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Hydrogeochemistry of the Chhota Shigri glacier meltwater, Chandra basin, Himachal Pradesh, India: solute acquisition processes, dissolved load and chemical weathering rates

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Abstract The chemical compositions of various ions in meltwater of the Chhota Shigri glacier were analysed during the observation period from May to October 2010. Total 164 samples of meltwater were collected in two times a day at 8.0 a.m and 6.0 p.m. Bicarbonate and calcium were the dominant anion and cation in meltwater of the investigation area. High ratios of $(Ca + Mg)$ versus TZ^+ and $(Ca + Mg)$ versus $(Na + K)$ demonstrate that hydrogeochemistry of the study area was mainly governed by carbonate type weathering. The average sulphate mass fraction of meltwater was computed to be 0.31 ± 0.12, showing dominancy of bicarbonate over sulphate. This excess bicarbonate would be generated by an alternative proton supply mechanism due to biological activities in the bed rock lithology and sulphide oxidation may be about the same as carbonation as a driver of chemical weathering at Chhota Shigri glacier. In general, major ions and total dissolved solid concentrations showed decreasing trend with increasing discharge from the study area. The average daily mean dissolved load of this glacier was much lower than that of the Gangotri glacier, which may be due to low meltwater runoff and lithology of the investigation area. The cation weathering rates of study area for early, peak and late melt seasons were computed to be 694, 1631 and 481 meq m^{-2} a^{-1}, respectively. The average value of chemical denudation rates of the Chhota Shigri glacier meltwater was found lower than that of the Dokriani glacier.

Introduction

Large areas in the Himalayas are covered by snow and glaciers (Srinivasulu and Kulkarni 2004), showing uneven glacier distributions having more concentration in the north-western regions as compared to north-eastern regions of the Himalayan mountain series (Mehta et al. 2013). Himalayan glaciers feed to various rivers such as Ganga, Brahmaputra, Indus, Yellow River and Yangtze. Over 1.4 billion population depend on these rivers water (Immerzeel et al. 2010). The Himalayan climate is robustly controlled by the mid-latitude westerlies and South Asian monsoon in the western and eastern side, respectively (Vaux et al. 2012). In the Western Himalayan region (Indian part), meteorological parameters such as temperature and precipitation are strongly regulated by local atmospheric circulations (Mohanty and Dimri 2004) and local topography (Dimri 2004).

Hydrogeochemical characteristics of glacier meltwater have been used to understand the processes responsible for solute acquirement in the subglacial environments (Raiswell 1984; Souchez and Lemmens 1987; Tranter et al. 1993; Brown et al. 1994). The solute acquisition processes comprise the chemical weathering of various types of rocks taking place in the environment of glacier (Rainwater and Guy 1961; Collins 1978; Hasnain and Thayyen 1996). The rate and degree of chemical weathering are regulated by

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various factors such as geological (lithology, slope and elevation) and climatic (runoff, precipitation, temperature and evapo-transpiration) (Gaillardet et al. 1999; Millot et al. 2003; West et al. 2005; Hren et al. 2007; Wu et al. 2008). Temporal variations in the ionic concentration of meltwater are probably due to the varying intensity of chemical weathering at values of different discharge (Kumar et al. 2009).

The hydrochemistry of the glaciers situated in the region of Central Himalaya has been studied on large scale by various workers (Chauhan and Hasnain 1993; Singh et al. 1998; Hasnain and Thayyen 1999; Ahmad and Hasnain 2000, 2001; Kumar et al. 2009; Singh et al. 2012, 2014, 2015a). However, relatively few hydrochemical studies are reported on Western Himalayan glaciers (Sharma et al. 2013; Singh and Ramanathan 2015, 2017; Singh et al. 2015b, c, d) and most of them are for short period of time. Beside these probably no documented works are available on dissolved load and chemical weathering rates of the Chhota Shigri glacier meltwater. So to fill this gap, we have focused on detailed study covering major ions chemistry and relationship between dissolved ions concentrations and discharge. The key objectives of this paper are to identify the sources of solutes in the glacier meltwater, temporal variations in the major ions concentration with discharge, dissolved load and chemical weathering rates of meltwater of the study area.

Location of the study area

The Chhota Shigri glacier lies between 32°11′–32°17′N and 77°29′–77°33′E in the Lahaul–Spiti, Himachal Pradesh, India. A well-defined snout of this glacier is located in a narrow valley at approximately 4055 m altitude from sea level (Azam et al. 2014; Singh et al. 2015d). Mainly, two tributary glaciers are feeding to the Chhota Shigri glacier from east and west (Ramanathan 2011). The valley of this glacier is 0.5 km wide near the snout and 2–3 km wide at the accumulation zone (Sharma 2007). East side of this glacier, Bara Shigri glacier (total area 131.1 km² and length 28 km) is situated (Dutt 1961; Berthier et al. 2007; Sangewar and Shukla 2009). The Chhota Shigri glacier expands from 6263 to 4050 m a.s.l having area including tributaries of 15.7 km² and total length of 9 km (Wagnon et al. 2007). The sampling site for collection of meltwater samples was situated on the stream of this glacier at 32°17′24.58″N and 77°31′55.21″E (Fig. 1).

