Climatic control on extreme sediment transfer from Dokriani Glacier during monsoon, Garhwal Himalaya (India)

AMIT KUMAR*, AKSHAYA VERMA, DWARIKA PRASAD DOBHAL,
MANISH MEHTA and KAPIL KESARWANI

Centre for Glaciology, Wadia Institute of Himalayan Geology, 33 GMS Road, Dehra Dun, India.

**Corresponding author. e-mail: amithydrocoin@gmail.com amitwalia@wihg.res.in*

In the Himalayas, most of the glaciers are covered by thick debris, especially in the ablation zone. Supraglacial debris cover might play an important role for sediment budget of the glaciated area or for the ablation of ice masses mantled in debris. During summer season, proglacial meltwater carries considerable amount of suspended sediment. The deglaciated area provides a ready source of sediment during Indian Summer Monsoon (ISM). The heavy sediment load from the glaciers affects the hydropower generation, irrigation and drinking water supply. Therefore, to understand the sediment delivery from glaciated basins, characteristics and variation of the suspended sediment concentrations in the proglacial meltwater stream, Dokriani Glacier, have been monitored during the ablation season (May–September). Suspended sediment samples were collected near the snout of Dokriani Glacier, Garhwal Himalaya, in 2010 and 2011. Results show that mean monthly suspended sediment concentrations (SSC) were 1499, 2303, 3845 and 1649 mg/l for the months June, July, August, and September, respectively, indicating highest concentration in August followed by July. Over the period of recording, daily mean suspended concentration in the melt stream varied from 13–9798.2 mg/l, which is very high, caused due to a flash flood event during the monitoring period. The mean daily suspended sediment concentration was computed to be 2196 mg/l. The suspended sediment concentration begins to increase with discharge from May and reduces in September. Present study provides TRMM (Tropical Rainfall Measuring Mission) derived and field based hydro-meteorological insight about severe rainstorms during the years 2010 and 2011 in the study area, which transported large amounts of sediment.

1. Introduction

It is known that glaciers reduce their ice mass and mass balance changes are induced by the growing debris covered area (Azam *et al.* 2012; Berthier and Vincent 2012) except for Karakoram anomaly (Hewitt 2005; Gardelle *et al.* 2012). Debris covered glaciers are common in many mountainous regions of the world. Observed retreat of glaciers is accompanied by increased extent of debris covered

area near the glacier snout (Scherler *et al.* 2011). Investigations of the elevation changes of ice mass indirectly suggested that debris covered area shows large lowering rates (Bolch *et al.* 2007; Nuimura *et al.* 2012). Bhambri *et al.* (2011) published that debris covered area in glaciers of Garhwal Himalaya are increasing at different rates (Bhagirathi basin 11.8% and Alaknanda basin 17.8%).

The Himalayan region is geologically active and structurally unstable; natural hazards related

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with climate and topographic instability are frequent. The climate of the high altitude region of the Himalaya plays a vital role in the melting of snow and glaciers, retreat or advancement of glaciers, flash floods, erosion, sediment transport, landslides, subsidence, glacial lake outburst floods (GLOF's), carbonate and silicate weathering, etc., (Haeberli and Beniston 1998; Singh *et al.* 2012). The important factors influencing the suspended sediment transfer from glaciated regions are the climatic variables like temperature and rainfall. Some of the major flashfloods and rainfall induced landslides in the Himalayan region over the past decade have been compiled in table 1.

Understanding the glacier regimes is important because they are the sources of information on high-mountain meteorology and hydrology, and paleoclimatic data (Meier *et al.* 2003). High altitude climatology is particularly important for water storage, groundwater replenishment and flood control.

It has been observed that during summer months, snow and glacier meltwater from Himalayan glaciers, transport suspended sediment at very high rates. For the Himalayan region, runoff and sediment transportation studies for some glaciers that have been carried out during the ablation season (May–September) and peak melting season (July and August) involve both glacier melting and monsoon rainfall. The middle and

lower part of basins transport large amounts of suspended sediment which cause silting of the reservoirs during this period. Therefore, meltwater and sediment transfer studies from the Himalayan glaciers have received more attention for the water resources management and hydropower development in the Himalayas (Collins 1996; Hasnain and Thayyen 1999; Bhutiyani 2000; Kumar *et al.* 2002; Pandey *et al.* 2002; Jain *et al.* 2003; Owen *et al.* 2003; Singh *et al.* 2003, 2005, 2010a; Haritashya *et al.* 2006, 2010; Ali *et al.* 2007).

