



Estimation of suspended sediment concentration and meltwater discharge draining from the Chaturangi glacier, Garhwal Himalaya

Harish Bisht¹ · Bahadur Singh Kotlia¹ · Kireet Kumar² · Prakash Chandra Arya³ · Saurabh Kumar Sah² · Manmohan Kukreti¹ · Pooja Chand¹

Received: 4 October 2019 / Accepted: 30 January 2020 / Published online: 5 March 2020
© Saudi Society for Geosciences 2020

Abstract

In this study, we present analysis of stream flow near the snout of Chaturangi glacier during the ablation season (June to September (JJAS)) in the year 2015 with an aim to estimate the sediment and water input into the Bhagirathi River from the glacier. In order to assess the variation in meltwater discharge from Chaturangi glacier and to determine its relationship with suspended sediment concentration (SSC), the meltwater and discharge data were analyzed from near the snout to avoid mixing of water and sediment from other glacier tributaries. The meltwater discharge was measured by area velocity method, and the SSC was calculated by vacuum filtration technique. During the entire ablation season (JJAS), marked seasonal variations were observed in the SSC and meltwater discharge. The higher variation is observed in suspended sediment load (SSL) ($C_v = 1.17$) than SSC ($C_v = 0.54$) because computation of SSL includes both discharge ($C_v = 0.76$) and SSC. The average monthly SSC for JJAS was found to be 0.99, 2.29, 4.20, and 1.84 g l⁻¹, respectively, and average monthly meltwater discharge for same period was observed as 5.83, 14.48, 39.81, and 12.69 m³ s⁻¹, respectively. It suggested that throughout the ablation season, the cumulative percentage delivery of SSC follows meltwater discharge. The average suspended sediment yield (SSY) for the entire ablation season was estimated to be 2264.03 ton/km², and consequent catchment denudation rate was measured as 0.85 mm. A strong positive correlation ($r^2 = 0.88$), found between the discharge and SSC, revealed that both the parameters are dependent on each other. Our results also suggest that the Chaturangi glacier is a major contributor for transportation of sediment into the Bhagirathi River, compared with other tributaries of the Gangotri glacier system.

Keywords Chaturangi glacier · Meltwater discharge · Suspended sediment concentration (SSC) · Suspended sediment load (SSL) · Suspended sediment yield (SSY)

Introduction

The Himalayan region stores about 9575 glaciers, covering an area of about 40,000 km² (Raina and Srivastava 2008), and the rivers originating from the Himalaya receive a significant

amount of water from the glacier melt (Singh et al. 2008). The hydrological investigations of glaciers are vital because they are freshwater source for drinking, irrigation, and hydroelectric power generation (Singh et al. 2006). The hydro-chemical and SSC analyses of the glacier meltwater is crucial with the advancement of geochemical studies as well as rising demands of fresh water in the low-lying areas (Bisht et al. 2018). Glacial streams are freshwater resources and face stress of pollution for the last few decades due to anthropogenic activities as well as natural phenomena. The water quality assessment is an increasingly important area in environmental studies (Zhang 2019). Keeping in view the changing water quality and depleting water resources, it is important to understand and monitor the hydrochemistry of water resources, because the polluted water not only threatens human health but also creates imbalance in aquatic ecosystem and economical development. In order to remove the dissolved pollutants

Responsible Editor: Broder J. Merkel

✉ Harish Bisht
harishbisht890@gmail.com

- ¹ Centre of Advanced Study in Geology, Kumaun University, Nainital 263002, India
- ² G. B. Pant National Institute of Himalayan Environment and Sustainable Development Kosi-Katarmal, Almora, Uttarakhand 263643, India
- ³ Indian Institute of Science, Bangalore, Karnataka 560012, India

(organic and inorganic), an effective adsorption technique, e.g., FeCl₃-activated carbon can be used (Jawaduddin et al. 2019). In addition, the understanding of polluted solute dispersion in soil is also important for protection of groundwater from being contaminated (Ekeleme and Agunwamba 2018). Measurements of water flow is an important feature of hydrology-related projects, which is as important as water quality monitoring (Gore and Banning 2017; Barbetta et al. 2017). The discharge calculation, sediment controlling, and hydrological modeling are being used in the glacial areas (Barbetta et al. 2017; Sefe 1996). The precise estimation of stage-discharge relationship is considered a key point for different applications of water resources engineering such as designing of hydraulic structures, management of water resources, and sediment analysis (Othman et al. 2019).

Geologically, young aged Himalayan mountains with large and active glaciers, steep valleys with frequent avalanching, high seismicity, intense monsoonal rainfall, and natural weathering processes support high erosion rates (Hasnain and Chauhan 1993). Weathering processes in the glacial region provide more material for stream transport than the non-glacial region as the glaciers are more active agents of erosion (Embleton and King 1975; Gardner 1986); therefore, the glacier-fed rivers yield high sediment than the non-glacial rivers (Harbor and Warburton 1992). Since the glaciers are the main geomorphic agents of erosion and are a vital source of suspended sediment load (Collins 1998), the suspended sediment input also depends on the amount of meltwater draining from the glacier (Drewry 1986). The monsoonal precipitation in glaciated region enhances the water flow resulting in the rapid runoff and increased erosion (Rieger 1981). An Artificial Neural Network (ANN) has convenient, flexible, and easy mathematical system to classify the nonlinear relationships between input and output data sets (Patel and Joshi 2017; Alani and Alobaidi 2018). The rainfall-runoff models play a significant role in water resource management, planning, and hydraulic design (Othman and Naseri 2011). Measurements of meltwater discharge are equally important to assess the melting rates of the glaciers (Srivastava et al. 2014). The glaciers of the Indian Himalayan region are partially covered by debris and sediment, which are transported to the glacier surface by erosion, debris flows, rock falls, and snow avalanches (Singh et al. 2016a, c). This loose material flows freely with ice melting, contributing to the suspended sediment load in meltwater discharge (Kostrezewski et al. 1989; Hasnain and Thayyen 1999; Kumar et al. 2002). Therefore, the suspended sediment load is directly dependent on the meltwater discharge in any glaciated catchment (Haritashya et al. 2006; Kociuba and Janicki 2014; Kociuba and Janicki 2018).

In the Chaturangi glacier catchment, mechanical weathering plays an important role to form the suspended sediment. Variability in rock type, basin area, sediment source,

atmospheric conditions, physicochemical conditions, tectonic setting, and the debris entrainment processes are generally responsible for variation in the concentration of suspended sediment in the glacier meltwater (Haritashya et al. 2006). The glacier catchments of eastern and central part of the Indian Himalaya deliver higher SSL than the western part due to active Indian Summer Monsoon (ISM), leading to high discharge (Kumar et al. 2018). The sedimentary system in the glaciated region can be defined by sediment sources, process of erosion and medium, and mode of transport, which affect the SSC in the meltwater and sediment yield (Iverson 1995; Krikbride 1995). The flow structure and morphology of the channel bed also plays a significant role to determine the sediment load (Bialik et al. 2014). To analyze these aspects, it is important to establish a long-term database of the SSL and SSC for the glacial catchment (Haritashya et al. 2006).

In the present study, we examined daily meltwater discharge and SSC of the Chaturangi glacier throughout the ablation season (JJAS). Although there are a number of studies conducted on the SSC and meltwater discharge draining from the Gangotri glacier (Kumar et al. 2002; Haritashya et al. 2006; Singh et al. 2006; Singh et al. 2014; Bisht et al. 2017), there are hardly any published records on the hydrological characteristics of its tributary glaciers. Therefore, our aim was to estimate the contribution of the Chaturangi glacier discharge and sediment concentration (SSC) in the Bhagirathi River. Further, we made an attempt to assess the variations in the SSC, SSL, and sediment yield and erosion rate of the Chaturangi glacier catchment for entire ablation season in the year 2015. In addition, the variation in meltwater discharge and its relationship with SSC was also calculated to determine the dependency of these parameters on each other.

