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Sediment transfer in the glaciofluvial environment — a Himalayan perspective

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Abstract The Alaknanda river, a major Himalayan proglacial stream, and its tributaries have been studied to evaluate sediment sources, production mechanisms, and transport pathways in the Alaknanda river basin. The study is based on a single-time sampling of the river and its tributaries and gives an insight into the suspended load pattern of the river from its source to its confluence with the other major Himalayan proglacial stream, the Bhagirathi. It is tentatively concluded that the suspended load of the Alaknanda is primarily due to natural processes and events and does not reflect the effects of human intervention.

Key words Alaknanda basin — Proglacial streams — Glaciofluvial environment — Sediment transfer

Introduction

The Himalaya is the great range of mountains that separates India, along its north-central and northeastern frontier, from China (Tibet), and extends between latitudes 26°20′ and 35°40′ N and between longitudes 74°50′ and 95°40′ E (Ives and Messerli 1989). The ranges extend over 2500 km in length from west to east and 200–400 km in width from north to south. This is the youngest mountain system in the world and includes the most erosion-prone regions in the world. The higher Himalayan ranges, with an average height of 6000 m, are the repositories of some of the highest and biggest glaciers in the world. Glaciers in the Indian Himalayas cover an area of 3.8×10^4 km^2 and account for 17 percent of the mountain area as compared to 2.2 percent in the Swiss Alps (Agarwal and Narain 1991). The Himalayan glaciers are broadly classified as belonging to the three major river systems, the Indus, Ganga, and the Brahmaputra. The Indus basin accounts for the largest number of glaciers (3358), followed by Ganga (1020), and the Brahmaputra (662). The Alaknanda basin, which constitutes a significant part of the Ganga basin, also contains numerous large and small glaciers, and all the streams in this catchment drain from the glaciated watersheds (both glaciers and snowfields).

We have tried to evaluate the source areas, production mechanisms, and transport pathways of sediments in the Alaknanda basin. This study includes the suspended load made available from the glaciated part of the catchment, additional inputs resulting from erosion by the swift-flowing stream and its tributaries, and from anthropogenic activity in the lower part of the Alaknanda basin. The Alaknanda was sampled from its source above of the township of Badrinath to Devprayag, before its confluence with the second major Himalayan proglacial stream, the Bhagirathi. All the major tributaries of the Alaknanda were sampled to estimate their contribution to the suspended load.

Alaknanda basin

The River Ganga at Devprayag is formed by the confluence of its two Himalayan proglacial streams, the Alaknanda and the Bhagirathi. The sources of the Alaknanda are the twin glaciers Satopanth and Bhagirath Kharak (elevation at snout 3800 m), 13 km from the town of Badrinath; the ice cave of Gaumukh at the snout of the Gangotri glacier (elevation 4100 m) is the source of the Bhagirathi. The Ganga after a run of 280 km cuts through the Himalayas at Sukhi near Rishikesh and turns southwest for another 30 km and descends onto the vast Indo-Gangetic plains at Haridwar. The discharge of the Alaknanda at the confluence in Devprayag is greater than that of the Bhagirathi. The maximum and minimum discharge values for the Ganga during the period 1990–1991 were 4061 m^3/s

