



Dynamics of suspended sediment load with respect to summer discharge and temperatures in Shaune Garang glacierized catchment, Western Himalaya

Rajesh Kumar¹ · Ramesh Kumar¹ · Shaktiman Singh¹ · Atar Singh¹ · Anshuman Bhardwaj² · Anupma Kumari³ · S. S. Randhawa⁴ · Ashok Saha⁵

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Abstract

The observed and predicted rise in temperature will have deleterious impact on melting of snow and ice and form of precipitation which is already evident in Indian Himalayan Region. The temperature-dependent entities like discharge and sediment load will also vary with the observed and predicted rise posing environmental, social and economic threat in the region. There is little known about sediment load transport in relation to temperature and discharge in glacierized catchments in Himalaya mainly due to the scarcity of ground-based observation. The present study is an attempt to understand the suspended sediment load and transportation in relation to variation in discharge and temperature in the Shaune Garang catchment. The result shows strong dependence of sediment concentration primarily on discharge ($R^2 = 0.84$) and then on temperature ($R^2 = 0.79$). The catchments with similar geological and climate setting were observed to have comparatively close weathering rate. The sediment load was found to be higher in the catchments in eastern and central part of Indian Himalayan Region in comparison with western part due to dominance of Indian Summer Monsoon leading to high discharge. The annual physical weathering rate in Shaune Garang catchment was found to be $411 \text{ t km}^{-2} \text{ year}^{-1}$ which has increased from $327 \text{ t km}^{-2} \text{ year}^{-1}$ in around three decades due to rise in temperature causing increase in discharge and proportion of debris-covered glacierized area.

Keywords Sediment load · Pro-glacial river discharge · Temperature · Shaune Garang catchment · Western Himalaya

Introduction

Hindu Kush Himalaya is the youngest and highest mountain range in the world and encompasses around 54,000 glaciers covering a total area of about $60,000 \text{ km}^2$ with nearly 6000 km^3 of ice volume reserves (Bajracharya and Shrestha 2011). Around 50% of the glacier area falling outside the polar region are in the Hindu Kush Himalaya, regulating the flow in all the major river basins in South Asia particularly during summer when all other sources are diminishing (Immerzeel and Verbeek 2010). These rivers are the main source of fresh water supply for agricultural, domestic and industrial usage in the densely populated downstream areas (Lu et al. 2016; Xu et al. 2009). The region is particularly vulnerable to changing climate due to their latitudinal and altitudinal position (Singh et al. 2016). The temperature trend shows systematic rise in Indian part of Hindu Kush Himalaya with accelerated warming in

✉ Ramesh Kumar
rameshkumar9234@gmail.com

¹ Department of Environmental Science, Sharda University, Greater Noida, India
² Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Lulea University of Technology, Lulea, Sweden
³ Environmental Biology Laboratory, Department of Zoology, Patna University, Patna, India
⁴ State Council for Science, Technology and Environment, Shimla, India
⁵ Ministry of Earth Science, New Delhi, India

recent decades while precipitation does not show any specific regional trend (Singh et al. 2016). The rise in temperature will affect the rate of snow and ice melt and type of precipitation in the region (Kumar et al. 2016; Oliva and Ruiz-Fernández 2016). This effect is already evident as several studies carried out in the region suggest continuous loss of mass of the glaciers in general with varying rate according to their location and few exceptions (Bolch et al. 2012; Immerzeel and Verbeek 2010; Singh et al. 2016). Although precipitation is predicted to increase in general, western and central in particular (Immerzeel et al. 2013; Lutz et al. 2014), the liquid precipitation will dominate in future forced by predicted increase in temperature (Singh et al. 2016). Precipitation is the key parameter controlling the erosion process in Himalaya (Bookhagen et al. 2005; Wulf et al. 2010). The sediment transport is primarily dependent on the hydrological entities of the catchment such liquid precipitation and discharge (Kumar et al. 2018; Sziło and Bialik 2017). In addition, the sediment load in the stream flow is contributed by erosion of land surface by glacier mass and transported in downstream areas (Hammer and Smith 1983; Kociuba and Janicki 2015; Wulf et al. 2010). The morphology and flow structure of the channel also plays an important role in determining the sediment load (Bialik et al. 2014). The glaciers in Himalayan region are partly covered by debris in general which is transported to the surface of the glacier by debris flows, snow avalanches, rockfall and rock avalanches (Bishop et al. 1998; Oliva and Ruiz-Fernández 2015; Singh et al. 2016). This loose matter is particularly free to flow with ice, melt water and liquid precipitation to the discharge channel increasing the sediment load in the discharge (Bruijnzeel and Bremmer 1989; Hasnain and Chauhan 1993; Hasnain and Thayyen 1999; Kostrzewski et al. 1989; Kumar et al. 2002; Szopińska et al. 2018). Therefore, the sediment load is directly dependent on discharge in a glacierized catchment and indirectly dependent on the meteorological entities like temperature and precipitation which directly affect discharge (Haritashya et al. 2006; Kociuba and Janicki 2014; Kociuba et al. 2014; Kociuba and Janicki 2018; Kumar et al. 2002; Sharma et al. 2013; Sziło and Bialik 2018). Since the hydropower potential of the region is enormous, the study of sediment load flux, its sources and temporal and spatial variation is critical for hydropower plant management as sediment load can significantly affect the abrasion and corrosion of hydropower plant turbines. In addition, the variation in sediment load can also change the long-term morphology as well as path of the streamflow channel (Kociuba and Janicki 2015; Kociuba 2016).

