QUANTIFICATION OF VARIABILITY IN DISCHARGE AND SUSPENDED SEDIMENT CONCENTRATION OF MELTWATER OF GANGOTRI GLACIER, GARHWAL HIMALAYA

H. Bisht[1*], S. Sah[1], K. Kumar[1], P.C. Arya[2] and M. Tewari[1]

[1]G. B. Pant National Institute of Himalayan Environment and Sustainable Development, Kosi-Katarmal, Almora, Uttarakhand, India
[2]Indian Institute of Science, Bangalore, Karnataka, India

***Correspondence:** harishbisht890@gmail.com

ABSTRACT

The daily suspended sediment concentration and meltwater discharge draining from the Gangotri glacier has been measured during the ablation season in year 2015 (May to September) and 2016 (June to September). The main purpose of the present study is to estimate the total discharge, suspended sediment concentration (SSC) and the contribution of both in the downstream regions. The total discharge volume and suspended sediment load (SSL) was 354.42×10^6 m^3 and 93.99×10^4 t for the year 2015 as well as 382.83×10^6 m^3 and 128.26×10^4 t for the year 2016. The maximum average discharge 39.71% and 40% have been observed during the month of August in the year 2015 and 2016 respectively. The temporal variation between meltwater discharge and suspended sediment is mainly influenced by the seasonal variability (rainfall and air temperature). Atmospheric temperatures and change in rainfall affect discharge which is reflected in the SSC. The meltwater discharge and SSC shows an increasing trend from June to August whereas a decreasing trend from August to September during both the years. A correlation coefficient (r^2) between discharge and SSC has been calculated, the r^2 values of 0.95 and 0.98 between discharge and SSC during 2015 and 2016 suggests a strong correlation between both parameters. The study suggests there is a positive correlation between discharge and SSC, to a large extent, the suspended load of the glacier meltwater is dependent on discharge.

Keywords: Gangotri glacier, Meltwater discharge, Seasonal variability, Suspended sediment.

INTRODUCTION

The Himalayas, a geodynamically active region, prone to violent crustal movements which are responsible for high seismic activity and large erosion rates (Valdiya 1998). Himalayan region (27°-36° N and 72°-96° E) contains a total of 9,575 glaciers covering an area of about 40000 km^2 (Raina *et. al.,* 2008). Himalayan rivers receive a considerable amount of water from snow and glacier melt (Singh *et al.,* 2008).Glaciers are the main geomorphic agents of erosion and are a vital source of suspended sediment load (Collins 1998). The glacier-fed rivers yield high sediment than the non-glacial rivers (Harbor *et al.,* 1992). In the Gangotri glacier catchment, mechanical weathering of rocks plays an important role in the generation of suspended sediment load. The suspended load also depends on the channel gradient, flow type, basin relief and surrounding crushed rocks or soil. The variability in rock type, basin area, sediment source, physicochemical conditions, atmospheric conditions, tectonic setting and the debris entrainment processes are generally responsible for the variation in concentration of suspended sediment in the glacier meltwater. In addition variation in the meltwater-discharge is mainly due to change in air temperature and solar insolation, in the different seasons (Kumar *et al.,* 2002).

Hydrological investigations of glaciers are important because they are the main source of fresh water for irrigation, hydroelectric power generation and drinking water supply (Singh *et al.,* 2006). Discharge measurement is important to assess the melting rates of the Gangotri glacier (Srivastava *et al.*, 2014). The study of suspended sediment concentration is necessary to avoid the technical disasters such as siltation of the reservoir and damaged turbines (Ostrem 1975). The continuous monitoring of the glaciers is extremely difficult because of rough topography, low temperatures, low oxygen levels and extreme climatic conditions. In the present study the daily meltwater discharge and suspended sediment concentration of the Gangotri glacier was investigated in detail during the whole ablation season (May to September).There several studies on the meltwater discharge draining from Gangotri glacier, but only a few of them discussion detail about the fluctuations in the daily discharge and suspended load for the whole ablation period. In the present study, attempts have been made to investigate daily variation (6:00 Am to 8:00 Pm) in the meltwater discharge and suspended sediment for the whole ablation season (May to September).