The climatic condition of the Chhota Shigri glacier is mainly characterized by cold winter (October–April) (Dobhal et al. 1995) and also influenced by Indian monsoon during summer from July to September and mid-latitude westerlies during winter from January to April, hence

situated in the monsoon-arid transition zone (Wagnon et al. 2007; Bookhagen and Burbank 2010). Very limited meteorological studies are available on this glacier. During the study period 1987–1989, variations between minimum and maximum temperatures at equilibrium line (4600 m a.s.l) were recorded from −5.2 to 10.5 °C, whereas near the snout minimum and maximum temperatures were recorded to be 4 and 16 °C, respectively (Dobhal et al. 1995).

Geologically, this glacier drains mainly through the Central Crystallines rocks situated in the range of Pir Panjal (Western Himalaya). This Crystalline axis contains mainly gneiss and migmatites (Kumar and Dobhal 1997). Different types of rocks like muscovite-biotite schist, schistose gneiss, augen gneiss, muscovite-quartzite, porphyritic granite and granite gneiss are found between the Bara Shigri and Chhota Shigri glaciers along with light grey green colour feldspar crystal in late-stage pegmatitic veins (Kumar et al. 1987).

Methodology

Meltwater sampling of this glacier was carried out during the whole melt season (May–October 2010). Total 164 samples of meltwater were collected on two times a day at 8 a.m and 6.0 p.m in clean, narrow necked polyethylene bottles (300 ml capacity). After meltwater sampling, pH and electrical conductivity (EC) were analysed by portable electrode. Filtration of meltwater samples was carried out by using pneumatic pump, filtration setup and 0.45 µm Milipore filter papers and stored in cold room at 4 °C for analysis of various dissolved ions.

Sodium, calcium, potassium and magnesium were measured by atomic absorption spectrophotometer (AAS). Dissolved silica, nitrate, sulphate, phosphate and bicarbonate were measured by molybdosilicate, brucine-sulphanilic acid, turbidimetric, ascorbic acid and acid titration methods, respectively (APHA 2005). Mercury(II) thiocyanate method was utilized for chloride analysis in the meltwater samples (Florence and Farrar 1971). Result of analytical accuracy was better than ±5% for the analysis of various cations and anions. Piper trilinear plot was plotted with the help of water quality analysis software Aquachem. Statistical Package for Social Sciences (SPSS) was used for statistical analysis.

Results and discussion

The statistical summary of the analytical data obtained from chemical analysis of the meltwater is presented in Table 1. Errors in the charge balance were calculated by the formula:
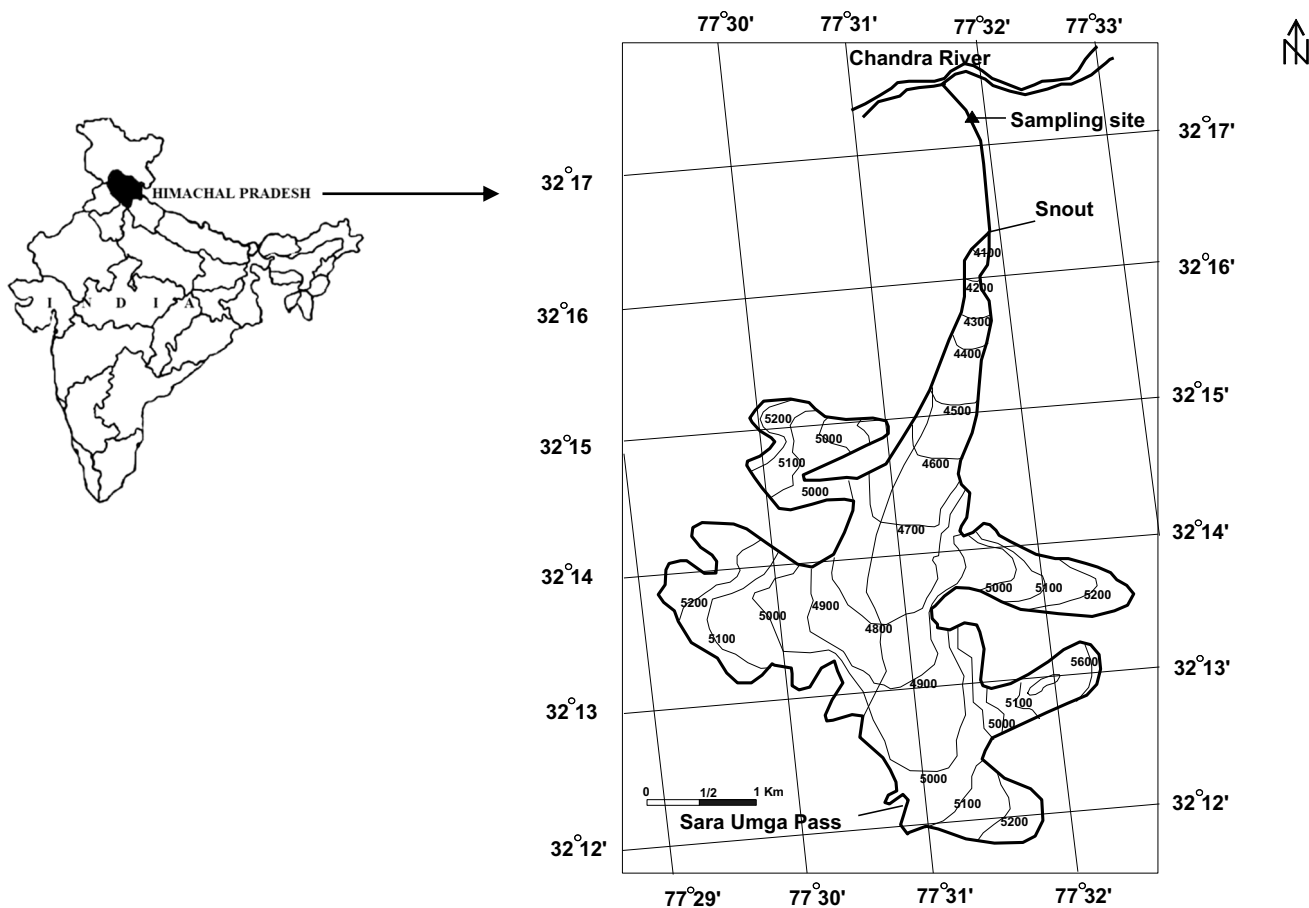
Fig. 1 Map of Chhota Shigri glacier with sampling site

