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Suspended sediment from the Gangotri Glacier: Quantification, variability and associations with discharge and air temperature

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Abstract

To understand the sediment delivery variation for a Himalayan Glacier (Gangotri Glacier, Garhwal Himalayas) and to determine its relationship with discharge and air temperature, suspended sediment samples and discharge data were collected near the glacier snout (4000 m) for four melt seasons during the period 2000–2003. These data were used to estimate suspended sediment concentration (SSC), suspended sediment load (SSL), sediment yield and erosion rate in the glacier melt stream (Bhagirathi). The monthly distribution of suspended sediment and its variability from year to year have been examined. Mean monthly SSC for May, June, July, August, September and October were found to be 1942, 2063, 3658, 2551, 734 and 136 mg l^{-1}, respectively. Maximum SSC in meltwater was observed in July followed by August. It was found that the cumulative percentage delivery of SSC precedes discharge throughout the melt season. Mean monthly total SSL for May, June, July, August, September and October during the study period was found to be 149, 423, 1220, 746, 143 and 5×10^3 ton, respectively. The strong variability is found in SSL ($C_v=1.1$) than SSC ($C_v=0.8$) because computation of SSL includes both discharge ($C_v=0.6$) and SSC. Delivery response of SSL in terms of percentage of total load is less in the early part of the melt season than in the later stage in comparison to that of discharge. This may be due to the fact that in the beginning of the melt season low melt rate conditions prevails and thus, the low discharge velocity could not flush out stored glacial sediment. It has been observed that 59–64% of the sediment passed through the channel by the time 50% of the total discharge passed. The average suspended sediment yield for the whole melt season from the study area was estimated to be about 4834 ton km^{-2} and corresponding erosion rate was 1.8 mm. The relationship between mean monthly SSC and discharge ($R^2=0.99$) is much better than the daily SSC and discharge ($R^2=0.40$) because variability of both parameters is averaged-out on monthly scale. Mean monthly SSC and mean monthly SSL provide a good exponential relationship with mean monthly air temperature. These results are relevant for planning and management of water resources in the high altitude areas and for designing hydropower projects.

1. Introduction

The glacial sedimentary system can be defined in terms of sediment sources, processes of erosion, and modes and medium of transport, all of which influence sediment concentration, load in

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the meltwater and sediment yield (Iverson, 1995; Krikbride, 1995). Meltwater runoff generated from glacierized basins carries a significant amount of suspended sediment (Jain et al., 2003). Glacier-fed streams carry sediments in suspended form and as bed load. Suspended sediment, characteristic of turbulent flows, refers to grains maintained in transport above the bed. The bed load is transported at the river bed mainly by sliding or rolling. The main sources of sediment in glacier-fed streams are the glacier, bedrock and channel systems (Benn and Evans, 1998). Hammer and Smith (1983) reported that most of the SSL is derived from subglacial (47%) and channel banks (47%) while a part of the sediment is also generated from the supraglacial (6%). Glacier erosion is higher in warm glaciers than in cold glaciers, as warm glaciers continuously move on their beds, while cold glaciers move occasionally (Iverson, 1995). Across the world, it has been reported that sediment yield is higher in glacierized basins than in non-glacierized basins (Guymon, 1974; Embleton and King, 1975; Jansson, 1988; Harbor and Warburton, 1993; Hallet et al., 1996). The delivery of sediments also depends on the amount of water draining through the glacier (Østrem, 1975a; Drewry, 1986). Proglacial streams carrying suspended sediment have practical significance where glacially derived waters are used for irrigation (Butz, 1989), hydropower (Bezinge et al., 1989; Singh et al., 2003) and common drinking purposes.

The Himalaya–Ganges–Brahmaputra system is one of the world's largest highland–lowland systems and transports a large quantity of sediment to oceans. The Himalayan and Tibetan regions cover only about 5% of the Earth's land surface but contribute about 25% of the dissolved load to the world's oceans (Raymo and Ruddiman, 1992). It is estimated that the present sediment yield of the Ganga–Brahmaputra Rivers system together is about one billion tonnes per year (Subramanian, 1993) in comparison to the global annual sediment of 15 billion tonnes per year (Milliman and Meade, 1983). According to Maybeck (1976), three major Himalayan Rivers, namely the Brahmaputra, the Ganges and the Indus carry about 9% of the total annual load from the continents to the oceans worldwide

Most of the Himalayan glaciers are debris covered (Bishop et al., 1998) and the rivers originating from these glacierized areas transport sediment at a very high rate (Bruijnzeel and Bremmer, 1989; Hasnain, 1996; Hasnain and Thayyen, 1999; Kumar et al., 2002; 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 (Hasnain and Chauhan, 1993). The present estimates of uplift rate for different parts of Himalayas vary from 0.6–6 mm yr^{-1} (Gansser, 1983; Rajal et al., 1986; Nakata, 1989; Jackson and Bilham, 1994). The Himalaya possesses fragile ecosystems susceptible to high denudation, the erosion rate being in the range of 2–12 mm yr^{-1} (Burbank, 1996). To analyze these aspects, there is need to establish a long-term database related to SSC (suspended sediment concentration) and SSL (suspended sediment load) for the glacierized basins in the Himalayan region, which is very limited at present. During the melt season, the snow and glacier melt runoff is of vital importance for hydroelectric power generation and irrigation. Hydropower projects in the high altitude Himalayan region, for example, the Maneri Bhali reservoir downstream of the present study area, receive a major portion of their water from the melting of glaciers. The peak flow season (July and August) involves glacier melt along with monsoon rainfall, the later more important in the middle and lower part of basins, and transports large amounts of suspended sediment, which causes silting of the reservoirs.

In this paper, an attempt is made to assess the variations in SSC, SSL, sediment yield and erosion rate. 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/SSL have been studied and compared with data available for other glaciers. Correlations of SSC with discharge and SSC and SSL with air temperature have also been established to understand the sediment transfer processes and dependency of sediment transport over meltwater discharge and air temperature.