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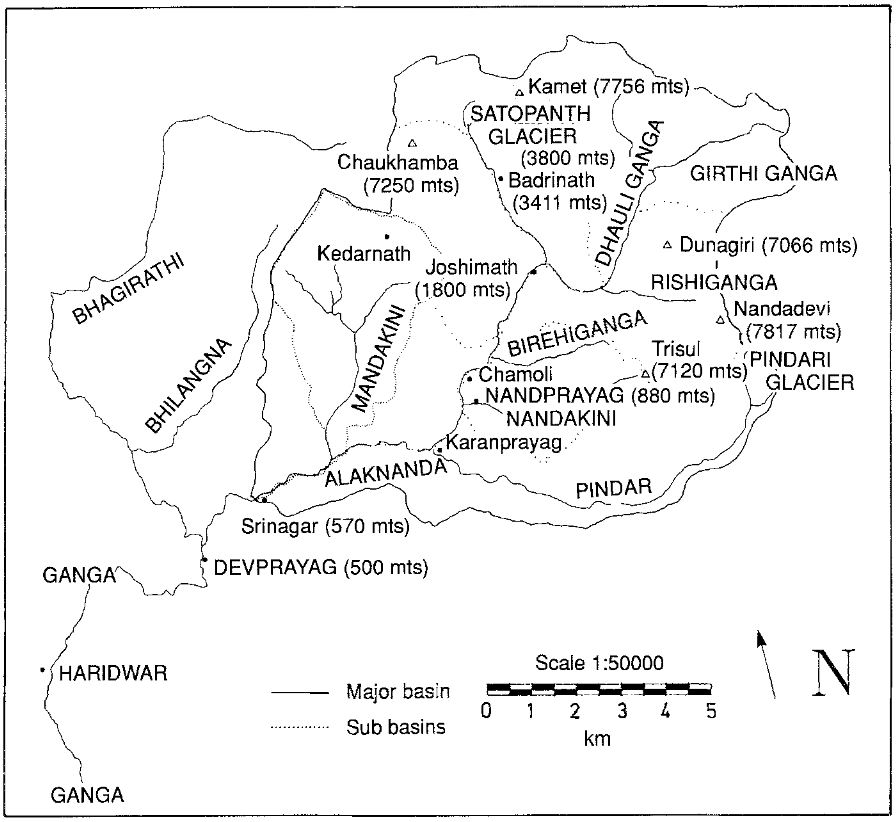


Fig. 1. Map of the Alaknanda basin

and 125 m^3/s (Anonymous 1991); the contribution of the Alaknanda to this discharge was 3000 m^3/s and 85 m^3/s. The Alaknanda basin (Fig. 1) is formed by the proglacial Alaknanda stream and its tributaries, which are mostly fed by snow- and icemelt and monsoonal precipitation. The first stream to join the Alaknanda on the left bank is the Saraswati near Mana village 3 km before Badrinath. It is joined by the Dhauliganga on the left bank at Vishnuprayag, before the township of Joshimath. The river is joined on the left bank by the Karamnasa Nadi, at the township of Helang, and by the Patalganga, Garurganga, and Birahiganga on the left bank before Chamoli town. The river then flows in a southerly direction and receives, on the left bank, the Nandakini at Nandprayag and the Pindar from the Kumaon Himalaya at Karanprayag; the river then flows in a westerly direction and receives, on the right bank, the Mandakini draining from the Kedarnath dome in the north. The Alaknanda then turns to the southwest and flows by Srinagar and joins the second major Himalayan proglacial stream, the Bhagirathi, at Devprayag to form the River Ganga.

The higher reaches of the Alaknanda basin are characterized by active glaciation. Glaciers, cirque basins, glacial lakes, U-shaped valleys, moraines, and avalanche slopes are common landforms in the region. This area has undergone the glacial advances and retreats that affected the Himalayan region in Pleistocene times. During the Pleistocene glacial advance, the Himalayan glaciers descended to 1500 m; the present positions of the glacier terminii are at an elevation of 4000 m. The river flows for a distance of 210 km from the source (elevation 3800 m) to Devprayag (elevation 500 m). The upper course is taken from the source to the township of Helang, at a distance of 65 km from the source. The river in its upper course flows through narrow and deep gorges and then enters its lower course at an elevation of 900 m. The annual rainfall in the Alaknanda basin ranges from 1000 to 1600 mm, and 75 percent of the rainfall occurs during the monsoonal months from July to September (Dasgupta 1975).

Geology of the basin

The Alaknanda and its tributaries drain through different rock types (Fig. 2); in the higher reaches of the catchment the river flows through the Central Crystallines, which are composed of migmatized and granitized metasediments (NC Agarwal and SK Mukhopadhyay, unpublished data 1978). After passing through the Main Central Thrust, (the MCT separates the Central Crystallines from the Lower Himalayas), the Alaknanda flows through the Berinag Formation, which consists of of a quartzitic sequence and a few crystalline limestone bands. Before its confluence with the Bhagirathi, the river flows through the Chandpur Formation, which consists of phyllites and micaceous greywacke. The tributaries of the Alaknanda flow through lithologies as diverse as quartzites, limestones, shales, and slates.

