

Dissolved ion chemistry and suspended sediment characteristics of meltwater draining from Chhota Shigri Glacier, western Himalaya, India

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Abstract Studies on dissolved ion chemistry and suspended sediment concentration of meltwater draining from Chhota Shigri Glacier were carried out in the year 2008 and 2009. The cationic and anionic concentrations follow the trend: $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ and $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^- > \text{PO}_4^{3-}$, respectively. The higher ratios of $(\text{Ca} + \text{Mg})/\text{TZ}^+$ and $(\text{Ca} + \text{Mg})/(\text{Na} + \text{K})$; strong correlations between Ca-Mg, Ca-HCO₃ and Mg-HCO₃; and low ratio of $(\text{Na} + \text{K})/\text{TZ}^+$ for both the years indicate that chemical characteristics of Chhota Shigri Glacier meltwater are mostly controlled by carbonate weathering followed by silicate weathering. The C ratio shows that dissolution and dissociation of atmospheric CO₂ is the major proton producer for glacier meltwater. Statistical analysis was used to identify different factors controlling dissolved ions chemistry of study area. There have been marked seasonal and diurnal variations in the total dissolved solid (TDS) and suspended sediment concentration of glacier meltwater observed during the sampling periods. TDS of meltwater is high during October (low discharge) and low during August (high discharge) in both years, implying that TDS is inversely correlated with discharge. On the other hand, suspended sediment concentration is higher during August (high flow regime) and low during October (low flow regime) during the sampling periods, generally following the discharge pattern of the glacier.

Keywords Meltwater chemistry · Weathering · Suspended sediment concentration · Seasonal and diurnal variations · Chhota Shigri Glacier · Western Himalaya

Introduction

The Himalaya, located along the south of the Tibetan Plateau, runs about 200–300 km from south to north and 2,400 km from west to east with an average elevation of about 6,000 m (Liu et al. 2010). There are more than 12,000 glaciers found in the Himalaya (Kaul 1999; ICIMOD 2001) covering an area of about 33,000 km² (Rai and Gurung 2005). Many rivers of Asia such as Ganges, Indus, Brahmaputra, Huang He or Yellow River, Yangtze, Mekong and Salween are fed by the glaciers of Himalaya. Hence, Himalayan glaciers are considered among the most important glaciers in the world because they contribute significantly to the continental solute budget (Kumar et al. 2009). Discharge of water from Himalayan glaciers contributes significantly to the overall runoff of the Himalayan rivers (Immerzeel et al. 2010) and it is important for drinking water supply, irrigation and hydroelectric power generation (Singh et al. 2006).

Dissolved ions chemistry of natural water provides important information about the geology of the area, material loads into the oceans, types of rock weathering and atmospheric precipitation (Xu et al. 2010). The chemical constituents of meltwater draining from glaciers are indicative of chemical weathering taking place below the glaciers (Lorrain and Souchez 1972; Reynolds and Johnson 1972; Raiswell 1984; Hasnain et al. 1989). High rates of physical and chemical weathering shown by drainage systems of higher Himalaya (Singh and Hasnain 1998) are attributed to high monsoonal rain fall, high seismicity of relatively younger Himalaya and

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frequent avalanching due to steep valleys (Sarin et al. 1992; Hasnain and Chauhan 1993).

Many hydrochemical and sediment transport studies have been carried out on Himalayan glaciers (Hasnain et al. 1989; Singh et al. 1995; Hasnain and Thayyen 1996, 1999a, b; Thayyen et al. 1999; Ahmad and Hasnain 2000, 2001; Kumar et al. 2002; Singh et al. 2003, 2005; Haritashya et al. 2006; Kumar et al. 2009; Haritashya et al. 2010; Singh et al. 2012, 2013, 2014; Sharma et al. 2013). Chemical characterisation of glacier meltwater is mainly controlled by the rock–water interaction, weathering of rock minerals, meltwater runoff and atmospheric precipitation (Singh et al. 1998; Ahmad and Hasnain 1999). In general, bicarbonate is the dominant anion in the meltwater draining from glaciers, whereas carbonation is the dominant chemical mechanism controlling the major ions chemistry of glacier meltwater (Kumar et al. 2009). Sediments present in the glacier meltwater are derived from various parts of the glacier such as ablation zone, accumulation zone and lateral moraines (Singh et al. 1995). Large amount of sediment materials such as moraines, debris and boulders are present in the ablation zone of a glacier; hence, this zone contributes large amount of sediment to the meltwater (Singh et al. 2003). A very limited number of studies are available on hydrochemical and sediment transport of the Chhota Shigri Glacier and none of them are detailed in discussion. Hence, in this paper, we have carried out detailed study covering sources of dissolved ions, weathering and geochemical processes controlling meltwater chemistry, seasonal and diurnal variations of total dissolved solid (TDS) and suspended sediment concentration in the glacier meltwater.

Study area

The Chhota Shigri Glacier is situated on the northern slope of Pir Panjal range of western Himalaya and falls in the Lahaul-Spiti district of Himachal Pradesh, India. Geographically, this glacier is located between 32°11'–32°17' N and 77°29'–77°33' E and is a valley-type glacier. The present snout of Chhota Shigri Glacier is situated at an elevation of about 4,055 m a.s.l. The shape of the snout is almost concave but some changes are observed in the shape of the snout every year. The length of this glacier is 9 km from snout to the accumulation zone near the Sara Umga Pass (4,900 m a.s.l.) and its width varies from 1.5 to 3.0 km (Nijampurkar and Rao 1992). Many small suspended glaciers and four tributaries are present in the drainage basin of Chhota Shigri Glacier. The total glacierized area is about 16.3 km² whereas Chhota Shigri Glacier area including tributaries is 15.7 km² (Wagnon et al. 2007). This glacier is oriented towards north but a variety of orientations is shown by its different tributaries (Azam et al. 2012). The Chhota Shigri Glacier stream flows in a NW direction, and about 2.5 km downstream from snout, it meets Chandra River. The sampling site was located at

32°17'24.58" N and 77°31'55.21" E on the Chhota Shigri stream at an elevation of about 3,900 m a.s.l., 2.0 km downstream from the snout of Chhota Shigri Glacier (Fig. 1).

Geology

Geologically, the Chhota Shigri Glacier falls in the Central Crystallines of the Pir Panjal range of the Himachal Himalaya and rests on the basement rocks composed of granite. This crystalline axis is mostly made up of meso-to-ketazonal metamorphites, migmatites and gneisses (Kumar and Dobhal 1997). Geological map of the Chhota Shigri Glacier and the surrounding area is shown in Fig. 2. Rohtang gneiss is the main lithological unit of the Chhota Shigri Glacier catchment, while some chalcopryrite is found in the lateral moraines up to an altitude of 4,700 m a.s.l (Kumar et al. 1987; Katoch 1989; Hasnain et al. 1989). Older Palaeozoic granite rocks are exposed in the upper Chandra Valley around 3 km upstream of Chhota Dara and Haimanta Formation overlies these with a tectonic break, in which fine-grained biotite–schists, black slates and phyllites are exposed (Kumar and Dobhal 1997).