In the present study, we assess the sediment load in the discharge stream of Shaune Garang catchment located in western part of Indian Himalayan region. Since,

glaciological, hydrological and meteorological entities are the main factors controlling the erosion and sediment load in a glacierized catchment we have also assessed the sediment load in relation to stream discharge and temperature change. As detailed in the documentation of Water Resources Information System (WRIS), Indian Space Research Organization, Government of India, there is a hydropower plant of 300 MW capacity operational at around 30 kms downstream of the Shaune Garang catchment (http://india-wris.nrsc.gov.in/wrpinfo/index.php?title=Baspa_Hydroelectric_Project_Hydroelectric_Project_JH00493) and a few more are proposed to be constructed in future. Therefore, the study area is very critical in terms of assessment of the temporal variation of sediment load and its relation to hydro-meteorology. Here, we are starting with a single glacierized catchment within Baspa basin based on data collection and availability to provide a first-hand assessment in this regard.

Study area

Shaune Garang catchment is located in the Western Himalaya between latitudes $31^{\circ}16'45''\text{N}$, $31^{\circ}18'\text{N}$ and longitudes $78^{\circ}18'30''\text{E}$, $78^{\circ}22'\text{E}$. The discharge from Shaune Garang catchment contributes to Baspa River which is a tributary of Sutlej (Fig. 1). Although the precipitation in the catchment is contributed by both the Western Disturbance and Indian Summer Monsoon (Kumar et al. 2016, 2018), the amount of summer precipitation is higher in comparison with winter in general (Wulf et al. 2010). The Western Disturbance is the weather system created due to the low pressure systems observed in the mid-latitude westerlies over the subtropical region of Asia and the Middle East causing precipitation dominated in north-western part of Himalaya during winter (Dimri 2004). In Shaune Garang catchment the ablation season starts from May and ends by the end of September (Kumar et al. 2016). The total area of the catchment above the discharge measurement gauge is 38.13 km^2 with non-glacierized area of about 75%, debris-covered glacierized area of 5% and debris-free glacierized area of 20%. The morphology of Shaune Garang catchment is presented in Fig. 2. The analysis of aspect of the catchment suggests that the maximum area of the catchment is North and North-West direction facing (Fig. 2). Furthermore, the maximum area of Shaune Garang catchment falls in mid-slope of 24° to 40° (Fig. 2). A detailed study of geological evolution of Baspa valley suggests that the Shaune Garang catchment is dominated by Rakcham group of granite (Dutta et al. 2017). Several studies in past for this study area have focused on studying the glacier dynamics (Sam et al. 2015), facies mapping (Bhardwaj et al. 2015a),

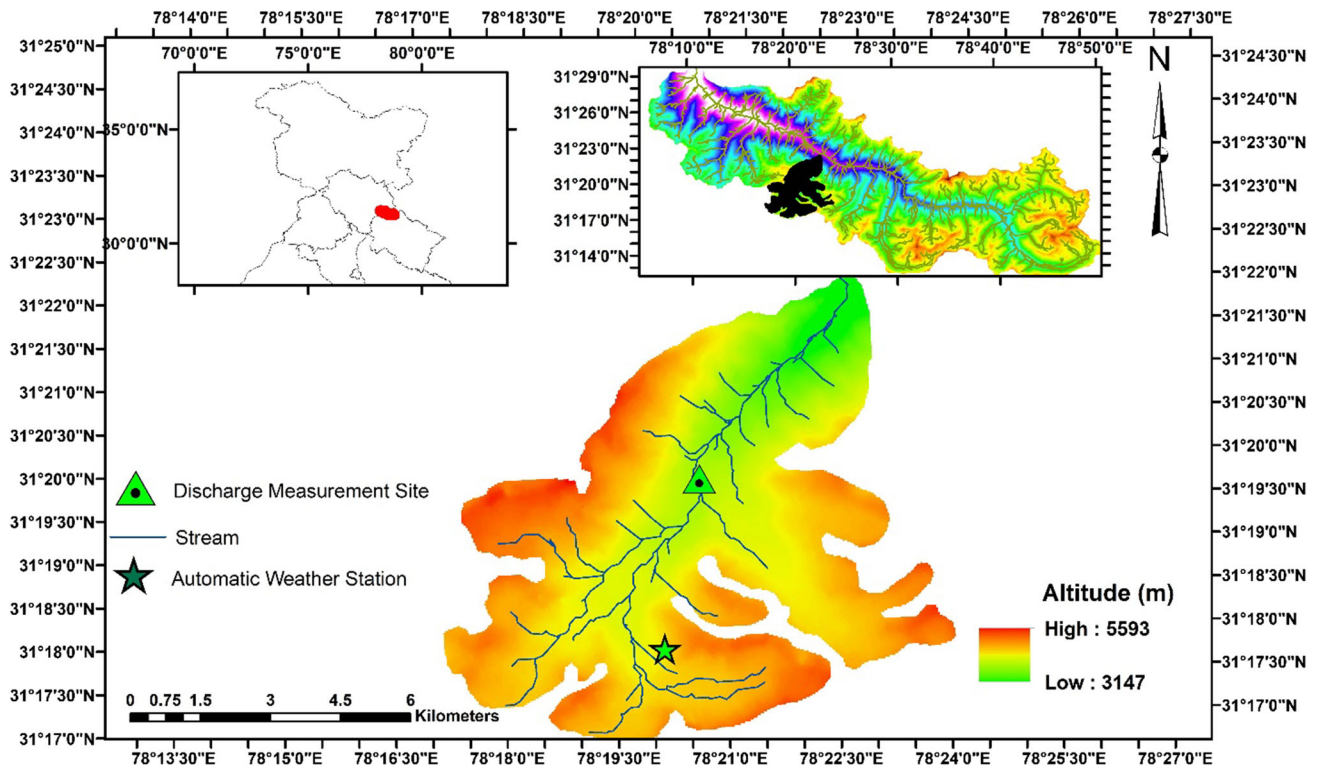
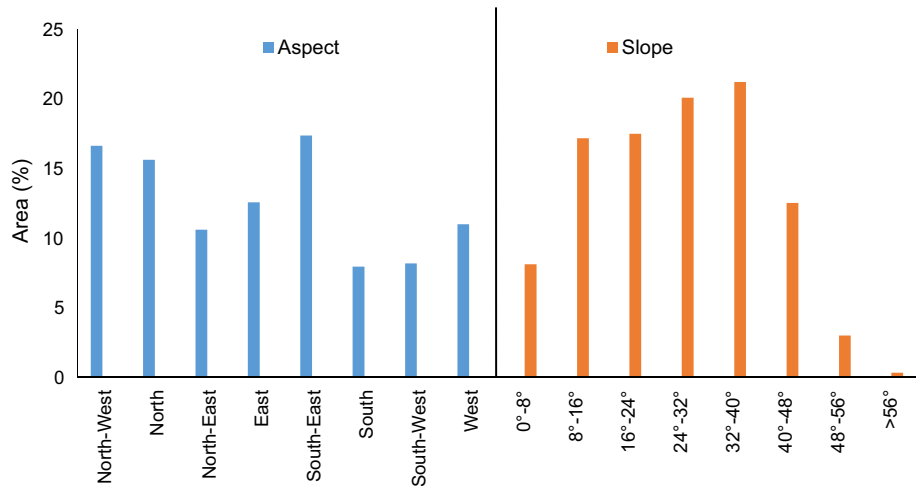


