

Climatic Influence on Hydrogeochemistry of Meltwater Draining from Chhota Shigri Glacier, Himachal Pradesh, India

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Received October 2, 2017; revised and accepted October 22, 2017

Abstract: This manuscript addresses climatic influence on hydrogeochemistry of Chhota Shigri glacier meltwater by comparing the major ions chemistry of 2009-10 with previously published meltwater chemistry data of 1987. The present comparative hydrogeochemical study between these data sets indicate that concentration of major anions like HCO_3^- increased nearly 104 times in 2009 and 103 times in 2010, SO_4^{2-} increased nearly 71 times in 2009 and 78 times in 2010 and Cl^- concentration increased nearly 3.0 times in 2009 and 13 times in 2010, in between 1987 and 2009-10. Whereas concentration of major cations like Na^+ increased nearly 20 times in 2009 and 19 times in 2010, K^+ increased nearly 35 times in 2009 and 38 times in 2010, Ca^{2+} increased nearly 16 times in 2009 and 23 times in 2010 and Mg^{2+} increased nearly 108 times in 2009 and 81 times in 2010, in between 1987 and 2009-10. These trends in increasing the dissolved ions concentration of glacier meltwater may be due to high air temperature that is reported in the study area (northwestern Himalaya), resulting in increasing the exposure of rock and weathering processes inside the glaciated valley. Mass balance and snout retreat study of the Chhota Shigri glacier is also supporting climatic influence enhancing the dissolved ions concentration in the meltwater of study area.

Keywords: Hydrogeochemistry; Meltwater; Himalayas; Chhota Shigri Glacier.

Introduction

Glacier is formed when accumulation rate of snow on the earth is higher than ablation rate of snow, and falling snow gets sufficient space and time to get recrystallized and metamorphosed into ice (SAC, 2016). It is considered as a good geoinicator of climate change study because of their capability in responding to climatic variations (Bolch et al., 2012; Vaughan et al., 2013). The Hindu Kush-Himalayan region contains

around 54,000 glaciers covering an area of about 60,000 km^2 (Bajracharya and Shrestha, 2011) whereas Indian Himalayan region contains total of 9575 glaciers having an area of 37,466 km^2 (Raina and Srivastava, 2008; Sangewar and Shukla, 2009). The mountain range of Indian Himalaya plays an important role in regulating the hydrological and meteorological characteristics of the Indian Peninsula (Bhutiyan, 1999). Climate warming over the mountainous region of the Himalaya decreases the glaciers which are major source of water

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for the people living in this region (Kulkarni et al., 2005, 2007). Many glaciers situated in the Himalayan region are retreating with different rates (Dobhal et al., 2004; Kulkarni et al., 2007; Venkatesh et al., 2012; Azam et al., 2012) whereas some glaciers have stable fronts (Bhambri et al., 2013; Bahuguna et al., 2014). The high retreat of Himalayan glaciers is largely affecting the available freshwater resources in the Asian region (Barnett et al., 2005; Winiger et al., 2005; Nogues-Bravo et al., 2007; IPCC, 2007). A significant rise in air temperature (1.6 °C) has been reported in the region of western Himalaya during the last century (Bhutiyan et al., 2007). The warming trend of atmospheric temperature is higher than the global average in western Himalayan region (Singh et al., 2016a).

Chemical characterization of glacier meltwater is very essential for the identification of nature and solute concentration embedded in the basal rock, and contribution from atmospheric sources (Ramanathan, 2011). Glacier meltwater acquires solute mainly from the rock weathering (rock-water interaction), atmospheric deposition and dust inside the snow pack (Tranter et al., 1996). In general, HCO_3^- and SO_4^{2-} are the dominant anions and Ca^{2+} is the major cation in the meltwater of Himalayan glaciers, and carbonate weathering is the dominant hydrogeochemical processes regulating solute chemistry of meltwater in the Himalayan region. Various literatures are available in hydrology, hydrochemistry, suspended sediment transport and mass balance study of Himalayan glaciers (Raina et al., 1977; Hasnain et al., 1989; Ahmad and Hasnain, 2000, 2001; Kumar et al., 2009; Thayyen and Gergan, 2010; Azam et al., 2012, 2016; Sharma et al., 2013; Singh et al., 2004, 2006, 2012a, 2013, 2014, 2015a, b, c, d, e, f, 2016b, 2017a, b, c; Pottakkal et al., 2014; Priya et al., 2016). The main aim of present review paper is to address various factors responsible for increasing the concentration of different ions in the Chhota Shigri glacier meltwater based on available data on hydrochemistry, mass balance and snout retreat of this glacier.

