Estimates and analysis of suspended sediment from a glacierized basin in the Himalayas

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Abstract The study deals with the sediment delivery pattern of a highly glacierized basin, the Gangotri Glacier basin (total area 556 km^2, glacierized area 286 km^2, elevation range 4000–7000 m) located in the Himalayan region. To carry out this study, suspended sediment samples and discharge data were collected near the snout of the glacier (4000 m a.s.l.) for four consecutive melt seasons 2000–2003 (May–October). The monthly distribution of suspended sediment concentration (SSC) and its variability from year to year has been examined. Mean monthly SSC for May, June, July, August, September and October was found to be 1942, 2063, 3658, 2551, 734 and 136 mg L^{-1}, respectively, showing maximum SSC in melt water in July followed by August. It was found that cumulative percentage delivery of SSC precedes discharge throughout the melt season. About 59–64% of the sediment passed through the channel by the time 50% of the total discharge had passed. Average seasonal values of sediment yield were estimated for the study basin.

Key words Gangotri Glacier; glacierized basins; melt season; suspended sediment concentration; suspended sediment yield

INTRODUCTION

Across the world it has been reported that sediment yield is higher in glacierized basins than in non-glacierized basins (Jansson, 1988; Harbor & Warburton, 1993; Hallet *et al.*, 1996). The delivery of sediments also depends on the amount of water draining through the glacier. Proglacial streams carrying suspended sediment have practical significance where glacially derived waters are used for irrigation (Butz, 1989) and for the planning, designing and operating of hydropower schemes (Bezinge *et al.*, 1989; Singh *et al.*, 2003).

Most of the Himalayan glaciers are debris covered and the rivers originating from these areas transport sediment at a very high rate (Bruijnzeel & Bremmer, 1989; Singh *et al.*, 2003). The geologically young age of the Himalayan mountain system, which is undergoing fast uplift and has large and active glaciers, supports the high sedimentation. The present estimates of uplift rates for different parts of the Himalayas vary from 0.6–6 mm year^{-1} (Nakata, 1989; Jackson & Bilham, 1994). Fission-track dating of rocks and geodetic levelling have provided evidence of fast uplift accompanied by denudation and exhumation of deep-seated rocks. The Himalaya possess fragile ecosystems susceptible to high denudation, the erosion rate being in the range of 2–12 mm year^{-1} (Burbank *et al.*, 1996). To analyse these aspects, there is a need to establish a long-term database related to suspended sediment concentration (SSC) for the glacierized basins in the Himalayan region.

During the melting season, the snow and glacier melt runoff is of vital importance for hydroelectric power generation and irrigation. Today, installation of hydropower projects in the Himalayan region is a priority. The peak season (July and August) for melting along with the monsoon rainfall, generally observed in the middle and lower part of basins, sees transport of large amounts of suspended sediments, which causes silting of the reservoirs. In this paper, an attempt is made to assess the magnitude of SSC and its variation over the time. For this purpose hydro-meteorological and suspended sediment data were collected for four melt seasons during the years 2000–2003 (May–October) near the snout of the Gangotri Glacier. The delivery patterns of discharge and SSC have been studied.

STUDY AREA

The Gangotri Glacier (Lat. 30°43′N–31°01′N and Long. 79°00′E–79°17′E) is the largest glacier of the Garhwal Himalayas. The proglacial melt water stream, known as the Bhagirathi River, originates from the snout of the Gangotri Glacier at an elevation of 4000 m.a.s.l. The Gangotri Glacier system, most commonly known as the Gangotri Glacier, is a cluster of many glaciers comprising the main Gangotri Glacier (length: 30.20 km; width: 0.20–2.35 km; area: 86.32 km^2) as the trunk part of the system. The major glacier tributaries of the Gangotri Glacier system are the Raktvarn, Chaturangi, Swachand and Maiandi glaciers, which merge with the trunk glacier from the northeast and the Meru, Kirti and Ghanohim Glaciers, which merge with the trunk glacier from the southwest. The altitudinal range of this glacier varies from 4000–7000 m. The total catchment area of the study basin up to the gauging site is about 556 km^2, of which more than 50% is covered by ice. Figure 1 shows the area of the Gangotri Glacier and the location of the snout and the gauging site. The average seasonal temperature near the snout of the glacier is about 9.4°C with an average seasonal rainfall of about 260 mm. The distribution of rainfall varies from year to year. Details of climatic conditions prevailing in the study area have been reported by Singh *et al*. (2004a).