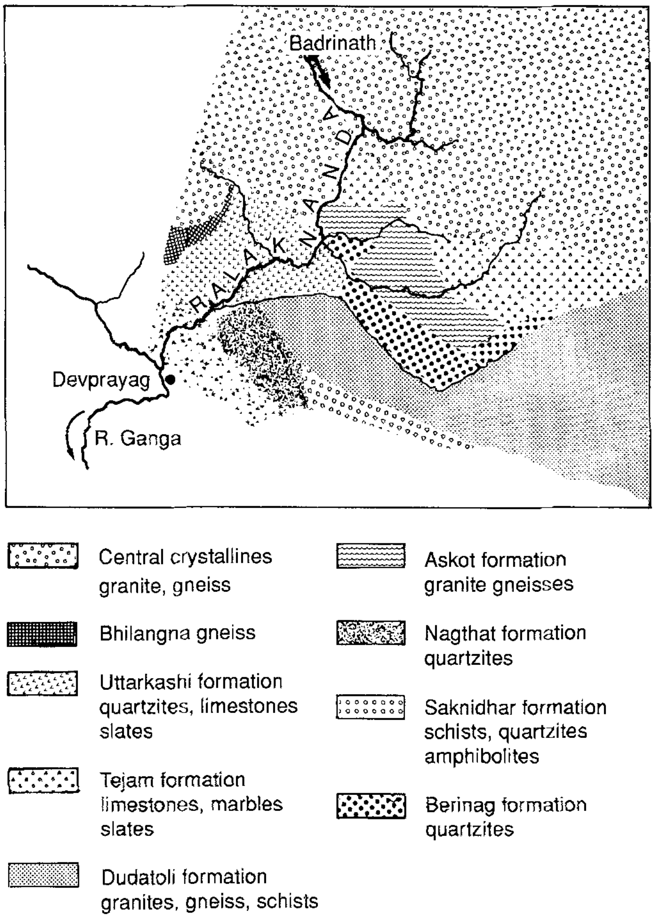


Fig. 2. Geology of the drainage basin

Hydrology of Alaknanda basin

The Alaknanda river basin, like the other Himalayan river basins, experiences a strongly seasonal climate; this is reflected in the monthly variations in the streamflow. Maximum flow takes place during June–September, when both rainfall and rates of snowmelt are at a maximum. The Himalayan rivers carry 69–83 percent of their annual flow during the summer monsoon months (June–September) (Bruijnzeel and Bremmer 1989). Discharge measurements for the Alaknanda and its tributaries is not readily available, and maximum and minimum discharges at Devprayag released by the Central Water Resources (CWC) have to be relied upon. However, the discharge of the Alaknanda at the glacier portal has been monitored during the sampling season. The data are given in Table 1.

Materials and methodology

The river was sampled from the source to its confluence at Devprayag with the river Bhagirathi (Fig. 3). One-liter water samples were collected at various locations along the stretch of the river and at points where it is joined by its tributaries. Suspended sediments were separated by filtration of water through 0.45-μm pore size membrane filters. The filters were then dried and weighed later.

Suspended sediment sources

Glacial erosion, erosion by streams, mass movements, and human activity (Fig. 4) all contribute to the suspended load of the proglacial Himlayan streams. The Himalayas are one of the most active tectonic regions in the world; this is evidenced by the high seismic activity in this region. Earthquakes of considerable intensity (>6 magnitude on the Richter scale) have affected the Himalayan ranges as well as the Indo-Gangetic plains. A recent earthquake (the Uttarkashi earthquake, 20 October, 1991) measured 6.6 on the Richter scale (Anonymous 1992).

Table 1. Suspended load and discharge at sampling locations

Location[a]	Distance from source (km)	Discharge (m^3/s)	Suspended load
1. Glacier	0	15–20	3.73×10^6 t/d
2. Mana	10	25	520 mg/l
3. Badrinath	13		525 mg/l
4. Pandukeshwar	35		2246 mg/l
5. Dhauliganga	53		519 mg/l
6. Joshimath	56		543 mg/l
7. Karamnasa Nadi	61		6.4 mg/l
8. Garurganga			3.4 mg/l
9. Patalganga			7.2 mg/l
10. Birahiganga			64.5 mg/l
11. River before confluence with Pindar			720 mg/l
12. Pindar			210 mg/l
13. River after confluence with Pindar			495 mg/l
14. River before confluence with Mandakini	131		1297 mg/l
15. Mandakini			55.4 mg/l
16. River after confluence with Mandakini			758 mg/l
17. Srinagar			414 mg/l
18. Devprayag	210		1.52×10^8 t/d