Area of Study

The Chhota Shigri glacier is a valley type glacier situated in the Lahaul-Spiti district of Himachal Pradesh state. It is a western Himalayan glacier approached from a distance of about 100 km away (by road) from the famous tourist spot Manali. This glacier is north facing and non-surging glacier located between 32°11'-32°17' N and 77°29'-77°33' E. Total length and area of the Chhota Shigri glacier is found to be about of 9.0

km and 15.4 km², respectively (Wagnon et al., 2007; Azam et al., 2016). This glacier is debris free glacier having debris covered area of only 3.5% (Vincent et al. 2013). The snout of Chhota Shigri glacier is located approximately 2.5 km south direction from the Chandra river. Geographically, snout of this glacier is situated at 32°16'12.4" N and 77°31'49.2" E having an elevation of about 4055 m a.s.l. (Singh, 2011, 2016). Various geomorphological features such as moraines, glacier table, crevasses, moulins etc. are found in the ablation zone of the glacier. The sampling site/gauging site for meltwater samples collection and discharge measurement was located at Latitude 32°17'24.58" N and Longitude 77°31'55.21" E, nearly 2.0 km downstream from the snout (Figure 1).

Geology of the Study Area

The area of Chhota Shigri glacier is situated in the Central Crystallines of Pir Panjal range in the western Himalayan. This Crystalline axis mainly contains migmatites, gneiss and meso-to-ketazonal metamorphites (Kumar and Dobhal, 1997). Rohtang gneiss is the dominant lithological unit of this glacier catchment, while in the lateral moraines at an elevation up to 4700 m a.s.l some chalcopryrite is also found (Kumar et al., 1987; Katoch, 1989; Hasnain et al., 1989). Different types of rocks such as granite, granite gneiss, schistose gneiss, porphyritic granite and muscovite-biotite schist are reported between the Chhota Shigri and Bara Shigri glaciers (Kumar et al., 1987). Presence of fine grained texture of brown biotite in the study area indicates intense heating effect, which shows periodic reheating of granitic rocks below the Chhota Shigri glacier (Rawat and Purohit, 1988).

Climate of the Study Area

The area around Chhota Shigri glacier is considered as a cold desert (Singh et al., 2012b). It is influenced by Indian monsoon during summer season (July to September) and mid-latitude westerlies during winter season (January to April), therefore located in the monsoon-arid transition zone (Wagnon et al., 2007; Bookhagen and Burbank, 2010). Few meteorological studies are available in the study area. Variations between maximum and minimum temperatures in the Chhota Shigri glacier were observed from 10.5 °C to -5.2 °C at equilibrium line altitude (4600 m a.s.l.), whereas near the glacier snout maximum and minimum temperatures were recorded to be 16 °C and 4 °C, respectively, during the study period 1987-1989 (Dobhal et al., 1995).