$$CBE = \frac{(TZ^+ - TZ^-)}{(TZ^+ + TZ^-)} \times 100$$

where TZ^- is total anions and TZ^+ is total cations. The average value of this error is <9%, showing the quality and reliability of the analytical results. Electrical conductivity (EC) is commonly used as surrogate measure of concentrations of total dissolved ions in meltwater (Collins 1979, 1981; Kang et al. 2000). Electrical conductivity values of the meltwater ranged from 12.7 to 68.8 µs/cm (36.8 ± 15.2 µs/cm), whereas pH values of meltwater ranged between 5.9 and 7.4 (6.6 ± 0.2) showing that the nature of meltwater fluctuated from acidic to slightly alkaline. Bicarbonate was the dominant anion and its concentrations ranged from 130 to 340 µeq/l (216 ± 46.1 µeq/l), constituting 61.7% of the total anions (TZ^-), whereas sulphate concentrations fluctuated in between 25.1 and 305 µeq/l (113 ± 74.9 µeq/l), which account for 32.4% of the total anions. Calcium was the major cation, and its concentrations varied from 52 to 258 µeq/l (150 ± 49.1 µeq/l), comprising 51.1% of the total cations (TZ^+). After calcium, magnesium was another abundant cation and its concentrations fluctuated from 27.1

to 141 µeq/l (74.2 ± 29.1 µeq/l), constituting 25.4% of the total cations. Dissolved silica concentrations of meltwater varied from 9.2 to 49.1 µmol/l (26.0 ± 11.8 µmol/l).
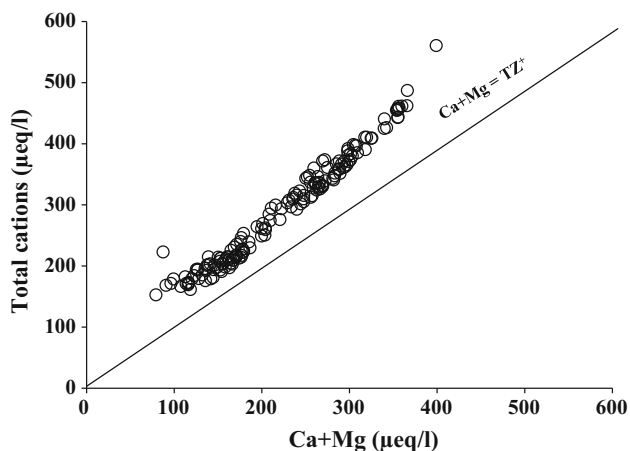
Solute acquisition processes

Presence of solute in the source water is determined either from weathering of rock minerals (crustal sources) or from snow and ice-melt (atmospheric sources) (Wadham et al. 1998, 2000). The plot between (Ca + Mg) and TZ^+ (Fig. 2) depicts strong relationship among the plotted points with equivalent ratios ranged from 0.39 to 0.83 (0.76 ± 0.06). Whereas, (Ca + Mg)/(Na + K) ratios varied from 0.64 to 4.78 with an average ratio of 3.32 ± 0.85. The plot between (Na + K) and TZ^+ (Fig. 3) demonstrates comparatively small input of (Na + K) to the TZ^+ with an average value of 0.24 ± 0.06. High (Ca + Mg)/(Na + K) and (Ca + Mg)/TZ^+ ratios and small input of (Na + K) to the TZ^+ show that hydrogeochemistry of the meltwater was mainly governed by carbonate type weathering with minor role from silicate type weathering. The plotted marks of glacier meltwater samples in (Ca + Mg) and SO_4 (Fig. 4) scatter plot depict a good correlation between the

Table 1 Chemical concentrations of meltwater samples collected from Chhota Shigri glacier

Parameters	Min	Max	Avg	SD
EC	12.7	68.8	36.8	15.2
pH	5.9	7.4	6.6	0.2
HCO_3^-	130	340	216	46.1
SO_4^{2-}	25.1	305	113	74.9
Cl^-	1.7	38.9	15.9	7.4
NO_3^-	0	9.7	3.5	2.3
PO_4^{3-}	0	11	1.5	1.2
H_4SiO_4	9.2	49.1	26	11.8
Ca^{2+}	52	258	150	49.1
Mg^{2+}	27.1	141	74.2	29.1
Na^+	18.6	87.8	37.9	10.9
K^+	11.5	112	30.8	11.6
TZ^+	153	561	293	89.8
TZ^-	186	594	349	109
TDS	15.1	47.1	27.9	8.5
$(Ca + Mg)/TZ^+$	0.39	0.83	0.76	0.06
$(Na + K)/TZ^+$	0.17	0.61	0.24	0.06
$(Ca + Mg)/(Na + K)$	0.64	4.78	3.32	0.85
Na/Cl	0.9	22.4	3.3	2.9
K/Cl	0.6	17.1	2.7	2.6
SMF	0.11	0.57	0.31	0.12