[a] Nos. 1–18 represent sampling locations shown in Fig. 3

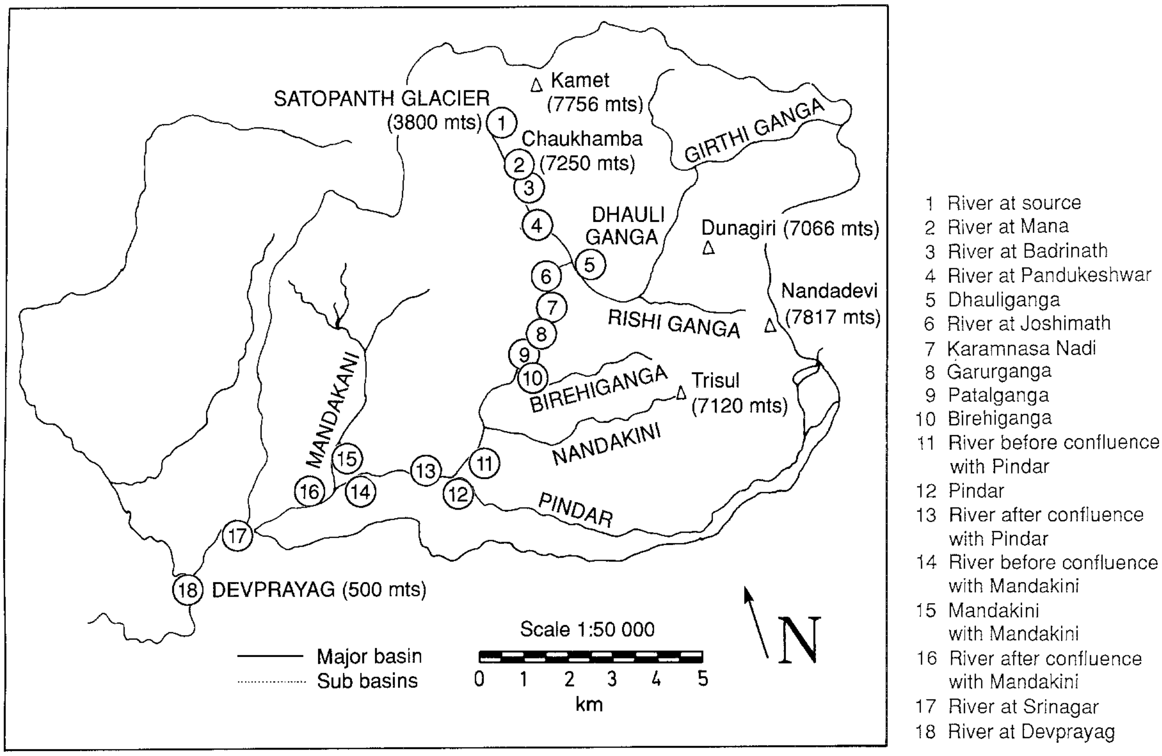


Fig. 3. Map showing the sampling locations

The upper reaches of the river are marked by very reduced levels of human activity and the river flows through well forested areas in this region. A significant contribution to the suspended load in the upper reaches is from the two major glaciers at the source. The load superimposed by the active glaciers is sufficient to cause failure in rocks and weaken the subglacial strata, which is subsequently removed by ice and water flow. A generalized model of the sediment transfer system in a typical Himalayan glacier is shown in Fig. 5. The model depicts the sources from which the debris is derived, the processes involved in acquiring material from these sources, and the pathways along which the debris is transported. Sediment transported by glaciers follows three basic routes: supraglacial, englacial, and subglacial. In case of glaciers where the exposed rock faces and walls occur immediately adjacent to the ice margins, debris released by freeze–thaw weathering and rock falls accumulates on the ice surface (Small 1987). This debris gives rise to the supraglacial lateral moraines, which are coarse, angular, and poorly sorted and undergo relatively little modification in clast shape and represent a passive mode of transport (Boulton 1978). The subglacial debris is a result of abrasion due to rock fragments forced against and dragged along the glacier bed by sliding ice; it is initally angular in shape and is later modified by comminution. Glacial meltwater streams carry sediments in the form of both suspended sediment load (including washload) and bedload in response to the plentiful supply of sediments to the streams by glacial processes (Gurnell 1987). The proportion of fine sediment in suspension is higher in the meltwater at the snout than in other fluvial environments because of a