2. 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 meltwater stream, known as the Bhagirathi River, originates from the snout of the Gangotri Glacier at an elevation of 4000 masl. The Bhagirathi River valley is a broad U-shaped valley with high sidewalls (30–50 m), which is a characteristic of its glacial origin. The Gangotri Glacier system (most commonly known as Gangotri Glacier), is a cluster of many glaciers with the main Gangotri Glacier (length: 30.20 km; width: 0.20–2.35 km; area: 86.32 km^2) as its trunk. It is a temperate mountain valley glacier, which flows in the northwest direction. The major glacier tributaries of the Gangotri Glacier system are the Raktvarn, Chaturangi, Swachand and Maiandi glaciers that merge with the trunk glacier from the North-east, and the Meru, Kirti and Ghanohim Glaciers that merge with the trunk glacier from the South-west. The altitude range of these glaciers varies from 4000 to 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. Fig. 1 shows the area of the Gangotri Glacier and locations of the snout and the gauging site.

The ablation zone of the Gangotri Glacier is covered with debris and supraglacial lakes. Detailed investigation of the mass balance of this glacier has not been carried out. However, several researchers have studied the retreat of snout and the average recession rate for Gangotri Glacier at present is reported to be about 19 m yr^{-1} (Ravishanker

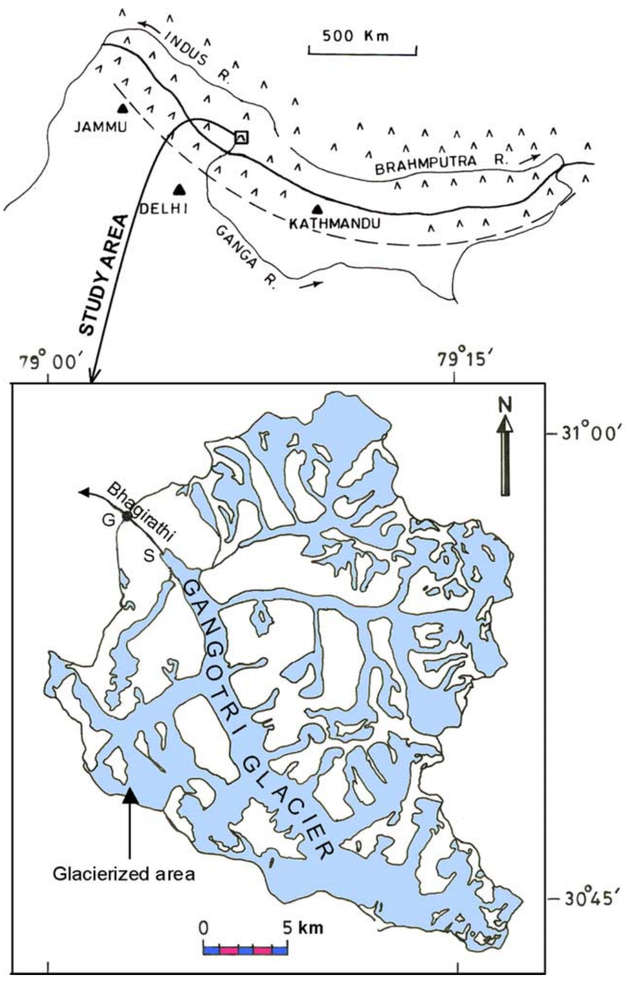

Fig. 1. Location map of the Gangotri group of glaciers. S, snout at Gomukh; G, gauging site 3 km downstream of the snout of the glacier.

and Srivastava, 2001; Prasad and Naithani, 2003). The average seasonal temperature near the snout of the glacier is about 9.4 °C while average seasonal rainfall is about 260 mm. The distribution of rainfall varies from year to year (131–369 mm). Details of such climatic conditions prevailing in the study area have been reported by Singh et al. (2005a).

3. Methodology

For field measurements, a suitable sampling and gauging site close to the Gangotri Glacier terminus was required. A reconnaissance survey of the river was carried out and a suitable gauging site based upon its terrain stability was selected about 3 km downstream from the snout of the Gangotri Glacier (Fig. 1). The river flows in a single channel at the site. No major streams joined the river between the snout and the gauging site, so there was no input of discharge or sediment from other streams before the gauging site. Furthermore, to channelize the flow of water for accurate streamflow measurements, a concrete wall and a stilling well were constructed. An automatic water level recorder was installed in the stilling well for continuous monitoring of variations in water level. A graduated staff gauge was also installed near the stilling well for manual observations of water level. For estimation of discharge, the velocity-area method was used and to compute the velocity of flow, wooden floats were used. The cross-section area of the channel was determined with the help of sounding rods at the beginning of the melt season and was rechecked at the end of the season. To measure velocity, the channel was divided into four segments. Because the surface velocity is higher than the mean velocity, the mean velocity was determined by multiplying the surface velocity by a factor of 0.90 (Singh and Ramasastri, 1999). After calibrating the water levels observed from the staff gauge and the water level recorder, a stage-discharge relationship (rating curve) was developed for each ablation season to convert water levels into discharges. The range of discharge used for constructing stage-discharge relationships for different years was 8–193.5 $m^3 s^{-1}$. Flow measurements may have $\pm 5\%$ of error, particularly during the peak melt period (July and August), when discharge is high (Singh et al., 2005b). Meteorological data (temperature and rainfall) were observed at the Meteorological Observatory established adjacent to the stream-gauging site.

For determination of suspended sediment in the melt stream, water samples were taken directly at the sampling site in a precleaned polyethylene bottle (500 ml) twice a day (0830 and 1730 h) during the melt season 2000–2003 (May–October). The samples were collected from the stream at about mid-depth, filtered at the site using Whatman-40 ash-less filter paper. The filter papers were properly stored in self-locked polythene small bags. These samples were transported to the laboratory (National Institute of Hydrology, Roorkee) and dried at 200 °C for 24 h. The SSC for each sample was determined by weighing. SSL was determined by multiplying SSC by discharge and expressed in tonnes. The present study only includes suspended sediment and the bed load has been ignored, necessarily because bed load data for the Gangotri Glacier could not be collected. This is a common difficulty in a proglacial stream (Warburton, 1990; Hallet et al., 1996), and for the Bhagirathi melt stream it was very difficult due to highly turbulent flow. Estimates of sediment yield based on sediment load were used to determine erosion rates for the basin during a melt season, using the following equation:

$$\text{Erosion rate(mm)} = \frac{\text{sediment yield} \times 1000(\text{kg km}^{-2})}{\text{bedrock density(kg m}^{-3})}$$

Under the given field conditions, the possibility of error in estimating the suspended sediment is expected to be about $\pm 5\%$ including samples collection and analysis.