Unit: EC in µs/cm; ionic concentration in µeq/l; H_4SiO_4 in µmol/l and TDS in mg l^{-1}

SD standard deviation, *SMF* sulphate mass fraction

Fig. 3 Scatter diagram between (Na + K) and total cations (TZ$^+$)
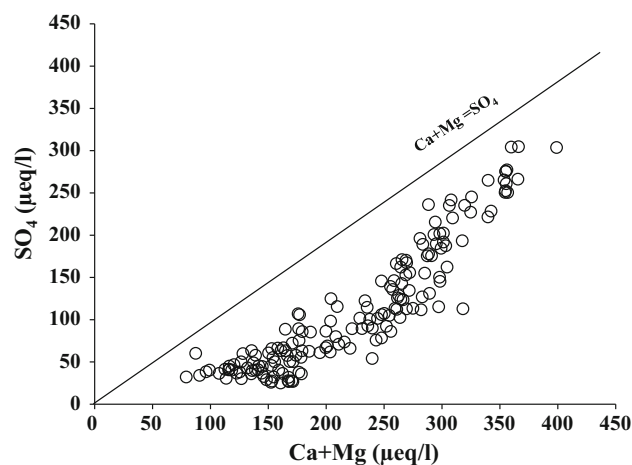
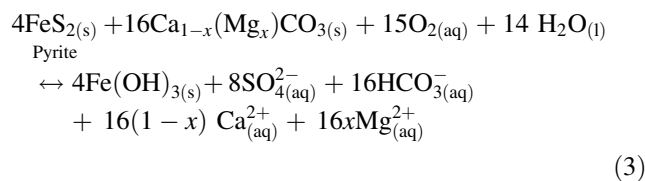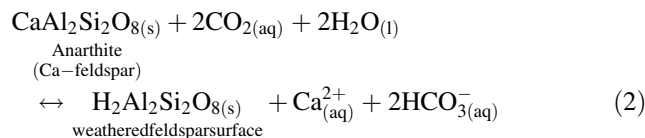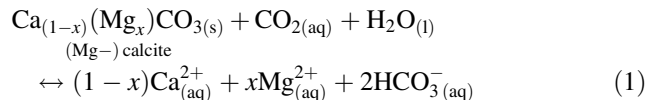**Fig. 4** Scatter diagram between (Ca + Mg) and SO$_4$

Fig. 2 Scatter diagram between (Ca + Mg) and total cations (TZ$^+$)

two data set; showing that sulphate minerals dissolution may supply sulphate in the glacier meltwater (Singh et al. 2015d).

The ratio of SO$_4$ to (SO$_4$ + HCO$_3$) is defined as sulphate mass fraction (SMF), which is used to describe the environments of chemical weathering. Here assuming that the other sources of SO$_4$ is low and unit of ions concentration is in equivalent (Tranter et al. 2002). If SMF value is <0.5, it signifies the importance of carbonation (Eqs. 1, 2) (Tranter et al. 2002), whereas if the value of SMF is 0.5, it shows that meltwater is obtained from the combination of oxidation of sulphide and dissolution of carbonate (Eq. 3) (Tranter et al. 2002).

$$\underset{(Mg-)\,calcite}{Ca_{(1-x)}(Mg_x)CO_{3(s)}} + CO_{2(aq)} + H_2O_{(l)}$$
$$\leftrightarrow (1-x)Ca^{2+}_{(aq)} + xMg^{2+}_{(aq)} + 2HCO^-_{3\,(aq)} \qquad (1)$$

$$\underset{\substack{Anarthite \\ (Ca-feldspar)}}{CaAl_2Si_2O_{8(s)}} + 2CO_{2(aq)} + 2H_2O_{(l)}$$
$$\leftrightarrow \underset{weathered\,feldspar\,surface}{H_2Al_2Si_2O_{8(s)}} + Ca^{2+}_{(aq)} + 2HCO^-_{3(aq)} \qquad (2)$$

$$\underset{Pyrite}{4FeS_{2(s)}} + 16Ca_{1-x}(Mg_x)CO_{3(s)} + 15O_{2(aq)} + 14\,H_2O_{(l)}$$
$$\leftrightarrow 4Fe(OH)_{3(s)} + 8SO^{2-}_{4(aq)} + 16HCO^-_{3(aq)}$$
$$+ 16(1-x)\,Ca^{2+}_{(aq)} + 16xMg^{2+}_{(aq)}$$
$$\qquad (3)$$

The average SMF value for meltwater of the Chhota Shigri glacier was calculated to be 0.31 ± 0.12, showing that dissolution of carbonate and sulphide oxidation (which provide SMF ratio of 0.5) cannot supply all the HCO_3^- to the meltwater. Therefore, hydrolysis of the carbonate may be arising before oxidation of sulphide (Tranter et al. 1997). In case of SMF value <0.5, excess of HCO_3^- over SO_4^{2-} would be produced by the presence of an alternative mechanism for supply of proton such as microbial oxidation of organic carbon in the bed rock (Wadham et al. 2000) and sulphide oxidation may be about the same as carbonation as a driver of chemical weathering at Chhota Shigri glacier.