The investigations on proglacial suspended sediment from meltwater are important for lower basin hydrology. Glaciers actively erode and transport material; meltwater transports the suspended sediment further downstream. It is well known that mountainous rivers with many glaciers in their basin have high concentrations of suspended sediment. This adversely affects hydraulic facilities, e.g., hydropower turbines. Unfortunately, there are very few reliable measurements of suspended sediment, though peak floods during melting season have been monitored or reported from the region. In this paper daily data on melt runoff and sediment concentrations of Din Gad River arising from Dokriani Glacier have been analyzed. The main objective of this study is to examine the impact of extreme events on the proglacial suspended sediment regime, as well as debris flow near the snout of Dokriani Glacier. The present study for 2010–2011

Table 1. *Recent records of major flash floods and landslides in the Himalaya.*

Type	Date	Area	Reference
Flash flood	August 2010	Dokriani Glacier, Uttarakhand }	Present study
Flash flood	August 2011		
Flash flood	September 2012	Okhimath, Uttarakhand	Rana <i>et al.</i> (2012)
Cloudburst	4–6 August 2010	Leh, J & K (Sabu and other streams)	Thayyen <i>et al.</i> (2013)
Rainfall induced landslide	18–21 September 2010	Uttarakhand (various places on Rishikesh–Mana highway)	Sati <i>et al.</i> (2011)
Rainfall induced landslide	2009	Munsiyari	Sarkar and Kanungo (2010)
Flash flood	1 August 2006	Phyang, Igu and Leh Nalla, J & K	Thayyen <i>et al.</i> (2013)
Flash flood	June 2005	Leh and Phyang Nalla (Ganglass), J & K	Thayyen <i>et al.</i> (2013)
Rainfall induced landslide	2003	Varunavat, Uttarkashi, Uttarakhand	Gupta and Bist (2004)
Cloudburst	16 July 2003	Kullu, Himachal Pradesh	Mazari and Sah (2004)
Cloudburst	10 August 2002	Tehri, Uttaranchal	Sah <i>et al.</i> (2003)
Cloudburst	31 August 2001	Tehri, Uttaranchal	Naithani <i>et al.</i> (2002)
Cloudburst/landslide	16 July 2001	Rudraprayag, Uttaranchal	Kumar <i>et al.</i> (2003)
Rainfall induced landslide	1998	Malpa and Okhimath, Uttarakhand	Sati <i>et al.</i> (2006)
High rainfall	11–19 August 1998	Guptkashi–Rudraprayag, Uttaranchal	Rautela and Paul (2001)
Flash flood	11 August 1997	Tehsil, Himachal Pradesh	Thakur (2000)
Landslide	24 February 1993	Jhakri, Himachal Pradesh	Thakur (2000)
GLOF/Flash flood	31 July 1991	Maling, Himachal Pradesh	Thakur (2000)

(a)

(b)

Figure 1. (a) View of the study area in Din Gad catchment located in Bhagirathi basin, Garhwal Himalaya. (b) View of the monitoring site under the bridge, meltwater flowing from Dokriani Glacier can be seen.

has been compared with previous work at Dokriani Glacier by Singh and Ramasastri (1999) and Singh *et al.* (2003, 2005).

2. Study area

Dokriani Glacier is a compound valley type glacier in the Din Gad River catchment, a tributary of Bhagirathi River, Garhwal Himalaya (figure 1a). The glacier occupies an area of 7 km², 46% of the total catchment area (15 km²). The length of the glacier is 5.5 km and its elevation ranges from 3910 m to 6200 m a.s.l. The total area of accumulation and ablation zone is approximately 4.7 and 2.3 km², respectively (Dobhal and Mehta 2010). The snout of the Dokriani Glacier is marked from where the stream Din Gad emerges. The glacier is confined to the valley region and has several avalanche zones in the accumulation and ablation areas. The glacier in its present form is bounded by left and right lateral moraines and supraglacial debris cover (figure 2).

3. Methodology

Meteorological observations play an important role in understanding generation mechanism of meltwater discharge from glaciers. In addition, meteorological variability is responsible for significant weather events which have affected mankind over the years. Keeping in view the importance of meteorological data observed at Himalayan

glaciers, meteorological observations such as air temperature, relative humidity, precipitation, sunshine hours, wind velocity have been measured near the snout of the glacier. An existing meteorological observatory was equipped near the snout of Dokriani Glacier in the year 2009; daily rainfall was measured in a rain gauge at ground level to avoid wind effects, thermometers were used to measure maximum and minimum, dry and wet bulb temperatures and were placed at a height of 2 m from the ground in a Stevenson screen to avoid the effects of direct solar radiation and precipitation. A wind vane and anemometer were also installed at a height of 2 m above the ground in order to measure the wind velocity. The time and frequency of meteorological data collection are given in table 2. To understand temporal and spatial variability in precipitation during study period data from Tropical Rainfall Measurement Mission (TRMM) of NASA has also been used for analysis.