Materials and methods

Study area

The Chaturangi glacier (latitude 30° 54' 08"–30° 54' 28" N and longitude 79° 15' 19"–79° 6' 18" E) is situated in the Uttarkashi district of Uttarakhand, India (Fig. 1). It is the longest inactive tributary glacier (not connected to the main trunk) of the Gangotri glacier system, although it was connected with the Gangotri glacier in 1971 (Vohra 1988). However, presently, it has been detached and lost its identity at the junction (Bisht et al. 2019). Presently, the Chaturangi glacier consists more than three active (connected with the trunk) tributary glaciers (Seeta, Suralaya, Vashuki, etc.)—all form the Chaturangi glacier system. The Chaturangi glacier is an east–west-flowing and 21.1-km-long valley-type glacier, occupying an area of about 43.83 km² (Bisht et al. 2019) with a catchment area of about 67.70 km² (Singh et al. 2015). The precipitation in the catchment is contributed by both the

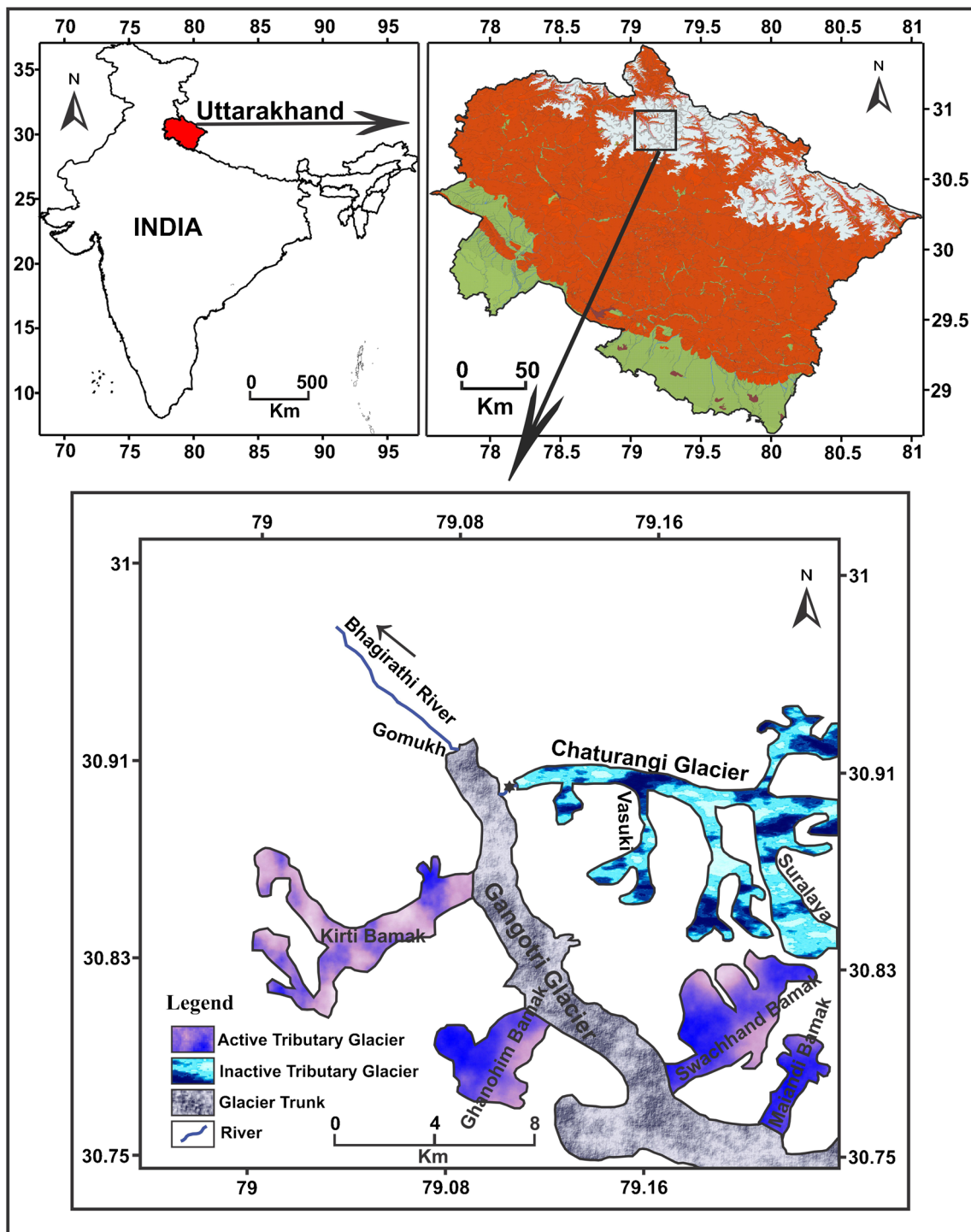


Fig. 1 Location map of the study area (Chaturangi glacier, Garhwal Himalaya India)

Indian Summer Monsoon and Western Disturbances (Hasnain and Thayyen 1999; Kumar et al. 2018).

The ablation zone of the glacier is partially covered by sediment like boulders, debris, and moraines which are transported on the glacier surface mainly through the erosion of valley walls due to downward movement of the glacier. A number of longitudinal and transverse crevasses in the

ablation zone are well exposed during the summer season when seasonal snow is melted from the ablation zone. The snout of the glacier is located at 4380 m msl where from the Chaturangi River originates (Bisht et al. 2019). The Chaturangi River flows with high velocity due to steep gradient of the valley floor. The shape of the glacier snout keeps changing due to subsidence at glacier portal and splitting of

large ice blocks from the terminus point (Fig. 2). Geologically, the study area falls above the Main Central Thrust (MCT), which comprises mostly the granite bedrocks, followed by mica schist and quartzite. The geomorphic setup of the region is formed due to the neotectonic activity (Bali et al. 2003), and the present landform is an integrated result of weathering processes and glacio-tectonic movements.

Meltwater discharge measurements

We used methodology as mentioned in the flow chart (Fig. 3). Suitable sampling site was selected about 1 km downstream of the Chaturangi glacier snout (Fig. 1). The site was selected to avoid water and sediment input from other tributaries and also because of comparatively low turbulence of stream. To measure water level, a staff gauge was installed on the left bank of channel. The water level of the Chaturangi River was measured by a staff gauge and a stage-discharge relationship (rating curve) was developed (Fig. 4) to convert water levels into discharges by using area velocity method. This method can be expressed by a simple equation (Hubbard and Glassar 2005) as follows:

$$Q = k(A \times V) \quad (1)$$

where Q is discharge ($\text{m}^3 \text{s}^{-1}$), k is correction factor (0.8) for calculating mean channel velocity, A is cross-sectional area of the channel (Fig. 5), and V is velocity of the stream flow.

The channel cross-section area of the stream was measured during the pre- and post-monsoon periods by standard survey technique using a sounding rod and measuring tape (Hubbard and Glassar 2005). In this technique, height of the water surface from the bed was measured across the stream channel at every 50 cm interval (Fig. 2b). To measure the flow velocity, the channel was divided into three segments and the velocity was measured at each segment. To compute the channel flow velocity, the wooden floats were used and the time traveled by

the floats was recorded through the stopwatch. The total traveling length of the float at gauging site was about 10 m. For reducing the error in the flow velocity, the readings were repeated three times and average value was measured for further computations. Since channelized water flow velocity decreases exponentially towards the river bed and the banks, the correction factor ($k=0.8$) (Hubbard and Glassar 2005) was applied to yield the mean channel velocity. Variation in the stages and velocity of the channel was recorded hourly (6:00 a.m. to 8:00 p.m.) during the entire ablation season to determine the hourly discharge measurements.

Measurements of suspended sediment concentration

The water samples (volume, 500 ml) for SSC were collected daily at hourly interval (6:00 a.m. to 8:00 p.m.) near the gauging site during the entire ablation period, and the sample bottles were rinsed with the source water. The samples were immediately filtered by the vacuum filtration method for measuring the SSC. In this method, a fixed volume of meltwater sample was poured from a pre-weighed $0.45 \mu\text{m}$ millipore membrane filters. These filter papers were properly packed in small polythene zip bags and transported to the laboratory at G.B. Pant National Institute of Himalayan Environment and Sustainable Development Kosi-Katarmal, Almora. The filter papers were dried in an oven at $100 \text{ }^\circ\text{C}$ for 24 h and then weighed as individual. The gain in weight of filter paper represents the concentration of suspended sediment, expressed in the term of mass per volume of filtered sample.

Measurements of suspended sediment load and erosion rate of the catchment

The SSL in meltwater discharge from Chaturangi glacier catchment was calculated by using the following formula (Haritashya et al. 2006).