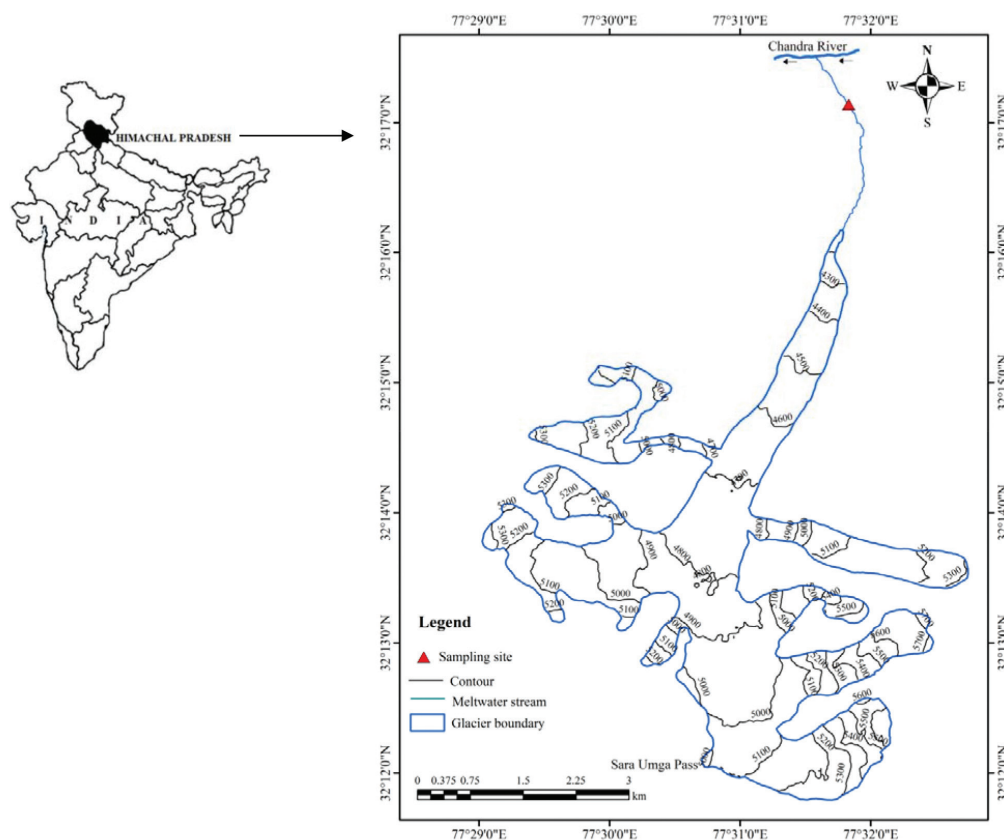


Figure 1: Map of the Chhota Shigri glacier.

Annual mean temperature at the Chhota Shigri glacier was observed to be -5.7°C , -5.6°C , -6.1°C and -5.7°C during the study period 2009-10, 2010-11, 2011-12 and 2012-13, respectively. Whereas annual mean relative humidity (RH) for these years was found to be 54 %, 50%, 52% and 50% (Azam et al., 2016). A study carried out by Azam et al. (2014a) shows that at decadal scale winter precipitation and summer temperature play a crucial role in regulating the pattern of mass balance of the study area. Another study carried out by Azam et al. (2014b) indicates that net radiation was the main part of surface energy balance constituting 80% of the total heat flux followed by turbulent sensible (13%), latent (5%) and conductive (2%) heat fluxes during the period of summer-monsoon.

Results and Discussion

Glacierized areas have a unique environment for chemical weathering characterized by huge amount of rock comminution and low temperature (Crompton et al., 2015). The rate of chemical weathering in the glacier environment is mainly controlled by geological factors such as lithology, elevation and slope, and climatic

factors such as temperature, precipitation and discharge (Gaillardet et al., 1999; Millot et al., 2003; West et al., 2005; Hern et al., 2007; Wu et al., 2008). CO_2 reacts with meltwater draining from glacier to form H_2CO_3 , which is a weak acid dissociated into H^+ and HCO_3^- . On the other hand sulphide oxidation also plays an important role in the generation of H^+ in meltwater (Garrels and Mackenzie, 1971). This acid hydrolysis is responsible for chemical weathering of rock in the glacier environment (Raiswell, 1984). Besides this, higher temperature is also playing an important role in chemical weathering of rocks by increasing the intensity of physical and chemical weathering of rock (Rogora et al., 2003).

Climatic influence on hydrogeochemistry of Chhota Shigri glacier meltwater is studied by comparing the dissolved ions chemistry of 2009-10 with previously published hydrogeochemical data of 1987 (Table 1, Figures 2 and 3) (Hasnain et al., 1989). Major anions concentration such as HCO_3^- increased nearly 104 times in 2009 and 103 times in 2010, SO_4^{2-} increased nearly 71 times in 2009 and 78 times in 2010, and Cl^- concentration increased nearly 3.0 times in 2009 and 13 times in 2010, in between 1987 and 2009-10.

On the other hand major cations concentration such as Na^+ increased nearly 20 times in 2009 and 19 times in 2010, K^+ increased nearly 35 times in 2009 and 38 times in 2010, Ca^{2+} increased nearly 16 times in 2009 and 23 times in 2010, and Mg^{2+} increased nearly 108 times in 2009 and 81 times in 2010, in between 1987 and 2009-10. Such a trend in increasing the solute concentration of meltwater may be due to warming that is reported in the northwestern Himalayan region (Bhutiya et al., 2007). High air temperature may be responsible for reducing the snow and ice cover over the surface of Chhota Shigri glacier and greater exposure of rocks in the glaciated valley, which may be enhancing weathering and hydrogeochemical processes in the study area, resulting in increasing the major ions concentration of the Chhota Shigri glacier meltwater (Singh et al., 2013).

