains in the Indus is produced by glacial erosion.

The Indus basin above Kotri

Even before the construction of dams and barrages diverted flow to irrigation and groundwater aquifers and substantially reduced flows across the Indus plain, sediment was deposited where the Indus and the Punjab rivers change gradient on leaving the mountains. Divergent estimates of annual mean pre-1947 runoff and sediment loads in the Indus, as of basin area (Table 1), suggest these data should be used with caution. The estimates of Meybeck (1976) are recycled from Holeman (1968), and Milliman & Meade (1983) consider that they probably relate to Darband, a station 800 km from the coast, immediately downstream of the site of Tarbela dam. The basin area of 958×10^3 km^2, however, encompasses the delta, as the studies were concerned with sediment delivery by major rivers to the oceans. No major tributaries enter the Indus between Besham and Darband, so that early estimates of both discharge and sediment load appear high by comparison with recent measurements at Besham (Table 1). Following the suggestion by Milliman *et al.* (1984) that 60% of the suspended load in the Indus is deposited before reaching the ocean, then pre-dam, the upper Indus basin would have contributed 80 Mt to the annual sediment load at Kotri, about 30% of the measured total from 20% of the area.

The rest of the flow and sediment load is largely supplied by the Kabul River (88.6×10^3 km^2, 10.6% of the Indus basin), which drains from the Hindu Kush, and by the Chenab and its tributaries (280.2×10^3 km^2, 33.7% of the area). Pre-dam and upstream-of-dam measurements of discharge and sediment flux in these international rivers are hard to find. The entire Chenab basin is gauged at Panjnad, after losing runoff from the Himalaya to the Punjab canals, but having gained monsoon runoff on the northern plains. The combined discharges of the Indus at Besham and the Chenab at Panjnad, loosely the "mountain headwaters" of the Indus (Table 2), exceed the total measured at Kotri pre-1947 by 68 km^3, indicative of the extent of loss to irrigation downstream (Table 1).

Much sediment must be transferred by the Chenab during snowmelt and monsoon floods, which result respectively from winter snowfall on the Himalaya and heavy summer rainfall. The few measurements in glacierized basins in the Himalaya provide an inadequate basis for assessment of the relative importance of glacial erosion and rainfall in determining annual sediment fluxes in areas receiving substantial quantities of monsoon rainfall (see Collins & Hasnain, 1995). Glaciers are smaller in the Chenab headwater basins and cover a smaller percentage of the area than in the Karakoram, and for that reason, in addition to the effects of the rainfall, contribute a smaller fraction of the sediment transferred by Himalayan rivers.

REGIONAL CLIMATIC INFLUENCES ON RUNOFF AND SEDIMENT TRANSFER FROM HIMALAYAN GLACIERS

Climatic conditions influence both runoff and sediment transport from glacierized basins. The temporal pattern of energy input in summer interacts with the amount of snow remaining to generate snowmelt runoff and to determine exposure of glacier ice to melting. Years with warm summers and little snow accumulation thus have high ice ablation but little runoff from snowmelt, and, conversely, years in which snowy winters are followed by cool summers have low ice melt but reasonable snowmelt. Basal sediment is flushed from the sub-sole on each occasion discharge rises to levels not previously reached in the season. In basins receiving summer rainfall, for example in the European Alps, high intensity rainfall events also promote sediment flushing events (e.g. Collins, 1996). Where rainfall contributes little runoff, as in the Batura basin, the influence of the ice-free part of the basin on fluvial sediment flux is minimal. Elsewhere, in the moist Himalaya, monsoonal precipitation in summer reduces ice melt by snowfall on glaciers raising albedo. Runoff from rainfall on lower slopes not only tends to offset reduced ice meltwater discharge but also contributes sediment. The impact of rainfall increases as the ice-free proportion of a basin increases downstream as basin dimensions enlarge. The difference in runoff regime between drier Karakoram and interior Himalayan basins and monsoonal Himalayan catchments (Collins & Hasnain, 1995) therefore probably leads to contrasting patterns of sediment flux along the long Himalayan arc between 70°E and 100°E.

CONCLUSION

The temporal pattern of sediment flux from Batura glacier confirms the need for frequent, if not hourly, sampling of the sediment content of river water to represent accurately sediment yield from partially-glacierized basins. The measured suspended sediment yield from the Batura glacierized basin, 6086 t km^{-2} $year^{-1}$, is high with respect to measurements obtained by comparable methods in other mountainous areas. If, in the arid Karakoram, the sediment is derived only from the glacier sub-sole, then the yield of 10 144 t km^{-2} $year^{-1}$ is particularly noteworthy. Sampled close to the glacier terminus over several seasons, sediment transport in meltwaters will reflect the actual rate of sub-glacial erosion, although in a particular year, the quantity of sediment evacuated will be a result of the sequence of sub-glacial hydrological events interacting with sediment storage at the sub-sole. High sediment yields certainly characterize the present regime of valley glacierization in the Karakoram, although changes in factors such as the throughput of meltwater, the mass balance, thickness and the sliding velocity of the glacier will have influenced past erosional activity. Present sediment yields, interpreted as rates of glacial erosion over long periods, suggest that glaciers have had a major impact on valley development.

Despite a glacier cover of only 28.5% in the area, sub-glacial sediment contributes about 60% of the yield of 4770 t km^{-2} $year^{-1}$ of suspended material from the Hunza River basin. The remainder is presumably derived primarily from alluvial material stored in terraces into which the Hunza is incising along its length. At Besham, just before the Indus enters the plain, the sediment yield is about 1228 t km^{-2} $year^{-1}$, of which the glacier contribution is probably at least 40%. The absolute yield of suspended sediment, and the glacier-supplied proportion thereof, both decline downstream. High rates of sediment yield in glacierized mountain basins are masked therefore when river loads are assessed for large basins such as the Indus. Much of the suspended load transported from the Karakoram and Himalaya is dumped on the plain, never reaching the Arabian Sea. Smaller basins which are defined with respect to individual tectonic or landscape units are the appropriate scale for assessment of meaningful rates of denudation.

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