Granite, granite gneiss, augen gneiss, schistose gneiss, porphyritic granite, muscovite-biotite schist, and milky-white muscovite–quartzite are found between Chhota Shigri and Bara Shigri glaciers with common occurrence of late stage pegmatitic veins having light grey green colour feldspar crystals (Kumar et al. 1987). Intense heating effect is seen from brown biotite having fine-grained texture, which shows periodic reheating of the underlying granitic rocks (Rawat and Purohit 1988). Small veins of antimony having pyrites traverse through the granites to the eastern side of the Chhota Shigri Glacier, very close to the paleo-snout of Bara Shigri Glacier. Just at the contact of these veins, a muscovite–quartz-rich rock is seen, which appears different from the main granitic rock (Kumar et al. 1987).

Climatic condition

Climate is one of the most important factors which influence the dynamics of the glacier (Ramanathan 2011). The climate regime of Chhota Shigri Glacier is influenced by both the winter mid-latitude westerlies and summer Asian monsoon, hence falls in the monsoon–arid transition zone. Here, in summer (July–September), most of the precipitation occurs due to the Asian monsoon, whereas significant amount of precipitation also occurs in winter (January–April) due to mid-latitude westerlies (Wagnon et al. 2007). Very short period of meteorological data is available on Chhota Shigri Glacier. Mean temperature observed on the surface of Chhota Shigri Glacier is about 3.4, 3.2, 3.2, 0.7 and –0.76 °C during the period 18 August–8 September

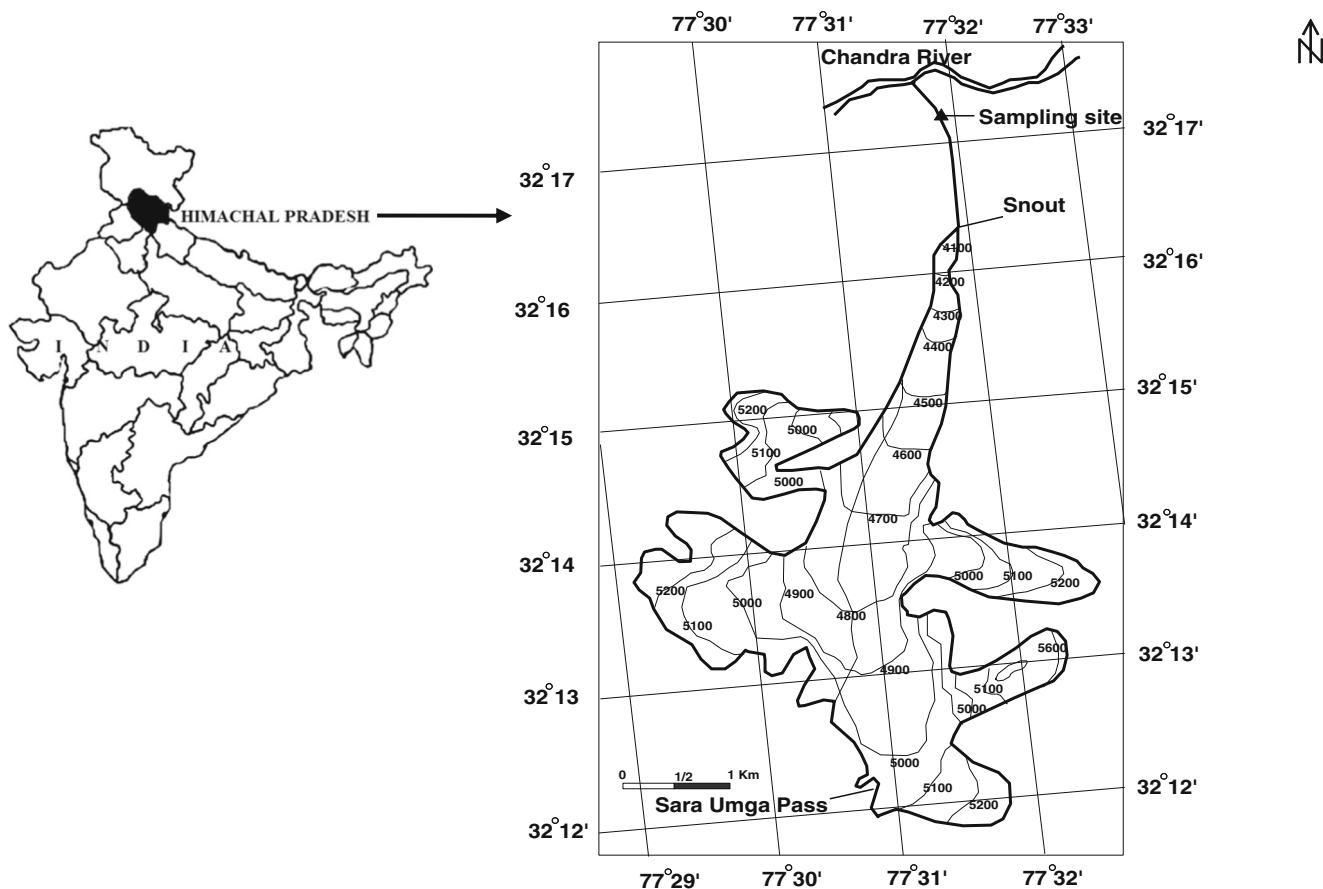


Fig. 1 Location of the study area showing sampling site

1986, 2 August–5 September 1988, 17 August–11 September 1989, 2–8 October 2003 and 18 August–10 October 2010, respectively. Whereas the corresponding mean relative humidity for these periods are 71, 78, 82, 70 and 63 %, respectively (Rizvi 1987; IMD 1987; Apte et al. 1988; Kulandaivelu et al. 1989; Upadhyay et al. 1989; Sharma 2007; JNU-IFCPAR 2010). Wind flows from south (Sara Umga pass) to north (Chandra river valley) with varying speeds between 3 and 15 km h⁻¹ (Purohit et al. 1991; Sharma 2007). The highest amount of precipitation was recorded on 15 August 1988 from the study area; otherwise, small amount of precipitation was measured (Upadhyay et al. 1989; Purohit et al. 1991). Generally, visibility is good in the morning, but deteriorates later in the day due to the presence of low stratus clouds occupying the valley (Rizvi 1987; Apte et al. 1988; Kulandaivelu et al. 1989; Upadhyay et al. 1989; Purohit et al. 1991).

