Characterization of Suspended Sediment in Meltwater from Gangotri Glacier

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Abstract— **Glacierised basins are significant sources of sediments generated by glacial retreat. In Himalaya, most of the glaciers are covered by thick debris, especially in the ablation zone. Supraglacial debris cover might play an important role for sediment budget of the glaciated area or for the ablation of ice masses mantled in debris. The glacier system includes sedimentation from different parts of the glacier such as the accumulation zone, ablation zone, snout and the lateral moraines, whereas bedrock system deals with glacier bottom ice and bedrock. During summer season, proglacial meltwater carries considerable amount of suspended sediment. The deglaciated area provides a ready source of sediment during monsoon. Estimation of suspended sediment transfer from glacierised basins is very important in reservoir planning for hydropower projects in Himalaya. Assessment of these sediments transported by the melt stream is important because it has direct influence on the capacity of the reservoirs. Suspended sediment yields in particular are viewed as a sensitive parameter of environmental change, since suspended sediment is broadly supply-controlled, while bed load is broadly hydraulically controlled; therefore, it is expected that suspended sediment fluxes are more responsive than bed load fluxes to climate-driven environmental change, other factors being equal. An assessment of suspended sediment concentration (SSC), load, yield and erosion rate has been undertaken for the Gangotri Glacier drainage basin (nearly 50% glaciated) located in the Garhwal Himalayas. . The proglacial melt water stream, known as Bhagirathi River, emerges out from the snout of the Gangotri Glacier at an elevation of 4000 m. The Gangotri Glacier system most commonly known as Gangotri Glacier, is a cluster of many glaciers comprising of main Gangotri Glacier (length: 30.20 km; width: 0.20 - 2.35 km; area: 86.32 km^2) as trunk part of the system. The flow data was collected from field observations near the snout of the glacier. To determine the mean suspended sediment concentration, load, yield and particle size in the Gangotri Glacier melt stream, two water samples at 0830 and 1730 hours were directly scooped from the channel at the gauging site in a cleaned polyethylene bottle (500 ml). Data were collected for four ablation seasons (2011–2013). Mean monthly SSCs, for May, June, July, August and September during the study period was 1,435, 1,677, 2,086, 1,499 and 528 ppm, respectively, indicating highest SSC in July, followed by August. For the entire melt season, the mean daily SSC was computed to be 1,445 ppm. Similar trends were also found for the sediment load and about 67% of the total suspended sediment load of the melt period was transported during the months of July and August. There is a wide variation in the daily concentration of suspended sediment and SSLs. Both sediment concentration and load were found to be highest in the monsoon months and nearly two-thirds of the total sediment load was transported in these 2 months.**

Keywords— Discharge, Glacier melt, Suspended Sediment Concentration, Suspended Sediment Load

I. INTRODUCTION

This Meltwater draining from glacier basins transports high suspended sediment loads (Gurnell 1987; Lawler *et al.* 1992; Jain *et al.* 2003) which present major problems for the management and use of the meltwater (Bezinge *et al*. 1989; Bogen 1989). The estimation and prediction of sediment transport from glacier basins is, therefore, of major management importance. It also has geomorphological significance for understanding the denudation systems of glaciated areas, estimating landscape denudation rates, and comprehending the impact that the sediment and discharge regimes of glacier-fed rivers have on the dynamics and morphology of Proglacial Rivers (e.g. Fenn & Gurnell 1987; Maizels 1983).

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 Suspended Sediment Load (SSL) is derived from subglacial (47%) and channel banks (47%) while a part of the sediment is also generated from the supraglacial (6%). 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). Hallet *et al*. (1996) have shown that specific sediment yields clearly tend to increase with the extent of glacial cover in the basin. On average, specific sediment yields for basins covered by more than 30% glacier cover were about one order of magnitude higher than for glacier free basins. Gurnell *et al.* (1994) compared the discharge and suspended sediment transport for an arctic and alpine glacier, which were of similar size. They reported stronger diurnal variations in the suspended sediment concentrations in the alpine proglacier river than in the arctic environment. The widely reported “exhaustion” in suspended sediment supply to alpine proglacial streams over the summer ablations season was not observed in the arctic basin. Further Gurnell *et al.* (1996) carried out an analysis of suspended sediment and discharge yield, and catchment characteristics from a sample of 90 glacier basins.