4. Results and interpretation

4.1. Suspended sediment concentration (SSC)

Analysis of hourly samples collected at an interval of 15 days during the ablation period 2001 (Singh et al., 2005b) suggests that the morning sample (0830 h) reflects the trough value while evening sample (1730 h) reflects the peak value of the diurnal SSC cycle. Therefore, it was considered appropriate to compute daily mean values of SSC using morning

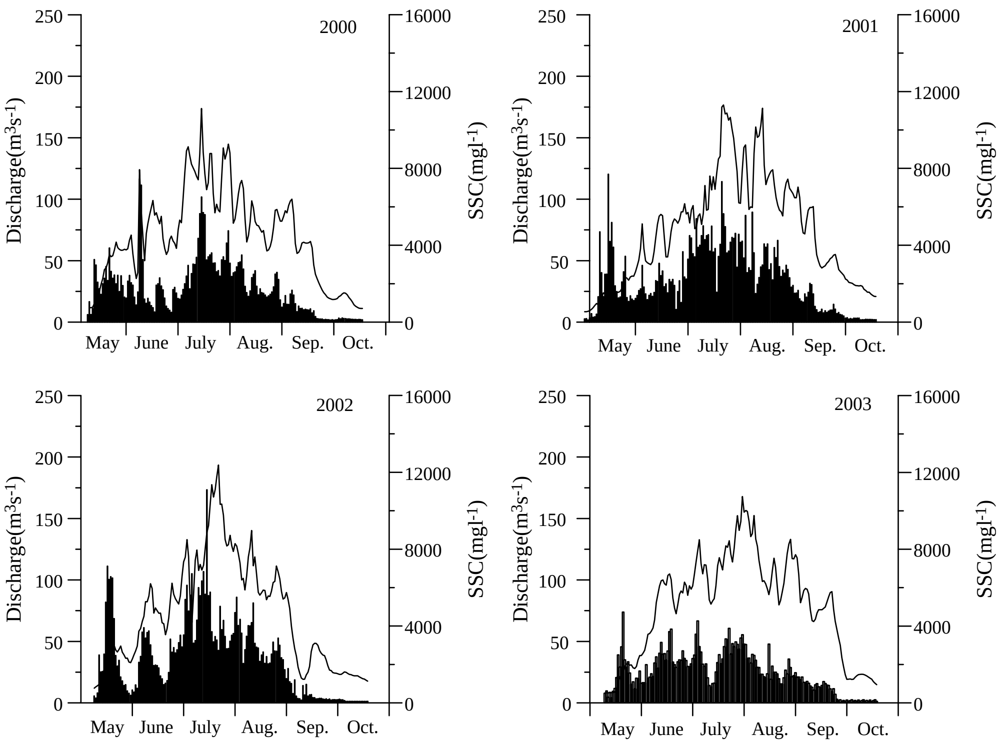

Fig. 2. Mean daily suspended sediment concentration (SSC) and discharge observed at the gauging site of the Gangotri Glacier during 2000, 2001, 2002 and 2003 melt seasons. (The line graph represents discharge whereas the bar graph represents SSC).

and evening observations. Daily mean SSC and discharge recorded at the gauging site for melt seasons in the years 2000, 2001, 2002 and 2003 are given in Fig. 2. Maximum daily mean SSC observed in May, June, July, August, September and October were found to be 7700, 7450, 11,093, 5720, 2020 and 320 mg l^{-1}, respectively. Daily mean SSC in the melt stream varied between 70 and 11,093 mg l^{-1}. For the entire sampling period, the mean daily SSC was found to be 1966 mg l^{-1}. Mean monthly SSC during the melt season 2000–2003 are 1942, 2063, 3658, 2551, 734 and 136 mg l^{-1}, for May, June, July, August, September and October, respectively. Table 1 shows the seasonal SSC for sample collected during different years. A comparison of seasonal SSC for the Gangotri Glacier with other Himalayan glaciers 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 and Ramasastri, 1999) shows that the average seasonal sediment concentration for Gangotri Glacier is much higher than the other glaciers.

The distribution of SSC over the ablation season for all years broadly follows the distribution of

Table 1
Suspended sediment concentration (mg l^{-1}) observed during different years near the snout of the Gangotri Glacier

Year	Daily maximum	Daily minimum	Mean (May–October)	σ	C_v
2000	7450	111	1764	1409	0.8
2001	7700	110	2191	1626	0.7
2002	11,093	80	2322	2009	0.9
2003	4730	70	1571	1029	0.7

streamflow. SSC rises rapidly with increasing discharge from May onwards, reaches its maximum in July and then decreases (Fig. 2). In the year 2000, the flow increased rapidly on 8 and 9 June due to very heavy rains (55.5 mm on 8 June and 49.6 mm on 9 June). After this rain event, the discharge returned to its normal trend. Maximum discharge as well as SSC was observed on 15 July, after which a decreasing trend occurred. Rainfall and higher average air temperature increased discharge and sediment transport from 27 July to 2 August 2000. The typical rising and falling trend of sediment concentration and discharge can be seen in the year 2001 except two highly deviating values between 31 July and 10 August. These may have been due to the presence of cloud cover, low air temperature and little rainfall on 31 July, 4 and 5 August, and 8–10 August (Fig. 2). SSC in 2002 has large variations, which can be explained by the variations in air temperature and cloud cover. Mean monthly air temperature for May, June, July, August, September and October 2002 were 9.0, 10.5, 12.2, 10.9, 6.1 and 5.4 °C. During May, September and October 2002, mean monthly temperature was found to be less than the mean monthly temperatures for the corresponding period in 2000 and 2001 (i.e. 9.8, 8.5 and 5.9 °C in May, September and October, respectively). By contrast for June, July and August 2002, mean monthly temperature is higher (10.5, 12.2 and 10.9 °C) than those for the corresponding period in 2000 and 2001 (i.e. 10.1, 11.7 and 10.8 °C, respectively). Besides, cloud cover was also less in May, June and July 2002 and more in August, September and October 2002 in comparison to 2000 and 2001. In other words, SSC was found to be dependent on the amount of meltwater draining from the glacier, which in turn depends on the prevailing air temperature. So, fluctuation in air temperature or cloud cover was found to affect the pattern of SSC in meltwater (Shcheglova and Chizhov, 1981; Kumar et al., 2002). A sudden decrease in flow from 6 September to 13 September 2002 was due to extremely bad weather conditions such as high rainfall (222.8 mm) and low air temperature 3.8 °C. In the year 2003, although the cumulative volume of discharge was high, the sediment flux was low throughout the melt season. This could be attributed to the fact that the rising and falling pattern of discharge was normal throughout the season without much variation and conditions did not allow for flushing out of sediment.