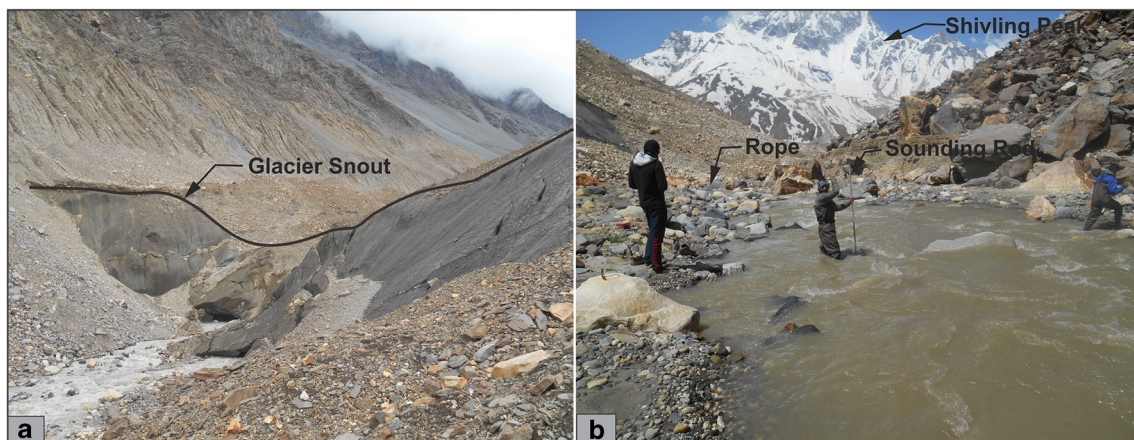


Fig. 2 a Snout of the Chaturangi glacier from which meltwater stream originates. b Measurement of the channel cross section of the Chaturangi glacier meltwater stream with the help of measuring tape and sounding rod

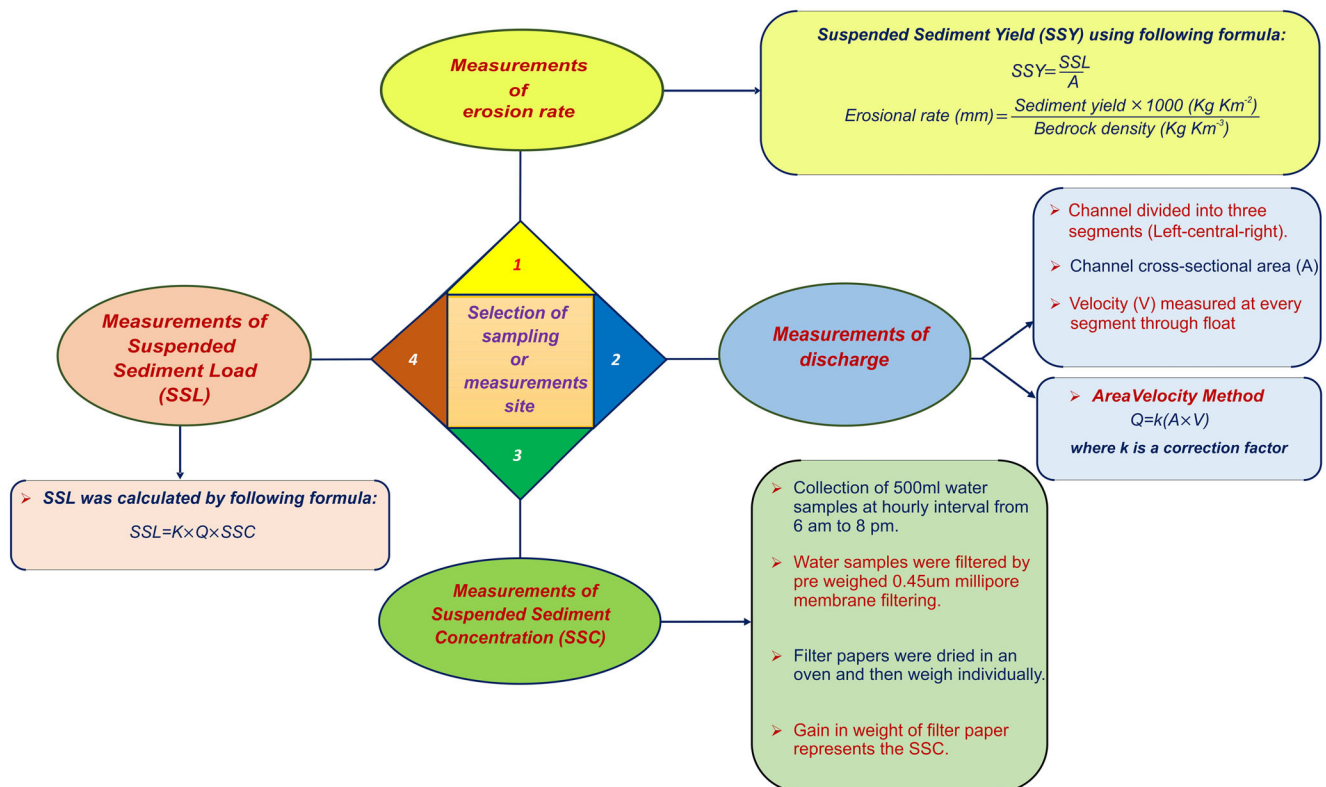


Fig. 3 Flow chart of research methodology

$$SSL = K \times Q \times SSC \tag{2}$$

where SSL is suspended sediment load in stream (ton), Q is stream discharge ($m^3\ s^{-1}$), SSC is suspended sediment concentration in meltwater ($g\ l^{-1}$), and K is conversion factor appropriate to the units used for Q .

This method is most common in the Indian Himalayan region. The SSL is also used to compute the SSY from per

unit basin area of the catchment by using the following formula (Kumar et al. 2018).

$$SSY = SSL/A \tag{3}$$

where SSY is suspended sediment yield per unit basin area ($ton\ km^{-2}$) and A is basin or catchment area (km^2).

The estimates of sediment yield based on suspended sediment load were applied to determined erosion rate of the basin

Fig. 4 Rating curve or stage discharge relationship developed for gauging site near the snout of Chaturangi glacier

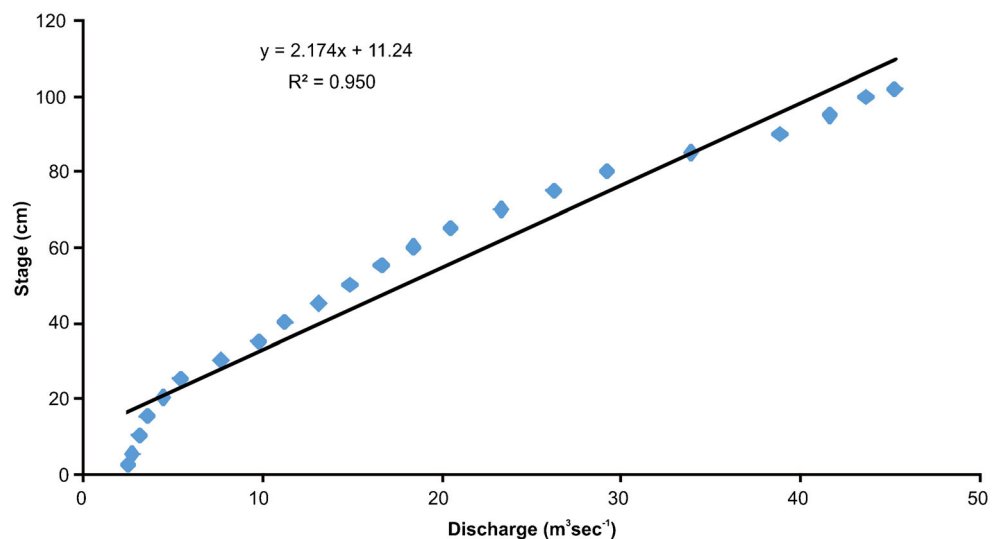
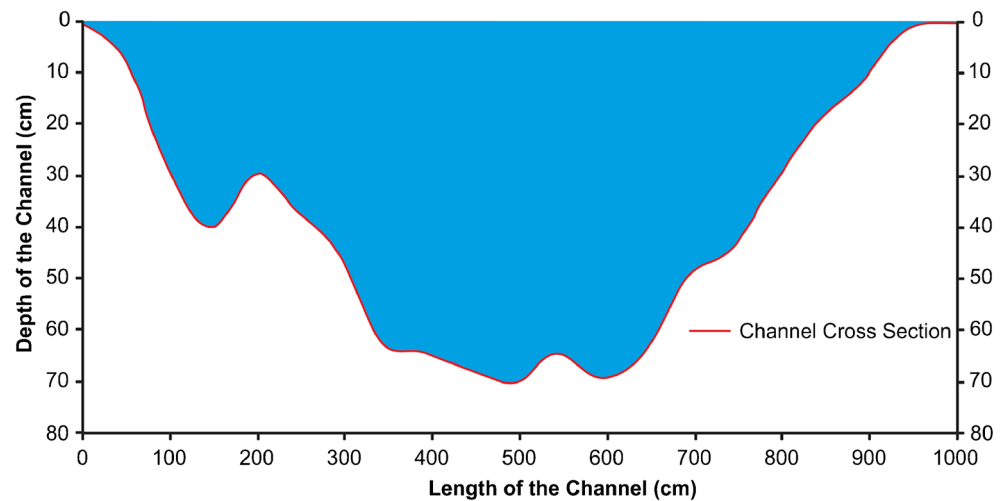