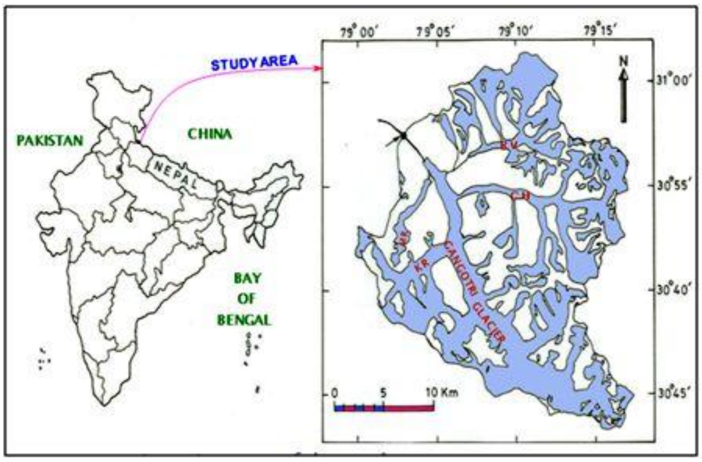
In the Himalayan region, however, measurements of sediment concentration has been carried out for only a very few glaciers for a short period. Quantification of suspended sediment load in high altitude areas becomes more important especially during the peak summer/monsoon period, as higher quantities of sediment due to intense melting or precipitation inputs may be detrimental to the hydroelectric electric power turbines and also lead to siltation of reservoirs. Most of the studies in the Himalayan region have been carried out for lower altitude basins/sites (Sharma *et al.* 1991; Rao *et al.* 1997). However there are a few studies on the Gangotri glacier basin Kumar *et al.* (2002) estimated the discharge volume and total suspended sediment for a period of two ablation seasons (1999 & 2000). The discharge volume was estimated to be 581.87 and 547.47 x 10^6 m^3, respectively, and the total suspended sediment was 165.62 and 104.99 x 10^4 t, respectively. Singh *et al.* (2005) studied the diurnal variability and hysteresis trend on the hourly discharge and SSC data for about 15 days. Diurnal variability in SSC was found to be much higher than the discharge. Hysteresis trends between discharge and SSC were established. Results indicate that, for the study glacier, clockwise hysteresis dominated for the entire melt season, indicating that most of the time the SSC led the discharge. During the peak melt period, anticlockwise hysteresis was also observed for a few hours. Haritashya *et al*. (2006) estimated the average suspended sediment yield for the whole melt season for the period 2000 to 2003 to be about 4834 ton km^2 and corresponding erosion rate was 1.8 mm. Further Haritashya *et al.* (2010) studied the particle size distribution for the period 2000 to 2006 and found dominance of silt size (0.002–0.06 mm) particles (71%) followed by sand size (0.06–0.6 mm) particles (24%) and clay size (< 0.002 mm) particles (5%) during the melt season, with increased variation as melt season progresses. Wulf *et al*. (2012) studies the Climatic and geologic controls on suspended sediment flux in the Sutlej River Valley, western Himalaya and found that in seven of eight catchments an anticlockwise hysteresis loop of monthly sediment flux, which appears to be related to enhance glacial sediment evacuation during late summer. The analysis emphasized the importance of unconsolidated sediments in the high-elevation sector that can easily be mobilized by hydrometeorological events and higher glacial-meltwater. The present study deals with estimation of the sediment yield from the Gangotri Glacier basin along with measurements of the grain size distribution of the suspended particles. Discharge and suspended sediment data collected during four ablation seasons (2008- 2011) have been used. Since a major part of the suspended sediment and runoff drains out during summer period, observations were made only for this period. The results are also compared with information available for glacierized basins in other parts of the world. The results of this study are extremely useful for planning and management of water resources in this region and for designing of hydropower projects. A total of 32 hydropower projects with a total installed capacity 4871 MW are being planned within this basin (IIT, 2011). There are 9 commissioned projects, 4 projects are under-construction and 19 are proposed projects.

The objectives of this study are: (i) to revise the estimate of the sediment concentration and load from a large debris covered Himalayan glacier (ii) Examine the effect of monsoon on the relationship between discharge and Suspended Sediment Concentration/Load from a large Himalayan glacier and estimate the particle size distribution.

II. STUDY AREA

The Gangotri Glacier (Lat. $30^0 43'$ N–$31^0 01'$ N and Long. $79^0 00'$ E–$79^0 17'$ 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 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.

Fig 1. Location and basin map of the Gangotri Glacier in the Garhwal Himalayas.



The main sources of sediment production in the glacier fed channels are the glacier system, bedrock system and channel system. The glacier system includes sedimentation from different parts of the glacier such as the accumulation zone, ablation zone, snout and the lateral moraines, whereas bedrock system deals with glacier bottom ice and bedrock. In the present study, observations were made near the snout of glacier and therefore, the channel system does not contribute much to the generation of the suspended sediment load. The Gangotri Glacier is a valley type glacier and the presence of large crevasses provides evidence of the movement of a large mass of ice down slope, which is accompanied by large amounts of sediment due to glacier bed erosion. Thousands of tonnes of debris are brought down by the glacier and dumped near the snout of glacier due to widespread glacial erosion, which serves as a major sediment source. The sediment produced by glacial erosion and fracturing of debris and rocks over wide areas of bed throughout the year is mobilised by meltwater flow with sufficient velocity and turbulence.