STUDY AREA

Gangotri glacier is one of the largest valley type glaciers in the Indian Himalayan Region. It originates from the Chaukhambha group of peaks and flows in the NW direction. It is situated in the Uttarkahsi district of Uttarakhand state and lies between the latitude 30º43´25´´ N to 31º01´21´´ N and longitude 79º02´31´´ E to 79º17´19´´ E (Fig. 1). Geologically the area falls above the Main Central Thrust (MCT) comprises mostly the bedrocks of granite followed by mica schist and quartzite. The snout of this glacier is located at an elevation of 4000 m msl, which is known as Gamukh. The proglacial stream i.e. the Bhagirathi river emerges out from the portal of Gangotri glacier, which is known as Ganga after the confluence with Alaknanda river at Deoprayag. Gangotri glacier comprises of four active tributary glaciers (Kirti Bamak, Swachhand Bamak, Maiandi Bamak and Ghanohlm Bamak) and two inactive tributary glaciers (Raktavarna Bamak and Chaturangi Bamak) which is together known as Gangotri glacier system. The present geomorphic setup of the region is due to the neotectonic activity (Bali *et al.*, 2000). The present landform study is an integrated result of weathering (mechanical and physicochemical) and glacio-tectonic movements.

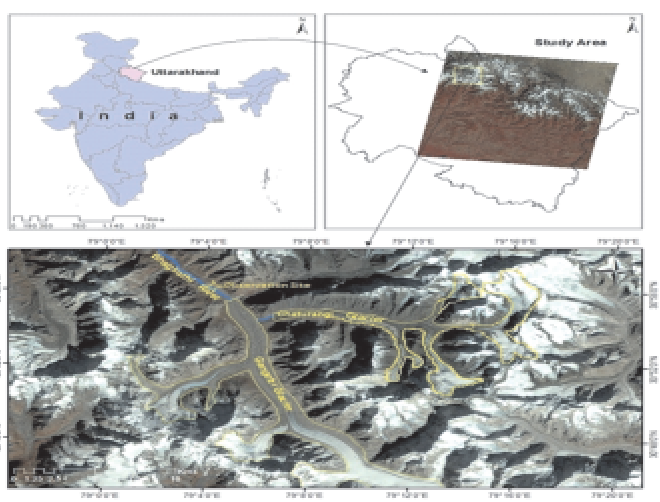

Fig. 1. Location map of the study area with observation site, the boundaries of the glacier body is highlighted showing Bhagirithi river originating from the snout

METHODOLOGY

An appropriate gauging and sampling site was selected about 1.5 km downstream from the present position of Gangotri glacier snout (Fig. 1). The site was selected near to the snout to avoid the influence of other tributaries. A staff gauge was installed at one side of the channel for manual observation of water level. The Area velocity method was used to calculate the channel discharge as the product of channel cross sectional area (m^2) and water flow velocity (m/s). The channel cross section area was measured two times during the pre-monsoon and post-monsoon period by standard survey technique using a ruler and a tape measure. In this technique, transect across the stream at 50 cm intervals, expressed as the height from the bed to the water surface was measured. To determine the flow velocity, the channel was divided into three segments, and the velocity was measured at each segment separately. The channel flow velocity was measured by timing floats (wooden float) over a flow length. Since channelized water flow velocity decreases exponentially towards the bed and the banks, so correction factor (k=0.8) has been applied to yield the mean channel velocity. The variation in stages was recorded hourly (6:00 Am to 8:00 Pm) during the ablation season (May to September) by using staff in order to draw rating curve (stage-discharge relationship) for hourly discharge measurement.