Even though weathering of rock is the main source of different cations and anions in the glacierized area due to the rock water interaction but atmospheric contribution may also have little input to the solute chemistry of the meltwater. There are very few studies that deal with atmospheric contribution to the chemical characterization of Western Himalayan glaciers meltwater (Sharma et al. 2013; Singh et al. 2015c, d). The plot between (Na + K) against Cl^- (Fig. 5) explains that the values of sodium and potassium dominated over chloride. The Na/Cl ratios ranged from 0.9 to 22.4 (3.3 ± 2.9), whereas the ratios of K/Cl in meltwater varied from 0.6 to 17.1 (2.7 ± 2.6). These ratios were significantly higher than the sea aerosols (K/Cl = 0.0176 and Na/Cl = 0.85) displaying minor input of these ions from atmospheric precipitation to the dissolved ions budget of the investigation area as reported by earlier researchers on various aquatic environment (Pandey et al. 1999; Kumar et al. 2009; Sharma et al. 2012, 2013; Singh et al. 2012, 2014, 2015a, c, d; Priya et al. 2016).

Nitrate and phosphate concentrations in the Chhota Shigri glacier meltwater were very low with respect to other dissolved ions showing good quality of meltwater in the investigation area. Anthropogenic activities due to shepherds with lots of goat and sheep in this glacier during
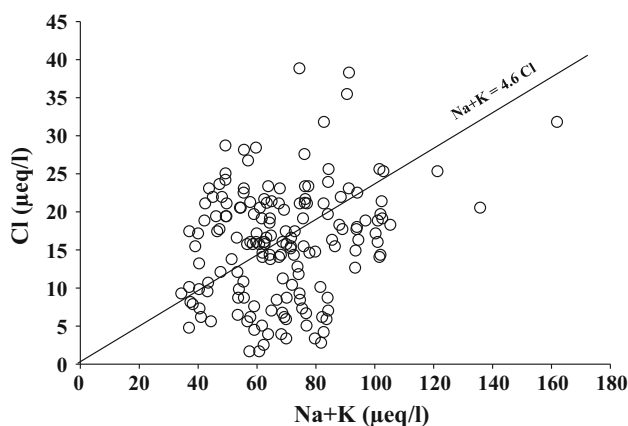

Fig. 5 Scatter diagram between (Na + K) and Cl

the observation period may be the probable source of NO_3^- and PO_4^{3-}. Atmospheric input (acidic NO_3^- aerosols) (Tranter et al. 1993) may be other possible source of NO_3^- in the meltwater.

Classification of hydrogeochemical facies

Classification of hydrogeochemical facies/water type of the study area can be made by plotting the values of dominant anions and cations in the Piper (1944) trilinear plot. Comparable qualities of water will fall together as groups in this diagram hence, used for determination of similarities and differences among them (Todd 2001). On the basis of Piper trilinear diagram (Fig. 6), it is clear that the percentage values of (Ca + Mg), i.e. alkaline earth metals were more than (Na + K), i.e. alkali metals. On the other hand percentage values of HCO_3, i.e. (weak acid) was more than (SO_4 + Cl), i.e. strong acid. Such type of trend in this diagram shows that carbonate type weathering was the main mechanism governing hydrogeochemistry of the investigation area (Singh et al. 2015d). This diagram indicates that most of the meltwater samples were Ca–HCO_3 type of water with minute contribution from Ca–SO_4 type of water.

Correlation coefficients between hydrogeochemical parameters

Numerically, correlation coefficient between hydrogeochemical parameters shows the degree to which one variable is statistically correlated with other variable (Vasanthavigar et al. 2013). Result of correlation matrix between various ions in meltwater of the study area is shown in Table 2. EC and TDS displayed significant correlation with HCO_3^-, SO_4^{2-}, H_4SiO_4, Ca^{2+}, Mg^{2+} and Na^+. Such types of good correlation imply that solute chemistry of this glacier was mainly controlled by these chemical parameters. Strong correlation exists between Ca–Mg, Ca–HCO_3 and Mg–HCO_3, indicating common provenance, which may be derived from carbonate weathering. Ca^{2+} and Mg^{2+} also displayed good correlation with SO_4^{2-} indicating similar source, probably derived from the dissolution of sulphate minerals (Singh et al. 2015c, d). H_4SiO_4 demonstrated potential correlation with Na^+ and moderate correlation with K^+. On the other hand, Na^+ was also moderately correlated with K^+, which may be generated from weathering of silicate type minerals.