Another important source of sediment from the study glacier is the presence of sediment material like boulders, debris and moraines over the glacier surface. During the active melting period supraglacial material remains in contact with melt- water and becomes a regular source of sediment. The ablation zone of the glacier contributes large amount sediment because a large amount of such material is found in this area and water travels by surface pathways in the ablation zone of the glacier. A part of the sediment material available on the glacier surface is also transported down through extensive longitudinal and transverse crevasses into englacial and subglacial tunnels. The material transported to the glacier bed is abraded and crushed into fine sediment particles within the glacier and bedrock system. From the features of the surface texture of the lateral moraines, it could be expected that chemical and mechanical processes might also mobilise the lateral moraines sediment into the glacier melt stream (Singh et al. 1995). For the study glacier, sediment transport follows three basic routes, namely, supraglacial, englacial and subglacial routes.

III. METHOD OF DATA COLLECTION AND ANALYSIS

A. *Method of Data Collection*

In order to determine daily mean suspended sediment concentrations and loads in the Gangotri Glacier melt stream, two water samples were collected every day from the gauging site at 0830 and 1730 hours, which represent the approximate timings of minimum and maximum concentrations, respectively. A known volume of water (500 ml) was collected from the stream at about mid depth and filtered on-site using Whatman-40 ashless filter paper. All possible data quality measures were taken in collection and analysis of the data. Particle size analysis was undertaken on the combusted sediment using a Malvern Mastersizer E instrument, which gives results in 32 size classes, ranging from 0.5 µm to 600 µm. Particle size analysis was undertaken for two years (2010 and 2011) and the size distributions were studied separately for each month of the ablation period. In total, 10 particle size analyses were made for the study period.

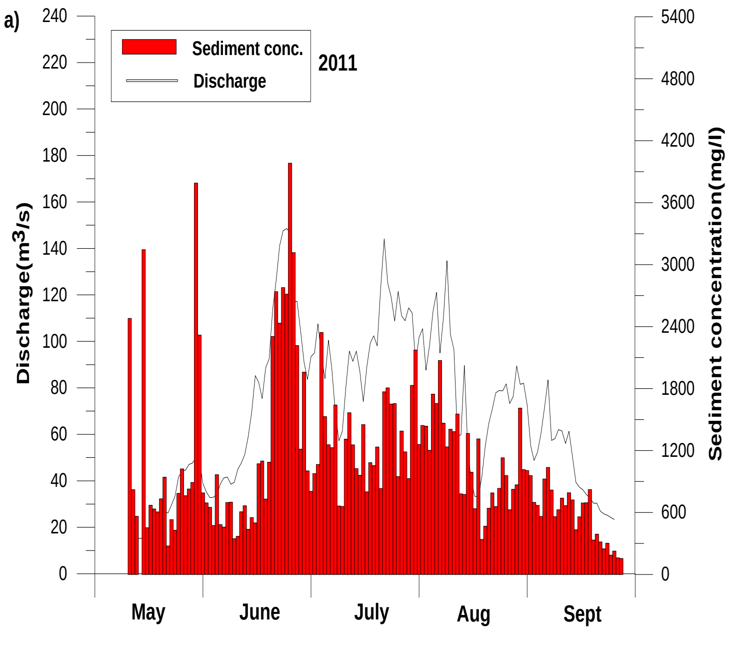
B. *Method of Data Analysis*

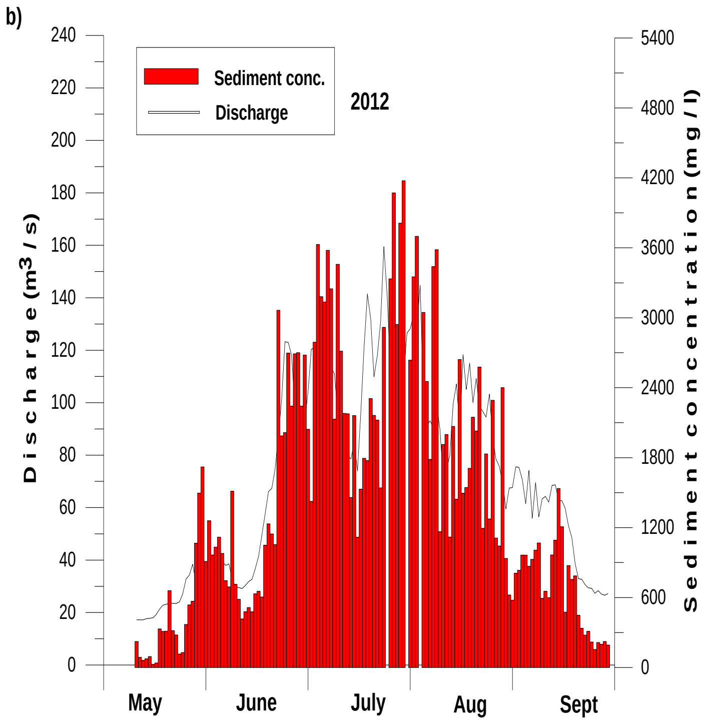
In the laboratory the collected sediment samples were dried in an oven at 200°C for a period of 24 hours and then suspended sediment concentration (SSC) for each sample was determined by weighing the individual sample. Flow data was observed at the monitoring station installed at site. Understanding the relation between discharge and suspended sediment concentration makes it possible to understand the impact of monsoon and other hydrological events. In most of the streams discharge is strongly correlated with sediment concentration but in the glacier fed channels the glacier system, bedrock system and channel system are the main sources of sediment generation. The correlation analysis of Suspended sediment concentration, Sediment load with discharge especially debris covered glacier indicates about the sedimentary system of the glacier.