continous supply of fine material from glacial erosion processes. The turbulent nature of the flow brings coarser material into suspension, and the low temperature of meltwaters $<2°C$ increases the viscosity of water, thereby reducing the falling velocity of suspended sediments, which are more evenly distributed in the stream cross section than in other fluvial environments (Drewry 1986). The glacial system is also characterized by natural events such as glacial lake outbursts (jokulhlaups), which lead to a sudden release of sediments to the proglacial streams. The middle and lower reaches of the river are more densely populated, and agriculture is the major occupation in this region. The hill slopes in this region have reduced forest and vegetation cover and are subjected to intensive land use by clearing of forests for agricultural purposes, fuelwood collection, and grazing by cattle. The expansion of agriculture is often cited as the reason for increased destabilization of hill slopes, soil erosion, and floods in the Indo-Gangetic plains. Population pressure has forced the people to higher elevations and steeper slopes, even above 2000 m, to cultivate what were once forested tracts (Valdiya 1985). Increased developmental activity in the hills has led to the construction of roads, over 44,000 km of roads now exist in the Himalayas; on an average 40,000–80,000 m^3 of debris is removed to build each kilometer of these roads and another 550 m^3/km to maintain them (Valdiya 1985). This means that 1760–3520 $\times 10^6$ m^3 of debris had to be removed to build the Himalayan roads and another 24.2 $\times 10^6$ m^3 are removed every year. The Alaknanda from its source to its confluence at Devprayag has a total run of 210 km, and the total length of road along its left bank is 230 km, this generates 1.26 $\times 10^5$ m^3 of debris every year.

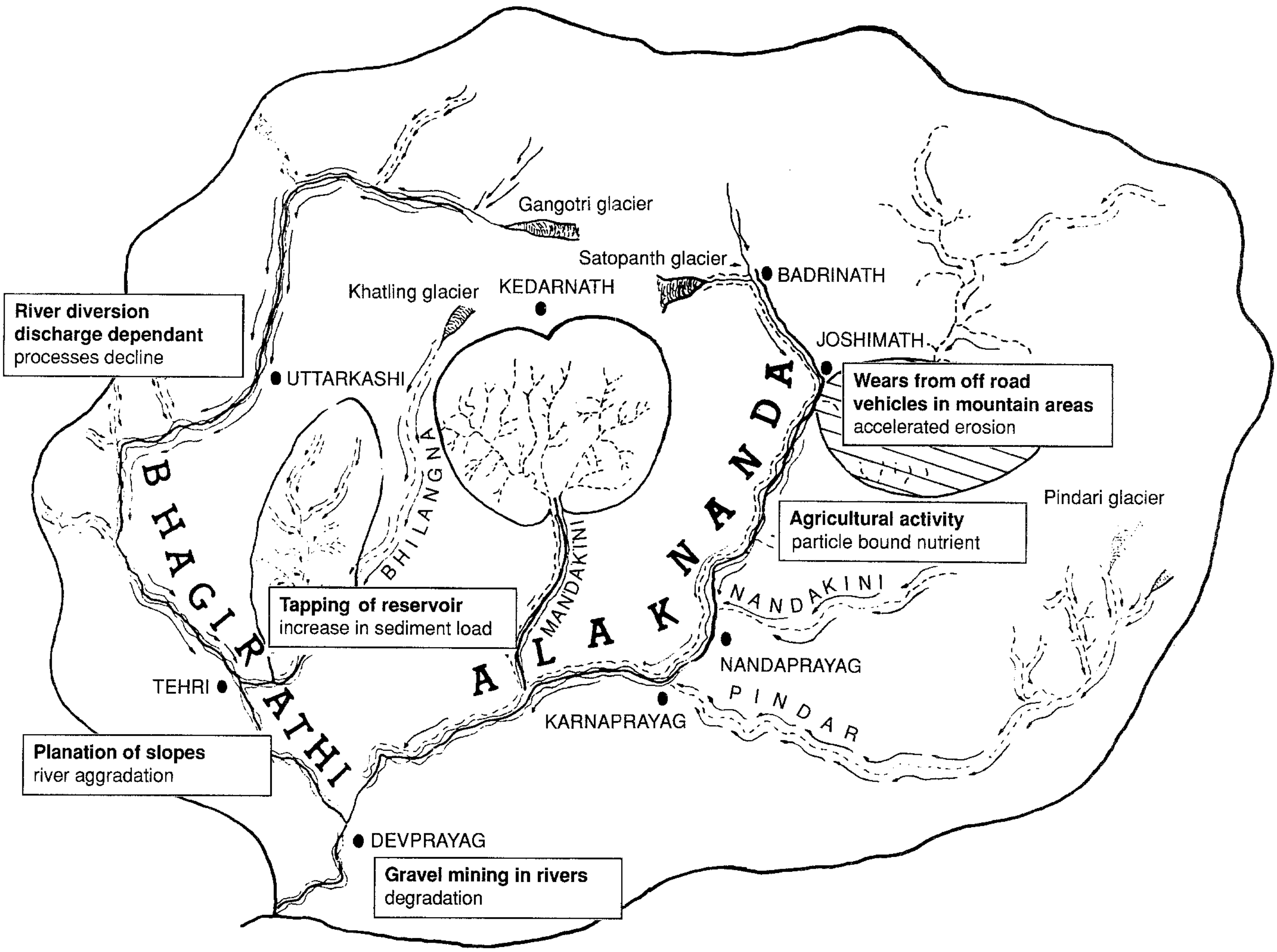
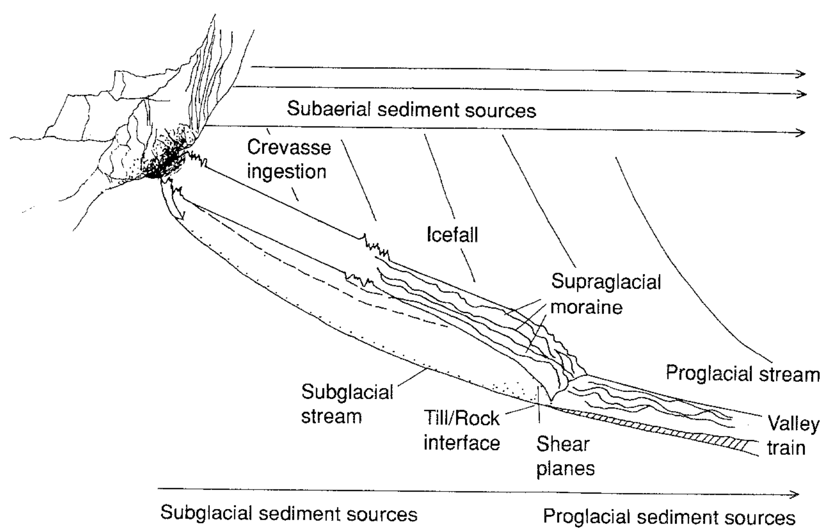