OBSERVATION OF DISCHARGE AND SUSPENDED SEDIMENT

As shown in Fig. 1, a discharge gauging site was established near the snout of the Gangotri Glacier at which discharge and suspended sediment data were collected. A stilling well was constructed and an automatic water level recorder was installed in the stilling well for continuous monitoring (24 hour) of variations in water level. A graduated staff gauge was also installed on the gauging site near the stilling well for manual observations of water level. For measurement of discharge, the velocity-area method was used and to compute the velocity of flow, wooden floats were used. For the measurement of velocity of discharge, the channel was divided into four segments. After calibrating the water levels observed from the staff gauge and the water level recorder, the stage–discharge relationship (rating curve) was developed for each ablation season and was used to convert water levels into discharges for that particular season. The cross-sectional area of the channel was determined with the help of

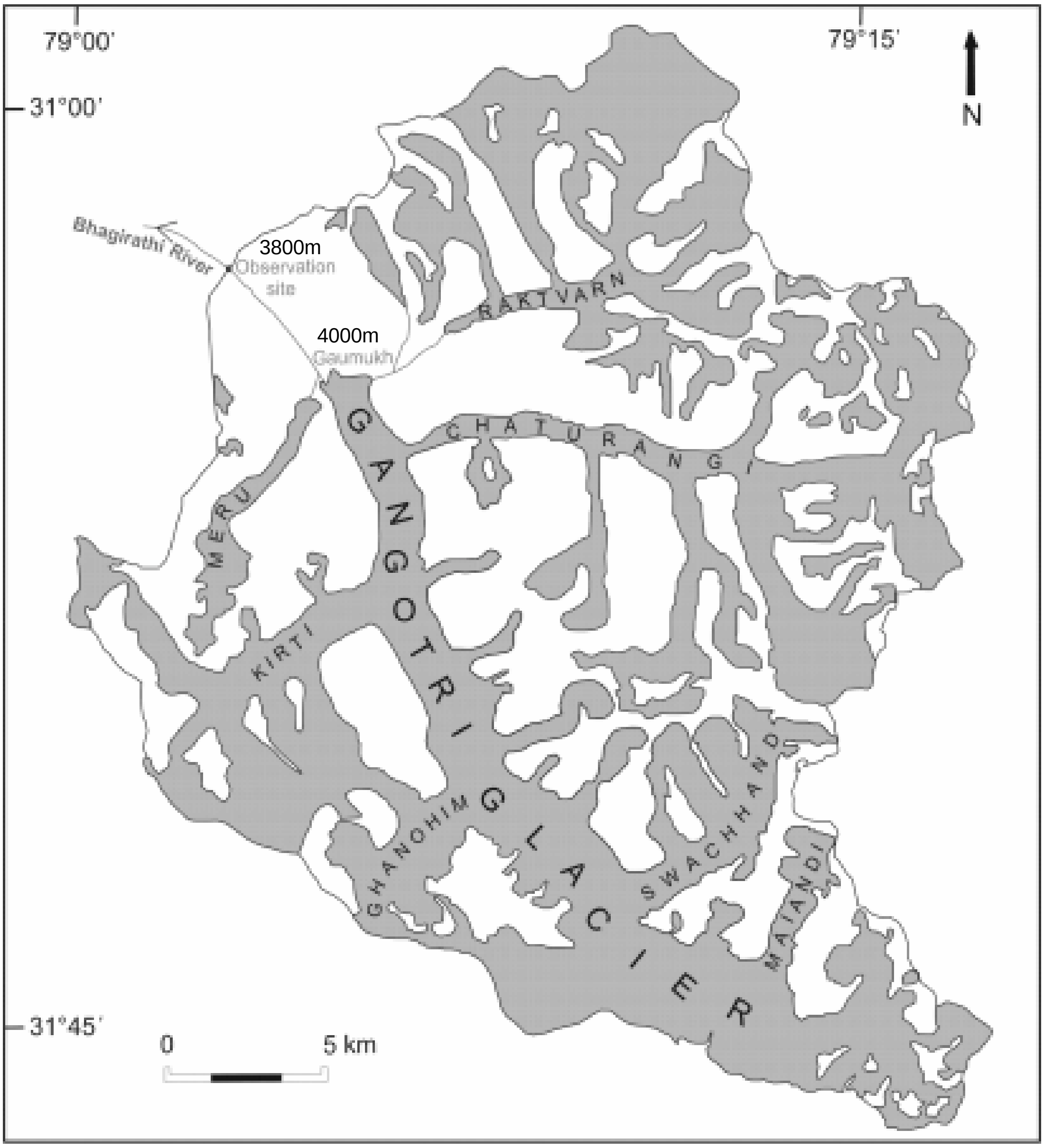

Fig. 1 Map showing location of the study area with the Gangotri Glacier system.

sounding rods at the beginning of the melt season and was rechecked at the end of the season. As discussed by Singh *et al*. (2004b), the flow measurements may have ±5% error particularly during the peak melt period (July and August) when discharge is high.