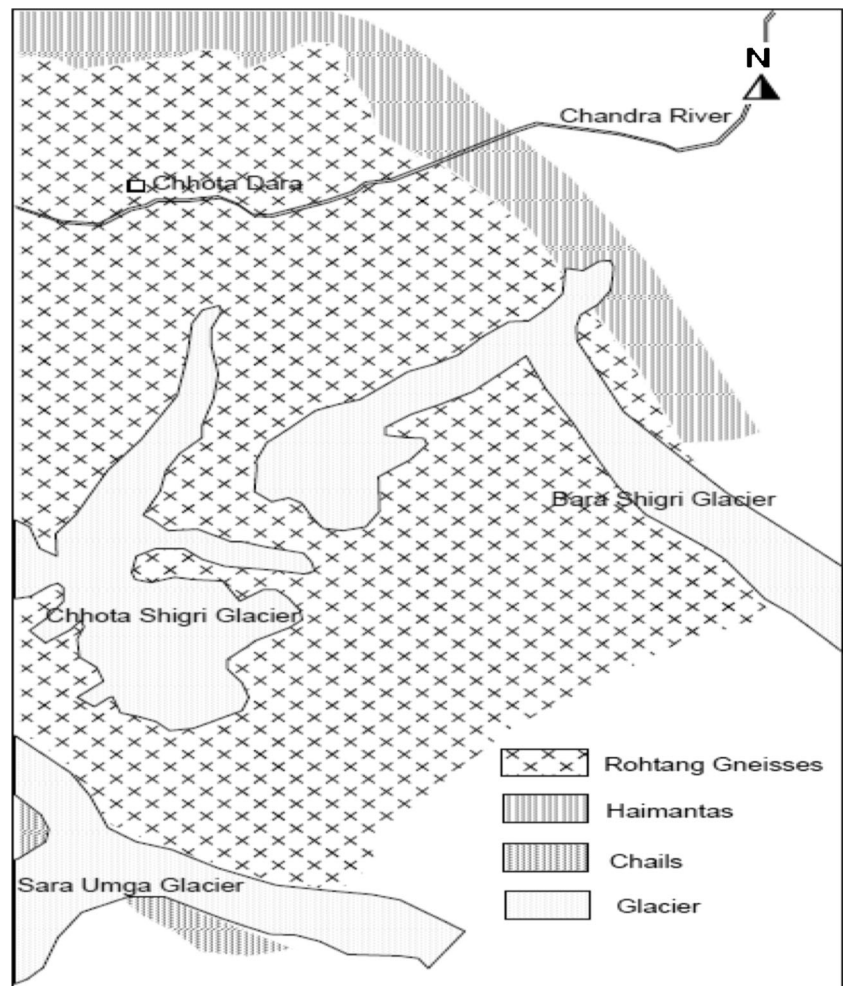
Materials and methods

Chhota Shigri Glacier meltwater samples were collected during the period from 19 August to 11 October 2008 (*n* = 63) and 2009 (*n* = 118) three times a day at 0800, 1300 and 1800 hours in 300 ml prewashed polyethylene bottles following the

method of Ostrem (1975). Twenty-four hour meltwater samples were collected on 20 August 2008. Electrical conductivity (EC) and pH were measured in the field immediately after the meltwater sample collection by using HACH-Sension 156 portable multiparameter meter. By using filtration setup and pneumatic pump, glacier meltwater samples were filtered through 0.45 μm Milipore membrane filter in the field. Suspended sediment collected on the filter paper was dried and weighed to determine total suspended matter. Bicarbonate was analysed by acid titration method (APHA 2005) in the field. The meltwater samples were transported to School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, and preserved at 4 °C in the cold room for analysis of different chemical parameters.

Sulphate analysis was carried out by turbidimetric method (APHA 2005). The molybdosilicate method and ascorbic acid method were used to measure the concentration of dissolved silica and phosphate, respectively (APHA 2005). Chloride was analysed by mercury(II) thiocyanate method (Florence and Farrar 1971) and nitrate was determined by brucine-sulphanilic acid method (APHA 2005). Atomic absorption spectrophotometer (Electronic Corporation of India Limited, AAS4141) was used for analysis of major cations (Ca²⁺, Mg²⁺, Na⁺ and K⁺). Analysis of Na⁺ and K⁺ were carried

Fig. 2 Geological map of Chhota Shigri Glacier including surrounding area (Source: Adapted from Kumar et al. 1987)



out in the emission mode, whereas Ca^{2+} and Mg^{2+} were analysed in the absorption mode. Precision of analytical result was better than $\pm 5\%$ for the measurement of dissolved ions. Plotting of Piper diagram was carried out by using Aquachem software. Correlation matrix and factor analysis of the meltwater samples were carried out using Statistical Package for Social Sciences.

Result and discussion

Dissolved ion chemistry

Results of chemical analyses of meltwater draining from Chhota Shigri Glacier are summarized in Table 1. The observed charge balance errors ($\text{TZ}^+ - \text{TZ}^- / \text{TZ}^+ + \text{TZ}^- \times 100$) were $< 10\%$, confirming the quality and reliability of the chemical analysis. EC value of the Chhota Shigri Glacier meltwater was $56.2 \pm 24.7 \mu\text{s}/\text{cm}$ (15.4–92.8) and 42.5 ± 17.1 (11.0–59.9) in 2008 and 2009, respectively. Meltwater of study area was acidic to slightly alkaline in nature with an average value of 6.7 ± 0.3 (6.3–7.3) in 2008 and 6.5 ± 0.3

(5.5–6.9) in 2009. Calcium and magnesium were the major cations accounting for 36.1 and 32.2 % of total cations (TZ^+) in 2008 and 38.5 and 36.6 % of total cations (TZ^+) in 2009, respectively. The average Ca^{2+} concentration was recorded as $128 \pm 48 \mu\text{eq}/\text{l}$ (47.4–193) in 2008 and $104 \pm 29.2 \mu\text{eq}/\text{l}$ (47.5–173) in 2009, whereas average Mg^{2+} concentration was found to be $118 \pm 49.0 \mu\text{eq}/\text{l}$ (20.0–175) in 2008 and $98.8 \pm 39.9 \mu\text{eq}/\text{l}$ (20.0–148) in 2009. The abundance order of cations in both years was $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$. Bicarbonate was the most dominant anion accounting for 60.1 % of the total anions (TZ^-) in 2008 and 66.8 % of the total anions (TZ^-) in 2009, whereas sulphate was the next dominant anion after bicarbonate constituting 36.9 % of total anions (TZ^-) in 2008 and 31.7 % of total anions (TZ^-) in 2009. The average HCO_3^- concentration was found to be $261 \pm 96.4 \mu\text{eq}/\text{l}$ (70.0–400) in 2008 and $219 \pm 67.3 \mu\text{eq}/\text{l}$ (110–320) in 2009, whereas average SO_4^{2-} concentration was recorded as $160 \pm 78.6 \mu\text{eq}/\text{l}$ (40.5–251) in 2008 and $104 \pm 45.5 \mu\text{eq}/\text{l}$ (22.6–190) in 2009. The average dissolved silica concentration was measured as $71.8 \pm 47.6 \mu\text{mole}/\text{l}$ (0.94–160) in 2008 and $33.4 \pm 18.7 \mu\text{mole}/\text{l}$ (3.2–57.3) in 2009.