IV. RESULT

A. *Suspended Concentration and Load*

A plot of daily mean suspended sediment concentration and discharge versus time for the Gangotri Glacier basin is given in Figs. 2(a) to (d). Over the period of record, daily mean suspended sediment concentrations in the melt stream varied from 28 to 8,409 mg l^{-1}. The suspended sediment concentration begins to increase with discharge from June onwards. However, the results indicate that discharge in the melt stream was less variable than suspended sediment concentration. Maximum daily mean suspended sediment concentrations observed in May, June, July, August and September were 6283, 8409, 6663, 4665 and 1536 mg l^{-1}, respectively. The mean monthly suspended sediment concentrations observed for individual months during the different years are shown in Fig. 3.





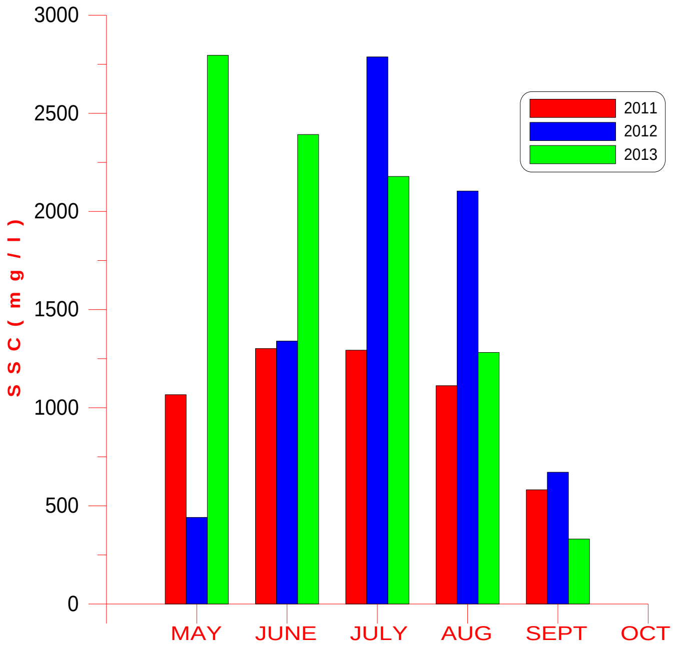


Fig. 3 | Mean monthly SSC observed for different months near the snout of Gangotri glacier during different summer seasons (2011-2013).