For determination of suspended sediment in the melt stream water, samples were taken directly from the channel at the sampling site in a pre-cleaned polyethylene bottle (500 ml) twice a day (08:30 and 17:30 h) during the melt season. The samples were collected from the stream at about mid-depth, filtered at the site using Whatman-40 ashless filter paper. The samples were dried at 200°C for 24 h in the laboratory. The

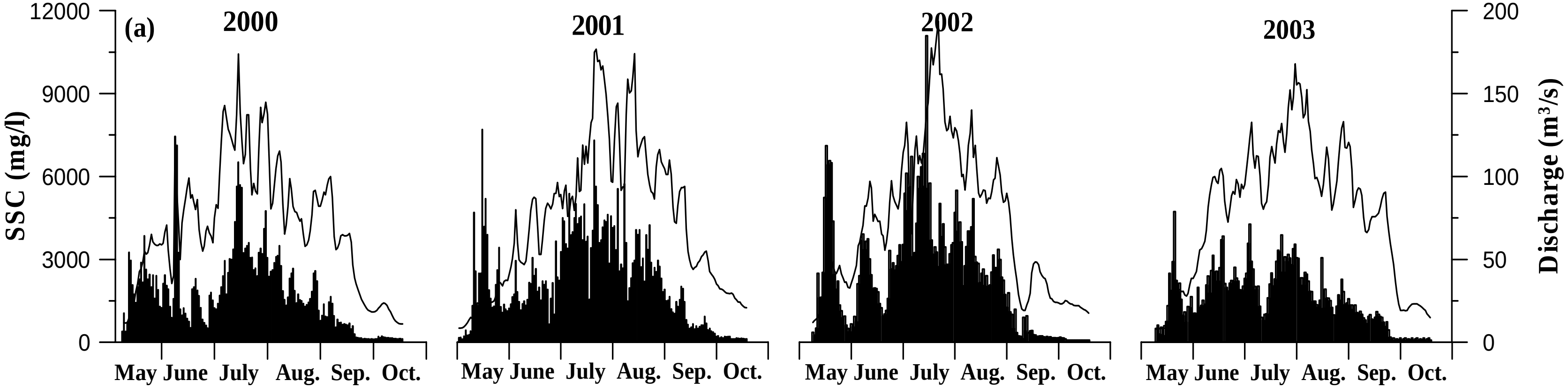

Fig. 2 Mean daily suspended sediment concentration (SSC) and discharge observed at the gauging site of the Gangotri Glacier during the 2000, 2001, 2002 and 2003 melt seasons. Line graphs represent discharge whereas bar graphs represent SSC.

SSC for each sample was determined by weighing the dried samples. Under the given field conditions, the possibility of error in suspended sediment estimations is expected to be about ±5%.

RESULTS

The morning (08:30 h) suspended sediment samples reflect the trough value while evening (17:30 h) samples reflect the peak value. Therefore, it was considered appropriate to compute daily mean values of SSC using morning and evening observations. Daily mean SSC and discharge recorded at the gauging site for the melt season in the years 2000, 2001, 2002 and 2003 are given in Fig. 2. It was observed that daily mean SSC in the melt stream varied between 70–11093 mg L^{-1}. For the entire sampling period, the average seasonal sediment concentration was found to be 1966 mg L^{-1}. Mean monthly SSC during the melt season 2000–2003 were 1942, 2063, 3658, 2551, 734 and 136 mg L^{-1} for May, June, July, August, September and October, respectively, while maximum values of SSC for the corresponding months were 7700, 7450, 11093, 5720, 2020 and 320 mg L^{-1}, respectively. The results from the Gangotri Glacier were compared with other glaciers located in the Himalayan region, such as the Dunagiri Glacier (236 mg L^{-1}) in the Dhauliganga-Alaknanda basin (Srivastava *et al*., 1999) and the Dokriani Glacier (748 mg L^{-1}) in the Dingad-Bhagirathi basin (Singh & Ramasastri, 1999). It is found that the average seasonal sediment concentration for the Gangotri Glacier is much higher than the other glaciers.