Daily data show that SSC in the meltwater stream is more variable ($C_v = 0.8$) than discharge ($C_v = 0.6$). Higher variability in SSC could be due to a sudden increase in sediment on a particular day because of some local phenomenon, such as a fall of moraine-laden ice blocks at the snout or rock/debris slide over the glacier. This C_v value is in agreement with the variability of SSC for another Himalayan glacier (Dokriani Glacier; Lat. 31°49′–31°52′ N and Long. 78°47′–78°51′ E) where Singh and Ramasastri (1999) have found a value of $C_v = 0.8$ for SSC.

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 meltwater precedes that of the corresponding value of discharge throughout the melt season. To understand the temporal behavior of the delivery of SSC and discharge, the dates corresponding to 10, 50 and 90% delivery of SSC and discharge were computed (Table 2). The percentage delivery of SSC was always in advance of the corresponding discharge percentage. Moreover, it was also found that percentage delivery distribution of SSC 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).

4.2. Suspended sediment rating curve

The foregone discussion has shown that SSC is closely linked to the meltwater discharge. Therefore, it is useful to prepare rating curves, which can estimate the SSC from the discharge. It is usually necessary to reduce the heteroscedasticity and linearize the SSC-discharge trend (Ferguson, 1977) by logarithmic-transformation of both discharge and SSC. The regression relationship between daily SSC and discharge was attempted for all years together (Fig. 4a). It is observed that for the daily data, the average coefficient of determination (R^2) for all the years (2000–2003) is 0.53. A relationship between mean monthly SSC and mean monthly discharge for all the years (2000–2003) was also investigated (Fig. 4b). A very strong relationship is observed

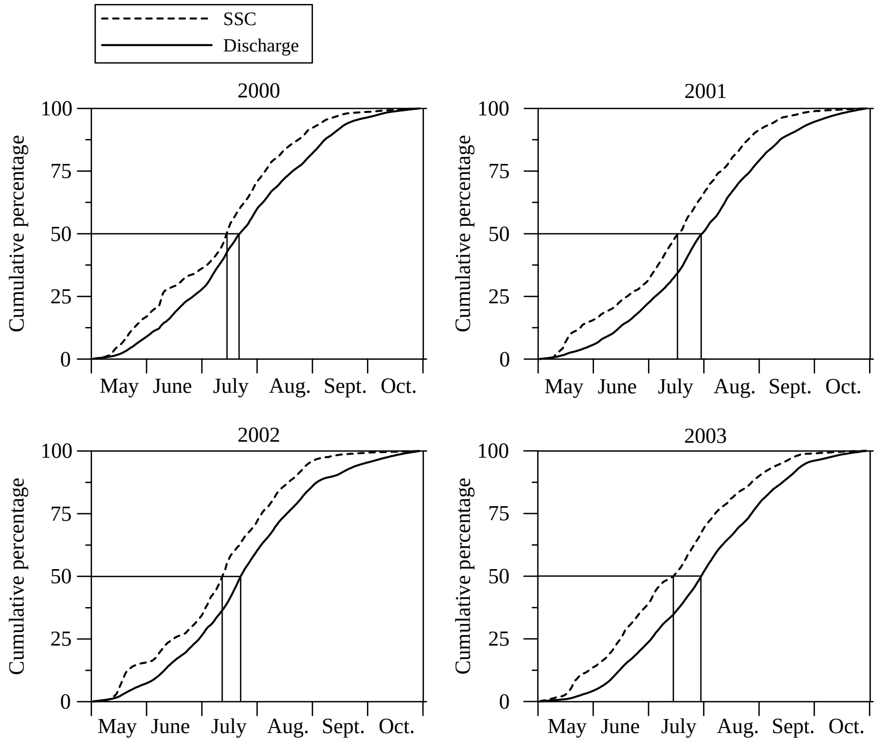

Fig. 3. Cumulative percentage of total discharge and suspended sediment concentration (SSC) curves for the Gangotri Glacier during 2000, 2001, 2002 and 2003 melt seasons.

between mean monthly values of SSC and discharge ($R^2=0.99$). The relationship between SSC and discharge improved significantly when mean monthly data were used. This shows that these two variables are not related on day-to-day basis, but they have a very high correlation on monthly basis. High correlation between mean monthly values may be due to suppression in variance and reduction in variability of both SSC and discharge on monthly scale (C_v for SSC=0.3; C_v for discharge=0.3) as compared to daily scale (C_v for SSC=0.8; C_v for discharge=0.6).

4.3. Suspended sediment load (SSL)

Since, sediment yield from glacierized basins depends primarily on meltwater, which is negligible during the non-melting period (November–April). In this study, estimates of suspended sediment made

Table 2
Comparison of dates of cumulative percentage distribution of SSC and discharge observed near the snout of the Gangotri Glacier

Year	Dates for cumulative percentage of SSC			Dates for cumulative percentage of discharge (Q)			Lead time		
	$SSC_{10\%}$	$SSC_{50\%}$	$SSC_{90\%}$	$Q_{10\%}$	$Q_{50\%}$	$Q_{90\%}$	$SSC_{10\%}–Q_{10\%}$	$SSC_{50\%}–Q_{50\%}$	$SSC_{90\%}–Q_{90\%}$
2000	21 May	15 July	28 August	02 June	23 July	13 September	12 days	8 days	16 days
2001	19 May	18 July	29 August	11 June	31 July	19 September	23 days	13 days	21 days
2002	18 May	13 July	23 August	07 June	23 July	13 September	20 days	10 days	21 days
2003	23 May	15 July	01 September	12 June	31 July	19 September	20 days	16 days	18 days