Table 1 Chemical composition of Chhota Shigri Glacier meltwater

Parameters	2008		2009	
	Range	Average±SD	Range	Average±SD
EC	15.4–92.8	56.2±24.7	11.0–59.9	42.5±17.1
pH	6.3–7.3	6.7±0.3	5.5–6.9	6.5±0.3
Ca ²⁺	47.4–193	128±48	47.5–173	104±29.2
Mg ²⁺	20.0–175	118±49.0	20.0–148	98.8±39.9
Na ⁺	17.4–90.4	58.3±23.9	16.6–59.9	38.8±10.9
K ⁺	6.56–87.0	51.7±23.0	12.1–47.1	28.9±7.5
HCO ₃ ⁻	70.0–400	261±96.4	110–320	219±67.3
SO ₄ ²⁻	40.5–251	160±78.6	22.6–190	104±45.5
Cl ⁻	0.56–26.5	10.6±5.63	0.3–13.0	3.3±2.8
NO ₃ ⁻	0–9.52	1.31±1.21	0–4.6	1.5±1.0
PO ₄ ³⁻	0–6.00	1.27±1.21	0–7.1	1.4±1.3
H ₄ SiO ₄	0.94–160	71.8±47.6	3.2–57.3	33.4±18.7
TZ ⁺	118–524	355±141	118–385	270±83.0
TZ	136–662	434±175	141–448	328±100
TDS	10.5–60.3	38.3±16.6	11.1–38.5	27.0±8.8
(Ca+Mg)/TZ ⁺	0.63–0.81	0.69±0.03	0.57–0.85	0.74±0.06
(Na+K)/TZ ⁺	0.19–0.37	0.31±0.03	0.15–0.43	0.26±0.06
(Ca+Mg)/(Na+K)	1.71–4.24	2.31±0.44	1.30–5.61	2.98±0.76
Ca/Na	1.68–3.46	2.26±0.32	1.36–6.46	2.73±0.68
Mg/Na	0.81–3.26	2.04±0.36	0.71–4.96	2.50±0.78
HCO ₃ /Na	3.46–6.62	4.64±0.71	3.47–8.77	5.65±0.86
Na/Cl	1.77–44.4	7.23±6.18	1.65–72.9	21.9±15.9
K/Cl	0.90–41.3	6.36±5.73	1.42–51.1	16.0±11.1
C ratio	0.53–0.80	0.64±0.07	0.47–0.84	0.69±0.08

Unit: EC in microsiemens per centimetre; ionic concentration in micro equivalent per litre; H₄SiO₄ in micromole per litre and TDS in milligram per litre

Sources of dissolved ions and mechanism controlling meltwater chemistry

The chemical characteristics of meltwater draining from the glacier in terms of dissolved ions can be explained on the basis of chemical weathering of various rock-forming minerals present in the glacier basin (Singh et al. 1998; Kumar et al. 2009). Carbonate and silicate weathering, sulphide oxidation and sulphate minerals dissolution are the major dissolved ions-producing processes in the glacier catchment (Bhatt et al. 2000; Ahmad and Hasnain 2001; Singh et al. 2012, 2014). The (Ca + Mg) vs TZ⁺ scatter plot (Fig. 3) shows that all sampling points fall above the 1:1 line and have good correlation among the sampling points with average equivalent ratios of 0.69±0.03 in 2008 and 0.74±0.06 in 2009 (Table 1). Whereas Na + K/TZ⁺ ratios were 0.31±0.03 in 2008 and 0.26±0.06 in 2009 (Fig. 4, Table 1). (Ca + Mg)/(Na + K) ratios were high, i.e. 2.31±0.44 in 2008 and 2.98±

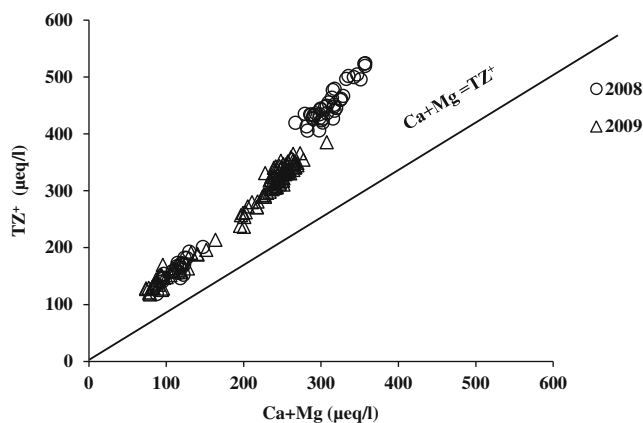


Fig. 3 Scatter plot between (Ca + Mg) vs total cations (TZ⁺)

0.76 in 2009. Higher contribution of (Ca + Mg) to the total cations (TZ⁺) and low ratios of (Na + K)/TZ⁺ for both years suggests that major source of dissolved ions in the meltwater of Chhota Shigri Glacier is carbonate weathering with relatively small contribution from silicate weathering, as reported by earlier workers (Sharma 2007; Ramanathan et al. 2009; Singh 2011). Main source of Na⁺, K⁺ and dissolved silica in the meltwater of study area are the weathering of silicate minerals such as feldspar, quartz, etc. The (Ca + Mg) vs (HCO₃ + SO₄) scatter plot (Fig. 5) indicates that all sampling points fall above 1:1 line and shows good correlation throughout the range of sampling points. This shows that excess of (HCO₃ + SO₄) over (Ca + Mg) is balanced by the alkalis (Na + K) from weathering of silicate minerals (Sharma et al. 2012; Khadka and Ramanathan 2012).

Natural waters draining only carbonates are characterized by high ratios of Ca/Na close to 50, Mg/Na close to 10 and HCO₃/Na close to 120 (Stallard 1980; Meybeck 1986; Negrel et al. 1993), whereas waters draining silicate-dominant lithology show low ratios of Ca/Na, i.e. 0.35±0.15; Mg/Na, i.e. 0.24±0.12; and HCO₃/Na, i.e. 2±1 (Gaillardet et al. 1999). The equivalent ratios of Ca/Na=2.26±0.32 in 2008 and 2.73±0.68 in 2009, Mg/Na=2.04±0.36 in 2008 and 2.50±0.78 in 2009, and HCO₃/Na=4.64±0.71 in 2008 and 5.65±0.86 in 2009 in the Chhota Shigri Glacier meltwater are higher than