Suspended Sediment Concentration (SSC) was measured by the vacuum filtration method. In this method, a fixed volume of water sample was poured from a pre-weighed 0.45µm Millipore membrane filters. These filter papers were stored in small polythene zip bags and transported to the laboratory at G.B. Pant National Institute of Himalayan Environment and Sustainable Development Almora. After this, the filter paper was dried in an oven at 100°C for 3-4 hours and then weighed; the gain in filter paper weight represents the concentration of suspended sediment, expressed in the term of mass per volume of sample filtered. The Suspended Sediment Load (SSL) expressed in tones, was also determined by multiplying the discharge and SSC. The average monthly rainfall and air temperature data (at 0.25° resolution) were downloaded from (http://neo.sci.gsfc.nasa.gov) and processed using Microsoft office excel 2007. The Statistical Package for Social Science (SPSS) version 10.5 was used for correlation matrix between three (Discharge, SSC, and SSL) observed parameters.

RESULT AND DISCUSSION

Variation in Suspended Sediment Concentration (SSC) and Suspended Sediment Load (SSL)

The variations in SSC were well recorded with the hourly monitoring of the Gangotri glaciermeltwater. The results suggest that the SSC is highest in the meltwater from 2 to 4 pm. The daily average SSC in Gangotri glacier meltwater varied from 0.09 g/l to 4.58 g/l in year 2015 and 0.27 g/l to 5.98 g/l in year 2016 during the ablation period. The mean daily SSC in Gangotri glacier meltwater varied significantly which is indicated by high coefficient of variation (CV) (0.8) in year 2015 and (0.6) in 2016.In the year 2015 the minimum and maximum SSC was observed in May and July respectively, whereas in 2016 minimum is recorded form June while maximum is recorded from the month of August. In 2015 the maximum and minimum SSC was observed in July (3.55 g/l) and May (0.16 g/l) respectively whereas in 2016 maximum and minimum SSC was observed in August (4.15 g/l) and June (0.93 g/l) respectively (Table 1). The daily average of SSC and discharges recorded at gauging site for the year 2015 and 2016 are shown in (Fig. 2 a & b). In this figure, an increasing trend was observed between Julian days (JD) (190 to 210) and (200 to 220) in year 2015 and 2016 respectively. The daily and monthly SSL was also calculated with the help of total discharge and SSC, shown in Table 2. The results showed that the maximum SSL (43.27×10^4 ton) and (64.25×10^4 ton) were transported in August month during the year 2015 and 2016 respectively. The minimum monthly suspended sediment flux for the year 2015 and 2016 is (0.28×10^4 ton) and (3.62×10^4 ton) recorded from the month of May in 2015 and June 2016. The magnitude of SSL and discharge varies from day to day, month to month and year to year (Haritashya *et al.*, 2006). According to the present study the mean daily SSL of Gangotri glacier meltwater was 9,349 ton/day, while in the year 2003 it was around 16,095 ton/day (Haritashya *et al.*, 2006). It shows the SSL of Gangotri glacier meltwater has decreased by 42% during the last 13 years. Despite this the annual variability in SSL (CV=1.1) for the year 2016 and 2003, which exhibit a similar pattern. A comparison between daily SSL derived from Gangotri glacierand other glaciers of the world is given in Table 3, which shows the SSL derived from Gangotri glacier meltwater is many times higher than the other valley glaciers.

Table 1. Monthly variations in discharge, ssc, rainfall and temperature in the study area

Month	Discharge (m3/s)		SSC(g/l)		Rainfall (mm)		Temperature (ºC)	
	2015	2016	2015	2016	2015	2016	2015	2016
May	6.69	-	0.16	-	46.09	-	0.07	-
June	13.95	15.01	0.79	0.93	184.57	100.97	4.21	8.89
July	45.17	50.35	3.55	3.67	290.18	429.50	8.07	6.41
August	51.78	57.81	3.12	4.15	234.95	221.19	9.17	9.59
September	15.69	20.93	1.14	2.01	39.63	80.71	7.24	9.15