Hydrological data (discharge and suspended sediment) for summer (May–September) 2010 and 2011 was collected using water level data at the existing gauging site, where a bridge crosses the meltwater stream of Dokriani Glacier (figure 1b). The gauging site was repaired with the use of stone walls and sandbags along the banks of the stream such that all the meltwater flows through the channelized section. Also the large boulders transported by the stream were removed from the channel in order to get laminar flow, as far as possible. The Velocity area method was used to estimate the discharge in the river. The cross section of the stream

Figure 2. Features showing (a) lateral moraines, (b) snout, (c) debris avalanche, and (d) proglacial zone observed at Dokriani Glacier during the field visit in summer and winter seasons.

Table 2. List of hydro-meteorological instruments, observations on time interval near the snout of Dokriani Glacier.

Instruments	Observations	Time of observations
Manual river gauge	Water level	Hourly (08:00 to 07:00 hrs)
Ordinary rain gauge	Rainfall	08:30 and 17:30 hrs
Maximum and minimum thermometers	Maximum and minimum temperature	08:30 hrs
Dry and wet bulb thermometers	Dry and wet bulb temperature	08:30, 11:30, 14:30, 17:30 and 20:30 hrs
Anemometer	Wind speed	08:30, 11:30, 14:30, 17:30 and 20:30 hrs
Wind wane	Wind direction	08:30, 11:30, 14:30, 17:30 and 20:30 hrs

Figure 3. Stage–discharge relationship for Dokriani Glacier during ablation season 2010 and 2011.

was measured using a graduated staff from the bridge over the stream. The cross sectional area measurements were repeated throughout the melt season in order to reduce errors. A manual stage was placed in the river cross section to read the water level. Surface velocity of the stream was measured by throwing floats in the stream for a 10 m section and the time required to cover the distance was recorded. For accuracy in velocity, the float readings were repeated at least three times and an average value was adopted for further computations. The surface velocity was then multiplied by a constant given for Himalayan streams to calculate the mean velocity of the stream (Singh *et al.* 2003; Thayyen *et al.* 2005; Ramanathan 2011). The velocity, mean velocity and discharge were calculated as following:

$$\begin{aligned}
 V_s &= D/T_d \text{ (m/s)} \\
 V_m &= C \times V_s \text{ (m/s)} \\
 Q &= A \times V_m \text{ (m}^3\text{/s)},
 \end{aligned}$$

where V_s is the surface velocity of the stream (m/s), D is the fix distance (m), T_d is the time of travel to cover the fix distance $[D]$ by float in s, V_m is

the mean velocity of the stream (m/s), C is the constant for mountain streams (0.85), Q is the discharge (m³/s), and A is the cross sectional area of the stream (m²).

Stage–discharge relationship for Dokriani Glacier has been developed to calculate discharge for the available water level records (figure 3).

$$S = 10.51 * \log(Q) + 13.54 \quad (R^2 = 0.98) \quad (2010)$$

$$S = 8.68 * \log(Q) + 16.74 \quad (R^2 = 0.92) \quad (2011),$$

where S is the stage or water level in cm and Q is the discharge in m³/s.

In order to estimate the suspended sediment, 500 ml high-density polyethylene (HDPE) narrow mouth bottles were deployed to collect meltwater samples at mid depth near the centre of the stream. The samples were filtered through ash less Whattmann filter paper (0.2 μ m) in the field and filters were packed and returned to the laboratory for weighing (Ostrem 1975; Gurnell *et al.* 1992; Haritashya *et al.* 2010). The weight of the blank filter papers was subtracted from the weight of

filter papers containing suspended sediment. The obtained suspended sediment concentration was then converted into mg/l.

4. Results

Hydro-meteorological records from the Himalayan region are rare because of poor accessibility, rugged terrain, and harsh weather conditions. These records are particularly needed for long-term planning and management of water resources such as reservoir operation, irrigation, flood and runoff forecasting and hydroelectric production.

Discharge and meteorological data is the first and foremost requirement to define the hydro-meteorological condition of any glacier. Meteorological data collected near the snout of Dokriani Glacier provides records for the melt season (May–September) during the years 2010 and 2011. Detailed records of meteorological observations and analysis over Dokriani Glacier can be found in Singh *et al.* (2007).