Fig. 1 The location map of Shaune Garang catchment showing the stream channels, discharge measurement site and Automatic Weather Station. The location of Shaune Garang catchment (in black color) in

Baspa basin and location of Baspa basin (in red color) in India has also been shown in inset

Fig. 2 The area-aspect and area-slope distribution of Shaune Garang catchment



glacial lake mapping (Bhardwaj et al. 2015b), discharge reconstruction (Kumar et al. 2016; Singh et al. 2018), and crevasse mapping (Bhardwaj et al. 2016). However, we do not have significant information on the dynamics of sediment load from the catchment, and in the present study, we have filled this research gap. There are four different glaciers in the catchment out of which Shaune Garang is the largest glacier with total area of 4.94 km² and is main contributor to stream discharge (Kumar et al. 2016). The

mid-elevation part of the catchment (4500–4800 m asl) is mostly covered by debris of varying thickness (Kumar et al. 2016). The meteorological parameters mainly temperature and precipitation are the main factors governing the sediment load and transport in the downstream areas. The temperature controls the melting of snow and ice in a glacierized catchment as well as the form of precipitation at a specific altitude (Singh et al. 2016). The event of liquid precipitation on the surface of the glacierized area in

Shaune Garang catchment is quite frequent (Kumar et al. 2016), which will increase with predicted rise in temperature (Singh et al. 2016). A very significant proportion of total annual precipitation in Baspa basin is contributed by Indian Summer Monsoon (Wulf et al. 2010). The liquid precipitation is the most important factor controlling the rate of erosion which affects the SSC in the stream flow. The temperature and precipitation were collected using an Automatic Weather Station (AWS-HOBO U-30 NRC) in the basin. The weather station was installed on the lateral moraine of glacier at an altitude 4569 m asl. The station was configured to collect the temperature and precipitation data at hourly interval. The temperature data were used to analyze the interrelationship with the discharge and SSL in the stream of the Shaune Garang catchment.

Materials and methods

Suspended solid concentration (SSC)

The glacial meltwater samples were taken in polyethylene bottle (250 ml) twice a day (08:00 h and 15:00 h) during the ablation period of 2014 and 2015. The samples were taken from 2nd August to 28th September in 2014 and 6th August to 24th September in 2015. In addition, water samples were collected at an hourly interval for 12 h (06:00 h to 18:00 h) once a week to estimate the spatial and temporal variation of the suspended solid concentration (SSC) in the streamflow. Standard sampling protocols were followed while taking the water sample to reduce the error involved. Before taking every sample, polyethylene bottle was rinsed with the source water which was being sampled. Furthermore, the water samples were taken from the middle of the stream channel to reduce biasness caused by reduced flow and added suspended solids on the banks of the channel. The collected samples of fixed volume (250 ml) were filtered on-site with a filtration setup using a filter paper of Millipore size 0.45 μm (Whatman filter paper). The filter papers along with water samples were then brought to Environmental Research Laboratory, Sharda University, for further analysis of SSC. The SSC was calculated by estimating the difference between the weight of new filter paper and the weight of the used filter paper after drying.

Discharge measurement

The discharge (Q) was measured at the discharge measurement site for the ablation season of 2014 and 2015. The area-velocity method of discharge measurement was used to estimate average daily discharge in the catchment. This method is most widely used method in Himalaya for

measurement of discharge because of its simplicity, less site development requirements and comparatively efficient results. The method can be expressed by a simple equation as follows:

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

where Q = discharge ($\text{m}^3 \text{s}^{-1}$), A = area of cross section (m^2), V = velocity (m s^{-1}).

There are two parameters namely velocity and area of cross section which needs to be measured regularly to calculate discharge. These parameters are measured twice daily (08:00 h and 15:00 h) on the site and averaged to calculate daily discharge in the channel. The stream gauge for measurement of discharge in the basin was developed around 3 kms downstream from the snout of Shaune Garang glacier. The site was selected on the basis of comparatively low turbulence and more linear movement of stream. The area of cross section of the river at the site was measured multiple times during the whole season and was calibrated twice daily using water level measurements. The velocity of stream was measured at three different level of depth in water channel using current meter (Make: Gurley Precision Instruments, USA; Model: Price). The average velocity measured by current meter was used to calibrate the velocity measurements done using float method. In addition to the twice daily discharge measurement, the discharge was also measured at hourly interval for 12 h (06:00 h to 18:00 h) once a week to estimate the hysteresis in the stream flow.