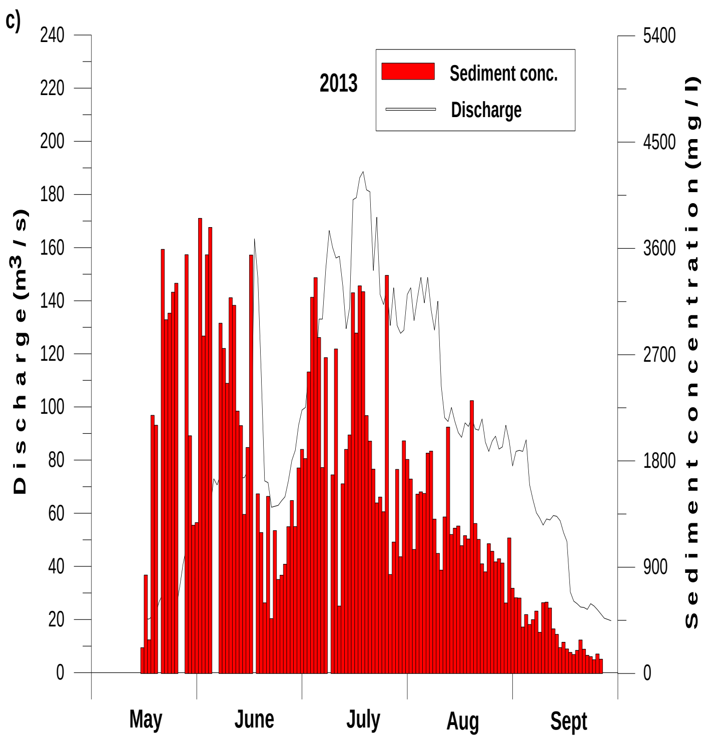
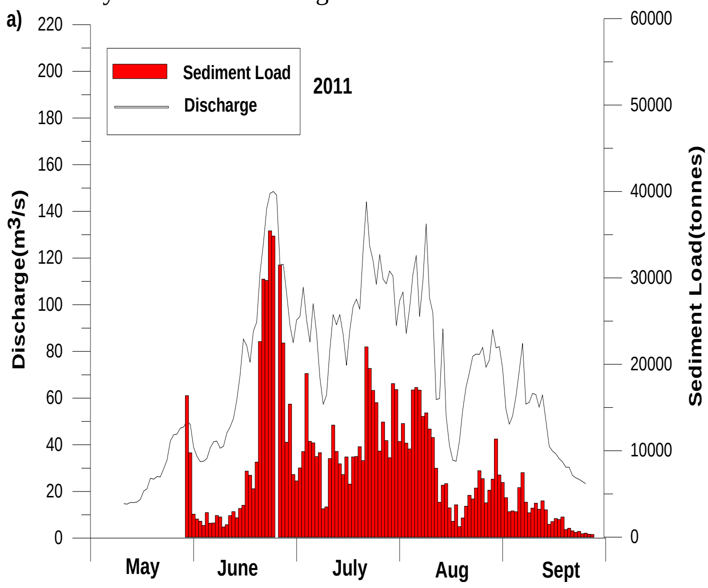
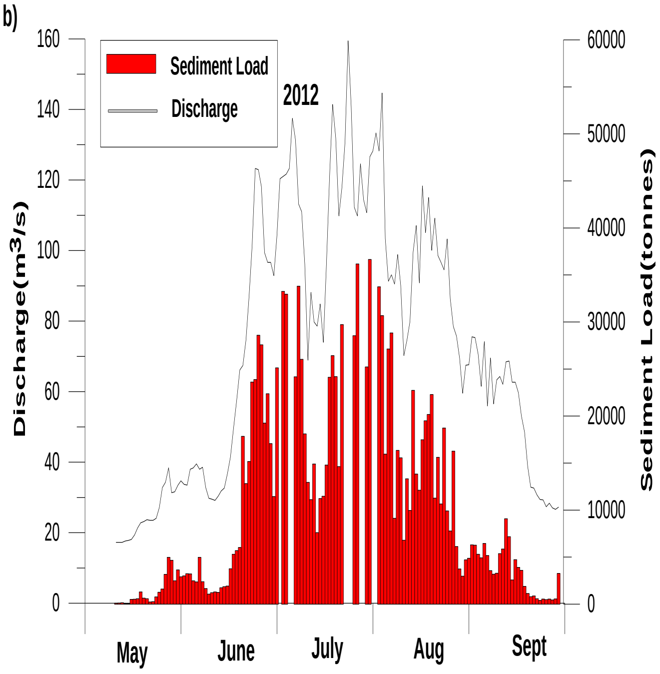


Fig 2 (a) (b) (c).| Observed Discharge and Suspended Sediment Concentration in the Gangotri Glacier melt stream during 2011 to 2013 ablation periods.

Mean monthly suspended sediment concentration, for May, June, July, August and September during the study period was 1435, 1677, 2086, 1499 and 528 mg l^{-1} respectively, indicating highest concentration in July followed by June. Sediment concentrations in the months of July and August were found to be about twice those in June, and about Six times those in September. For the entire melt season, the mean daily suspended sediment concentration was computed to be 1445 mg l^{-1}. The variation in daily suspended sediment load and daily mean discharge during the ablation period is shown in Figs. 4(a) to (d). Daily suspended sediment loads ranged between 45 and 1,07,817 tonnes at the gauging site. The monthly distribution of suspended sediment load for the different years is shown in Fig. 5.





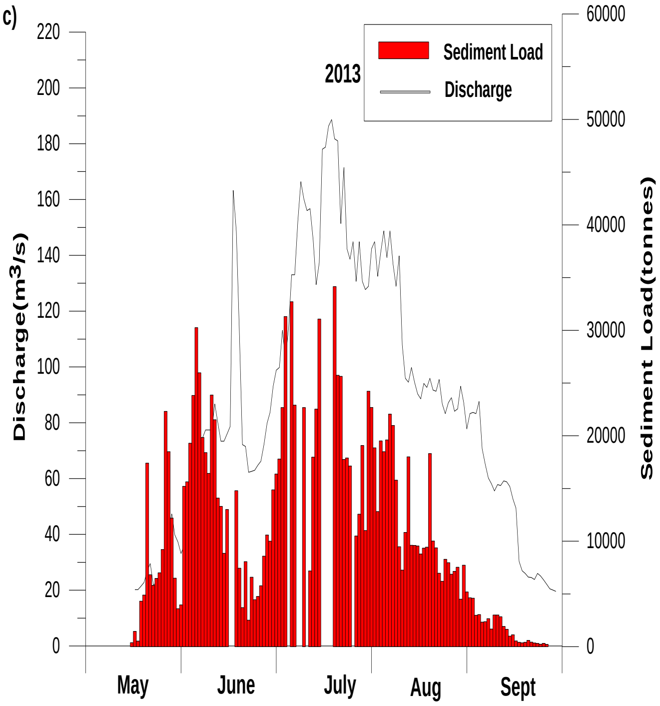


Fig 4 (a) (b) (c). Discharge observed and Suspended Sediment load during different summer seasons (2011-2013) near the snout of Gangotri Glacier.