It can be noted from Fig. 2 that the distribution of SSC over the ablation season broadly follows the distribution of streamflow. SSC rises rapidly with increasing discharge from May onwards, reaches its maximum in July and then decreases. To study the delivery pattern of SSC and discharge, the cumulative percentage distributions of both SSC and discharge were computed for each melt season (Fig. 3). The percentage delivery of cumulative SSC in the melt water precedes that of the corresponding value of discharge throughout the melt season. To understand the temporal behaviour of the delivery of SSC and discharge, the dates corresponding to 10%, 50% and 90% delivery of SSC and discharge were computed. The delivery of SSC in terms of percentage of total delivered SSC in the season was always in advance relative to the corresponding discharge percentage. Furthermore, it was noted that the percentage delivery distribution was earlier (~19 days) in the beginning (May and June) and end (September and October) of the melt season in comparison to the peak-melting season, i.e. July and August, (~12 days).

Estimates of suspended sediment yield were made for different melt seasons. For the 2000, 2001, 2002 and 2003 melt seasons sediment yield was computed to be 4099, 5518, 5843 and 3876 tonnes km^{-2}, the average being 4834 tonnes km^{-2}. The year-to-year variability in sediment yield might be due to several factors such as variation in prevailing weather conditions, glacier dynamics and thermal regime/variation in discharge and type of subglacial drainage system (Hallet *et al*., 1996; Hodson, *et al*., 1998; Singh *et al*., 2003).