Fig. 5 Cross-sectional area of the channel of Chaturangi glacier meltwater stream



during ablation period, using the following equation (Haritashya et al. 2006).

$$\text{Erosion rate (mm)} = \frac{\text{sediment yield} \times 1000 \text{ (kg km}^{-2}\text{)}}{\text{bedrock density (kg m}^{-3}\text{)}} \quad (4)$$

Results and discussion

Variation in glacier meltwater discharge

Variation in meltwater discharge during ablation period in 2015 is shown in Fig. 6. The hydrograph pattern clearly reveals that the increasing trend of discharge begins from June, attains its highest value in August and subsequently starts decreasing. In the beginning of the ablation season, the hydrograph limb is almost flat and this flatness indicates that no significant changes occurred during early part of the ablation season because of less melting due to weak solar insolation. This is perhaps because of stronger storage characteristics of the glaciers and poor drainage network due to the occurrence of seasonal snow cover result in a delayed response of melt water (Singh et al. 2005). As the ablation season advances, strong melting takes place due to the availability of higher solar insolation and a larger extent of exposed surface ice of the glacier. During the entire ablation period (JJAS) in 2015, daily meltwater discharge varied from 3.85 to 54.85 m³ s, and the mean values varied significantly as indicated by high coefficient of variation (CV = 0.76). This variability in meltwater discharge in glacierized catchment is possibly due to difference in temperature patterns (Kumar et al. 2002). Monthly average meltwater discharge during the ablation months of June, July, August, and September in 2015 was recorded as 5.83, 14.48, 39.81, and 12.69 m³ s⁻¹, respectively (see Table 1). The minimum (5.83 m³ s⁻¹) and maximum (39.81 m³ s⁻¹) discharge was observed in June and August,

respectively. The total meltwater discharge volume for the individual month was also calculated for the entire ablation period. Individually, the discharge volume was recorded as 15.11, 38.78, 106.63, and 32.89 × 10⁶ m³ for June, July, August, and September, respectively (Table 1). The results show that the discharge volume was higher in August, contributing about 55.13% of the total discharge volume. This is mainly due to high liquid precipitation and higher solar insolation (Kumar et al. 2018).

Transportation and variation in SSC and SSL

The SSC delivery by a glacier meltwater stream has significant implications on its channel morphology, geochemical cycling, material fluxes, water quality, and biotic and aquatic ecosystems, supported by the stream (Joshi et al. 2016). Furthermore, suspended sediment, recognized as an important vector for transport of nutrients and contaminants, has significant control on biological and geo-morphological processes in rivers (Singh and Chen 1982). Due to its likely impact on biotic and aquatic habitats and other water management processes, accurate estimation of sediment, transported by the Himalayan rivers is significant. The primary source of sediment in any glacier meltwater stream is debris cover on the glacierized and non-glacierized area, weathering and erosion of surrounding rocks and glacial moraines (Haritashya et al. 2006; Srivastava et al. 2014). The variations in SSC were recorded by daily monitoring of the meltwater, draining from the Chaturangi glacier. The daily average SSC varied from 0.38 to 4.97 g l⁻¹ during the ablation period in 2015. The mean daily SSC varied considerably, as evidenced by coefficient of variation (CV = 0.54). For the entire ablation period, average daily SSC at gauging site are shown in Fig. 6. It is clear that the SSC shows an increasing trend from June onwards, reaching its highest value in August and subsequently starts decreasing. The same trend was also observed in the

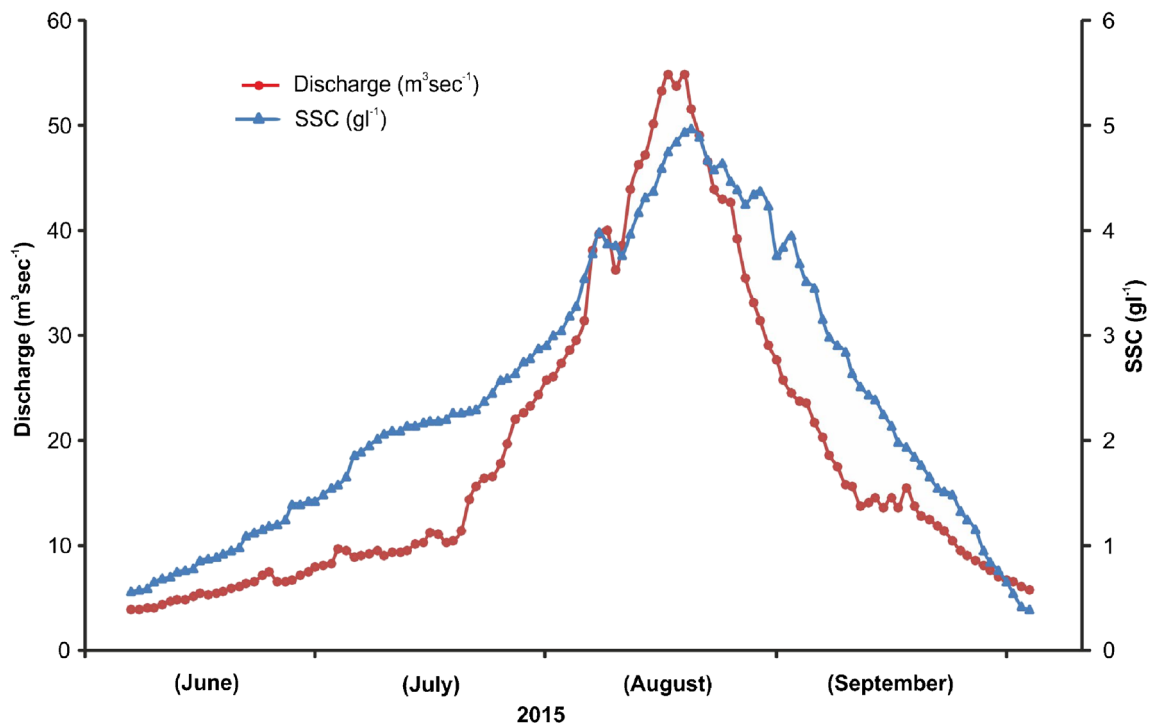


Fig. 6 Graph showing mean daily trend between the discharge and SSC values, derived from the Chaturangi glacier meltwater during the whole ablation period (JJAS) of 2015

meltwater of Chhota Shigri glacier Lahaul-Spiti valley (Singh et al. 2016b). The monthly average SSC during the ablation month of June, July, August, and September in 2015 was calculated as 0.99, 2.29, 4.20, and 1.84 g l^{-1} , respectively (Table 1). The minimum (0.99 g l^{-1}) and maximum (4.20 g l^{-1}) SSC was observed in June and August respectively although at times, unusually high SSC peaks were observed which may be related to the sudden slumping of sediment laden portal ice into the stream (Singh et al. 2005). Daily and monthly SSL were also calculated with the help of total discharge and SSC. The average daily SSL varied significantly from 187.60 to 23,396.60 ton day^{-1} , which is indicated by the higher coefficient of variation ($\text{CV} = 1.17$). Higher variation in the SSL compared with the SSC is probably due to the combined effect of discharge and SSC. According to our study, mean daily SSL of the Chaturangi glacier is 5399.15 ton day^{-1} . However, total SSL of the main trunk (Gangotri glacier) is 9349 ton day^{-1} (Bisht et al. 2017). Our results show that the Chaturangi glacier contributes more than half (~57.75%) of the total sediment load into the Bhagirathi

River, and we suggest that the Chaturangi glacier is a major contributor for transportation of sediment load, compared with other tributary of the Gangotri glacier system. The monthly average SSL for the ablation months (JJAS) was found as 1.49, 8.88, 44.89, and 6.05×10^4 ton, respectively (Table 1). Additionally, the SSC the SSL were also minimum (1.49×10^4 ton) and maximum (44.89×10^4 ton) in June and August, respectively. We have observed that the degree of SSC and SSL is higher in August compared with other months primarily due to more discharge resulting from high liquid precipitation (Kumar et al. 2018). These observations are in agreement with other studies in the Himalayan region, showing added transportation of the suspended sediment during the monsoon period (Singh and Hasnain 1998; Haritashya et al. 2006; Kumar et al. 2018). In order to understand the regional suspended sediment load and its transportation, we compared our results with other glaciers of Indian Himalaya and other regions (see Table 2). Also, to determine the variability in SSL within the basin, the daily mean SSL values were converted into daily mean SSL per unit basin area (SSY) and the results