R-mode factor analysis

For the explanation of relationships among different hydrogeochemical parameters of the Chhota Shigri glacier meltwater, R-mode factor analysis is used here. Table 3

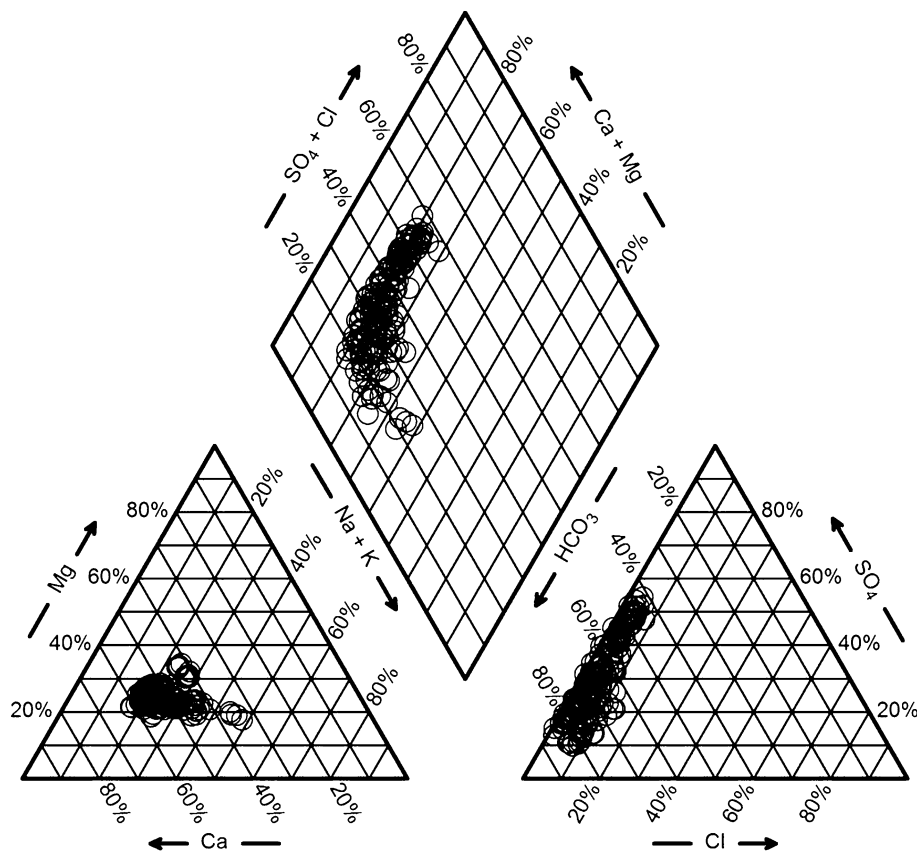**Fig. 6** Piper plot for major cations and major anions

Table 2 Correlation analysis of chemical composition of Chhota Shigri glacier meltwater

	EC	PH	HCO$_3$	SO$_4$	Cl	NO$_3$	PO$_4$	H$_4$SiO$_4$	Ca	Mg	Na	K	TDS
EC	1.00												
pH	0.31	1.00											
HCO$_3$	0.78	0.24	1.00										
SO$_4$	0.88	0.17	0.51	1.00									
Cl	0.25	0.08	0.08	0.19	1.00								
NO$_3$	0.55	0.27	0.75	0.22	0.09	1.00							
PO$_4$	0.15	0.14	0.03	0.09	0.18	0.01	1.00						
H$_4$SiO$_4$	0.96	0.37	0.78	0.85	0.20	0.58	0.14	1.00					
Ca	0.90	0.09	0.70	0.89	0.18	0.46	0.10	0.86	1.00				
Mg	0.98	0.35	0.70	0.89	0.29	0.48	0.19	0.94	0.87	1.00			
Na	0.78	0.23	0.67	0.77	0.26	0.33	0.15	0.78	0.71	0.81	1.00		
K	0.47	0.09	0.53	0.42	0.19	0.28	0.00	0.59	0.31	0.44	0.59	1.00	
TDS	0.97	0.25	0.82	0.90	0.22	0.54	0.10	0.96	0.93	0.94	0.84	0.56	1.00

shows factor analysis results of the meltwater. Three factors were identified as a significant contribution of factors because its eigenvalue was greater than one, which explained about 76.9% of the total variance in this result. The eigenvalue and variance in the data set were 7.64 and 58.8% for factor 1, 1.23 and 9.49% for factor 2 and 1.13 and 8.66% for factor 3. Factor 1 demonstrated strong loading for Ca^{2+}, Mg^{2+}, HCO$_3^-$, SO$_4^{2-}$, H$_4$SiO$_4$, K$^+$,

Na$^+$, TDS and EC. This factor described role of silicate and carbonate type weathering, dissolution of sulphate containing minerals and oxidation of sulphide controlling hydrochemistry of the investigation area. In the factor 2, pH and NO$_3^-$ have potential loading, showing possible role from atmospheric precipitation as well as anthropogenic input. Cl$^-$ and PO$_4^{3-}$ showed strong loading for factor 3, which may explain the role of atmospheric precipitation

Table 3 R-mode factor analysis of meltwater samples

Variables	Factor 1	Factor 2	Factor 3	Communalities
EC	0.920	0.300	0.151	0.958
pH	–	0.737	0.329	0.653
HCO_3	0.726	0.536	−0.180	0.846
SO_4	0.926	–	0.177	0.892
Cl	0.220	–	0.611	0.427
NO_3	0.399	0.745	−0.209	0.758
PO_4	–	0.151	0.777	0.627
H_4SiO_4	0.891	0.365	0.125	0.943
Ca	0.917	–	–	0.854
Mg	0.901	0.259	0.250	0.941
Na	0.848	0.113	0.185	0.765
K	0.576	–	–	0.345
TDS	0.965	0.240	–	0.993
Eigen value	7.643	1.234	1.126	
% of variance	58.789	9.490	8.662	
% of cumulative variance	58.789	68.279	76.940	

along with anthropogenic activities inside the Chhota Shigri glacier.