Fig. 4. Suspended sediment sources in the river basin

Fig. 5. Generalized model of sediment transfer mechanism in a Himalayan glacier basin



Results and discussion

The results of the sampling program are illustrated in Fig. 6. The suspended sediment load is maximum (2163 mg/l) in the proglacial stream near the glacier portal. This drops to 520 mg/l near Mana village, about 10 km from the glacier snout, and is 525 mg/l at Badrinath. The suspended load rises again to 2246 mg/l at Pandukeshwar, 35 km from the source. This is probably due to the steep drop in the river course (147 m/1000 m) from Badrinath (elevation 3411 m) to Pandukeshwar (1200 m). At Vishnuprayag, 58 km from the source, the Alaknanda is joined by one of its major tributaries, the Dhauliganga (suspended load 519 mg/l), and after the confluence the suspended load of the Alaknanda is 543 mg/l. At Helang, at a distance of 61 km from the source, the Alaknanda is joined on its left bank by one of its minor tributaries, the Karamnasa Nadi (suspended load 6.4 mg/l), and by the Patalganga (suspended load 7.2 mg/l) and the Garurganga (suspended load 3.4 mg/l) further downstream. The Alaknanda is joined by the Birahiganga (suspended load 64.5 mg/l) before the township of Chamoli. The reason for the higher suspended load of the Birahiganga is found in the floods that ravaged the Alaknanda valley in July 1970, when large landslides and landslips were activated by a cloudburst (275 mm of rain fell in a few hours) in the Kuari Khal mountain divide (elevation 3700 m). All the streams emerging from the mountain divide, which drain into the left bank of the Alaknanda, experienced very high levels of flow. The Alaknanda rose by 30 m to 60 m above the normal level at certain places; the flood brought an estimated 9.1×10^6 m^3 of silt and rock into the Alaknanda (Agarwal and Narain 1991). Gohana Tal (a lake 5 km × 2 km formed by a landslide in 1894), on the Birahiganga, which was 200 m deep, received so much silt that it was silted up (Krishnaswamy 1980); the higher suspended load of the Birahiganga could be due to removal of the sediment from the erstwhile lake. The Pindar (suspended load 210 mg/l), draining from the Pindari glacier, joins the Alaknanda on the left bank at Karanprayag. The other major tributary, the Mandakini (suspended load 55 mg/l), joins the Alaknanda on the right bank at Rudraprayag. The Alaknanda at Srinagar (elevation 500 m) has a suspended load of 414 mg/l and before the confluence with River Bhagirathi at Devprayag the Alaknanda has a suspended load of of 585 mg/l.