Table 1 The mean monthly discharge, suspended sediment concentration (SSC), and suspended sediment load (SSL) in meltwater draining from the Chaturangi glacier during the ablation season of year 2015

Month	Discharge ($\text{m}^3 \text{s}^{-1}$)	Discharge volume ($\times 10^6 \text{ m}^3$)	SSC (g l^{-1})	SSL ($\times 10^4 \text{ t}$)
June	5.83	15.11	0.99	1.49
July	14.48	38.78	2.29	8.88
August	39.81	106.63	4.20	44.89
September	12.69	32.89	1.84	6.05

Table 2 Comparison between suspended sediment load, suspended sediment yield, and rate of erosion for Chaturangi glacier catchment and other glaciers in Indian Himalayan region and other parts of the world during the melt season

Glaciers	Region	Basin area (km ²)	Suspended sediment		Erosion rate of the catchment (mm)	Reference
			Load (× 10 ⁶ t)	Yield (t km ⁻²)		
Chaturangi	Uttarakhand	67.7	0.63	2264	0.85	Present study
Gangotri	Uttarakhand	556.47	2.69	4834	1.82	Haritashya et al. (2006) and Wulf et al. (2012)
Dokriani	Uttarakhand	14.81	0.04	2700	1.02	Singh et al. (2003) and Wulf et al. (2012)
Chhota Shigri	Himachal Pradesh	34.7	0.058	1689	–	Singh et al. (2016b)
Raikot	Nanga Parbat Kashmir	100	0.4	4000	1.5	Gardner and Jones (1984) and Wulf et al. (2012)
Siachin	Karakoram	1782.17	1.26	707	0.27	Bhutiyan (2000) and Wulf et al. (2012)
Changme	Sikkim	4.49	0.003	668	0.25	Puri (1999) and Wulf et al. (2012)
Haut	Switzerland	11.7	0.05	4500	1.7	Hodgkins et al. (1997)
Scott Turnerbreen	Svalbard, Arctic	12.8	0.006	530	0.2	Hodgkins et al. (1997)
Batura	Gilgit-Baltistan Pakistan	649.03	3.95	6086	2.3	Collins (1998) and Wulf et al. (2012)
Langtang	Nepal	326.53	0.08	245	0.09	Ohta et al. (1987) and Wulf et al. (2012)

indicate that the SSL per unit basin area of Chaturangi glacier catchment is lower than other valley glaciers, followed by Dokriani and Gangotri glaciers in Uttarakhand (Table 2). The low SSY values from Chaturangi glacier are primarily due to its large basin area, compared with the Dokriani glacier.

Relationship between meltwater discharge and suspended sediment

The relationship between discharge and SSC is a consistent indicator for characterizing sediment transport (Williams 1989). The sediment yield in glacier catchment depends chiefly on meltwater which is insignificant during the non-ablation period (November to April) (Haritashya et al. 2006). By using daily discharge and SSC data, we made an attempt to obtain discharge and SSC together with best linear fit for individual month (Fig. 7) and such a relationship was examined for early (June, July), peak (August), and late (September) melt period. We observed a strong relationship between discharge and SSC during the early melt period ($R^2 = 0.91$) and late melt period ($R^2 = 0.94$), whereas, a weak relationship ($R^2 = 0.56$) was viewed during the peak melt period. Strong relationship in early melt season is largely due to the rising meltwater discharge and increased sediment availability. Rapidly increased discharge during August, without an analogous rise in SSC, has contributed to a less strong relationship during the peak melt period. A scatter plot between mean daily discharge and SSC was also prepared for the entire ablation season (Fig. 8) and a strong relationship ($R^2 = 0.88$) was observed between mean daily discharge and SSC. The strong coefficient of

determination ($R^2 = 0.88$) indicates close relationship between discharge and SSC on daily basis during the study period. The magnitude of SSL and discharge vary from day to day, month to month and year to year (Haritashya et al. 2006). Therefore, on the basis of average values for the whole ablation season, we found that about 53.13% of total discharge was released in August, transporting about 73.21% of the total sediment load. In the month of June, the discharge contributes about 7.81%, transporting 2.43% of the sediment load. These results also show that the SSL correspondingly fluctuates with the discharge. This pattern is common for most of the glaciers (e.g., Chhota Shigri, Dokriani, Dunagiri, Gangotri, etc.) of the Indian Himalaya (Hasnain and Thayyen 1999; Singh et al. 2014; Srivastava et al. 2014; Singh and Ramanathan 2018). Hasnain and Thayyen (1999) in their 6-month observations of sediment transport from the Dokriani glacier, also stated that the monsoonal months of July and August account for 64% of the total discharge, 70% of the total sediment transport and 74% of the monsoonal rainfall. Our study suggests that the variations in suspended sediment concentrations in meltwater are related to the climatic conditions and flow regimes of the streams.

The results also indicate higher variability in SSL (CV = 1.17), compared with the meltwater discharge (CV = 0.76) and the similar pattern of SSL variability has also been observed in the Gangotri and Dokriani glaciers (Singh and Ramashastri 1999; Kumar et al. 2002; Haritashya et al. 2006). Higher SSL variability with respect to meltwater discharge suggests that the transportation of the sediment is not only controlled by the capacity of stream but also by the

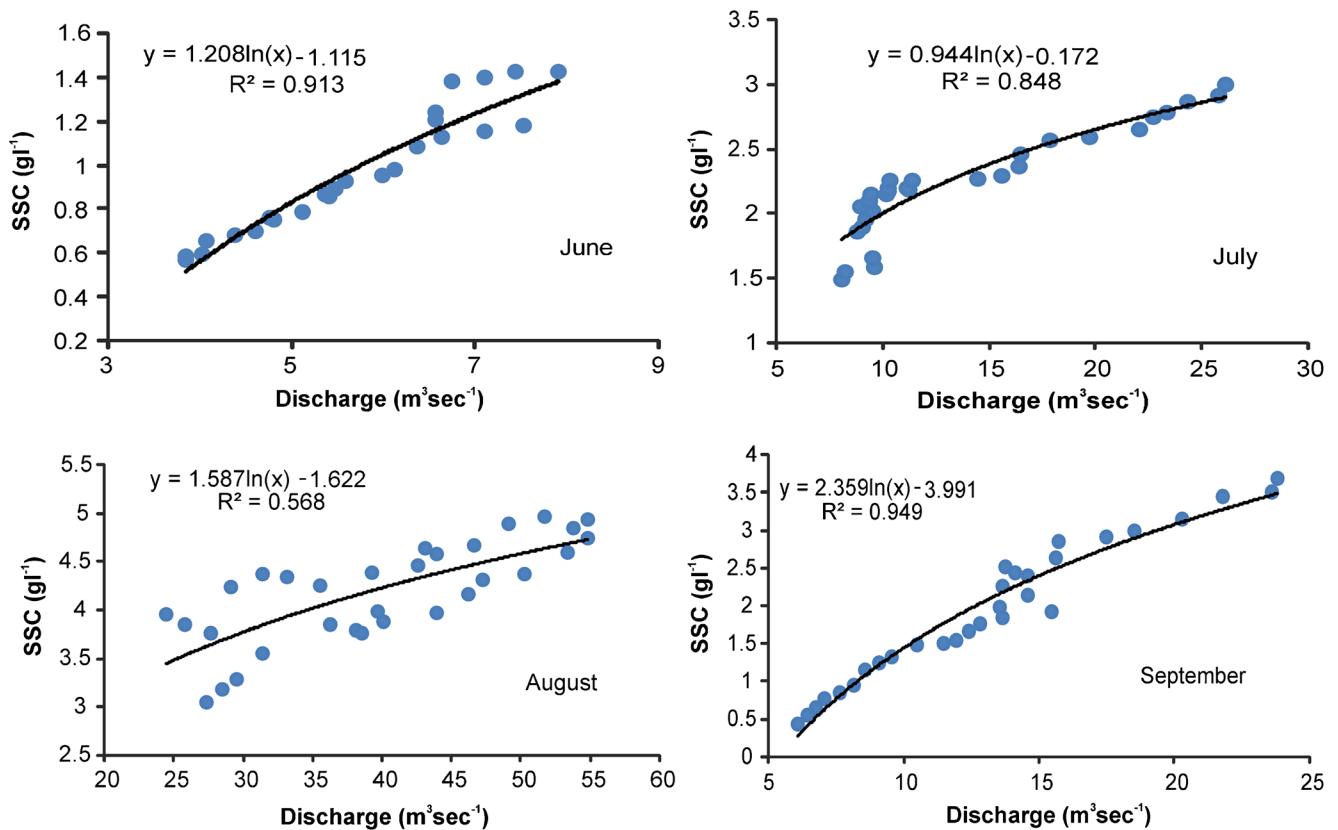
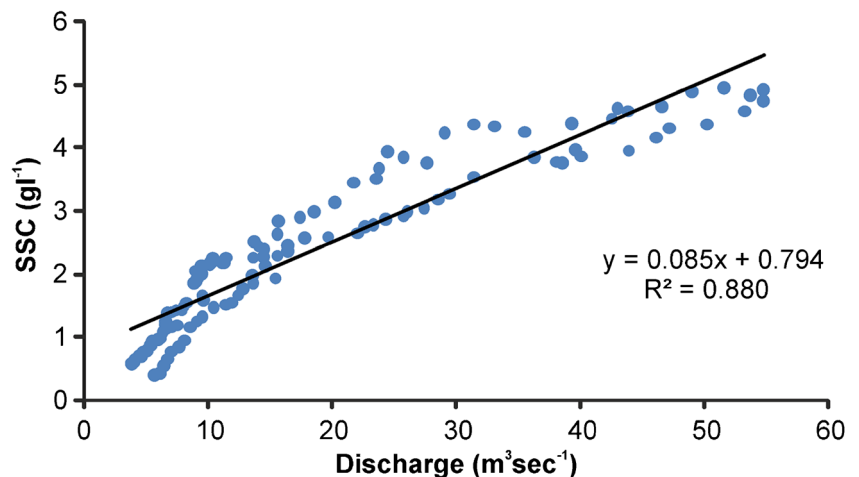