Temporal variations in the dominant anions and cations concentration with discharge

Temporal variations in the dominant anions and cations concentration of glacier meltwater are function of discharge. In general, dissolved ions concentrations showed decreasing trend with increasing meltwater runoff from the glacier. Daily mean meltwater runoff from this Shigri glacier for May–October, 2010 was computed to be 1.2, 3.3, 7.6, 7.9, 2.9 and 0.2 $m^3 s^{-1}$, respectively (Singh et al. 2016). Discharge patterns indicated that August received maximum runoff followed by July, June, September, May and October. Temporal variations in the concentrations of major anions, major cations, TDS and discharge are shown in Fig. 7a–c. Generally, concentrations of TDS and major ions of the Chhota Shigri glacier meltwater were minimum during high flow period (July and August) and maximum during low flow period (September and October). Intense melting takes place during peak melt season due to the presence of large coverage of exposed glacier ice, small snow cover area and higher temperature (Singh et al. 2005, 2006; Han et al. 2010). High discharge increased dilution of the major ions, resulting in low concentrations of major cations, major anions and TDS in the meltwater of the study area during peak flow period, whereas reduction in meltwater runoff occurred during late melt period because of low solar insolation (Singh and Hasnain 1998; Pandey et al. 1999), due to resultant of this rise in TDS and major ions concentrations of the meltwater.

Dissolved load

Dissolved load was calculated by meltwater runoff and total dissolved solid (TDS) of the study area. Daily mean dissolved load for May–October, 2010, was calculated to be 3.41, 9.49, 14.1, 13.2, 7.42 and 0.77 t day^{-1}, respectively. The average daily mean dissolved load during the study period was computed to be 8.06 t day^{-1}. Maximum dissolve load was monitored in July, constituting 29.2% of the total dissolved load after that August 27.3%, June 19.6%, September 15.3%, May 7.0% and October 1.6% of the total dissolved load. Even though TDS (total dissolved solid) concentration in the meltwater of investigation area was low in July and August as compared to the other months, but dissolved load was maximum due to high discharge in the month of July and August. The average daily mean dissolved load of the investigation area was too lower than the Gangotri glacier (250 t day^{-1}) (Singh et al. 2014), may be due to low discharge and geology of the Chhota Shigri glacier.

Chemical denudation rates

Proglacial streams at high altitude are most active driving force for weathering and erosion (Singh and Hasnain 2002). Evaluation of chemical denudation rates includes contribution of the portion of different elements delivered to the water stream in dissolved state from rock weathering in the catchment (Chakrapani et al. 2009). Geochemical denudation rates in the glacierized area are accelerated by the huge supply of mechanically abraded fresh debris from the glacier (Yde et al. 2005). The cation weathering rates

Fig. 7 (a–c) Temporal variations in the major ion concentration with discharge

(a)

(b)

(C)
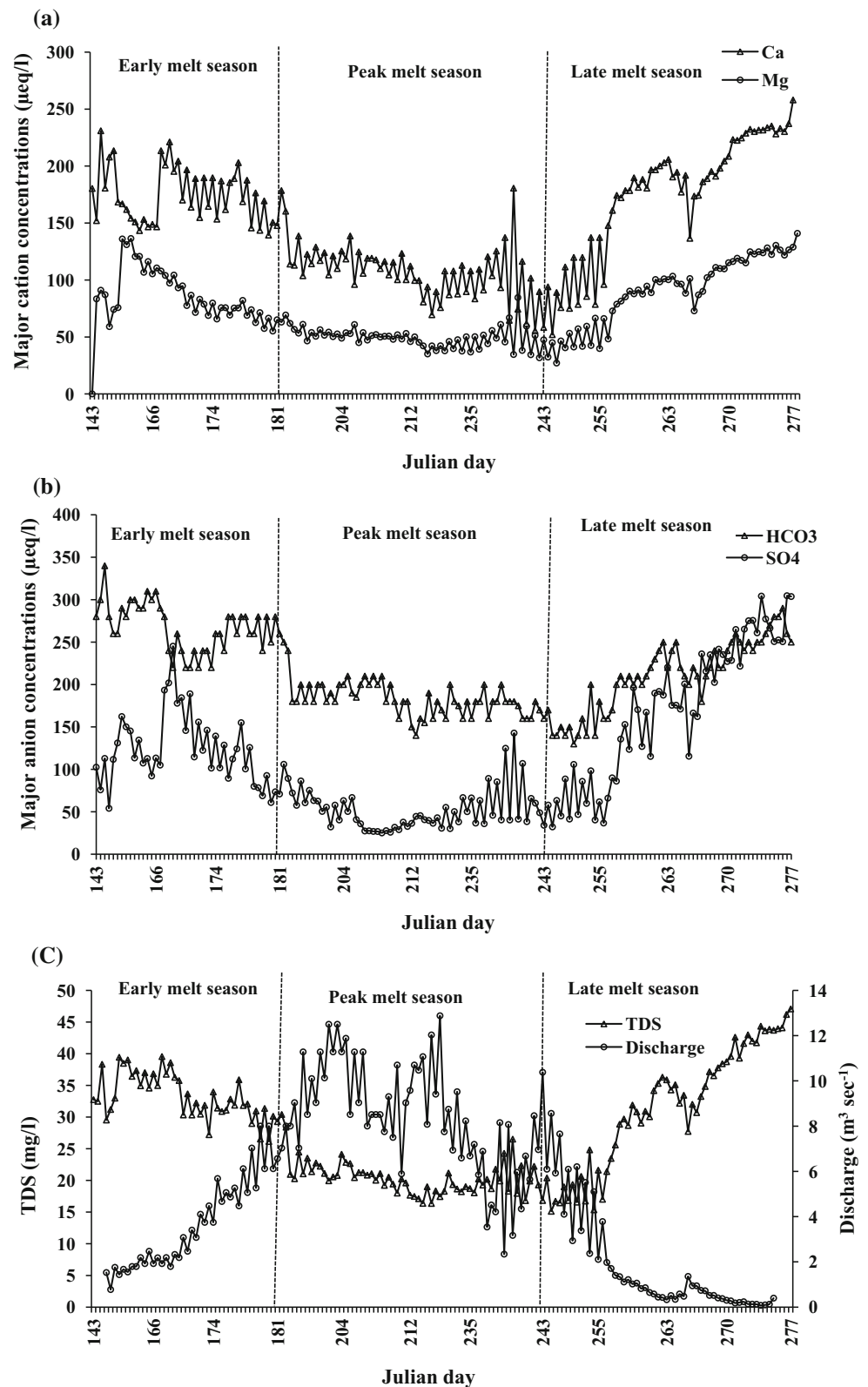
were computed from discharge, major cations concentrations and catchment area of this glacier. The cation weathering rates of the meltwater of study area for early (May–June), peak (July–August) and late melt (September–October) seasons were calculated to be 694, 1631 and 481 meq m^{-2} a^{-1}, respectively. Although major cations