4.1 Precipitation (*P*)

Precipitation is an important factor, which plays a vital role in the mobilisation of suspended sediment. It is observed that the months of August and September have maximum rainfall in the melting season. June 8 and September 16, 2010 are snowfall events that occurred during the ablation period due to drastic reduction of air temperature. Distribution of daily rainfall observed at Dokriani Glacier is shown in figure 4. Monthly rainfall measured at Dokriani Glacier were 154.40, 339.20, 427.80, 379.80 and 50.60 mm for 2010 and 258.9, 377.2, 610.0, 192.3 and 25.2 for 2011 in June–October, respectively. Total rainfall observed at Dokriani Glacier is 1351.8 and 1463.6 mm during the melting season (June–September) for the years 2010 and 2011, respectively. The published data for the years 1995–1998, shows an average total rainfall of 1041.0 mm for the melting period as compared to 1370.0 mm for 2010–2011 (table 3). In order to understand the changes in the precipitation pattern we compared the rainfall intensities, which were 16.1, 14.5 and 10.4 mm/hr for

Figure 4. Daily maximum and minimum temperature and rainfall observed at Dokriani Glacier during the melting season of 2010 and 2011.

Table 3. Temperature and rainfall distribution at Dokriani Glacier for 1995–1998 and 2010–2011.

Temp. (°C) Years	Maximum		Minimum		Mean		Years	Rainfall (mm)	
	1995–1998*	2010–2011	1995–1998*	2010–2011	1995–1998*	2010–2011		1995–1998*	2010–2011
June	12.8	13.2	4.4	2.3	9.5	7.8	June	186	207
July	12.8	13.2	7.9	5.1	10.5	9.1	July	245	358
August	12.8	13.3	7	5.4	9.7	9.3	August	376	519
September	10.8	12.6	3.3	2.5	8.5	7.6	September	234	286
Average	12.3	13	5.7	3.8	9.5	8.4	Total	1041	1370

*Singh and Ramasastri (1999).

1996, 1997 and 1998 (Singh and Ramasastri 1999), respectively as compared to the peak intensity of 21.0 and 27.5 mm/hr for 2010 and 2011, respectively (TRMM derived plots of rainfall intensity, figure 5).

4.2 Air temperature (T)

Mountain systems are sensitive to climate change and temperature trends in the Himalayan region show that temperature increases are greater in the uplands than lowlands (Shrestha *et al.* 1999).

Mean monthly maximum and minimum temperature over Dokriani Glacier for the years 2010 and 2011 were 13.2, 13.2, 13.3, 12.6 and 10.7°C and 2.3, 5.1, 5.4, 2.5 and –3.0°C during the months of June–October, respectively. The mean monthly maximum and minimum temperatures were highest in August followed by July. The same trend was observed for average temperature and the mean monthly average temperatures were 7.8, 9.1, 9.3, 7.6 and 3.9°C during the months of June–October, respectively. Daily variations in maximum, minimum and mean temperature are illustrated in figure 4. The mean monthly maximum, minimum and average temperatures for 1995–1998 and 2010–2011 are given in table 3. It is observed that while the maximum temperature rose by about 0.5°C, the minimum and mean temperature declined by 2° and 1°C, respectively for 2010–2011 as compared to 1995–1998. This could be one of the factors affecting the variations in discharge, suspended sediment, amount and intensity of rainfall in 2010–2011 as against 1995–1998.

4.3 Discharge (Q) and suspended sediment concentration (SSC)

Glacier melt runoff represents the integrated basin response to various climatic inputs, with precipitation and temperature being the most important (Haritashya *et al.* 2006).

Hydrological data at Dokriani Glacier is only available for months from May to mid August, for

the years 2010 and 2011. This is due to the fact that flash floods occurred at the gauging site between 15th and 25th August in 2010 and 2011, which washed out the discharge site. The major reason for the occurrence of these flash floods was continuous rainfall during the year 2010, in which a particular rainstorm lasted for 7 days (17th to 24th August) accounting for 182.2 mm of rainfall along with maximum SSC of 8178.1 and 9798.2 mg/l, while in 2011 high intensity rainfall took place for 2 days (16th and 17th August) accounting for approximately 259 mm rainfall along with high SSC of 3270.6 mg/l.

In order to study the variability of discharge and SSC, the data has been compared with previously recorded data (1995–1998), at the same discharge site (Singh and Ramasastri 1999). The discharge shows increasing trend from May, reaches its highest value in July and then starts reducing. The distribution of daily discharge and SSC for the available data of Dokriani Glacier are given in figure 6. The mean monthly discharge observed during months of May, June, July, and August were 0.6, 1.2, 4.9 and 7.9 m³/s and 3.6, 7.7 and 9.0 m³/s for June, July and August for the years 2010 and 2011, respectively. Average discharge was found to be 5.7 m³/s for the years 2010–2011 against 10.0 m³/s for 1995–1998 (table 4).