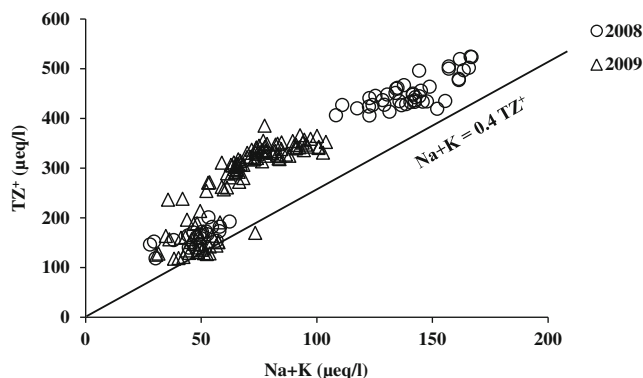


Fig. 4 Scatter plot between (Na + K) vs TZ⁺

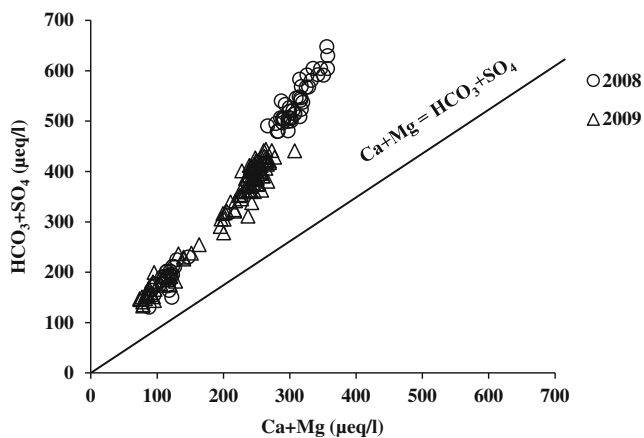
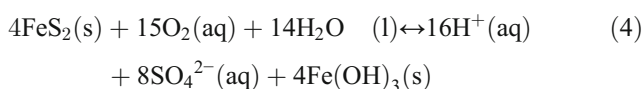
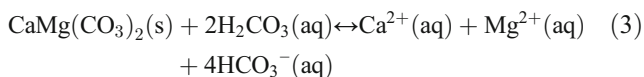
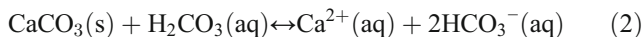
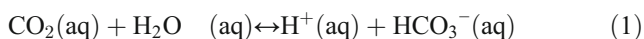


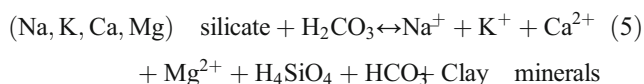
Fig. 5 Scatter plot between (Ca + Mg) vs (HCO₃ + SO₄)

those of meltwater draining silicate lithology and lower than that draining carbonate rocks. These ratios show that the dissolved ions chemistry of meltwater draining from Chhota Shigri Glacier is influenced by weathering of carbonate and silicate minerals.

Most of the base cations are derived from acid hydrolysis (Raiswell et al. 1980). For acid hydrolysis, aqueous protons are required, derived from two main sources (Raiswell 1984; Tranter et al. 1993; Brown et al. 1996; Hasnain and Thayyen 1999a). The first possibility for the production of aqueous proton is the dissociation of dissolved atmospheric CO₂ (Eq. 1) whereas second possible source is pyrite oxidation (Eq. 4).



The general reaction of silicate minerals weathering with H₂CO₃ can be written as (Pandey et al. 1999; Anshumali and Ramanathan 2007)



The relative importance of two major proton delivery mechanisms, i.e. carbonation and sulphide oxidation, can be evaluated by (HCO₃/HCO₃+SO₄) ratio, known as the C ratio (Brown et al. 1996). If C ratio is 1, it shows the significance of carbonic acid weathering where dissolution and dissociation

of atmospheric CO₂ are mainly producing protons (Eqs 1 and 2). Whereas C ratio of 0.5 signifies coupled carbonate dissolution and sulphide oxidation reactions and protons are derived from the oxidation of sulphide (Eq. 4). The average C ratio for the meltwater draining from the Chhota Shigri Glacier was 0.64±0.07 in 2008 and 0.69±0.08 in 2009, which shows that dominance of carbonate dissolution and dissociation and dissolution of atmospheric CO₂ are the major proton producer (Brown et al. 1996; Hasnain and Thayyen 1999a; Singh and Hasnain 2002).

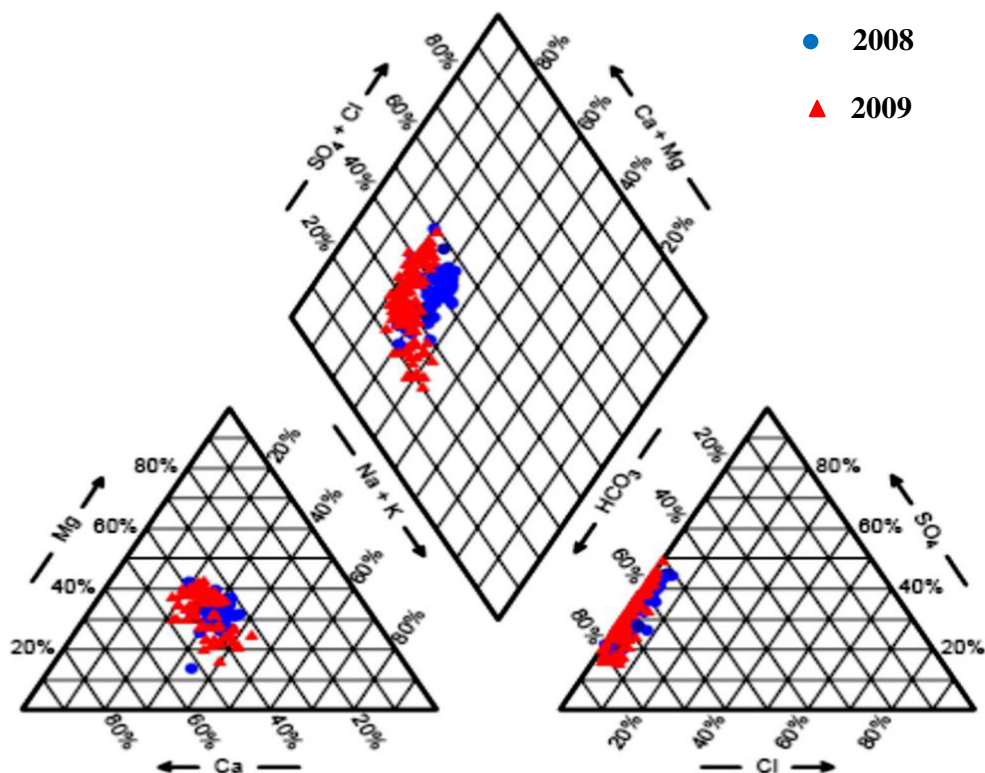
Water classification

Hydrogeochemical evolution including identification of water types of meltwater can be evaluated by plotting the concentrations of major anions (HCO₃⁻, SO₄²⁻ and Cl⁻) and cations (Ca²⁺, Mg²⁺, Na⁺ and K⁺) in the Piper trilinear diagram (Piper 1944). This diagram consists of one lower left and one lower right side triangular diagrams and a central diamond-shaped diagram. The relative composition of major anions and cations are plotted in the two triangular diagrams, while the central diamond-shaped diagram represents overall characteristics of meltwater combining the composition of major anions and cations. The Piper plot (Fig. 6) showed that majority of meltwater samples were CaHCO₃-type water with small contribution from MgHCO₃ type of water in 2008, whereas in 2009 a majority of meltwater samples were also CaHCO₃-type water but with considerable number of MgHCO₃-type water also being represented. The Piper plot pattern indicates that alkaline earth metals (Ca + Mg) exceed alkalis (Na + K) and weak acid (HCO₃⁻) exceeds strong acid (SO₄ + Cl). Such a combination suggests that the major source of dissolved ions in Chhota Shigri Glacier meltwater is carbonate weathering.