Suspended sediment load (SSL)

The suspended sediment load (SSL) in discharge from Shaune Garang catchment was calculated by following Eq. 2 (Haritashya et al. 2006). This is the most common method used in Himalaya to calculate SSL. The coefficient (K) is a constant which is based on the specific weight of sediment.

$$\text{SSL} = K \times Q \times \text{SSC} \quad (2)$$

here SSL = suspended sediment load in stream discharge (t day^{-1}), Q = Stream discharge ($\text{m}^3 \text{s}^{-1}$), SSC = suspended solid concentration in the stream water (mg l^{-1}), K = conversion factor appropriate to the units used for Q , C and Q_s .

The SSL can be used to compute SSL per unit basin area using Eq. 3.

$$\text{SSL} = \frac{\text{SSL}}{A_b} \quad (3)$$

here SSL = suspended sediment load per unit basin area ($\text{t day}^{-1} \text{ km}^{-2}$), A_b = area of Basin (km^{-2}).

Then, SSL per unit basin area used to compute physical weathering rate (PWR) using Eq. 4.

$$\text{PWR} = \text{SSL} \times 365 \quad (4)$$

here PWR = physical weathering rate ($\text{t km}^{-2} \text{ year}^{-1}$),
SSL = suspended sediment load per unit basin area
($\text{t day}^{-1} \text{ km}^{-2}$).

Results and discussion

Transportation of suspended sediment

The primary source of sediment in a stream from a catchment is from the debris present over the surface of the glacierized part and rocks, moraines and debris present in the non-glacierized part of the basin (Haritashya et al. 2006; Singh et al. 2004; Srivastava et al. 2014). The amount of sediment erosion and transport from higher reaches of a glacierized catchment controls sediment load in the reservoir which can affect the operational cost as well as life of hydropower plant. The daily mean SSC during the ablation month of August and September of 2014 was found to be 64.5 and 44.8 mg l^{-1} , respectively, and similarly, in 2015, it was 73.2 and 41.0 mg l^{-1} for August and September, respectively. The daily mean SSL in the months of August and September in 2014 was observed to be 49.5 and 22.00 t day^{-1} , respectively, while it was 70.19 and 30.1 t day^{-1} in August and September, respectively, for 2015. The results show that the magnitude of SSC and SSL in August is higher in general when compared to September primarily due to high liquid precipitation and high temperature in August leading to more discharge. The debris-covered part of the catchment is more exposed to erosion during the ablation season in comparison with other months when they are fully or partially covered by seasonal snow. The exposed debris rocks in the glacierized and non-glacierized part of the catchment are the primary source of high SSC and SSL in the stream during melt season in addition to high discharge. This observation is in agreement of the other studies in Himalaya which shows more transport of suspended solid during the melt season (Haritashya et al. 2006; Singh and Hasnain 1998). To understand the regional suspended sediment load and transportation, the results from the present study have been compared with results from other glacierized catchments in the Indian Himalayan Region and is summarized in Table 1. For interbasin comparison, the daily mean SSL has been converted to daily mean SSL per unit area. The results shows that the daily mean SSL per unit area of Shaune Garang catchment has increased from the study undertaken during 1981–1991 to 2014–2015. The main reason for increased flux of sediment

can be attributed to the increased in debris cover proportion of the glacierized area and increased discharge (from 4.58 cu.m/sec in 1983–1989 to 8.86 cu.m/sec during 2014–2015) in Shaune Garang catchment during this period caused by rise in temperature in the basin (Kostrzewski et al. 1989; Kumar et al. 2016, 2014). Dokriani catchment was found to have highest rate of SSL per unit basin area among all the studied glaciers in Indian Himalayan Region. The glacierized catchments in Uttarakhand were found to have more SSL per unit area in comparison with the other glaciers in Indian Himalayan Region. This is because of more liquid precipitation due to Indian Summer Monsoon in this part of Indian Himalayan Region (Jeelani and Deshpande 2017). The annual yield of sediment from the catchment is another parameter which shows rate of annual weathering (Table 1). The data shows that the annual physical weathering rate is highest in Gangotri basin followed by Dokriani catchment. The weathering in this part of Indian Himalayan Region is more in comparison with other parts primarily due to more liquid precipitation causing more erosion, which is also evident by high discharge. The rate of physical weathering is also affected by proportion of glacierized and non-glacierized area in a basin. The rate of physical weathering as well as SSL per unit basin area in Shaune Garang catchment was found to be comparatively more close to Gara (Table 1). The Shaune Garang catchment and Gara catchment are located very close to each other geographically with similar orientation leading to similarity geological and meteorological setting in both the basins.

Temperature and discharge

As discussed earlier, the temperature controls the rate of melting of snow and ice in addition to controlling the form of precipitation at a specific altitude. The temperature was measured in the field at hourly interval and the observation was converted to daily mean. The observed discharge and temperature for 2014 and 2015 are shown in Fig. 3. The discharge matches well with temperature in general except for the days with high precipitation events. The high precipitation caused high discharge in the stream flow of the catchment even when the temperature was low showing anti-clock hysteresis loop in the data. To understand the interrelationship of temperature and discharge, correlation was calculated for the ablation season of 2014 and 2015 (Fig. 4). The coefficient of determination between temperature and discharge was found to be 0.68 ($n = 34$, $p < 0.01$) and 0.78 ($n = 41$, $p < 0.01$) for the ablation season of 2014 and 2015, respectively. The strong coefficient of determination (R^2) indicates discharge is well interrelated with temperature during study period with little more closer in the year 2015. The results of the study

Table 1 Comparison of suspended sediment load of some of the Himalayan melt water channels of different states of India