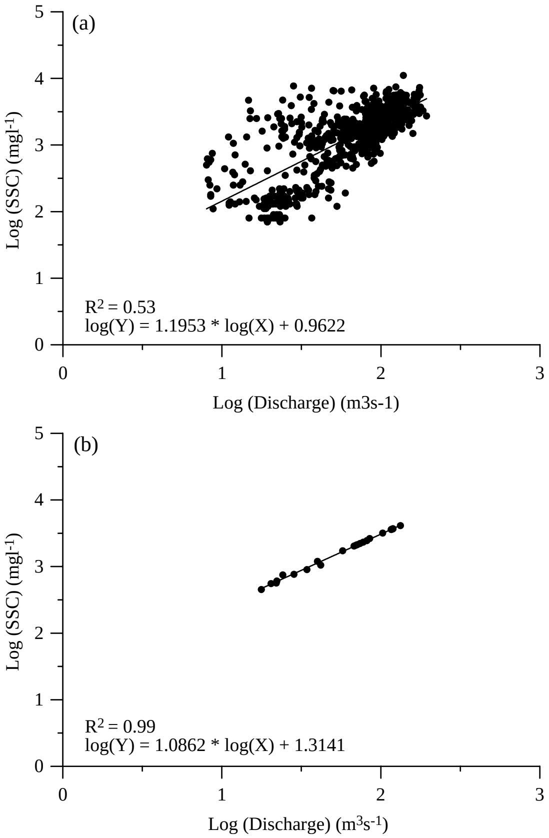

Fig. 4. Relationship between log transformed values of suspended sediment concentration (SSC) and discharge for melting season 2000–2003 using (a) mean daily values, and (b) mean monthly values.

only during the ablation period may be considered representative total suspended sediment yield.

Variability in SSL for the Gangotri Glacier has been compared with other glaciers located in different parts of the world. The result shows that annual variability of SSL for the Gangotri Glacier melt stream is higher ($C_v = 1.1$) than for Norwegian glaciers ($C_v = 0.22$–0.48, Østrem, 1975b) and Alpine glaciers ($C_v = 0.22$, Collins, 1990). The data for the Gangotri Glacier for the year 2000–2003 exhibit a similar pattern of high variability in SSL (Table 3). Singh and Ramasastri (1999) also observed high variability in SSL ($C_v = 1.4$) for the Dokriani Glacier. Results suggest that SSL ($C_v = 1.1$) for the Gangotri Glacier is more variable than SSC ($C_v = 0.8$) as well as discharge ($C_v = 0.6$). This high variability in sediment load with respect to discharge suggests that at many times, sediment transport is limited not by stream capacity but by sediment availability (Alley et al., 1997).

Variation in daily SSL with discharge during the ablation period is shown in Fig. 5(a). Daily SSL ranged between 84 and 132,647 ton, with an overall average for the 4-year period of 16,095 ton day^{-1}. The monthly distribution of SSL and discharge for the different years is shown in Fig. 5(b). Mean monthly total SSL values for May, June, July, August, September and October were 149, 423, 1220, 746, 143 and 5×10^3 ton, respectively. The total annual SSL from the Gangotri Glacier using daily data has been estimated to be 2.28, 3.07, 3.25 and 2.16×10^6 ton for 2000, 2001, 2002 and 2003, the average being 2.69×10^6 ton. In the Himalayas, limited data are available to compare the results from other glaciers. Table 4 provides a comparison of SSL for other Himalayan, Alpine and Arctic Glaciers, suggesting that SSL derived from the Gangotri Glacier is several times higher than for other glaciers.

The magnitude of the discharge and SSL varies from day to day, month to month and year to year (Fig. 5a,b). On the basis of average values for the four melt seasons it is found that about 24% of the total discharge passed in May and June, and transported 22% of total sediment. For the month of July discharge amounted 31%, and this carried nearly 45% of the sediment. In the month of August, the discharge contributes about 27% and the corresponding SSL is also about 27%. This means even though the discharge

Table 3
Suspended sediment load (ton) observed during different years near the snout of the Gangotri Glacier

Year	Daily maximum	Daily minimum	Mean (May–October)	σ	C_v
2000	97,831	120	13,897	16,302	1.2
2001	110,527	84	17,736	18,816	1.1
2002	132,647	122	19,571	21,661	1.1
2003	51,498	102	13,062	11,978	0.9

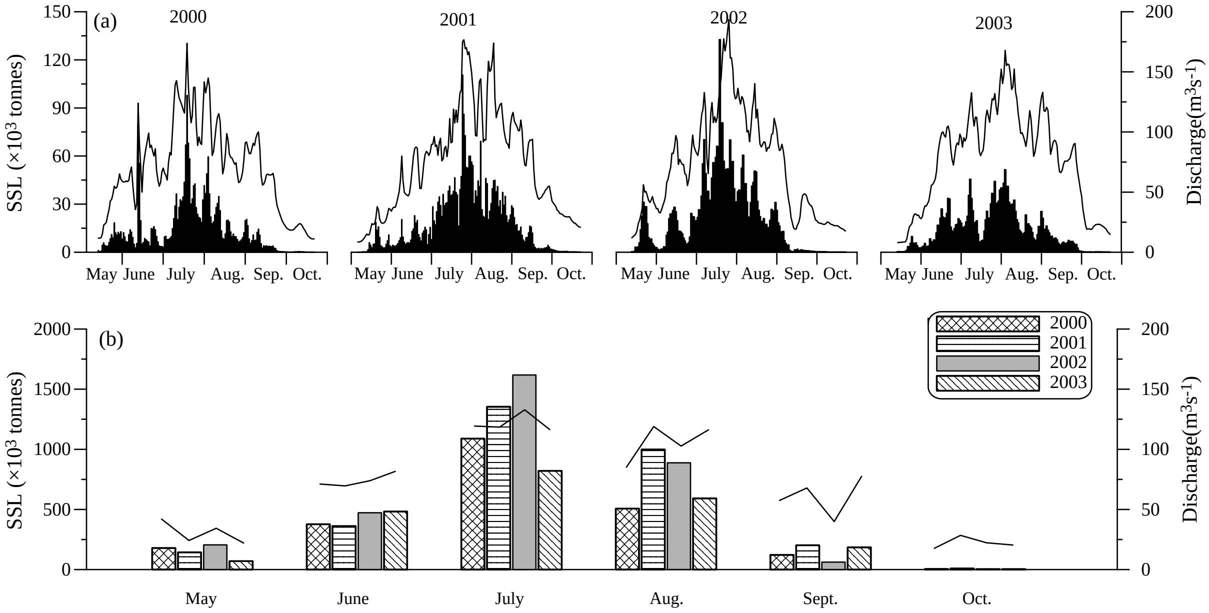

Fig. 5. (a) Mean daily suspended sediment load (SSL) and discharge, and (b) mean monthly SSL and discharge observed at the gauging site of the Gangotri Glacier during 2000, 2001, 2002 and 2003 melting seasons. (In both figures the line graph represents discharge whereas the bar graph represents SSL).