Atmospheric and anthropogenic impact on meltwater chemistry

There have been various studies on the contribution of atmospheric sources to the chemical composition of river water (Meybeck 1983; Biksham and Subramanian 1988; Sarin et al. 1989; Pandey et al. 1999; Jha et al. 2009; Kumar et al. 2009; Sharma et al. 2012; Singh et al. 2012). The importance of atmospheric inputs can be evaluated by considering the elements to chloride ratio because of abundant concentration of chloride in the seawater and relatively low concentration in most of the rocks (Dudeja et al. 2011). The (Na + K) vs Cl scatter plot (Fig. 7) indicates that Na⁺ and K⁺ concentrations are much higher than Cl⁻ in the study area for both years. The average ratios of Na/Cl and K/Cl are 7.23±6.18 and 6.36±5.73 in 2008 and 21.9±15.9 and 16.0±11.1 in 2009, respectively; much higher than for marine aerosols (i.e. Na/Cl=0.85 and K/Cl=0.0176) indicating relatively minor contribution from atmospheric precipitation to the chemical composition of

Fig. 6 Piper diagram for concentration of dissolved ions



Chhota Shigri Glacier meltwater (Pandey et al. 1999; Kumar et al. 2009; Dudeja et al. 2011; Sharma et al. 2012; Singh et al. 2012)

Trace amount of NO_3^- and PO_4^{3-} was reported from the meltwater of Chhota Shigri Glacier, which indicates the palatability of the meltwater. Tourists and shepherds with lots of sheep and goats arrive in the study area during the sampling period. Hence, anthropogenic activities may be one of the possible sources of NO_3^- and PO_4^{3-} in the study area, with additional inputs of NO_3^- from acidic NO_3^- aerosols (Tranter et al. 1993) (Eq. 6).

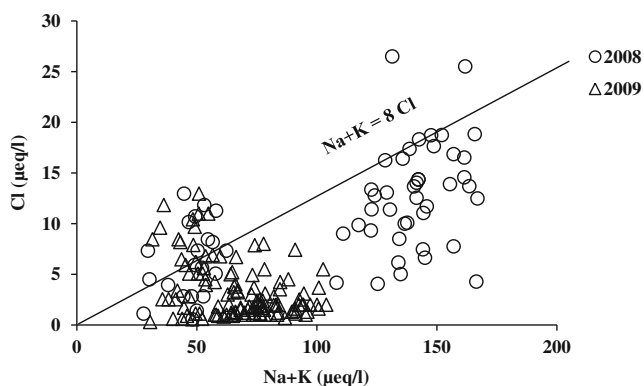
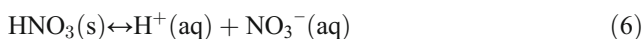


Fig. 7 Scatter plot between (Na + K) vs Cl

Effective CO_2 pressure

The effective CO_2 pressure (pCO_2) of meltwater draining from the glacier can be used to characterize the various hydrological weathering environments (Sharp 1991; Wadham et al. 1998). Open and closed system weathering conditions are kinetic phenomena, which depend on those factors affecting the weathering rates (i.e. rock minerals availability and reactivity) and the rate of extent of CO_2 transfer to the glacier meltwater (Raiswell 1984; Raiswell and Thomas 1984; Thomas and Raiswell 1984). The average pCO_2 values ($10^{-2.5}$ atm in 2008 and $10^{-2.3}$ atm in 2009) for Chhota Shigri Glacier meltwater were higher than the atmospheric pCO_2 ($10^{-3.5}$ atm) showing disequilibrium with respect to atmosphere. The higher values of pCO_2 of meltwater are due to open system weathering, low temperature, high turbulence and dominant carbonate weathering process in the study area (Ahmad and Hasnain 2001; Singh et al. 2012). The pCO_2 values for the study area are close to the earlier reported value for Gangotri and Chhota Shigri glaciers (Singh et al. 2012; Sharma et al. 2013).

Statistical analysis

Correlation matrix and factor analysis are one of the important statistical tools widely used in statistical analysis of hydrochemical data. Statistical analysis gives better information than graphical analysis about sources of dissolved ions in

the study area as it considers a finite number of variables (Srivastava and Ramanathan 2008).

Correlation matrix

Sources of dissolved ions in glacier meltwater can be evaluated on the basis of association among the dissolved ions (Singh et al. 1998; Ahmad and Hasnain 2001). The correlation matrix is a bivariate method, which shows how much one variable predicts the other variable (Kumar et al. 2007). The correlation matrix of meltwater samples of Chhota Shigri Glacier for both years is shown in Tables 2 and 3. EC was strongly correlated with TDS ($r^2=0.990$ in 2008 and $r^2=0.974$ in 2009) showing that as the concentrations of all dissolved ions/constituents increase, electrical conductivity also increases (Rajmohan and Elango 2004; Srivastava and Ramanathan 2008). Good correlation was observed between Ca^{2+} and Mg^{2+} ($r^2=0.951$ in 2008 and $r^2=0.963$ in 2009), Ca^{2+} and HCO_3^- ($r^2=0.972$ in 2008 and $r^2=0.866$ in 2009) and Mg^{2+} and HCO_3^- ($r^2=0.955$ in 2008 and 0.894 in 2009) showing common source, which may be carbonate weathering. Na^+ displayed strong correlation with K^+ ($r^2=0.946$ in 2008 and $r^2=0.925$ in 2009), while H_4SiO_4 showed good correlation with Na^+ ($r^2=0.836$ in 2008 and $r^2=0.776$ in 2009) and K^+ ($r^2=0.805$ in 2008 and $r^2=0.730$ in 2009) indicating similar source, i.e. silicate weathering. Ca^{2+} showed strong correlation with SO_4^{2-} ($r^2=0.968$ in 2008 and $r^2=0.888$ in 2009), whereas Mg^{2+} also showed good correlation with SO_4^{2-} ($r^2=0.954$ in 2008 and $r^2=0.888$ in 2009). These associations indicate that probably pyrite oxidation and sulphate mineral dissolution are the source of these ions in the study area.

Factor analysis

The aim of factor analysis is to explain the observed relationship among the variables in terms of simpler relations (Jha et al. 2009). Factor analysis is a multivariate, exploratory, statistical tool that can be used to explain the variability in a dataset (Singh and Hasnain 2002; Boruvka et al. 2005). Here, R-mode factor analysis was used because it has numerous positive features, which can be used for the interpretation of hydrogeochemical data (Lawrence and Upchurch 1992). Results of factor analysis of Chhota Shigri Glacier meltwater are given in Table 4. If the eigenvalue is greater than 1, it is a significant contributing factor (Briz-Kishore and Murali 1992; Singh et al. 2012). Two factors were extracted showing eigenvalue >1 , which control the dissolved ions chemistry of Chhota Shigri Glacier meltwater in 2008. These two factors explained about 80.8 % of the total variability. Factor 1 explained about 71.9 % of variance in dataset, showing strong loading of EC, H_4SiO_4 , HCO_3^- , SO_4^{2-} , Cl^- , Ca^{2+} , Mg^{2+} , Na^+ , K^+ and TDS. This factor shows contribution from carbonate and silicate minerals weathering, sulphide oxidation, sulphate minerals dissolution, evaporates dissolution and atmospheric precipitation. Factor 2 represents 8.9 % of the variance in the dataset, having positive loading for NO_3^- . This factor may be attributed to atmospheric deposition along with anthropogenic activities taking place in the basin area.