Table 1: Comparison between hydrogeochemical characteristics of Chhota Shigri glacier between 1987 and 2009-10

Parameters	*Previous study (1987)	**Present study (2009)	***Present study (2010)
EC	-	42.5	36.8
pH	-	6.5	6.6
TDS	-	27.0	27.9
Na^+	0.045	0.892	0.872
K^+	0.032	1.127	1.201
Ca^{2+}	0.128	2.080	3.000
Mg^{2+}	0.011	1.186	0.890
HCO_3^-	0.128	13.36	13.18
SO_4^{2-}	0.070	4.992	5.424
Cl^-	0.043	0.117	0.564

Unit: EC in $\mu\text{S}/\text{cm}$, Major ions and TDS in mg/l

*Hasnain et al., 1989

**Singh et al., 2015a

***Singh et al., 2017b

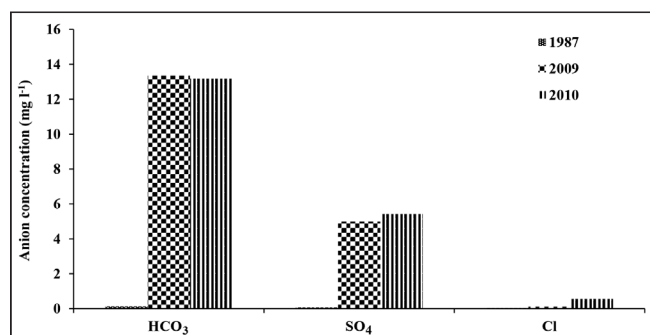


Figure 2: Comparison between the concentration of major anions in meltwater during 1987 and 2009-10.

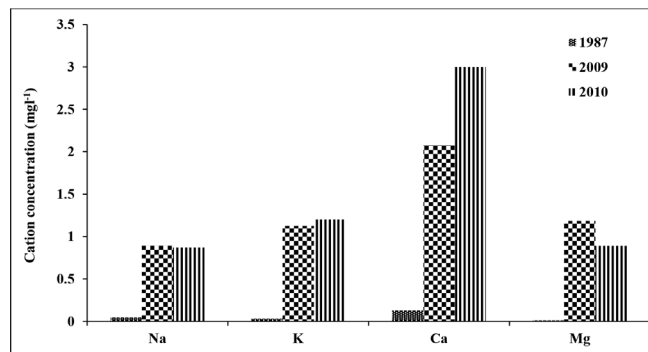


Figure 3: Comparison between the concentration of major cations in meltwater during 1987 and 2009-10.

Mass Balance and Snout Retreat

Mass balance is one of the important glaciological methods used for the assessment of growth or decline of water stored inside the glacier (Tawde et al., 2016). Long term study on the mass balance of glacier is very essential to correlate the observed changes of glacier with present climate change (Engelhardt et al., 2017). There are various methods such as glaciological method (Wagnon et al., 2007), geodetic method (Vincent et al., 2013), accumulation area ratio (AAR) and equilibrium line altitude (ELA) methods (Kulkarni, 1992; Kulkarni et al., 2004), remote sensing method (Berthier et al., 2007) etc. which are used for mass balance study of glacier. In the Indian Himalayan region first mass balance study was carried out by Geological Survey of India (GSI) on the Gara glacier in 1974 (Raina et al., 1977).

Mass balance and snout retreat play an important role in the assessment of climatic impact on glacier. Annual glacier wide mass balance of the Chhota Shigri glacier is shown in Figure 4. This figure indicates that mass balance of the study area showed negative value. The annual glacier wide mass balance of the Chhota Shigri glacier was found to be -1.43 , -1.24 , 0.13 , -1.43 , -1.00 , -0.95 , 0.12 , 0.32 , 0.06 , -0.46 ,

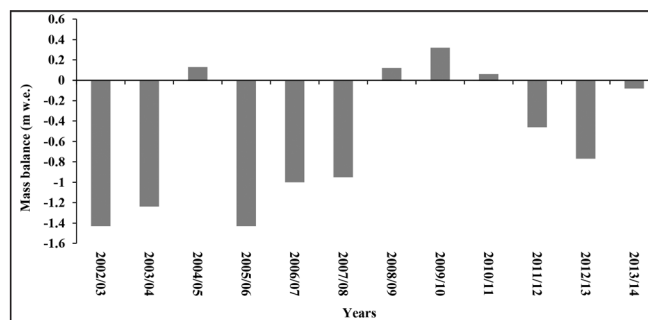


Figure 4: Annual glacier wide mass balance of the Chhota Shigri glacier during 2002-2014. (Source: Azam et al., 2016)