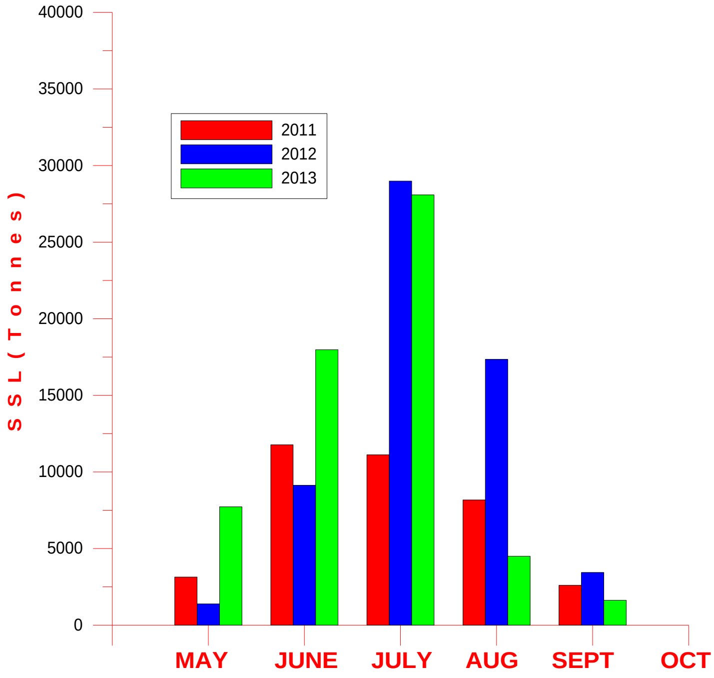


Fig. 5. Mean monthly Suspended Sediment load observed for different months near the snout of Gangotri glacier during different summer seasons (2011-2013).

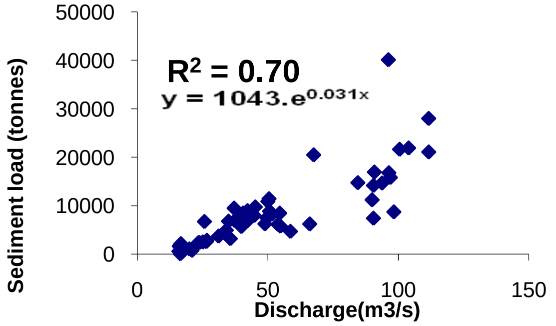
Mean monthly total suspended sediment loads for May, June, July, August and September during the study period was found to be 12, 388, 681, 300, 76 $\times10^3$ tonnes respectively. The average total suspended sediment load for the melt season was computed to be 1.63×10^6 tonnes. The total suspended sediment from the Gangotri Glacier was estimated to be 1.09, 1.84 and 1.96×10^6 tonnes for 2011, 2012 and 2013. As with concentration, maximum sediment loads from this glacierized basin occurred in July, followed by August. Prominent peaks in the suspended sediment load were associated with anomalously high water discharges. The highest daily suspended sediment load (107817 t) in the melt stream was observed on 17th June, 2013. During this period high rainfall occurred, which contributed to higher amount of sediment as well as discharge. During high rainfall events, greatly enhanced suspended sediment concentrations are possible from debris and moraine covered glacierized basins. The large variations in suspended sediment concentration and load during the melt season, as observed in the present study, are attributed to the location of the sediment sources, development of the drainage network, exhaustion and replenishment of the sediment supply and differences in travel distance between sediment source areas and the location of measuring station. As the ablation season progresses, the concentration of sediment first increases due to availability of sediment within the subglacial channels and then reduces due to evacuation of the sediment from the drainage system.

V. RELATIONSHIP BETWEEN SUSPENDED SEDIMENT CONCENTRATION, LOAD AND DISCHARGE

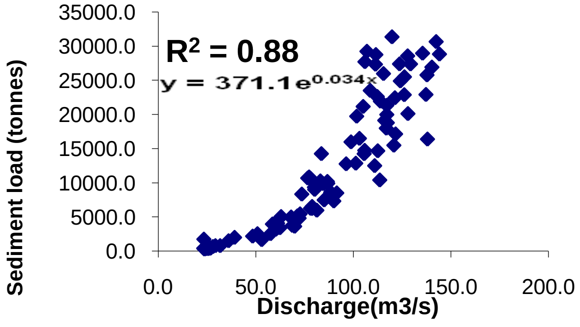
Observed daily mean sediment concentration and mean discharge were used for computing load, but attempts were also made to establish the relationship between discharge and concentration/load and to explore the effect of monsoon on this relationship. Fig. 6(c) shows the relationships between suspended sediment concentration and suspended sediment load and discharge using 3 years (2011-2013) data. Results indicate a poor relationship between suspended sediment concentration and discharge for the study basin (r^2=0.41), but this was improved when suspended sediment load was related to discharge (r^2=0.70). Such improvement reflects the presence of discharge as a common variable in both the dependent and independent variables, and the relationship improves because of such inherent correlation.