Two factors were also identified having eigenvalue >1 , which controls the meltwater chemistry of the study area in 2009. The total variance explained by these two factors is 77.4 %. Factor 1 has strong positive loading for EC, pH, H_4SiO_4 , HCO_3^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , Na^+ , K^+ and TDS and accounts for 69 % of the variance in the dataset. This factor

Table 2 Correlation matrix of measured parameters of Chhota Shigri Glacier meltwater in 2008

	EC	pH	H_4SiO_4	HCO_3^-	SO_4	Cl	NO_3	PO_4	Ca	Mg	Na	K	TDS
EC	1.000												
pH	-0.775**	1.000											
H_4SiO_4	0.905**	-0.632**	1.000										
HCO_3^-	0.965**	-0.706**	0.829**	1.000									
SO_4	0.961**	-0.781**	0.869**	0.919**	1.000								
Cl	0.559**	-0.486**	0.468**	0.500**	0.527**	1.000							
NO_3	0.202	-0.135	0.122	0.190	0.179	0.060	1.000						
PO_4	-0.045	0.079	0.003	-0.084	-0.072	-0.049	-0.068	1.000					
Ca	0.973**	-0.732**	0.858**	0.972**	0.968**	0.525**	0.166	-0.063	1.000				
Mg	0.958**	-0.784**	0.858**	0.955**	0.954**	0.492**	0.211*	-0.096	0.951**	1.000			
Na	0.968**	-0.782**	0.836**	0.953**	0.960**	0.613**	0.207	-0.045	0.963**	0.941**	1.000		
K	0.947**	-0.702**	0.805**	0.953**	0.911**	0.583**	0.191	-0.093	0.941**	0.893**	0.946**	1.000	
TDS	0.990**	-0.742**	0.924**	0.971**	0.970**	0.538**	0.181	-0.057	0.982**	0.968**	0.967**	0.945**	1.000

**Correlation is significant at the 0.01 level; *correlation is significant at the 0.05 level

Table 3 Correlation matrix of measured parameters of Chhota Shigri Glacier meltwater in 2009

	EC	pH	H ₄ SiO ₄	HCO ₃	SO ₄	Cl	NO ₃	PO ₄	Ca	Mg	Na	K	TDS
EC	1.000												
pH	0.833**	1.000											
H ₄ SiO ₄	0.952**	0.838**	1.000										
HCO ₃	0.878**	0.668**	0.860**	1.000									
SO ₄	0.892**	0.816**	0.833**	0.633**	1.000								
Cl	-0.449**	-0.366**	-0.379**	-0.413**	-0.454**	1.000							
NO ₃	-0.169*	-0.043	-0.111	-0.175*	-0.137	-0.060	1.000						
PO ₄	-0.497**	-0.332**	-0.427**	-0.472**	-0.415**	0.251**	0.154*	1.000					
Ca	0.961**	0.803**	0.919**	0.866**	0.888**	-0.439**	-0.155*	-0.473**	1.000				
Mg	0.986**	0.834**	0.948**	0.894**	0.888**	-0.438**	-0.165*	-0.495**	0.963**	1.000			
Na	0.787**	0.629**	0.776**	0.904**	0.605**	-0.373**	-0.209*	-0.348**	0.739**	0.797**	1.000		
K	0.722**	0.556**	0.730**	0.862**	0.528**	-0.306**	-0.140	-0.317**	0.676**	0.727**	0.925**	1.000	
TDS	0.974**	0.809**	0.958**	0.946**	0.842**	-0.442**	-0.160*	-0.478**	0.960**	0.982**	0.869**	0.815**	1.000

**Correlation is significant at the 0.01 level; *correlation is significant at the 0.05 level

explains contribution from weathering of carbonate and silicate minerals associated with sulphate minerals dissolution and sulphide oxidation. Factor 2 accounts for 8.4 % of variance in the dataset and indicates strong loading of NO₃⁻. This factor may be responsible for contribution from atmospheric deposition and anthropogenic activities.

Seasonal and diurnal variations of the total dissolved solid

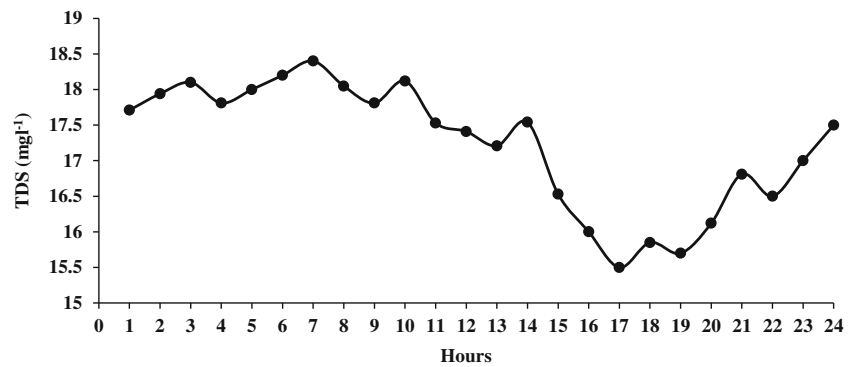
Generally, meltwater draining from glacier shows seasonal and diurnal variation of the dissolved ions concentration.

Different weathering intensities of glacier meltwater at different values of runoff are responsible for variation in the dissolved ions concentration with time (Kumar et al. 2009). Daily mean TDS concentration for August, September and October 2008 was measured to be 15.7±2.28, 47.9±3.1 and 50.6±4.88 mg l⁻¹, respectively, whereas daily mean TDS concentration for August, September and October 2009 was found to be 13.8±1.67, 31.0±6.11 and 32.1±1.68 mg l⁻¹, respectively. Hence, TDS shows high values during October (low flow period) and low during August (high flow regime) in both years. Such a trend is observed because of low supply of solar

Table 4 Factor analysis of Chhota Shigri Glacier meltwater samples for both years

Variables	2008			2009		
	Factor 1	Factor 2	Communalities	Factor 1	Factor 2	Communalities
EC	0.988		0.984	0.979		0.961
pH	-0.791	-0.102	0.637	0.836	0.205	0.741
H ₄ SiO ₄	0.897		0.805	0.952		0.910
HCO ₃	0.959	0.123	0.935	0.927	-0.117	0.874
SO ₄	0.969	0.101	0.949	0.864	0.172	0.776
Cl	0.601		0.362	-0.480	-0.441	0.425
NO ₃	0.134	0.631	0.417	-0.184	0.852	0.759
PO ₄		-0.811	0.658	-0.514	0.115	0.277
Ca	0.976		0.960	0.956		0.918
Mg	0.959	0.144	0.941	0.982		0.966
Na	0.978		0.966	0.867	-0.188	0.787
K	0.946	0.127	0.911	0.808	-0.186	0.688
TDS	0.989		0.985	0.995		0.989
Eigen value	9.35	1.16		8.973	1.099	
% of variance	71.921	8.927		69.02	8.453	
% of cumulative variance	71.921	80.848		69.02	77.473	

Fig. 8 Diurnal variations in TDS concentration of Chhota Shigri Glacier meltwater



energy during October reducing the discharge and dilution of the solute concentration; hence, TDS value of Chhota Shigri Glacier meltwater is high in October. On the other hand, during August, high incoming solar radiation increases the discharge and dilution of solute concentration (Singh and Hasnain 1998; Singh et al. 2006), resulting low TDS value of glacier meltwater during August.