−0.77 and −0.08 m w.e. during the study period 2002/03, 2003/04, 2004/05, 2005/06, 2006/07, 2007/08, 2008/09, 2009/10, 2010/11, 2011/12, 2012/13 and 2013/14, respectively with a mean value of −0.56 m w.e. (Azam et al., 2016). Here mass balance of the study area is discussed in the support of climatic influence enhancing the solute concentration of glacier meltwater. Negative mass balance of the investigation area is responsible for glacier vacating part of the area occupied by it; due to this more exposure of rock occurred in the region of Chhota Shigri glacier resulting in increasing the hydrogeochemical processes and various ions concentration in the glacier meltwater between 1987 and 2009-10 (Singh et al., 2013). Not only Chhota Shigri glacier showed negative mass balance but various other glaciers situated in its surrounding area (western Himalayan region) also showed negative mass balance (Table 2) supporting glaciers vacating area occupied by these glaciers in the region of western Himalaya.

Glacier recession and advancement are the most important evidence for changes in the geometry of glacier (Dobhal et al., 2004). Most of the Himalayan glaciers are in the state of recession since end of the little ice phase (~1850s) (Mayewski and Jeschke, 1979; Oerlemans 2005; Bhambari and Bolch, 2009; Bahuguna et al., 2014). Shifting of glacier snout position due to climate change is one of the best indicators of glacier recession or advancement over the period of time (Dobhal et al., 2004). Chhota Shigri glacier is also in the state of recession like other Himalayan glaciers. The average retreat of this glacier was found to be 7.0 m/year during the study period 1962-2010 (GSI, 1999; Azam et al., 2012). Study carried out by Kulkarni et al. (2007) on the basis of field observation and remote sensing data shows that Chhota Shigri glacier retreated about 53.3 m/year between 1988 and 2003.

Retreat of glacier snout is responsible for the exposure of rock earlier occupied by glacier, which may be enhancing weathering processes in the Chhota Shigri glacier, resulting in increasing the solute concentration of meltwater. Bara Shigri and Hamtah glaciers are situated nearer to the Chhota Shigri glacier showing average retreat of 29.8 m/year during 1906-1995 (GSI, 1999) and 16.8 m/year during 1980-2010, respectively (Pandey and Venkataraman, 2013). These glaciers are also supporting exposure of rock due to retreat of snout in the western Himalayan region.

Conclusions

The present study investigates various factors responsible for increasing the solute concentration in the Chhota Shigri glacier meltwater, based on comparative hydrogeochemical, mass balance and snout retreat studies of the investigation area. The comparative meltwater chemistry between two data sets indicates that concentration of various anions and cations in the meltwater of study area has been increased by 3 to 108 times between 1987 to 2009-10. Such a trend in increasing the different ions concentration in the meltwater of Chhota Shigri glacier may be due to climate warming that is reported in the region of northwestern Himalaya (Bhutiyan et al., 2007), which reduces snow and ice cover area of this glacier, resulting in increasing the exposure of rock as well as weathering and hydrogeochemical processes in the study area. Negative mass balance and snout retreat of the Chhota Shigri glacier is also responsible for the exposure of rock earlier occupied by it, which may be increasing hydrogeochemical processes and various ions concentration in the meltwater of study area between 1987 and 2009-10.

Table 2: Mean annual glacier wide mass balance of the western Himalayan glaciers

<i>Glacier</i>	<i>Region</i>	<i>Period</i>	<i>Mean annual glacier wide mass balance (m w.e.a⁻¹)</i>	<i>Reference</i>
Gara	Baspa basin, Himachal Pradesh	1974-1983	-0.324	Raina et al., 1977
Hamtah	Chandra basin, Himachal Pradesh	2000-2009	-1.46	GSI, 2011
Gor-Garang	Baspa basin, Himachal Pradesh	1976-1985	-0.38	Sangewar and Siddiqui, 2007
Shaune-Garang	Baspa basin, Himachal Pradesh	1981-1991	-0.42	GSI, 1992
Naradu	Baspa basin, Himachal Pradesh	2000-2003	-0.40	Koul and Ganjoo, 2010
Chhota Shigri	Chandra basin, Himachal Pradesh	2002-2014	-0.56	Azam et al., 2016

Acknowledgements

We express our gratitude to Department of Science and Technology (DST), Government of India for financial assistance to carry out this research work. The authors are also grateful to IRD, CIFIPRA, SAC Ahmadabad, GLACINDIA, CHARIS and INDICE for partial funding given to us. Virendra Bahadur Singh is thankful to SERB (Science and Engineering Research Board), DST, Government of India for granting NPDF (National Postdoctoral Fellowship) (Reference No. PDF/2016/000286) to him.

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