Fig. 7 Log-transformed relationship between discharge and SSC data for the individual month (June, July, August, and September), 2015

availability of sediment in the catchment (Alley et al. 1997). In addition, the higher variability might also be due to local phenomena, such as the falling of moraine filled ice blocks (Bisht et al. 2017). The relationship between discharge and SSC were also looked at by plotting daily trend for these two variables for the entire ablation period (Fig. 6), indicating that both the discharge and SSC are increased from June onward with highest values in August, and suggesting that both are positively correlated with each other, though at times, the higher SSC was observed without a periodic rise in discharge,

perhaps due to sub-glacial sediment flushing events caused by outburst of the glacial lake (Thayyen et al. 1999; Kumar et al. 2002). Most of the previous studies in other glaciated region have also suggested that the meltwater discharge in a glacialized catchment is positively correlated with the SSC (Singh and Ramashastrri 1999; Srivastava et al. 2014). The contribution of different components (e.g., solar insolation, rain, snow and ice melt) is an essential factor, controlling the amount of discharge and consequently the sediment load (Kumar et al. 2016).

Fig. 8 Scatter plot between mean daily discharge and SSC data for ablation season of 2015



Suspended sediment yield and erosion rate of the catchment

Sediment is a natural part of the stream, which is influenced by the surrounding geology. The natural processes that added sediment in streams include in-stream scouring of a river bed and banks and erosion of the sediment within the catchment from any exposed debris, soil, and natural slip. The catchment scouring is dependent on the bed rock density and constituent particles because currents in the river create vorticity which causes scouring of soil and bed rock in and around the catchment (Yamini et al. 2018). Sumer et al. (1992) showed that the formation of scouring by the waves is different from the scouring by the current but the maximum scour depth will be increased by nearly 2.36 times by 50% increase in the current and wave velocity (Yamini et al. 2018). In glaciated catchment of high mountainous environment, the sediment transfer through glacier meltwater erosion is one of the main hydrological mechanisms. The SSY is the total suspended sediment load outflow from a per unit area of the catchment quantifiable at one point during a specific time period (Singh and Singh 2001). The responses of SSY and discharge are related to each other, but the magnitude and frequency of the yield varied monthly and yearly (Haritashya et al. 2006). The glacial catchments of Uttarakhand are found to have more SSL per unit catchment area, compared with other Indian glaciers (Table 2). This is because of more liquid precipitation due to Indian Summer Monsoon causing more erosion, which is also evident by high discharge (Jeelani and Deshpande 2017). The annual yield of sediment from the catchment is another parameter which indicates rate of annual weathering and is affected by proportion of glacierized and non-glacierized areas in a basin (Kumar et al. 2018). The sediment yield during the different month of the melt season (JJAS) was 220.08, 1311.66, 6630.72, and 893.64 ton km⁻², respectively, and the average sediment yield was found to be 2264.03 ton km⁻². The monthly variability in sediment yield might be due to various factors, e.g., glacier dynamics, variation in prevailing weather conditions, type of sub-glacial drainage system and variation in discharge (Collins 1990; Hodson et al. 1998; Singh et al. 2003). Sometimes the sediment supply is not equal to the rate of sediment transport in the glacial meltwater streams (Collins 1979), and this is due to partial flushing of sediment in the beginning of the melt season (Singh and Singh 2001). Because of this, the highest sediment yield may not correspond to the higher discharge of glacier meltwater (Haritashya et al. 2006). The amount of SSY derived from the Chaturangi glacier catchment was compared with Indian other glaciers (see Table 2). Comparing these results, we found that the SSY of Chaturangi glacier (2264.03 ton km⁻²) is comparable with the Dokriani glacier (2700 ton km⁻²) and Chhota Shigri glacier (1689 ton km⁻²) (Singh et al. 2003, 2016b) which indicate more or less similar

rate of sediment delivery during the melt season (Table 2). In glaciated region, the erosion rate of the catchment may differ by several orders of magnitude, for examples, Polar glaciers have erosion rate as 0.01 mm year⁻¹, while it varies from 10 to 100 mm year⁻¹ for large and fast moving temperate glaciers in tectonically active areas (Hallet et al. 1996). In the Himalaya, the erosion rate in Gangotri, Dokriani, and Rakiot glacier catchments is measured as 1.8, 1, and 1.5 mm, respectively (Gardner and Jones 1984; Singh et al. 2003; Haritashya et al. 2006). Based on our database from the year 2015 and using a standard bedrock density of 2.7 g cm⁻³ (Hallet et al. 1996; Singh et al. 2003), the erosion rate of Chaturangi glacier was estimated as 0.85 mm, and this is in concurrence with the erosion rate of Dokriani glacier catchment. This suggests that both the glaciers are active and contributing a considerable amount of sediment flux into the Bhagirathi River.

Conclusion

The present study dealt with the quantification and variability of discharge, SSC and SSL, delivering from the Chaturangi glacier. We infer that the temporal variation in meltwater discharge and suspended sediment is mainly influenced by seasonal variability. The daily average SSC varied significantly from 0.38 to 4.97 g l⁻¹, while the average daily SSL varied from 187.60 to 23,396.60 ton day⁻¹. Higher variation in SSL (CV = 1.17), compared with the SSC (CV = 0.54) is possibly due to a combined effect of discharge and SSC. The discharge volume was higher in month of August, contributing about 55.13% of the total discharge volume, mainly due to higher solar insolation and high liquid precipitation. This study also provides insight to the response of SSC and SSL with meltwater discharge. The obtained results conclude that the glacier meltwater discharge and SSC are strongly correlated with each other, though at times, the peak of discharge is higher than the SSC possibly due to outburst of the supra-glacial lakes. The pattern of discharge and SSC clearly indicate that both the variables show increased values from June onwards, attaining the highest values in August and subsequently start decreasing. We infer that the Chaturangi glacier contributes about 57.75% of the total sediment load into the Bhagirathi River and thus, it is a largest contributor for the transportation of sediment, compared with other tributaries of the Gangotri glacier system. Furthermore, the erosion rate of the Chaturangi glacier catchment is estimated to be 0.8 mm which is almost similar to the Dokriani glacier catchment. The pattern of suspended sediment yield during the entire ablation season suggests that the sediment transport in meltwater stream is mainly controlled by debris cover, surrounding rock material, glacier movement and moraine laden ice. The present study also suggests that the meltwater discharge and sediment yield from all the inactive tributary glaciers

(Raktavarna, Thelu, and Meru) should be studied in detail to establish a long-term record for the catchment of Gangotri Glacier system. The pattern of discharge and SSC, estimated in our study, may be helpful for planning, development, and management of water resources in the high altitude region and maintaining hydropower projects, and to avoid the mechanical disasters such as siltation in the reservoirs and damaging of turbines.