Glacier	Region	Basin Area (km ²)	SSL (t day ⁻¹)	SSL per unit basin area (t day ⁻¹ km ⁻²)	Physical weathering rate (t km ⁻² year ⁻¹)	References
Changme Khangpu	Sikkim	4.5	18	4.00	1460*	Puri (1999)
Dunagiri	Uttarakhand	17.9	47	2.63	958*	Srivastava et al. (2014)
Gangotri	Uttarakhand	556	11673	20.99	7663	Singh et al. (2014)
Tipra Bank	Uttarakhand	41.6	40	0.96	351*	Puri and Swaroop (1995)
Dokriani	Uttarakhand	16.3	447	27.76	2800	Singh and Ramashastri (1999)
Neh Nar	Jammu and Kashmir	8.1	6	0.74	270*	Raina (2009)
Chhota Shigri	Himachal Pradesh	45	135	3.00	1095	Singh and Ramanathan (2018)
Gara	Himachal Pradesh	17	22	1.29	472*	Raina (2009)
Patsio	Himachal Pradesh	7.82	2.83	0.36	132	Singh et al. (2015)
Shaune Garang	Himachal Pradesh	33.5	30	0.90	327*	Raina (2009)
Shaune Garang	Himachal Pradesh	38.13	42.92	1.13	411	Present study

*The Physical Weathering Rate has been calculated for comparison in present study using SSL and Basin Area mentioned in referred sources

corroborate the fact that the variation in discharge in a glacierized catchment is primarily controlled by change in temperature. The mean temperature in general and minimum in particular is rising in the basin with a rate higher than other parts of the globe (Kumar et al. 2014; Singh et al. 2016). The effect of this rise in temperature is already evident on discharge from Shaune Garang catchment, where the discharge was found to be increasing (Kumar et al. 2016). This increase in discharge will reach a critical point after which there will be a sudden decrease primarily caused by shrinking glacierized part of the catchment.

Temperature and suspended sediment concentration (SSC)

The suspended sediment concentration (SSC) was measured at daily scale and was used with daily discharge to calculate suspended sediment load (SSL). A study by Srivastava et al. 2014, suggested that SSC may increase in exponential alternation with small variation in air temperature. Since the sediment concentration in downstream area is directly correlated with discharge (Figs. 3, 4), the sediment concentration should ideally be correlated to temperature. To analyze the relationship between temperature and SSC, coefficient of correlation was calculated for the ablation season of the year 2014 and 2015 (Fig. 5). The coefficient of determination (R^2) between temperature and SSC was found to be 0.62 ($n = 32$, $p < 0.01$) and 0.72 ($n = 36$, $p < 0.01$) during 2014 and 2015, respectively. The good coefficient of determination (R^2) shows that the SSC is well correlated with temperature throughout the study

period. The coefficient of determination was found to be higher in 2015 in comparison with 2014. The finding of the present study supports that SSC dependence on the temperature. During the cloud-free days, air temperature was observed to reach its peak at around 14:00 h, whereas discharge and therefore SSC reach at its peak at around 17:00 h, with a general delay of around 3 h on an average. This delay is caused by the time taken by the SSC from the upper reaches and glacierized area in the catchment to reach the discharge gauge through stream flow. Conclusively, change in the temperature trend indirectly compelled variation in the sediment evacuation, due to its control on discharge which is the main driver of sediment transport (Fig. 6).

Discharge and suspended sediment concentration (SSC)

Several studies show that discharge in the stream from a glacierized catchment is positively correlated to SSC (Priya et al. 2016; Srivastava et al. 2014; Singh and Ramashastri 1999). The contribution of different components like snow and glacier ice melt and rain and base flow to the overall discharge is an important factor which controls the discharge and therefore the sediment load. An analysis of discharge data reconstructed for 1985 to 2008 in Shaune Garang catchment suggests that the ice and snow melt is the highest contributor to the overall discharge (Kumar et al. 2016). The average daily discharge of Shaune Garang Glacier during the month of August and September, 2014 was observed to be 8.41 and 5.16 m³ s⁻¹, respectively,

Fig. 3 Graph showing the comparison of temperature (°C) and discharge ($\text{m}^3 \text{s}^{-1}$) for the part of ablation season of a 2014 and b 2015