Suspended Sediment Load

a)



b)



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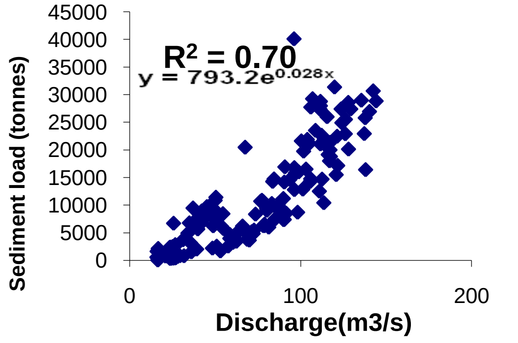
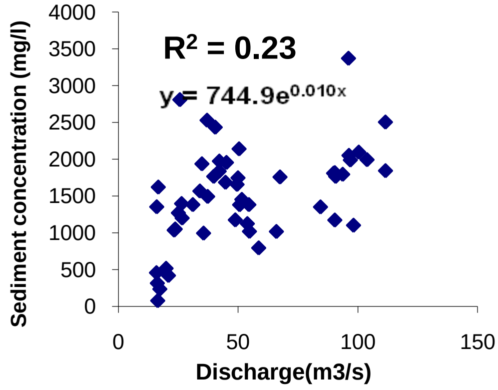


Suspended Sediment Concentration

a)



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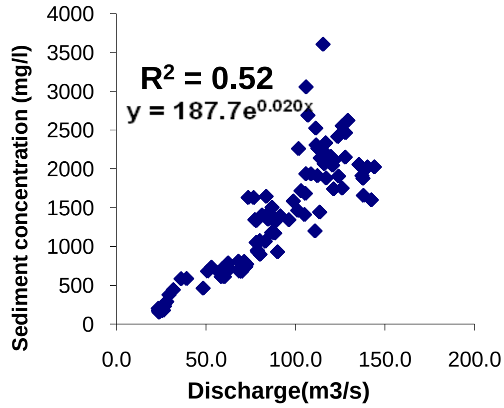


c)

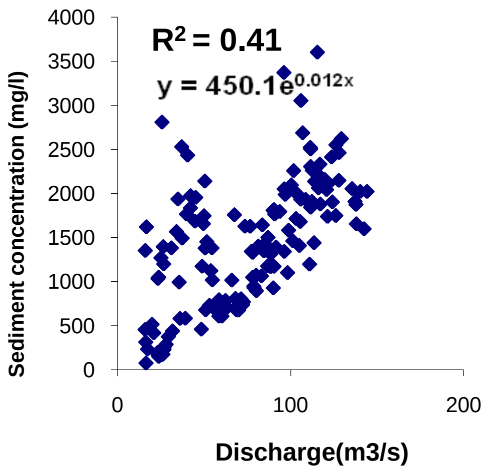


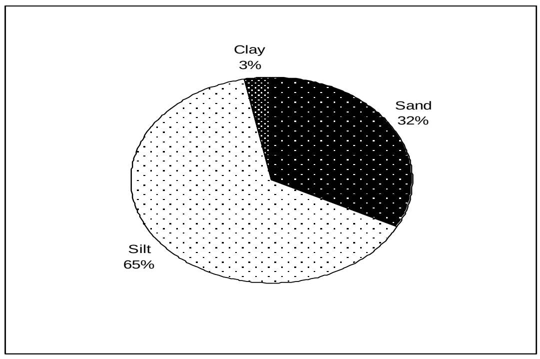
Fig 6. Relationship between Suspended sediment load and concentration and Discharge for summer season (2011-2013) data: a) May- June b) July-Sept c) for all days.

The occurrence of monsoon can be expected to influence the relationship between discharge and suspended sediment concentration/load. In order to investigate the impact of monsoon on these relationships, the data set was split into pre-monsoon (May- June) and post monsoon (July- Sept) and separate relationships were established (Figs. 6(a) and (b)). Linear regression of suspended sediment concentration and discharge data provided r^2 values of 0.23 and 0.52 for May-June and July- Sept, respectively. The corresponding values of r^2 for sediment load versus discharge relationships were 0.70 and 0.88. These results indicate that r^2 did not improve for either case by splitting the data. It is thought that sudden increases in sediment concentration in some events, without a corresponding increase in discharge, contributed to this poor relationship. As discussed earlier, the movement of the glacier, slumping of the heavily sediment laden portal ice into the stream, occurrence of rainstorms, landslides and rockslides in the ablation zone and near the snout of the glacier, are all considered responsible for such variation in the sediment load of the glacier melt stream. A similar pattern between flow and suspended sediment has been observed in the other glacier melt streams in the Himalayan region (Singh 1993).