Table 4 Cation denudation rates of some selected glaciers situated in the different region of world

Glacier	Region	Cation denudation rates (meq m^{-2} a^{-1})	References
Longyearbreen	Spitsbergen, Svalbard	322	Yde et al. (2008)
Gornergletscher	Swiss Alps	1010	Metcalf (1986)
Kuannersuit	West Greenland	683–860	Yde et al. (2005)
Haut Glacier d'Arolla	Swiss Alps	640–685	Sharp et al. (1995)
Dokriani	Central Himalaya, India	4160	Hasnain and Thayyen (1999)
Chhota Shigri	Western Himalaya, India	935	Present study

concentrations were minimum during peak melt season but due to the presence of high discharge during this period, cation denudation rates were high, whereas during late melt season even though major cations concentrations were high but due to the presence of relatively low discharge during this period, cation denudation rates were minimum in the study area. The chemical weathering rates were calculated from meltwater runoff, dissolved solute concentrations contributed from chemical weathering and catchment area of this glacier. The chemical weathering rates of the meltwater of study area were computed to be 32.8, 60.0 and 25.2 t km^{-2} year^{-1} for early, peak and late melt seasons, respectively. Its value was higher during the peak melt period as compared to early and late melt period, may be due to the presence of high discharge from this glacier during the peak melt period. The average chemical weathering rates of the investigation area were lower than the Dokriani glacier (321 t km^{-2} year^{-1}). This may be due to the presence of high southwest monsoonal rainfall and supraglacial moraines in the Garhwal Himalayan glacier such as Dokriani glacier (Hasnain and Thayyen 1999). Average cation weathering rates of the study area and its comparison with various glaciers are given in Table 4. This table indicates that cation denudation rate of the investigation area was higher than the Longyearbreen, Kuannersuit and Haut Glacier d'Arolla glaciers and lower than the Gornergletscher and Dokriani glaciers.

Conclusions

The present study has focused on chemical characterization of meltwater of the Chhota Shigri glacier, aiming to know about the solute chemistry, weathering and hydrogeochemical processes regulating hydrochemistry and seasonal change in the major ions concentration with discharge. The pH values of meltwater ranged between 5.9 and 7.4 (6.6 ± 0.2) showing that nature of meltwater is fluctuating from acidic to slightly alkaline. The major anions and cations composition in µeq/l are $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^- > PO_4^{3-}$ and $Ca^{2+} > Mg^{2+} > Na^+ > K^+$, respectively. The predominance of calcium and magnesium

to the TZ$^+$ is described by high ratios of (Ca + Mg) to total cations and (Ca + Mg) to (Na + K), showing dominancy of carbonate type weathering as dominant source of solutes in the Chhota Shigri glacier meltwater. Low ratio of sulphate mass fraction (SMF) of meltwater indicates that dissolution of carbonate and oxidation of sulphide cannot supply all the HCO_3^- to glacier meltwater (Tranter et al. 1997). Here, excess of HCO_3^- over SO_4^{2-} would be generated by microbial oxidation of organic carbon (another proton supply mechanism) in the bed rock of Chhota Shigri glacier (Wadham et al. 2000). The Piper trilinear diagram indicates that Ca–HCO$_3$ is the major hydrogeochemical facies with small contribution from Ca–SO$_4$ type of hydrogeochemical facies. Multivariate statistical methods were used for the identification of solute sources and weathering processes regulating solute acquisition in meltwater of this glacier.

Concentrations of TDS and major ions show inverse relationship with meltwater runoff, meaning their concentrations are minimum during peak flow period (July–August) because of more runoff resulting in dilution of various ions. Hence, major ions and TDS concentrations of meltwater are minimum during peak melt season, whereas their concentrations are maximum during end of melt season (September–October) because of less runoff and low dilution of major ions in the meltwater. The cation weathering rates of meltwater are high during peak melt season because of more runoff and low during late melt period due to low runoff from the investigation area.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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