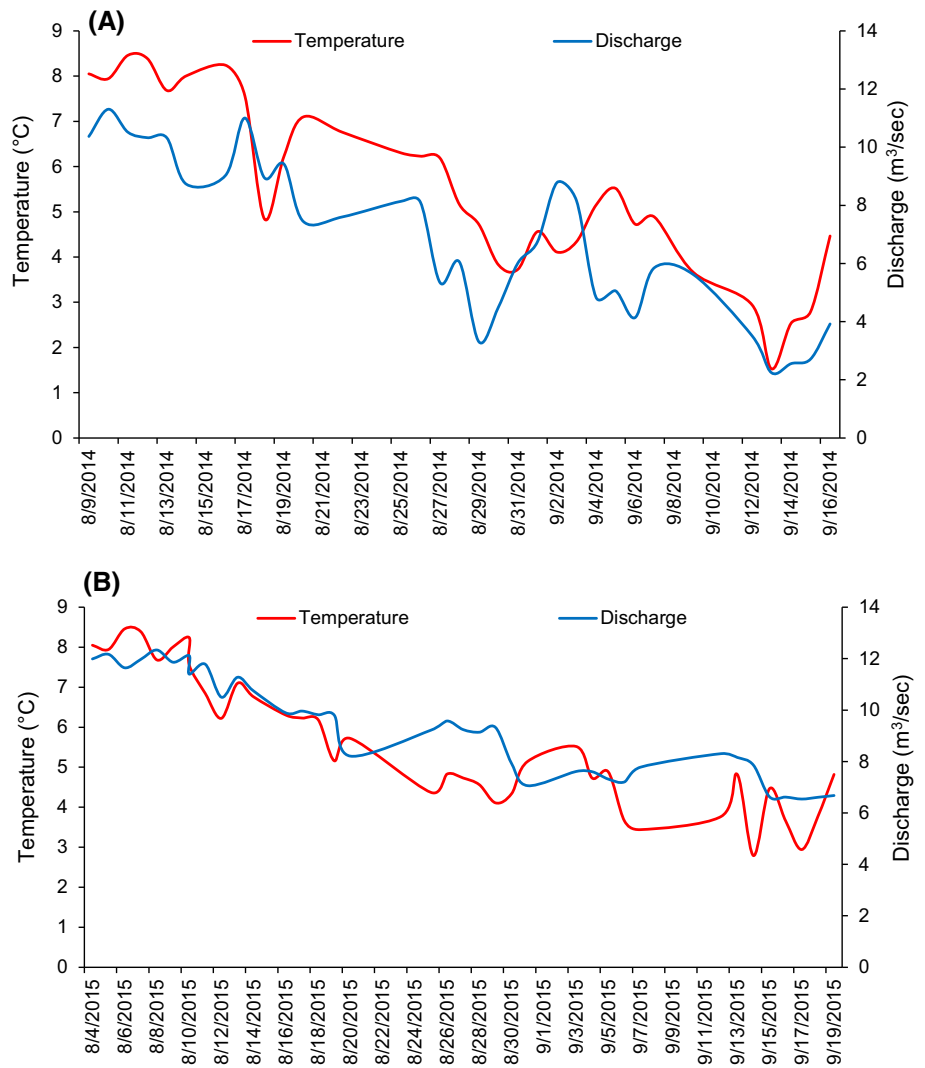
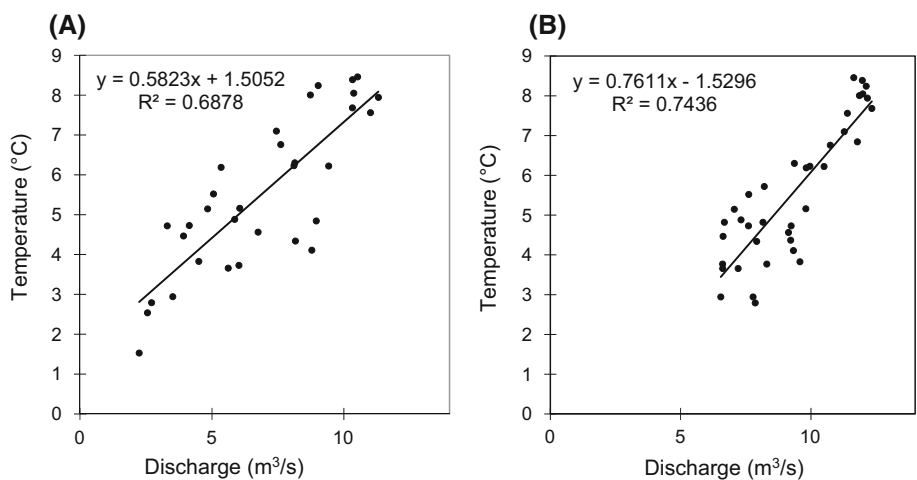


Fig. 4 Graph showing the scatter plot between temperature (°C) and discharge ($\text{m}^3 \text{s}^{-1}$) for the part of ablation season of a 2014 and b 2015



while in August and September, 2015, it was observed to be 10.88 and $6.67 \text{ m}^3 \text{ s}^{-1}$, respectively (Table 2). The volume daily mean discharge in the catchment was

observed to be 72.6 and $44.5 \times 10^4 \text{ m}^3$ in August and September, respectively, in 2014, while it was found to be 94.0 and $57.6 \times 10^4 \text{ m}^3$ in August and September,

Fig. 5 Graph showing the comparison of temperature (°C) and suspended sediment concentration (mg l⁻¹) for the part of ablation season of **a** 2014 and **b** 2015

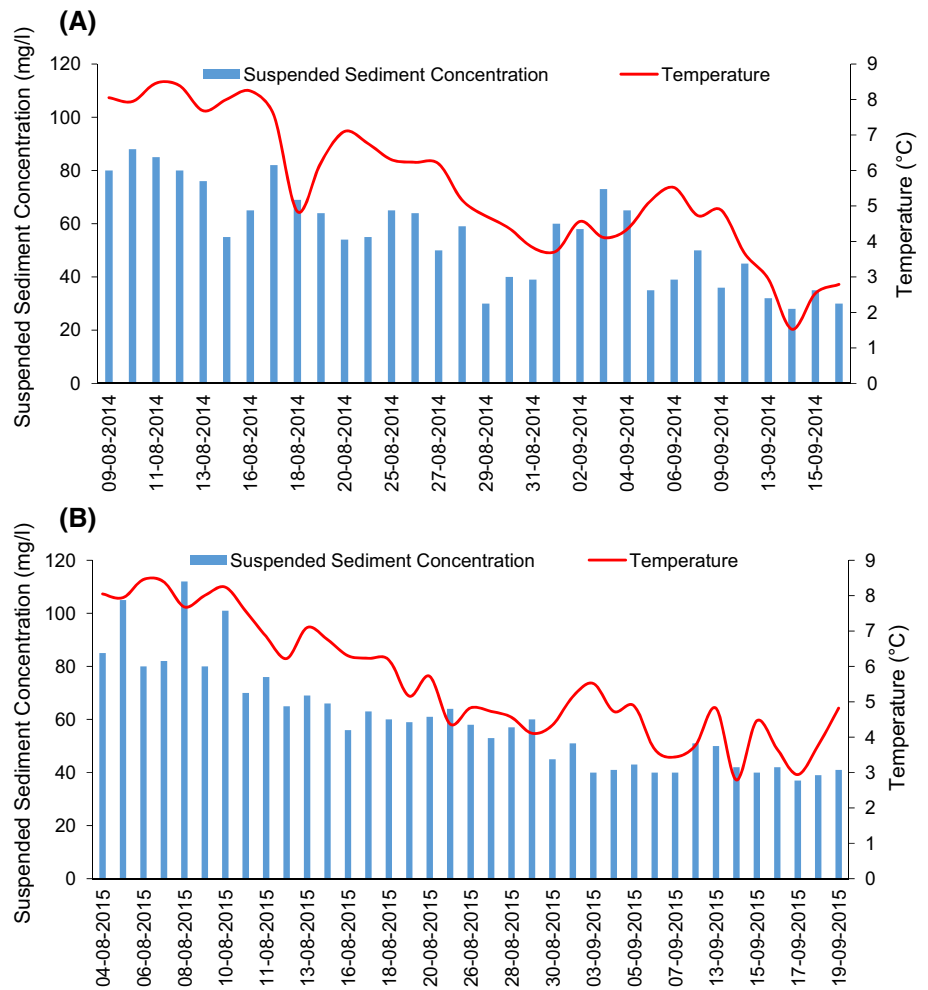
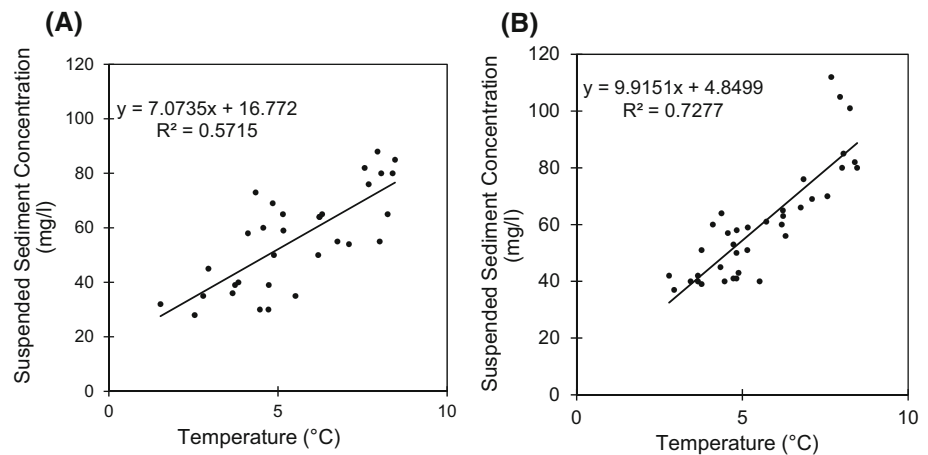