Acknowledgments We express our gratitude to G.B. Pant National Institute of Himalayan Environment and Sustainable Development, Kosi-Katarmal, Almora for providing analytical facilities and healthy research environment. A very special gratitude goes to Jagdish Chandra Pandey, Nikesh Chandra Pandey, Vikram Negi, and Naveen Chandra Joshi for their continuous efforts and assistance during the field work.

Funding information The authors are thankful to the Department of Science and Technology, Government of India, New Delhi for the financial support.

References

- Alani RRA, Alobaidi BHK (2018) Prediction of sediment accumulation model for trunk sewer using multiple linear regression and neural network techniques. *Civil Eng J* 5(1):82–92. <https://doi.org/10.28991/cej-2019-03091227>
- Alley RB, Cuffey KM, Evenson EB, Strasser JC, Lawson DE, Larson GJ (1997) How glaciers entrain and transport basal sediment: physical constraints. *Quat Sci Rev* 16:1017–1038. [https://doi.org/10.1016/S0277-3791\(97\)00034-6](https://doi.org/10.1016/S0277-3791(97)00034-6)
- Bali R, Awasthi DD, Tiwari NK (2003) Neotectonic control on the geomorphic evolution of the Gangotri Glacier Valley, Garhwal Himalaya. *Gondwana Res* 6:829–838. [https://doi.org/10.1016/S1342-937X\(05\)71028-5](https://doi.org/10.1016/S1342-937X(05)71028-5)
- Barbetta S, Moramarco T, Perumal M (2017) A muskingum-based methodology for river discharge estimation and rating curve development under significant lateral inflow conditions. *J Hydrol* 554:216–232. <https://doi.org/10.1016/j.jhydrol.2017.09.022>
- Bhutiyani M (2000) Sediment load characteristics of a proglacial stream of Siachen Glacier and the erosion rate in Nubra valley in the Karakoram Himalayas, India. *J Hydrol* 227:84–92. [https://doi.org/10.1016/S0022-1694\(99\)00174-2](https://doi.org/10.1016/S0022-1694(99)00174-2)
- Bialik RJ, Karpinski M, Rajwa A, Luks B, Rowinski PM (2014) Bedform characteristics in natural and regulated channels: a comparative field study on the Wilga River, Poland. *Acta Geophys* 62:1413–1434. <https://doi.org/10.2478/s11600-014-0239-0>
- Bisht H, Sah S, Kumar K, Arya PC, Tewari M (2017) Quantification of variability in discharge and suspended sediment concentration of Meltwater of Gangotri Glacier, Garhwal Himlaya. *Envis Bulletin Himalayan Ecol* 25:10–16
- Bisht H, Arya PC, Kumar K (2018) Hydro-chemical analysis and ionic flux of meltwater runoff from Khangri Glacier, West Kameng, Arunachal Himalaya, India. *Environ Earth Sci* 77:1–16. <https://doi.org/10.1007/s12665-018-7779-6>
- Bisht H, Rani M, Kumar K, Sah S, Arya PC (2019) Retreating rate of Chaturangi glacier, Garhwal Himalaya, India derived from kinematic GPS survey and satellite data. *Curr Sci* 116:304–311. <https://doi.org/10.18520/cs/v116/i2/304-311>
- Collins DN (1979) Sediment concentration in melts waters as an indicator of erosion processes beneath an Alpine glacier. *J Glaciol* 23:247–225. <https://doi.org/10.3189/S0022143000029877>
- Collins DN (1990) Seasonal and annual variations of suspended sediment transport in meltwater draining from an Alpine glacier: proceedings of two Lausanne symposium. IAHS Publ 193:439–446
- Collins DN (1998) Suspended sediment flux in meltwaters draining from Batura glacier as an indicator of the rate of glacial erosion in the Karakoram Mountains. *Quat Proc* 6:1–10
- Drewry D (1986) *Glacial geological processes*. Arnold, London
- Ekeleme AC, Agunwamba JC (2018) Experimental determination of dispersion coefficient in soil. *Emerging Sci J* 2(4):213–218. <https://doi.org/10.28991/esj-2018-01145>
- Embleton C, King AM (1975) *Glacial geomorphology*. Arnold, London
- Gardner JS (1986) Recent fluctuations of Rakhiot glacier Nanga Parbat, Punjab Himalaya, Pakistan. *J Glaciol* 32:527–529. <https://doi.org/10.3189/S0022143000012247>
- Gardner JS, Jones NK (1984) Sediment transport and yield at the Rakhiot glacier, Nanga Parbat, Punjab Himalaya. In: Miller KJ (ed) *The international Karakoram project 1*. Cambridge University Press, Cambridge, pp 184–197
- Gore JA, Banning J (2017) Discharge measurements and streamflow analysis. *Methods Stream Ecol* 1:49–70. <https://doi.org/10.1016/b978-0-12-416558-8.00003-2>
- Hallet B, Hunter L, Bogen J (1996) Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. *Glob Planet Chang* 12:213–235. [https://doi.org/10.1016/0921-8181\(95\)00021-6](https://doi.org/10.1016/0921-8181(95)00021-6)
- Harbor J, Warburton J (1992) Glaciation and denudation rates. *Nature* 356:751. <https://doi.org/10.1038/356751a0>
- Haritashya UK, Singh P, Kumar N, Gupta RP (2006) Suspended sediment from the Gangotri glacier: quantification, variability and associations with discharge and air temperature. *J Hydrol* 321:116–130. <https://doi.org/10.1016/j.jhydrol.2005.07.037>
- Hasnain SI, Chauhan DS (1993) Sediment transfer in the glaciofluvial environment—a Himalayan perspective. *Environ Geol* 22:205–211. <https://doi.org/10.1007/BF00767405>
- Hasnain SI, Thayyen RJ (1999) Discharge and suspended-sediment concentration of meltwaters, draining from the Dokriani glacier, Garhwal Himalaya, India. *J Hydrol* 218:191–198. [https://doi.org/10.1016/S0022-1694\(99\)00033-5](https://doi.org/10.1016/S0022-1694(99)00033-5)
- Hodgkins R, Tranter M, Dowdeswell JA (1997) Solute provenance, transport and denudation in a high Arctic glaciated catchment. *Hydrol Proc* 11:1813–1832. [https://doi.org/10.1002/\(SICI\)1099-1085\(199711\)11:14<1813::AID-HYP498>3.0.CO;2-C](https://doi.org/10.1002/(SICI)1099-1085(199711)11:14<1813::AID-HYP498>3.0.CO;2-C)
- Hodson A, Gurnell A, Tranter M, Bogen J, Hagen JO, Clark M (1998) Suspended sediment yield and transfer processes in a small high-Arctic glacier basin, Svalbard. *Hydrol Process* 12:73–86. [https://doi.org/10.1002/\(SICI\)1099-1085\(199801\)12:1<73::AID-HYP564>3.0.CO;2-S](https://doi.org/10.1002/(SICI)1099-1085(199801)12:1<73::AID-HYP564>3.0.CO;2-S)
- Hubbard B, Glassar N (2005) *Field techniques in glaciology and glacial geomorphology*. Wiley, England
- Iverson NR (1995) Processes of erosion. In: Menzies J (ed) *Modern glacial environments—processes, dynamics and sediments*. Butterworth-Heinemann Ltd, Oxford, pp 241–259
- Jawaduddin M, Memon SA, Bheel N, Ali F, Ahmed N, Abro AW (2019) Synthetic grey water treatment through FeCl₃-activated carbon obtained from cotton stalks and river sand. *Civil Eng J* 5(2):340–348. <https://doi.org/10.28991/cej-2019-03091249>
- Jeelani G, Deshpande RD (2017) Isotope fingerprinting of precipitation associated with western disturbances and Indian summer monsoons across the Himalayas. *J Earth Syst Sci* 126:108–113. <https://doi.org/10.1007/s12040-017-0894-z>
- Joshi R, Kumar K, Adhikari VPS (2016) Modelling suspended sediment concentration using artificial neural networks for Gangotri glacier. *Hydrol Process* 30:1354–1366. <https://doi.org/10.1002/hyp.10723>
- Kociuba W, Janicki G (2014) Continuous measurements of bedload transport rates in a small glacial river catchment in the summer season