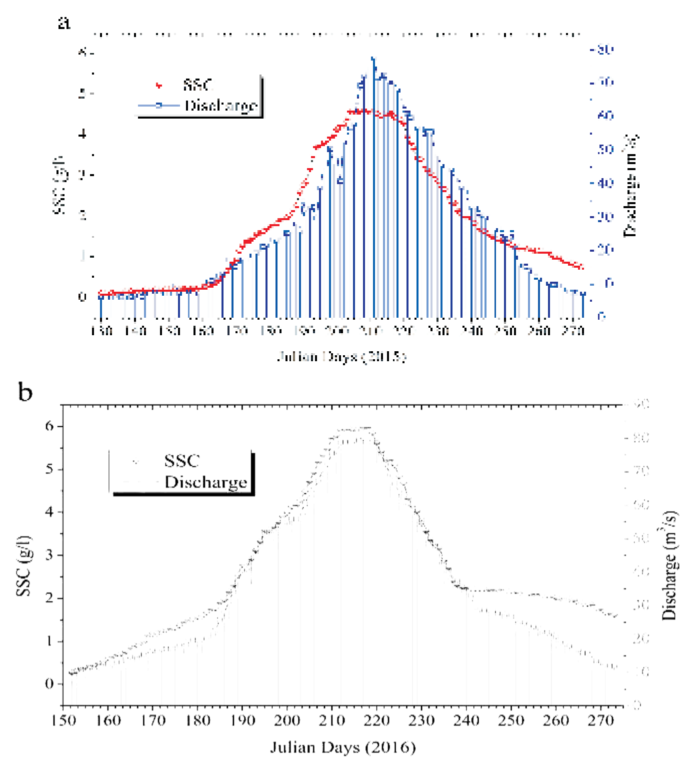

Fig. 2. Daily variations in suspended sediment concentration and meltwater discharge of Gangotri glacier meltwater recorded during the entire ablation season in year 2015 (a) 2015 (b) 2016

Variation in glacier meltwater discharge

During the study period (May to September), meltwater discharge varied from (6.16 m^3/s to 77.13 m^3/s) and (10.07 m^3/s to 79.88 m^3/s) in the year 2015 and 2016 respectively. The mean of daily discharge of meltwater varies significantly, indicated by high CV (0.7) in 2015 and (0.6) in 2016.This variability is possibly due to difference in meltwater discharge or difference in temperature patterns (Kumar *et al.*, 2002). The highest daily meltwater discharge values 77.13 m^3/s and 79.88 m^3/s were observed in the July 2015 and August 2016 respectively. In addition, the minimum daily meltwater discharge values 6.16 m^3/s and 10.07 m^3/s were observed in May, 2015 and June 2016 respectively. The average monthly discharge values show that the maximum values 51.78 m^3/s and 57.81 m^3/s were observed in August 2015 and 2016 respectively. Furthermore, a minimum discharge value 6.69 m^3/s and 15.01 m^3/s were identified in May 2015 and June 2016 (Table 1). The total meltwater discharge volume was calculated for the whole ablation season. The results show that the total discharge volume was higher in 2016 (382.83×10^6 m^3) than 2015 (354.42×10^6 m^3) (Table 2). In the years, 2015 and 2016 about 73% to 75% of the total discharge volume was drained in the month of July and August. The results of the present study are compared with the previous studies conducted in 1999-2000 (Kumar *et al.*, 2002). The discharge of Gangotri glacier has fallen in 2015-2016 as compared to 1999-2000. Lower discharge rates are possible because of a decrease in retreating rate of Gangotri glacier which was 25 m/yr in 1999 (Tangri *et al.*, 2004) and 10 m/yr in 2016 (Singh *et al.*, 2016).