reduces a little in comparison to July, the SSL reduces sharply. After that, in September and October the discharge is about 18% but the SSL is much less about 6%. This pattern is common for all observation years (2000–2003). In May–June the area of melting is limited and the temperature is not high, and these factors may account for lower sediment loads in the early stages of the melt season (Shcheglova and Chizhov, 1981). During the short period of intensive melting (July to August) nearly 72% of the sediment from glacier zone is washed out. During the last two months of the melt season (September and October) although sufficient melting is taking place, the resultant sediment load is much reduced. This may be due to the fact that the major portion of the sediment has been flushed out by the meltwater in the preceding months and in the later part of the season the remaining limited amount of subglacial sediment or morainic material is washed out from the valley walls (Østrem, 1975b; Collins, 1990).

Although the daily, monthly and annual SSL varies significantly from 2000 to 2003, the seasonal delivery

Table 4
Mean daily suspended sediment load (SSL) from the Gangotri Glacier and other glaciers in the Himalayan, Alpine and Arctic regions

Glacier	Region	Basin area (km^2)	SSL (ton day^{-1})	Source
Gangotri	Uttaranchal, Himalayas	556	16,095	Present study
Gornergletscher	Switzerland, Alps	82	1086	Collins (1990)
Ebbabreen	Svalbard, Arctic	51.5	624	Kostrzewski et al. (1989)
Austre Brøggerbreen	Svalbard, Arctic	31.6	186	Repp (1988)
Dunagiri	Uttaranchal, Himalayas	17.9	47	Srivastava et al. (1999)
Dokriani	Uttaranchal, Himalayas	16.1	447	Singh and Ramasastri (1999)
Scott Turnerbreen	Svalbard, Arctic	12.8	126	Hodgkins (1999)
Erikbreen	Svalbard, Arctic	12.4	175	Vatne et al. (1992)
Changme Khangpu	Sikkim, Himalayas	4.5	18	Puri et al. (1999)

(Kostrzewski et al., 1989; Puri et al., 1999)

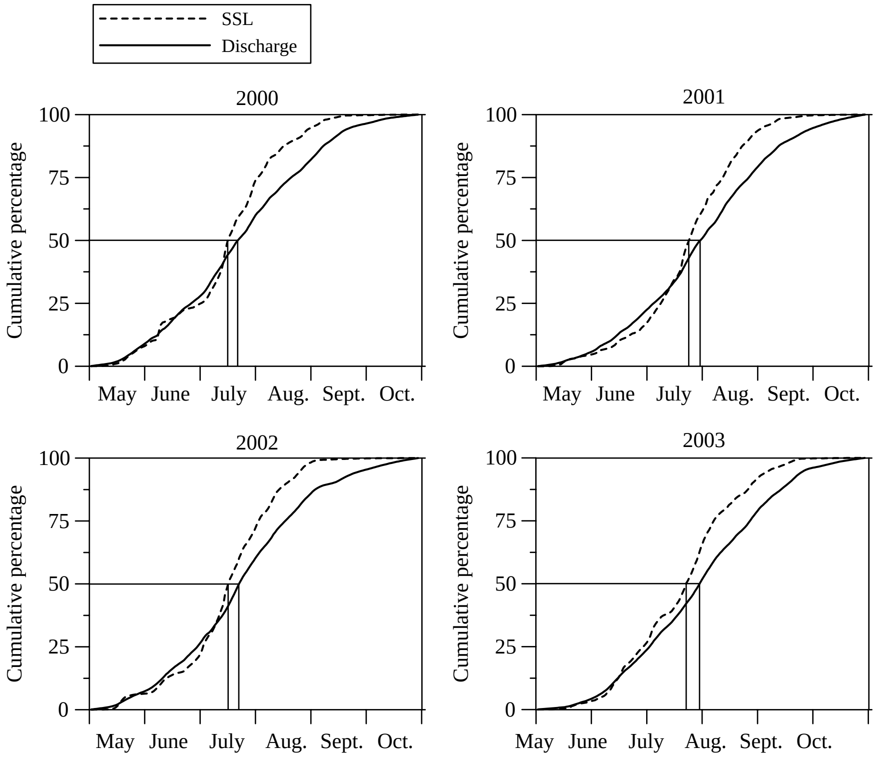

Fig. 6. Cumulative percentage of the total discharge and suspended sediment load (SSL) curves for the Gangotri Glacier during the 2000, 2001, 2002 and 2003 melt seasons.

pattern of SSL and discharge during the melt period remains similar. To investigate this further, the cumulative percentage of SSL and discharge were computed. The study shows that the percentage delivery of SSL is lower than the discharge in the early part of the melt season whereas in the later part of the melt season the reverse trend is observed (Fig. 6). Comparing Fig. 3 with Fig. 6, it can be noted that there is a difference in the percentage delivery pattern of SSC and SSL with respect to discharge. Such a difference in percentage delivery pattern of SSL is because SSL is the product of SSC and discharge, resulting in changes in distribution of cumulative percentage delivery of SSL. The percentage delivery of SSL and discharge for all the years shows a similar trend (i.e. SSL overtakes discharge in the second week of July.) However, sometimes, as in 2003, this process occurred earlier (15 June). This is possibly due to low air temperatures (i.e. mean monthly temperature for May 2003 is 6.65 °C) during the early part of the year, which resulted in the lower discharge (22.0 $m^3 s^{-1}$) and SSL (70×10^3 ton). An increase in temperature (i.e. mean monthly temperature for June 2003 was 10.5 °C) and resultant higher discharge (81.7 $m^3 s^{-1}$) during the second week of June transported a large quantity of sediment (482.6×10^3 ton), which had not been flushed out earlier and was available in the basin. Fig. 6 also shows the general pattern that 50% of the total SSL passes earlier than 50% of the total discharge. The average lead-time of 50% SSL corresponding to the 50% discharge is about 6 to 8 days (Table 5). The delivery of SSL against 50% of total discharge for 2000, 2001, 2002 and 2003 was 59, 61, 61 and 64%, respectively. A comparison of above delivery pattern of SSL for Gangotri Glacier with that of Gornergletscher, Switzerland (Collins, 1990) shows a similar trend in terms of early delivery of SSL than discharge. Although delivery of SSL at Gornergletscher overtakes discharge earlier than the Gangotri Glacier.