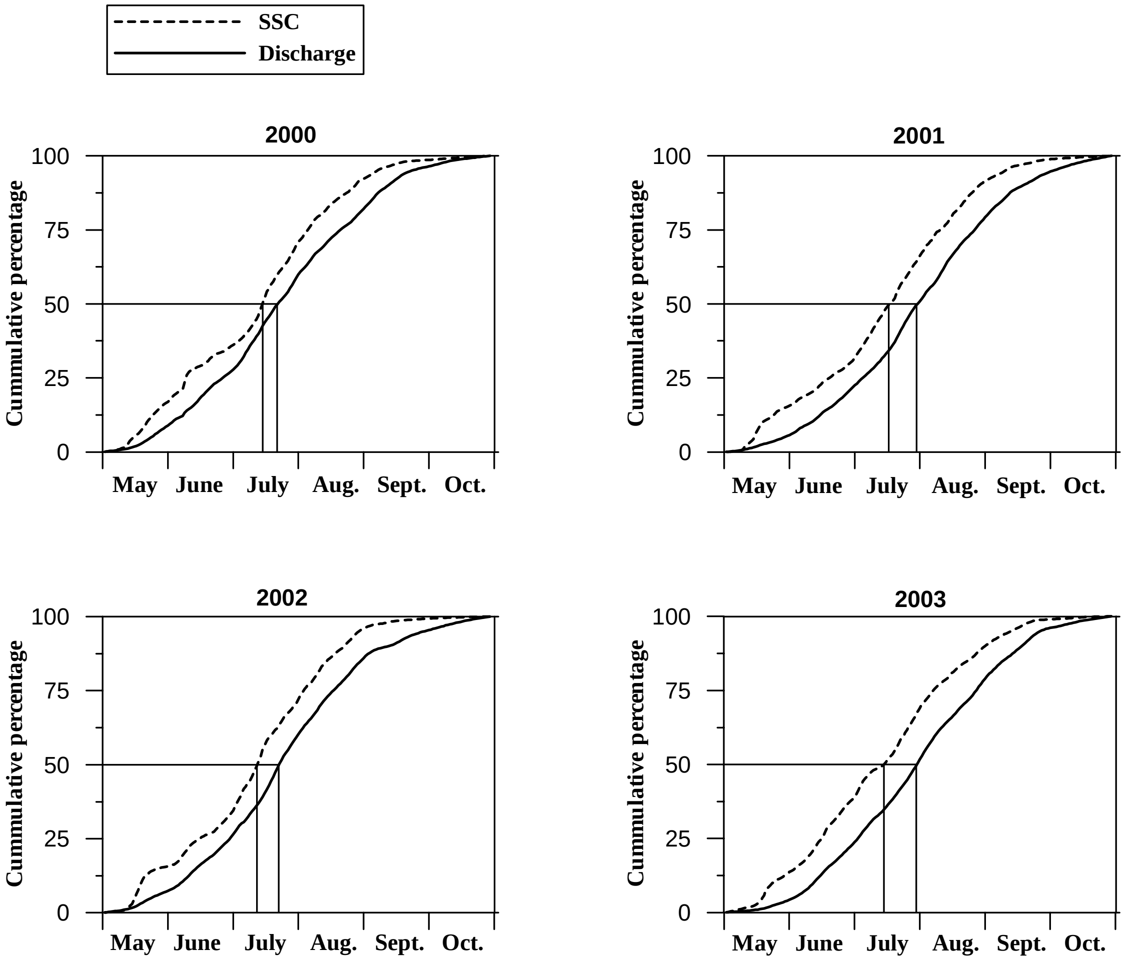

Fig. 3 Relationship between cumulative percentage of the total discharge and suspended sediment concentration (SSC) near the snout of the Gangotri Glacier.

CONCLUSIONS

Based on the observations of four ablation seasons (2000–2003), the important findings from the study are as follows:

1. The delivery of suspended sediment concentration broadly followed the pattern of melt water discharge. Daily mean concentration of suspended sediment varied between 70–11093 mg L^{-1}. For the whole ablation season, the average value of SSC was 1966 mg L^{-1} and that of sediment yield was 4834 tonnes km^{-2}.
2. The SSC is relatively higher in the initial ablation period than the later part of ablation period for near-similar values of discharge.
3. The percentage delivery of cumulative SSC was found to be higher throughout the ablation period as compared to the discharge.
4. The months of July and August, which represent the peak melt period for Himalayan glaciers, contribute nearly 75% of the total sediment, whereas September and October carry only ~6%.

REFERENCES

Bezinge, A., Clarke, M. J., Gurnell, A. M. & Warburton, J. (1989) The management of sediment transported by glacial melt-water streams and its significance for the estimation of sediment yield. *Ann. Glaciol.* **13**, 1–5.

Bruijnzeel, A. & Bremmer, N. N. (1989) Highland and lowland interaction in the Ganges-Brahmaputra river basin: a review of published literature. Occasional paper no. 11, International Center for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal.

Burbank, D. W. *et al.* (1996) Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas. *Nature* **379**, 48–50.

Butz, D. (1989) The agricultural use of melt water in Hopar settlement, Pakistan. *Ann. Glaciol*. **13**, 35–39.

Hallet, B., Hunter, L. & Bogen, J. (1996) Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. *Global Planetary Change* **12**, 213–235.

Harbor, J. & Warburton, J. (1993) Relative rates of glacial and nonglacial erosion in alpine environments. *Arctic & Alpine Res*. **25**, 1–7.

Hodson, A., Gurnell, A., Tranter, M., Bogen, J., Hagen, J. O. & Clark, M. (1998) Suspended sediment yield and transfer processes in a small High-Arctic glacier basin, Svalbard. *Hydrol. Processes* **12**, 73–86.

Jackson, M. & Bilham, R. (1994) Constraints on Himalayan deformation inferred from vertical velocity fields in Nepal and Tibet. *J. Geophys. Res*. **99**(B), 13897–13912.

Jansson, M. (1988) A global survey of sediment yield. *Geogr Ann.* **70** (A), 81–98.

Nakata, T. (1989) Active faults of the Himalaya of India and Nepal. In: *Tectonics of Western Himalayas* (ed. by L. L. Malinconico & R. J. Lillie), 243–264. Geol. Soc. Am. Spec. Paper 232.

Singh, P., Haritashya, U. K., Ramasastri, K. S. & Kumar, N. (2004a) Prevailing weather conditions during summer seasons around Gangotri Glacier. *Curr. Sci.* **88**, 753–760.

Singh, P., Haritashya, U. K., Ramasastri, K. S. & Kumar, N. (2004b) Diurnal variations in discharge and suspended sediment concentration, including runoff-delaying characteristics, of the Gangotri Glacier in the Garhwal Himalayas. *Hydrol. Processes* **19**, 1445–1457.

Singh, P., Ramasastri, K. S., Kumar N. & Bhatnagar, N. K. (2003) Suspended sediment transport from the Dokriani Glacier in the Garhwal Himalayas. *Nordic Hydrol*. **34**, 221–244.

Singh, P. & Ramasastri, K. S. (1999) Project report on Dokriani Glacier. National Institute of Hydrology, Roorkee, India.

Srivastava, D., Swaroop, S., Mukerji, S., Gautam, C. K. & Roy, D. (1999) Suspended sediment yield and its variation in Dunagiri Glacier melt stream, Garhwal Himalaya. In: Abstracts. of the Symp. on Snow, Ice and Glaciers, A Himalayan Perspective (Lucknow, India).