Table 2. Total discharge volume and suspended sediment load (SSL) of Gangotri glacier meltwater in the year 2015 and 016

Month	Discharge Volume ($\times10^6$ m^3)		Total Suspended Sediment Load ($\times10^4$ t)	
	2015	**2016**	**2015**	**2016**
May	17.92	-	0.28	-
June	36.16	38.90	2.85	3.62
July	120.98	134.85	42.95	49.49
August	138.69	154.83	43.27	64.25
September	40.67	54.25	4.64	10.90
Total	**354.42**	**382.83**	**93.99**	**128.26**

Relationship between meltwater discharge and suspended sediment

The relationship between SSC and discharge is a good indicator for characterizing sediment transport (Williams 1989). The sediment yield in glacier catchment depends mainly on meltwater which is insignificant during the non-ablation period (November to April) (Haritashya *et al.*, 2006). To understand the relationship between meltwater discharge and SSC, hourly discharge and suspended sediment (6:00 Am to 8:00 Pm) was measured during the whole ablation season (May-September). A correlation matrix is a bivariate method generally used to measure the relationship between two variables and degrees of dependency of one variable to another variable. A correlation matrix is constructed between discharge, SSC and SSL. The matrix shows that a strong positive discharge-SSC ($r^2 = 0.95$) correlation and discharge-SSL ($r^2 = 0.97$) correlation in the year 2015 (Table 4). The similar pattern of correlation between discharge-SSC ($r^2 = 0.98$) and discharge-SSL ($r^2 = 0.97$) was also observed in the year 2016 (Table 4). It indicates that SSC and SSL generally increase with an increase in glacier meltwater discharge. There is a higher variability in SSL (CV=1.1) than meltwater discharge (CV=0.7) and SSC (CV=0.8) in year 2015. The same pattern of higher variability was also observed in Dokriani glacier (Singh *et al.*, 1999) and past study in Gangotri glacier (Kumar *et al.*, 2002; Haritashya *et al.*, 2006). The higher variability in sediment load with respect to discharge suggests that the transport of sediment is not only controlled by the capacity of the stream but also by the availability of sediment (Alley *et al.*, 1997). Furthermore, the higher variability might be due to local phenomena, such as the falling of moraine filled ice blocks and sediment transport from the sheared and crushed rock material. Several studies (Bezinge 1987; Bogen 1989) suggested that the glacier area might influence on the suspended sediment transport. The relationship between meltwater discharge and SSC were examined by plotting daily trend for these two variables in

Table 3. Comparison between mean daily suspended sediment load derived from Gangotri glacier meltwater and other glaciers in different part of the world

Glacier	Region	SSL (ton day^{-1})	Source
Gangotri	Uttarakhand, Himalayas	9349	*Present study
Chota Sigri	Himanchal, Himalayas	135	(Singh *et al.*, 2015)
Dunagiri	Uttarakhand, Himalayas	47	(Srivastava *et al.*, 1999)
Scott Turnerbreen	Svalbard, Arctic	126	(Hodgkins 1999)
Changme Khangpu	Sikkim, Himalayas	18	(Puri *et al.*, 1999)
Dokriani	Uttarakhand, Himalayas	447	(Singh *et al.*, 1999)
Ebbabreen	Svalbard, Arctic	624	(Kostrzewski *et al.*, 1989)
Austre Brøggerbreen	Svalbard, Arctic	186	(Repp 1988)
Erikbreen	Svalbard, Arctic	175	(Vatne *et al.*, 1992)
Gornergletscher	Switzerland, Alps	1086	(Collins 1990)

Source: Kostrzewski et al., 1989; Puri et al., 1999 Except[*]

both the years 2015 and 2016 (Fig. 2 a & b). The results showed that discharge and SSC are highly correlated to each other. But sometimes higher SSC was observed without a sporadic rise in discharge, which is probably due to subglacial sediment flushing events caused by glacial lake outburst (Kumar *et al.*, 2002; Thayyen *et al.*, 1999). In the present study, the discharge and SSC are showing a strong correlation (0.95 and 0.98) throughout the ablation season, while in the previous studies (Kumar *et al.*, 2002) a better correlation was not observed throughout the ablation season. This might be due to a source of sediment transport and solute dynamics of meltwater drained from the glacier. The results also suggests that the temporal variation in relationship between discharge and suspended sediment is mainly influenced by the following factors such as runoff, relief, geology (rock type, tectonic disturbances, weathering and erosion of surrounding rock and abrasion through the glacier), basin area and seasonal variability (rainfall, snowfall, air temperature and cloud cover).