In comparison to 1995–1998, higher SSCs were found in the present study (figure 7). The mean monthly SSCs for the period June–September were 1499, 2303, 3845 and 1649 mg/l for 2010–2011 as compared to 452, 934, 965 and 275 mg/l for 1995–1998. The maximum SSC for both the periods is in August followed by July. The mean SSCs for the melt season (June–September) for the periods 1995–1998 and 2010–2011 are 656 and 2324 mg/l, respectively (table 4).

5. Discussion

Erosion in the Himalayan region is mainly controlled by the intensity of the Indian Summer Monsoon, but short lasting events can be responsible for more than half of the suspended

Figure 5. Three hourly TRMM derived rainfall intensity and total rainfall from 11th to 20th August 2010 and 2011 for Dokriani Glacier.

sediment transported by the rivers. The variability can be attributed to changes in discharge, precipitation rates and intensity, vegetation cover, geology/lithology of the region as well as seismic activity. There are numerous instances of recent disasters caused by heavy rainfall in the hilly terrains of the Himalayas.

It may be noted that though the discharge has decreased considerably in 2010–2011 as compared to 1995–1998, the SSC has increased four folds. Temperature plays an important role in meltwater generation and sediment transfer. Also the rise in temperature in the days immediately after the snowfall events of June 8 and September 16, 2010 caused the fresh snow to melt and therefore mobilised the sediment, while the decrease in discharge during 2010–2011 as compared to 1995–1998 could be due to the fact

that the overall mean and minimum temperatures had decreased in the basin. The increased rainfall intensity could be attributed to the changes in temperature (maximum, minimum and mean).

The increased intensity of rainfall during 2010–2011 is a significant factor for the cause of flash flood and high suspended sediment concentrations. The high intensity rainfall mobilises a large amount of sediment from the deglaciated area near the snout. Another important factor is the mobilisation of sediment from the glacier surface in the ablation zone as well as debris flow/landslides from valley walls and unstable lateral moraines (figure 2c), which erode under the influence of high intensity rainfall events and act as a major source for suspended sediment. It has been established that high intensity rain increases the scouring capacity by 4 times, the carrying capacity by 32 times

Figure 6. Discharge and SSC at Dokriani Glacier during the ablation season of 2010 and 2011.

Table 4. Observed discharge and SSC at Dokriani Glacier for 1995–1998 and 2010–2011.

	1995	1996	1997	1998	1995–1998*	2010	2011	2010–2011
Q (m ³ /s)								
June	7.2	6.5	6.5	4.2	6.1	1.2	3.6	2.4
July	13.0	11.2	10.0	7.0	10.3	4.9	7.7	6.3
August	10.9	11.1	24.2	7.6	13.5	7.9	9.0	8.4
Average	10.4	9.6	13.6	6.3	10.0	4.6	6.8	5.7
SSC (mg/l)								
June	289	851	444	225	452	233	2766	1499
July	819	1046	1269	600	934	1929	2677	2303
August	985	1014	1164	696	965	4226	3464	3845
September	–	–	275	275	275	576	2723	1649
Average	698	970	788	449	656	741	2907	2324

*Singh and Ramasastri (1999).

Figure 7. SSC observed near the snout of Dokriani Glacier.

Figure 8. Synoptic view of deglaciated area of Dokriani Glacier since 1995 to 2010.

and particle size carried by 64 times (Tempany and Grist 1958). Though the debris cover has not been quantified in the present study due to small basin area and lack of high resolution satellite data, there is photographic evidence of increasing debris cover and deglaciation over Dokriani Glacier (figure 8). Further studies should concentrate on better characterization of sediment flux within the basin in order to improve our understanding of dynamics at the basin scale. It would provide useful information on suspended sediment behaviour across river basins and contribute to improve sediment transfer models.

The threat to lives and property posed by severe storms highlights the immediate need to establish a good network of Automatic Weather Stations and hydrological monitoring in mountainous regions. Long-term records would provide more accurate representations of hazard zonation and frequency of events in mountainous areas. Also validation of remotely sensed data such as that of TRMM with field observations may be very useful in the future for getting meteorological data (temperature, rainfall, etc.) of remote places. An approach using field data from monitoring sites in combination with remote sensing is essential in high mountain hazard management and disaster mapping. The identification and monitoring of such hazardous sites can

at least predict the probable area of occurrence of future disasters.

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