Table 5
Comparison of dates of cumulative percentage distribution of SSL and discharge observed near the snout of the Gangotri Glacier

Year	Dates for cumulative percentage of SSL			Dates for cumulative percentage of discharge (Q)			Lead/lag time		
	$SSL_{10\%}$	$SSL_{50\%}$	$SSL_{90\%}$	$Q_{10\%}$	$Q_{50\%}$	$Q_{90\%}$	$SSL_{10\%}$–$Q_{10\%}$	$SSL_{50\%}$–$Q_{50\%}$	$SSL_{90\%}$–$Q_{90\%}$
2000	04 June	17 July	24 August	02 June	23 July	13 September	2 days lag	6 days lead	20 days lead
2001	16 June	25 July	28 August	11 June	31 July	19 September	5 days lag	6 days lead	8 days lead
2002	09 June	17 July	19 August	07 June	23 July	13 September	2 days lag	6 days lead	25 days lead
2003	13 June	23 July	30 August	12 June	31 July	19 September	1 day lag	8 days lead	20 days lead

The pattern of overtaking is clearer in the Gangotri Glacier than the Gornergletscher. This may be because the Gangotri melt season is longer (May–October) than the Gornergletscher (June–September).

The occurrence of rainstorms has a significant impact on glacier runoff as well as the sediment flux. According to Tempany and Grist (1958), heavy rain occurred in short period influences the increase of sediment in meltwater more than the increase in melt runoff. For the Gangotri Glacier, it is found that on a rainy day SSL increased 7.8 times whereas discharge increased only 1.8 times. Hasnain (1996) observed in Dokriani Glacier, Garhwal Himalayas, that there a nine-fold increase occurs in sediment load with only a 1.25 times increase in flow discharge during a rainy day. However, it is important to note, that local storms lead to both increased discharge and sediment but the timing of the occurrence of storm during the melt

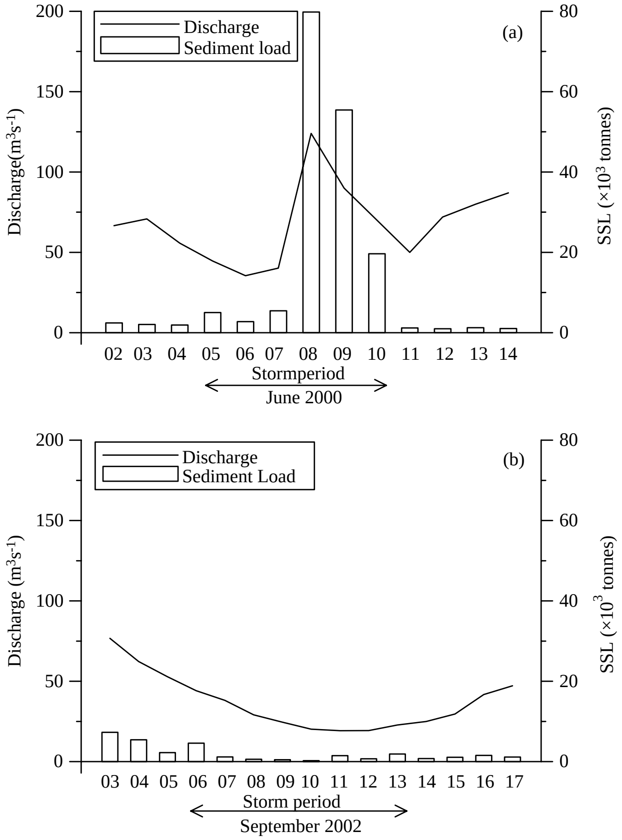

Fig. 7. Daily discharge and suspended sediment load (SSL) observed during rain storms in: (a) June 2000 and (b) September 2002.

season is very important in governing the total sediment in meltwater. For example, a storm, lasting from 5 to 10 June 2000 provided total rainfall of 131.5 mm and carried 19% of June's discharge but 45% of the SSL (Fig. 7a). However, another storm, (6–13 September 2002), provided a total rainfall of 222.8 mm and carried 18% of the month's discharge but only 18% of SSL of this month (Fig. 7b). The difference between the two events is that the first event occurred at the beginning of the melt season when large quantities of stored sediment were available for flushing out, whereas the second storm occurred towards the end of the melt season when the sediment supply was depleted. These two examples reflects that although rainstorm affects the sediment evacuation but mostly it depends on the time season of the rain event.

4.4. Sediment yield and erosion

Sediment yield is the total sediment outflow from a catchment measurable at one point during a specific period of time (Singh and Singh, 2001). Sediment yields during the different melt seasons 2000, 2001, 2002 and 2003 were 4099, 5518, 5843 and 3876 ton km^{-2}, the average being 4834 ton km^{-2}. The year-to-year variability in sediment yield may be due to several factors, including variation in prevailing weather conditions, glacier dynamics and thermal regime and variation in discharge and type of subglacial drainage system (Collins, 1990; Hallet et al., 1996; Hodson et al., 1998; Singh et al., 2003). Moreover, sometimes the sediment produced in a year may not be flushed out concurrently; and, therefore, influences the sediment transport of subsequent years (Singh and Singh, 2001). Thus, the sediment supply may not be equal to the rate of sediment transport every year (Collins, 1979). For this reason, the largest sediment yields may not correspond to the years of high discharge in the Gangotri Glacier (for example in the year 2003, as discussed in Section 4.1). The responses of sediment yield and discharge are similar but the frequency and the magnitude of yield varied from year to year.

Hodgkins et al. (1997) compared sediment yields of Scott Turnerbreen, Svalbard (basin area: 12.8 km^2; glacierized area 32%) and Haut Glacier d'Arolla, Switzerland (basin area: 11.7 km^2; glacierized area 54%). Without considering bed load measurements, it was observed that at Scott Turnerbreen (90-day melt season) the sediment yield was 530 ton km^{-2} whereas in Haut Glacier d'Arolla (170-day melt season) it was 4500 ton km^{-2}. The low yield at Scott Turnerbreen, a cold-based glacier, is due to the short melt season and low specific water flux. While comparing these results with the Gangotri Glacier (basin area: 556 km^2; Glacierized area 51%; ~170-day melt season) it was found that the sediment yield of Gangotri Glacier (4834 ton km^{-2}) is comparable to the Haut Glacier d'Arolla suggesting similar rate of delivery of sediments during the melt season.