- (Spitsbergen). *Geomorphology* 212:58–71. <https://doi.org/10.1016/j.geomorph.2013.05.001>
- Kociuba W, Janicki G (2018) Effect of meteorological patterns on the intensity of streambank erosion in a proglacial gravel-bed river (Spitsbergen). *Water* 10:320. <https://doi.org/10.3390/w10030320>
- Kostrezewski A, Kaniecki A, Kapuscinski J, Kilmezak R, Stach A, Zwolinski Z (1989) The dynamics and rate of denudation of glaciated and non-glaciated catchments, Central Spitsbergen. *Pol Polar Res* 10:317–367
- Krikbride MP (1995) Processes of transportation. In: Menzies J (ed) *Modern glacial environments—processes, dynamics and sediments*. Butterworth-Heinemann Ltd, Oxford, pp 241–259
- Kumar K, Miral MS, Joshi PYS (2002) Discharge and suspended sediment in the meltwater of Gangotri Glacier, Garhwal Himalaya, India. *Hydrol Sci J* 47:611–619. <https://doi.org/10.1080/02626660209492963>
- Kumar R, Singh S, Kumar R, Singh A, Bhardwaj A, Sam L, Randhawa SS, Gupta A (2016) Development of a glaciohydrological model for discharge and mass balance reconstruction. *Water Resour Manag* 30:3475–3492. <https://doi.org/10.1007/s11269-016-1364-0>
- Kumar R, Kumar R, Singh S, Singh A, Bhardwaj A, Kumari A, Randhawa SS, Saha A (2018) Dynamics of suspended sediment load with respect to summer discharge and temperatures in Shaune Garang glacierized catchment, Western Himalaya. *Acta Geophys* 66:1109–1120. <https://doi.org/10.1007/s11600-018-0184-4>
- Ohta T, Fukushima Y, Suzuki M, Motoyama H, Kawashima K, Kubota H (1987) Suspended sediment yield in a glaciated watershed of Langtang valley, Nepal Himalayas. *Bulletin Glacier Res* 5:19–24
- Othman F, Naseri M (2011) Reservoir inflow forecasting using artificial neural network. *Int J of the Phys Sci* 6(3):434–440. <https://doi.org/10.5897/IJPS10.649>
- Othman NY, Saleh ZA, Omran ZA (2019) Development of stage-distance-discharge relationship and rating curve using least square method. *Civil Eng J* 5(9):1959–1969. <https://doi.org/10.28991/cej-2019-03091385>
- Patel AB, Joshi GS (2017) Modeling of rainfall-runoff correlations using artificial neural network—a case study of Dharoi watershed of a Sabarmati River basin, India. *Civil Eng J* 3(2):78–87. <https://doi.org/10.28991/cej-2017-00000074>
- Puri VMK (1999) Glaciohydrological and suspended sediment load studies in the melt water channel of Changme Khangpu Glacier, Mangam district, Sikkim. *Symposium on Snow, Ice and Glaciers-Himalayan Prospective*, Lucknow, pp 1–5
- Raina VK, Srivastava D (2008) *Glacier atlas of India*. Geological Society of India, Bangalore
- Rieger HC (1981) Man versus mountain—the destruction of Himalayan ecosystem. In: Lall JS (ed) *Himalaya*. Oxford University Press, pp 351–376
- Sefe FTK (1996) A study of the stage-discharge relationship of the Okavaiigo River at Mohembo, Botswana. *Hydrological Sci J* 41(1):97–116. <https://doi.org/10.1080/02626669609491481>
- Singh VP, Chen VJ (1982) On the relation between sediment yield and runoff volume. In: Singh VP (ed) *Water Resources Publications*, Littleton, pp 555–570
- Singh AK, Hasnain SI (1998) Major ion chemistry and weathering control in a high altitude basin: Alaknanda River, Garhwal Himalaya, India. *Hydrol Sci J* 43:825–884. <https://doi.org/10.1080/02626669809492181>
- Singh VB, Ramanathan AL (2018) Suspended sediment dynamics in the meltwater of Chhota Shigri glacier, Chandra basin, Lahaul-Spiti valley, India. *J Mt Sci* 15:68–81. <https://doi.org/10.1007/s11629-017-4554-1>
- Singh P, Ramasastri KS (1999) Temporal distribution of Dokriani Glacier melt runoff and its relationship with meteorological parameters. Technical report submitted to Department of Science and Technology, Government of India
- Singh P, Singh VP (2001) *Snow and glacier hydrology*. Kluwer Academic Publishers, The Netherlands
- Singh P, Ramasastri KS, Kumar N, Bhatnagar NK (2003) Suspended sediment transport from the Dokriani Glacier in the Garhwal Himalayas. *Nordic Hydrol* 34:221–244. <https://doi.org/10.2166/nh.2003.0005>
- Singh P, Haritashya UK, Ramasastri KS, Kumar N (2005) Diurnal variations in discharge and suspended sediment concentration, including runoff-delaying characteristics, of the Gangotri glacier in Garhwal Himalayas. *Hydrol Process* 19:1445–1457. <https://doi.org/10.1002/hyp.5583>
- Singh P, Haritashya UK, Kumar N, Singh Y (2006) Hydrological characteristics of the Gangotri Glacier, Central Himalayas, India. *J Hydrol* 327:55–67. <https://doi.org/10.1016/j.jhydrol.2005.11.060>
- Singh P, Haritashya UK, Kumar N (2008) Modelling and estimation of different components of stream flow for Gangotri Glacier basin Himalayas. *Hydrol Sci J* 53:309–322. <https://doi.org/10.1623/hysj.53.2.309>
- Singh VB, Ramanathan AL, Pottakkal JG, Kumar M (2014) Seasonal variation of the solute and suspended sediment load in Gangotri Glacier meltwater, central Himalaya, India. *J Asian Earth Sci* 79: 224–234. <https://doi.org/10.1016/j.jseae.2013.09.010>
- Singh VB, Ramanathan AL, Sharma P, Pottakkal JG (2015) Dissolved ion chemistry and suspended sediment characteristics of meltwater draining from Chhota Shigri Glacier, western Himalaya, India. *Arabian J Geosci* 8:281–293. <https://doi.org/10.1007/s12517-013-1176-y>
- Singh S, Kumar R, Bhardwaj A, Sam L, Shekhar M, Singh A, Kumar R, Gupta A (2016a) Changing climate and glacio-hydrology in Indian Himalayan region: a review. *Wiley Interdiscip Rev Clim Chang* 7: 393–410. <https://doi.org/10.1002/wcc.393>
- Singh VB, Ramanathan AL, Pottakkal JG (2016b) Glacial runoff and transport of suspended sediment from the Chhota Shigri glacier, Western Himalaya, India. *Environ Earth Sci* 75:695–613. <https://doi.org/10.1007/s12665-016-5271-8>
- Singh DS, Tangri AK, Kumar D, Dubey CA, Bali R (2016c) Pattern of retreat and related morphological zones of Gangotri Glacier, Garhwal Himalaya India. *Quat Int J*:1–10. <https://doi.org/10.1016/j.quaint.2016.07.025>
- Srivastava D, Kumar A, Verma A, Swaroop S (2014) Characterization of suspended sediment in Meltwater from glaciers of Garhwal Himalaya. *Hydrol Process* 28:969–979. <https://doi.org/10.1002/hyp.9631>
- Sumer BM, Fredsøe J, Christiansen N (1992) Scour around vertical pile in waves. *J Water Port Coast Ocean Eng* 118(1):15–31. [https://doi.org/10.1061/\(asce\)0733-950x\(1992\)118:1\(15](https://doi.org/10.1061/(asce)0733-950x(1992)118:1(15)
- Thayyen RJ, Gergan JT, Dobhal DP (1999) Particle size characteristics of suspended sediment and subglacial hydrology of Dokriani Glacier, Garhwal Himalaya, India. *Hydrol Sci J* 44:47–61. <https://doi.org/10.1080/02626669909492202>
- Vohra CP (1988) *Gangotri glacier, Indian Mountaineer, Indian Mountaineering Foundation*, pp 51–58
- Williams GP (1989) Sediment concentration versus water discharge during single hydrologic events in rivers. *J Hydrol* 111:89–106. [https://doi.org/10.1016/0022-1694\(89\)90254-0](https://doi.org/10.1016/0022-1694(89)90254-0)
- Wulf H, Bookhagen B, Scherler D (2012) Climatic and geologic controls on suspended sediment flux in the Sutlej River Valley, western Himalaya. *Hydrol Earth Syst Sci Discuss* 9:541–594
- Yamini OA, Mousavi SH, Kavianpour MR, Movahedi A (2018) Numerical modeling of sediment scouring phenomenon around the offshore wind turbine pile in marine environment. *Environ Earth Sci* 77:776–715. <https://doi.org/10.1007/s12665-018-7967-4>
- Zhang L (2019) Big data, knowledge mapping for sustainable development a water quality index case study. *Emerging Sci J* 3(4):249–254. <https://doi.org/10.28991/esj-2019-01187>