A number of models applicable for examining the relationship between suspended sediment concentration and discharge for glacierized catchments are discussed by Fenn *et al.* (1985) and Hodgkins (1996, 1999). However, a good time series for both variables with data covered at short time intervals is needed for this purpose. Such data were not available in the present case. Willis *et al.* (1996) suggested that the existing models, which use either regression relationships between sediment concentration and discharge or transfer function techniques to predict sediment concentrations, may be improved, if the changing pattern of sediment supply to a proglacial stream in response to subglacial drainage changes are incorporated. In order to develop an improved understanding of sediment transfer processes and drainage system structure for the glaciated region of the Himalayas, the short-term data needed for such studies are being collected by authors for other glacierized basins.

VI. Suspended Sediment Particle Size Distribution

In a proglacial stream, the mineralogical composition of rocks and sediment generation processes are the main factors, which affect the grain size distribution of the suspended sediment. Analysis of the particle size distribution of suspended sediment in proglacial streams becomes very important if the water is used in hydropower generation. The efficiency of these hydropower schemes is affected by the type and size of suspended particles.



2011

Fig. 7. Total Monthly % of Sand, Silt and Clay for summer season 2011.

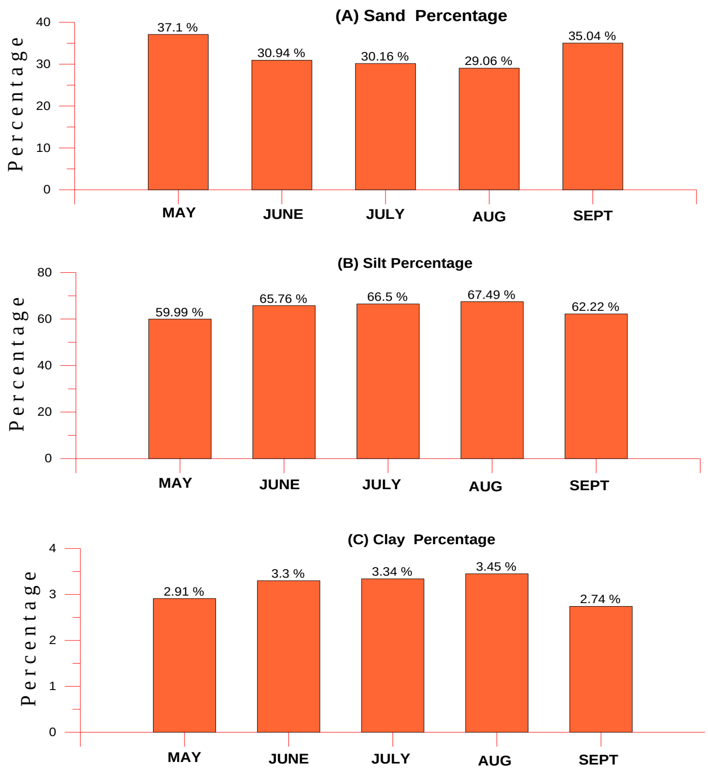


Fig. 8. Monthly Specification of (A) Sand, (B) Silt and (C) Clay percentage for summer season 2011.

In order to characterize the grain size distribution of suspended sediment for a particular month, all the sediment samples collected twice a day during that particular month were mixed to make a representative sample for that month and then analysed. The results were grouped into three size categories. The average content of clay, silt and sand for 2011 was observed to be 3, 65 and 32% of the total suspended sediment load as show in Fig 7. The silt content was found to be dominant. The silt content was found to be at a maximum in the month of July and August which can be explained (Fig: 8) by the higher meltwater runoff, which removes sediment from a larger surface area of the glacier and from its bed as well. As reported by Fenn and Gomez (1989), the sediment load of the outflow stream of the Glacier de Tsidjiore Nouve, Switzerland was also dominated by the silt-sized particles. The results obtained from the present study show no significant variation in the clay, silt and sand contents of sediment during the ablation period, suggesting that the sediment generation and delivery processes from the different sediment sources in the basin do not change significantly during the entire melt period.

CONCLUSION

The paper quantified the suspended sediment concentrations, loads and yields, and erosion rates for the Gangotri Glacier basin. The following conclusions are drawn from the study:

- There is a wide variation in the daily concentration of suspended sediment and suspended sediment loads.
- Both sediment concentration and load were found to be highest in the monsoon months and nearly two third of the total sediment load was transported in these two months.
- The particle size distribution indicates that the load is predominately composed of silt-sized grains.

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