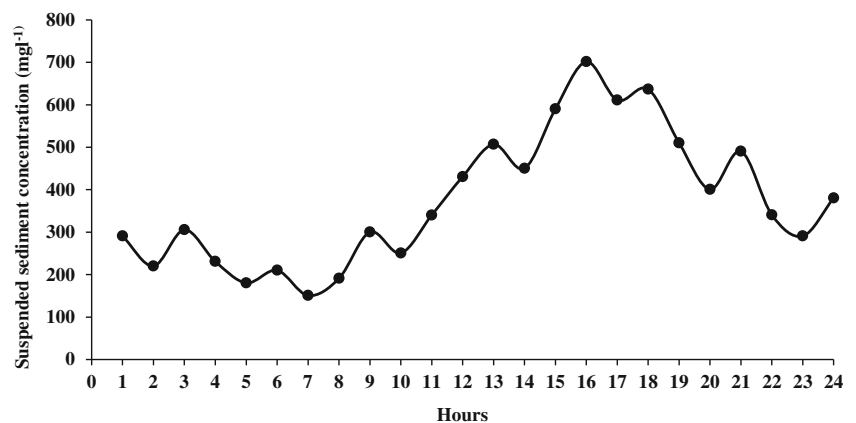
A distinct diurnal variation in the TDS of meltwater draining from Chhota Shigri Glacier was observed. High TDS was observed in the morning which decreased in the evening and again showed increasing trend in night (Fig. 8). The discharge from Chhota Shigri Glacier shows peak runoff in evening between 1400 and 1700 hours and reaching minimum runoff in the morning at around 0700 hours (Sharma 2007; JNU-IFCPAR 2009). Thus, TDS shows inverse relationship with discharge, i.e. TDS is low during high discharge and high during the low discharge. The observed diurnal variation in the TDS of meltwater could be explained by the model of Rainwater and Guy (1961), Collins (1983) and Kumar et al. (2009). According to this model, low supply of solar radiation in the morning reduces the discharge and dilution of subglacial meltwater. At pressure melting, the subglacial meltwater produced has higher dissolved ions concentration because of longer contact with solute-rich base and higher residence time. On the other hand, englacial channels become active due to increase in solar insolation in the

afternoon. As a resultant of this, huge amount of subglacial meltwater is available for runoff and after certain lag of time; discharge is maximum in evening causing dilution of TDS of glacier meltwater.

Suspended sediment characteristics

Suspended sediment concentration in the meltwater draining from Himalayan glaciers is highly variable because of the influences of climate, sediment sources variability, tectonic setting, debris entrainment processes and types of rock and weathering (Kumar et al. 2002). Daily mean suspended sediment concentration for August, September and October 2008 was found to be 376 ± 229 , 40.1 ± 17.8 and 12.0 ± 7.24 mg l⁻¹, respectively, whereas daily mean suspended sediment concentration for August, September and October 2009 was observed to be 368 ± 225 , 34.5 ± 29.9 and 8.85 ± 3.16 mg l⁻¹, respectively. Suspended sediment concentration is high during August (high flow period) and low during October (low flow period) in both years. Such variation in the suspended sediment concentration is attributed to climate and development of the drainage network of the basin (Pandey et al. 1999; Singh et al. 2003). High discharge (due to high incoming solar radiation), increased stream area cross section and more availability of glacial debris are the major factors behind the high suspended sediment concentration in August (Singh and

Fig. 9 Diurnal variations in the suspended sediment concentration of Chhota Shigri Glacier meltwater



Hasnain 1998; Pandey et al. 1999; Haritashya et al. 2006). Whereas suspended sediment concentration is much lower in October because of low discharge (due to low supply of incoming solar radiation), sediment evacuation by the drainage system in the preceding months and remaining small amount of subglacial sediment or morainic material flushed out from the valley walls of the glacier in the later part of the ablation season (Ostrem 1975; Collins 1990; Singh and Hasnain 1998).

Diurnal variations in the suspended sediment concentration of Chhota Shigri Glacier meltwater are given in Fig. 9. Suspended sediment concentration shows lower concentration in the morning and increase in the evening. It reaches to its maximum concentration at 1600 hours, then again follows decreasing trend at night. Such types of trend in diurnal variations in suspended sediment concentration can be explained by variation in meltwater runoff from glacier. In case of Chhota Shigri Glacier, minimum discharge is observed in the morning at around 0700 hours, whereas maximum discharge is observed in evening at 1400–1700 hours (Sharma 2007; JNU-IFCPAR 2009). The results indicate that suspended sediment concentration is directly correlated with discharge, i.e. suspended sediment concentration is low during low discharge and high during high discharge. In the morning, low temperature and low solar radiation are responsible for low discharge; hence, suspended sediment concentration is low. Whereas from morning to evening, addition of meltwater from subglacial channels leads to increased discharge from glacier; hence, suspended sediment concentration is high in evening (Singh et al. 1998).

Conclusion

The hydrogeochemical study of meltwater draining from Chhota Shigri Glacier indicates that meltwater is slightly acidic in nature. Calcium and magnesium are the major cations, whereas bicarbonate is the major anion followed by sulphate for both years. High contribution of (Ca + Mg) to total cations (TZ^+), high ratio of (Ca + Mg)/(Na + K), good correlation between calcium and magnesium, calcium and bicarbonate, magnesium and bicarbonate, and low (Na + K)/ TZ^+ ratio suggest that major source of dissolved ions in glacier meltwater is carbonate weathering followed by silicate weathering. Piper plot shows that alkaline earth metals (Ca + Mg) dominated over alkalis (Na + K), while weak acid (HCO_3^-) exceeds strong acids ($SO_4 + Cl$). This further confirms that dissolved ions chemistry of study area is mostly controlled by carbonate weathering.

Trace amount of NO_3^- and PO_4^{3-} was reported from the study area, indicating palatability of meltwater. Correlation matrix and factor analysis results for both years indicate that dissolved ions chemistry of Chhota Shigri Glacier meltwater

is regulated by carbonate and silicate weathering, oxidation of sulphide, dissolution of sulphate minerals, atmospheric precipitation and anthropogenic activities. Distinct seasonal and diurnal variation in TDS and suspended sediment concentration of meltwater were observed. TDS is inversely correlated with discharge, whereas suspended sediment concentration is directly correlated with discharge.

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