Fig. 6 Graph showing the scatter plot between temperature (°C) and suspended sediment concentration (mg l⁻¹) for the part of ablation season of **a** 2014 and **b** 2015



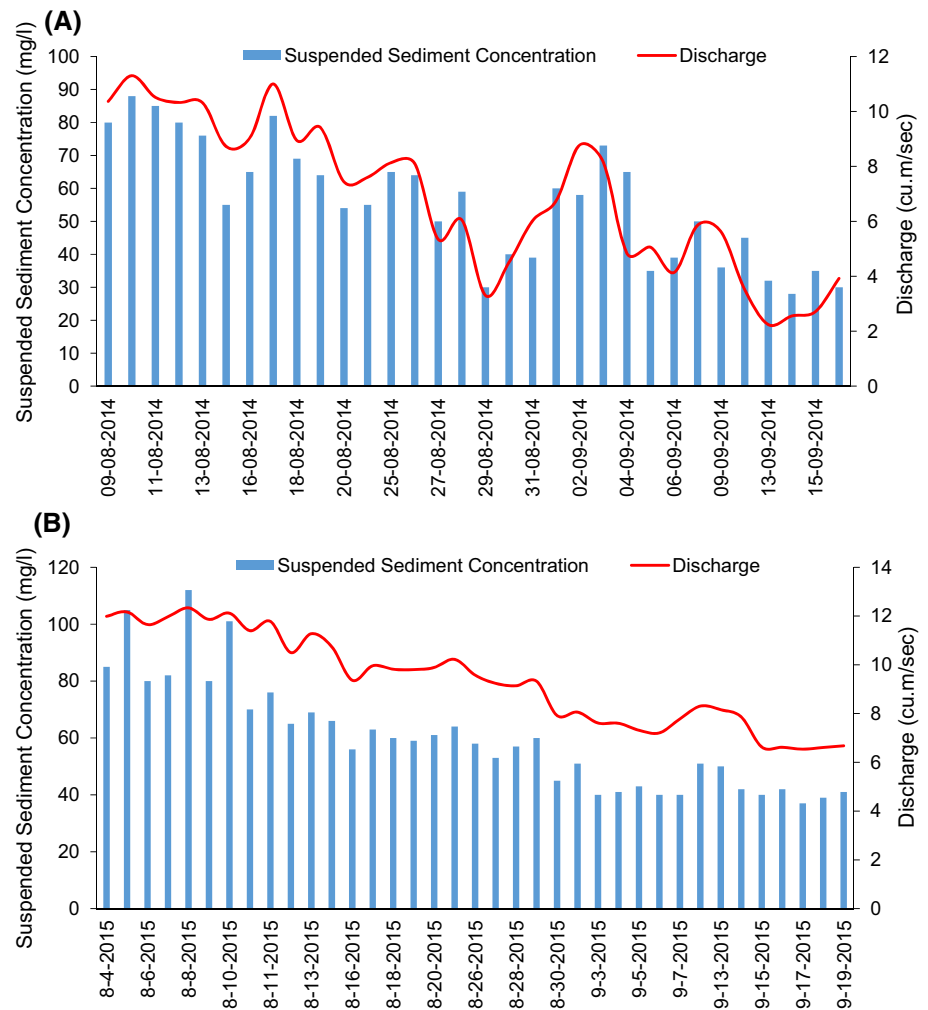
respectively, in 2015 (Table 2). The results indicate that discharge is higher in the month of August in both study periods, due to the higher temperature and rain compared to September. The analysis of hourly measurement of discharge which was done once a week suggests that the discharge increases after 13:00 h and reaches its peak around 17:00 h. The subglacial stream flow discharge

primarily controls the flow of accumulated sediment in the glacier bed and therefore regulates the concentration of sediments downstream. The comparison of discharge and SSC is presented in Figs. 7 and 8. Figure 7 shows that the hydrograph during 2014 and 2015 matches well with the variation in SSC. The scatter plot of SSC versus discharge (Fig. 8) shows a good correlation between SSC and