The discharges of the proglacial Alaknanda stream near the glacier portal during the sampling period measured between 15 and 20 m^3/s and go up to 25 m^3/s at Mana 10 km downstream as it is joined by some minor tributaries on the way. The suspended sediment load near the glacier is 3.73×10^6 tonnes/day, and this goes down to 1.12×10^6 tonnes/day. Thus, almost 70 percent of the suspended sediment load obtained from the glaciers at the source goes into temporary storage in the alpine watershed and is subsequently removed during periods of increased discharge during the monsoonal months. The smaller tributaries of the Alaknanda are characterized by low suspended sediment load; however, this situation is altered during storm events as described earlier. The total suspended load carried by the Alaknanda at Devprayag is 1.52×10^8 tonnes/day (using discharge values supplied by CWC). While the total discharge of the Alaknanda at Devprayag is 120 times greater than that at the glacier, the total suspended load goes up by only 40 times, despite the fact that the Alaknanda in its lower course flows through an area marked by susceptible lithologies and increased developmental activities.

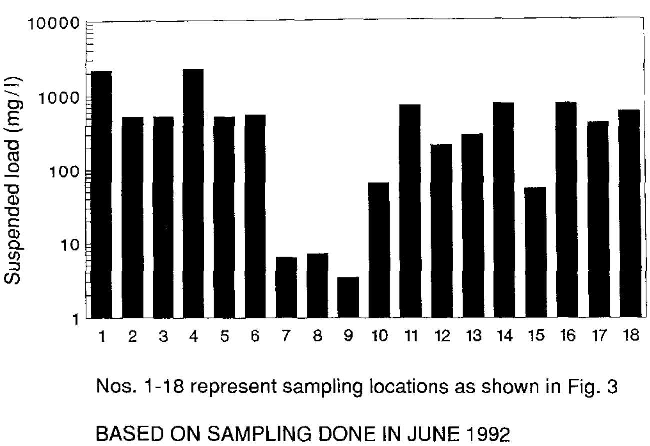


Fig. 6. Suspended load of the River Alaknanda and its tributaries

Conclusions

Natural erosion in the Himalayas is an important phenomenon, the denudation rates in the Himalaya are high, if not the highest in the world. This is due to the active glaciation above 4000 m on susceptible lithologies and structures with high seismic activity. The Himalayan glaciers are covered by a thick layer of debris as a result of extensive avalanches and contributions from the valley wall, and this is made available for transport by the swift proglacial streams. Selected denudation rates for the Himalayas range from 0.5 to 20 mm/yr (Ives and Messerli 1989). Despite the wide range, these are very high when compared to the denudation rates elsewhere in the world and suggest a very dynamic environment when the high rate of tectonic uplift of 4–5 mm/yr (Ives and Messerli 1989) and the intensity of seismic activity are taken into account.

The bulk of the suspended load made available by the glacier goes into temporary storage within the alpine basin and is removed during periods of high discharges. The smaller tributaries are characterized by lower suspended loads. Most of the suspended sediment transport takes place during June–September. The effect of human intervention cannot be accurately gauged from the data available due to the absence of representative data and the difficulty of assessing the high-magnitude events in this naturally dynamic region. Thus, it is possible to suggest that the sediment transfer in the Alaknanda basin is the result of natural processes and events and that the rate of erosion due to human activities are overshadowed by them. A more definite conclusion can be drawn by a comprehensive study of the suspended and chemical load over a longer time series.

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