Table 4. A correlation matrix between Discharge, SSC, and SSL in Gangotri glacier catchment for the year (a) 2015 and (b) 2016

(a)	**Discharge (m^3/s)**	**SSC (g/l)**	**SSL (ton/day)**
Discharge (m^3/s)	1		
SSC (g/l)	0.951	1	
SSL (ton/day)	0.968	0.944	1
(b)			
Discharge (m^3/s)	1		
SSC (g/l)	0.980	1	1
SSL (ton/day)	0.973	0.972	

Influence of meteorological parameter on discharge and suspended sediment

The meteorological parameter (rainfall and temperature) was used to determine the temporal variation in discharge and SSC. The precipitation and air temperature are one of the major controlling factors for the glacier melt (Young 1981). The variability in temperature, precipitation and other meteorological factors mainly effects on the sediment yield and basin runoff (Haritashya *et al.*, 2006). The results obtained from the analysis of processed modis data indicate that the average rainfall was higher in 2016 (208.09 mm) than 2015 (159.08 mm) (Table 2). The higher average rainfall in 2016 ablation season is mainly responsible for the higher discharge and SSC. The average air temperature of the study area is also higher in 2016 (8.51ºC) than 2015 (5.75ºC) which is also responsible for the high meltwater discharge (Table 2). The temperature fluctuation influence discharge which results in the variation of SSC. This trend was also observed during previous studies (Srivastava *et al.*, 2014), which indicates that small fluctuation in air temperature could give rise to higher variation in SSC. The close examination of meteorological data along with discharge and SSC suggests that they are highly correlated to each other. Several studies (Singh *et al.*, 2006; Singh *et al.*, 1999; Kumar *et al.*, 2002) also showed strong correlation between the meteorological parameters and SSC in different glaciers.

CONCLUSION

The current study deals with the quantification of discharge and suspended sediment concentration, and its variation. This study also provides insight into the response of suspended sediment with meltwater discharge. The results obtained from this study concluded that the meltwater discharge and suspended sediment concentration are strongly correlated to each other. But sometimes the peak of discharge is higher than the suspended sediment peak which is probably due to glacial lake outburst. Despite this the average daily meltwater discharge and suspended sediment follows the same pattern during entire ablation season in year 2015 and 2016. In the initial ablation period, the concentration of suspended sediment was lower and higher in the middle of ablation season (July to August) in both the years 2015 and 2016. This study suggested that 42% decrease in SSL than the previous study on Gangotri glacier in year 20003, with no change in coefficient of variation. It also suggested that the decrease in total discharge volume during the ablation season from 1999 to 2016. The results from the present study agree that the temporal variability in discharge and suspended sediment depends on the local climatic conditions. To decipher the impact of local climatic conditions on the variation in discharge and suspended sediment the meteorological parameters were also used. Through close examination of meteorological data along with meltwater discharge and suspended sediment the present study concludes that in normal conditions, the meltwater discharge and suspended sediment are positively correlated and the concentration of suspended sediment mainly depends on the discharge. The results also suggest that the variability in the rainfall and air temperature mainly influence the meltwater discharge as well as suspended sediment of the catchment. The pattern of suspended sediment during the entire ablation season is both the years suggested that the sediment transport in meltwater stream is mainly controlled by glacier movement, moraine laden ice, meteorological parameters and surrounding rocks. Finally, the study suggests that meltwater discharge and sediment yield from all the inactive tributary glaciers (Chaturangi, Raktavarna, Thelu and Meru) should be estimated to establish a long-term database for the whole catchment of Gangotri glacier system. Because it will open a more appropriate picture about relationship between meltwater discharge and suspended sediment as well as delaying characteristic of meltwater in future.

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