According to Hallet et al. (1996), glacial erosion rates may vary by several orders of magnitude for different parts of the world, being of the order of 0.01 mm yr^{-1} for polar glaciers and thin temperate plateau glaciers on crystalline bedrock, and about 10–100 mm yr^{-1} for large and fast moving temperate glaciers in tectonically-active regions. Small temperate glaciers in the Swiss Alps show erosion rates of 1–2 mm yr^{-1} (Bezinge, 1987). In the Himalayas, the melt period erosion rate in the Dokriani Glacier is 1.0 mm (Singh et al., 2003); the Rakiot Glacier in Nanga Parbat is 1.4–2.1 mm (Gardner and Jones, 1984). The Hunza River in western Karakoram Himalayas has an annual erosion rate of 1.8 mm yr^{-1} (Ferguson, 1984). The erosion rate in Gangotri Glacier based on 4 years melt period data and using a standard bedrock density of 2700 kg m^{-3} (Hallet et al., 1996; Singh et al., 2003) was found to be 1.8 mm. The erosion rate for Gangotri Glacier is comparable to the erosion rate reported from the other parts of the Himalayas as well as from the Swiss Alps. This suggests the presence of large and active glaciers, tectonic activity seismicity, and steep valleys with frequent avalanching in these regions.

4.5. Relationship between sediment concentration and load with air temperature

Air temperature influences glacier melt and results in water generation. As described in the previous section, a good correlation has been found between mean monthly discharge and SSC. Therefore, an attempt has been made to understand the relationship between mean monthly air temperatures and mean

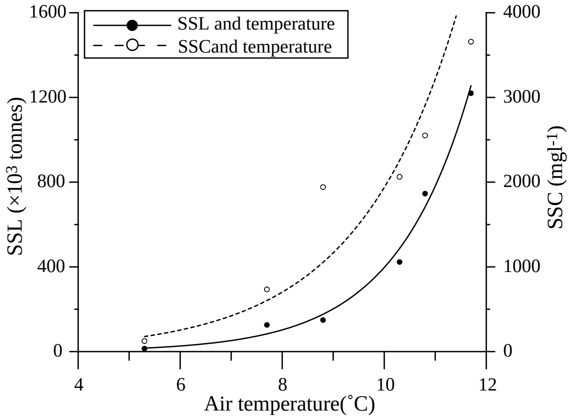

Fig. 8. Mean monthly suspended sediment concentration (SSC) and suspended sediment load (SSL) against mean monthly air temperature observed 3 km from the snout of the Gangotri Glacier during the 2000, 2001, 2002 and 2003 melting seasons.

monthly suspended sediment concentration (SSC) and load (SSL) using the 2000–2003 data for the Gangotri Glacier. As shown in Fig. 8, an exponential relationship has been obtained in both the cases and it can be presented in the form of following equation

$$\text{SSL} = a \exp(bT)$$

where, T is the mean monthly air temperature, and a and b are the estimated coefficients. The coefficient of determination between SSC and air temperature (R^2 = 0.92), and between SSL and air temperature (R^2 = 0.98) suggests a strong relationship and dependency of sediment evacuation over the air temperature. This relationship is even better than the correlation coefficient observed for other glacierized basin in the Pamir region, which varied between 0.57 and 0.97 (Shcheglova and Chizhov, 1981). A good relationship between discharge and temperature (R^2 = 0.73) for the Gangotri Glacier has also been observed by Singh et al. (2005c). This suggests that both melting of glacier and sediment evacuation is temperature driven.

5. Concluding remarks

The present study deals with quantification of the suspended sediment concentration and load, its variation, and its association with stream discharge and temperature on the basis of data collected from the Gangotri Glacier located in the Himalayan region for four ablation seasons (2000–2003). The important findings from the study are as follows:

1. Daily mean SSC varied between 70 and 11, 093 mg l^{-1} with an average being 1966 mg l^{-1}. Broadly, the SSC follows the pattern of meltwater discharge. The SSC is relatively higher in the initial ablation period, compared to the later part of ablation period, for near-similar values of discharge. Given percentage deliveries of cumulative SSC were found to be relatively advanced throughout the ablation period as compared to the discharge. A considerable variation has been found in SSC (C_v = 0.8).
2. The daily SSL for Gangotri Glacier ranges between 84 and 132,642 ton with the average being 16,095 ton day^{-1}. A comparison with Norwegian and Alpine glaciers suggests a high annual variability of SSL in the Himalayan region. The months of July and August, which represent the peak melt period for Himalayan glaciers, contribute ~75% of the total sediment, whereas September and October carry only ~6%. Normally, in July and August, the glacier bed observes hydraulic re-organization after passage of peak flow, which may be the reason for high sediment discharge during that period. As a whole in September and October, the drainage system remains stable, maintaining only the background levels of sediment flux. The delivery pattern of SSL in terms of percentage of total cumulative load is lower than the discharge during the early melt season but as the season advances this delivery pattern of SSL becomes higher than discharge. In general, it was noted that, by the time 50% of the discharge passed, 59–64% of sediment has been carried away.
3. The average sediment yield for a melt period in the basin is found to be very high (4834 ton km^{-2}) than Svalbard (Hodgkins et al., 1997), Pamir and Tien Shan region (Shcheglova and Chizhov, 1981) and is comparable to the available records of Haut Glacier d'Arolla. The erosion rate for the Gangotri is estimated to be 1.8 mm, which is quite comparable to the erosion rates reported for other Himalayan glaciers.
4. A rating curve between SSC and discharge has been established. The mean daily SSC and

discharge data shows an average correlation ($R^2=0.40$). However, on the other hand, the relationship between mean monthly SSC and discharge shows a high degree of correlation ($R^2=0.99$). The lower correlation for the daily scale and very high correlation for mean monthly data indicate that the two variables are weakly correlated at the diurnal scale but have a very high correlation due to suppression of variance by averaging at the monthly scale. A strong exponential relationship was found between sediment concentration and air temperature ($R^2=0.92$) as well as between sediment load and air temperature ($R^2=0.98$). This is due to the dependency of sediment load on melt runoff, which in turn is controlled by the air temperature.

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