Table 2 The minimum, maximum and mean discharge (cu m/s) from Shaune Garang catchment during the study period

Discharge (cu m/s)	2014			2015		
	August	September	Mean	August	September	Mean
Minimum	3.3	2.24	2.24	9.23	6.54	6.54
Maximum	11.31	8.78	11.31	12.33	9.32	12.33
Mean	8.41	5.16	6.89	10.88	6.67	8.77

Fig. 7 Graph showing the comparison of suspended sediment concentration (mg l^{-1}) and discharge ($\text{m}^3 \text{s}^{-1}$) for the part of ablation season of **a** 2014 and **b** 2015



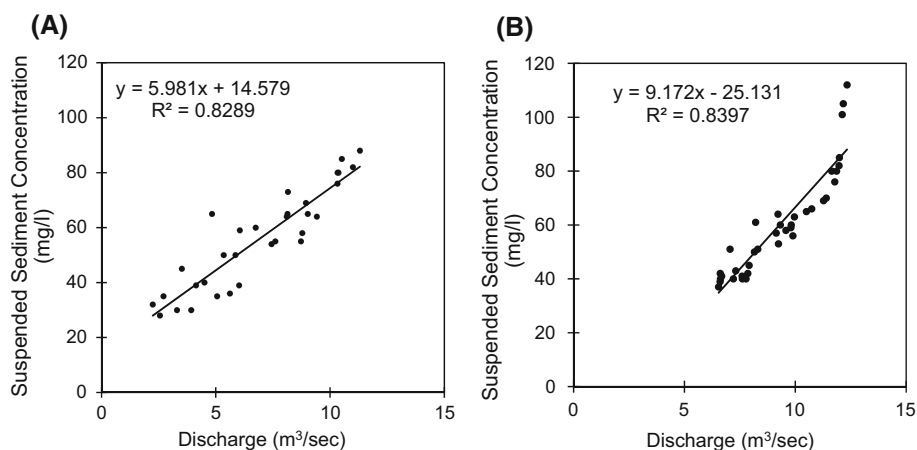
discharge in ablation months of August ($R^2 = 0.88$, $n = 16$, $p < 0.01$) and September ($R^2 = 0.78$, $n = 18$, $p < 0.01$) for the year 2014. Similarly, the coefficient of determination was found to be ($R^2 = 0.78$, $n = 19$, $p < 0.01$) and ($R^2 = 0.78$, $n = 22$, $p < 0.01$) for August and September, respectively.

Conclusion

The present study investigates the dynamics of suspended sediment concentration in the stream flow from Shaune Garang catchment in relation to the variation in discharge

and temperature for the ablation season of 2014 and 2015. The results largely show strong dependence of sediment load on discharge and temperature in the basin. The correlation results of sediment concentration with temperature show opposite trend on days with high precipitation due to low temperature and high discharge. The comparison of results from various studies (Puri 1999; Srivastava et al. 2014; Singh et al. 2015; Singh and Ramashastri 1999; Singh et al. 2004; Raina 2009; Puri and Swaroop 1995; Singh et al. 2018, 2014) in Indian Himalayan region as discussed in the results section shows that in case of majority of closely located catchments the geological and climatic settings primarily control the sediment load in its

Fig. 8 Graph showing the scatter plot between suspended sediment concentration (mg l^{-1}) and discharge ($\text{m}^3 \text{s}^{-1}$) for the part of ablation season of **a** 2014 and **b** 2015



stream flow making the regional observations quite heterogeneous. This is also evident when we compare Geological Survey of India's (Raina 2009) SSL per unit basin area values for Gara catchment ($1.29 \text{ t day}^{-1} \text{ km}^{-2}$) to our SSL per unit area values for Shaune Garang catchment (1.13) (Table 1) as both these catchments have similar geological, topographical and climatic setting and are displaying similar sedimentation characteristics. Therefore, although we are starting with a single glacierized catchment within Baspa basin to provide a first-hand assessment in this regard, in case of future availability of similar datasets for more glaciers within the basin, we can safely compare and extrapolate the results to provide basin-wide estimates. The annual sediment yield in Shaune Garang catchment has increased by $84 \text{ t km}^{-2} \text{ year}^{-1}$ in comparison with field measurements made three decades ago and reported in 2009 (Raina 2009). The main reason might be an increase in proportion of debris-covered glacierized area in the catchment (Kumar et al. 2016) caused by increased melting due to rise in temperature (Carenzo et al. 2016). The loose debris material on the surface of the glacier is washed out with melt water (Tomecka-Suchon et al. 2017). In addition, the increase in temperature (Kumar et al. 2014; Singh et al. 2016) has also caused proportionately more liquid precipitation in the basin (Kumar et al. 2016) causing increased erosion in the catchment (Costa et al. 2018). Also, the receding glaciers in these regions display high volumes of pro-glacial sediments (Costa et al. 2018) which might further be contributing to increasing SSL. However, we believe that these findings of increasing sediment load prompt detailed geophysical investigations in future studies to narrow down the most prominent causal factors. Similar to Shaune Garang glacier, there are more than 100 glaciers (Mir et al. 2017) and associated catchments within the Baspa basin and all of them have shown significant melting during the past decades (Mir et al. 2017). Thus, we expect a similarly increasing contribution to sediment load in their discharge to the Baspa River making the already

operational or planned downstream hydropower plants more vulnerable to the frictional decay and sediment filling. The planning of hydropower project and reservoir in glacierized basin requires the knowledge of sediment concentration and transport at different elevations. Also, the sediment concentration has significant ecological impact in downstream areas (Stovin and Guymer 2013). Therefore, it is important to carry out long-term observation of the temporal variation in the sediment load in general and its characterization for hydropower management in the region in particular.

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