

Hydrochemistry and dissolved solute load of meltwater in a catchment of a cold-arid trans-Himalayan region of Ladakh over an entire melting period

Namrata Priya, Renoj J. Thayyen, AL. Ramanathan and Virendra Bahadur Singh

ABSTRACT

The hydrochemical study of meltwater draining from a catchment dominated by snowmelt in a cold-arid trans-Himalayan region of Ladakh, India, was carried out for an entire melting season (May–September) during the year of 2010. Cation concentration in the meltwater shows a consistent trend of $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ for this period. Carbonate weathering has been identified as the dominant process controlling the dissolved ion chemistry of meltwater in the study area. There are indications that atmospheric aerosols contain alkaline dust, sea salt and anthropogenic aerosols like NO_3 and SO_4 that might have also added some solute to the system. Meltwater chemistry has been showing an intra-annual variation with highest concentration for most of the dissolved solutes during the late melt period, pointing towards the contribution of ground ice melt to the catchment runoff. The lowest concentration during the peak melt period is due to higher contribution from snow melt which has less residence time to interact with rock. Cationic denudation rate for this catchment has been estimated as $778 \text{ meq m}^{-2} \text{ a}^{-1}$, while the average total dissolved solids flux for early, peak and late melt period is 0.64 t day^{-1} , 3.02 t day^{-1} , 1.31 t day^{-1} , respectively.

Key words | carbonate weathering, cold-arid regime, denudation rate, Himalaya, hydrochemistry, Ladakh range

Namrata Priya
AL. Ramanathan (corresponding author)
Virendra Bahadur Singh
School of Environmental Science,
Jawaharlal Nehru University,
New Delhi,
India
E-mail: alrjnu@gmail.com

Renoj J. Thayyen
National Institute of Hydrology,
Roorkee,
Uttarakhand,
India

INTRODUCTION

Major Himalayan rivers such as the Ganga, Brahmaputra and Indus carry a significant contribution from snow and glacial melt (Bahadur *et al.* 1978; Pandey *et al.* 1999; Kaser *et al.* 2010; Wulf *et al.* 2010). A recent study using an isotopic technique shows that the glacial melt contributes to 15% of the total runoff in the Gaerqu River catchment, located in the source region of the Yangtze River, China (Liu & Yao 2016). Another related study shows a poor relationship of glacial discharge with suspended sediment concentration due to hysteresis effect in glacial melt stream in Gangotri Glacier (Arora *et al.* 2014). A variation in glacial and periglacial area influencing the water quality was observed in glacier originating rivers (Jones & Parker 2015). These studies

indicate that melting, discharge, land use change and related factors influence the water quality changes in glacier regions.

Meltwater hydrochemistry has often been used as a tool to explain the complex weathering processes occurring in the cryospheric system (Sharma *et al.* 2013; Singh & Ramanathan 2015; Singh *et al.* 2015a, 2015b). Understanding the solute load carried by runoff is significant as it can ultimately influence the solute loads of global ocean water (Sharma *et al.* 2013). Increased anthropogenic activities in mountains could influence the stream chemistry significantly at lower elevations. This issue is more potent in the cold-arid region of Ladakh, where water is scarce and settlement is restrained along the foothill zones of the mountain.

Hence, understanding the headwater solute acquisition process in this unique climate system of the Himalaya could play a key role in managing the water quality at lower altitudes. The main source of solutes in a catchment which is predominately covered with snow includes atmospheric deposition, soil water interaction and biological processes (Clow & Mast 1995; Clow & Sueker 2000). Meltwater chemistry changing with time and space leads to the significance of long-term hydrochemical study for identifying the relative contributions from natural and anthropogenic sources (Ramanathan 2011). The present study is conducted in the upper Ganglass catchment of the Ladakh mountain range which comes under the cold-arid glacio-hydrological regime of Himalaya (Figure 1) (Thayyen & Gergan 2010). Although significant research has been carried out to understand the hydrochemistry and solute load of meltwater in the monsoon regime (Singh & Hasnain 1998; Hasnain & Thayyen 1999; Singh et al. 2006, 2014; Arora et al. 2014), no such work is available for the cold-arid regime covering the entire snow melt period. Further, this is significant for better understanding the role of the weathering process in the headwater regions of Himalaya with negligible monsoon rains. Hence, this paper aims to elucidate hydrochemical

characteristics of stream water under cold-arid conditions and its intra-annual variation, along with assessment of chemical weathering rates and annual total dissolved solids (TDS) fluxes from the catchment.

STUDY AREA

The study has been undertaken in the upper Ganglass catchment of the Ladakh mountain range (Jammu and Kashmir, India) with a latitude and longitude of $34^{\circ} 17' 4.5''$ N and $77^{\circ} 33' 48.12''$ E, respectively. Extending to an altitude of 4,700–5,745 m above sea level (a.s.l.), this site has a catchment area of 15.8 km² with 3.92% as glacier cover (Phuche glacier). The entire catchment experiences snowfall in winter. Long-term mean annual precipitation in the region recorded at valley bottom at Leh (3,500 m a.s.l.) is only 115 mm and the glacial and snow melt streams are a lifeline for the population constrained along the streams at the foothill zone. These streams finally act as a source of feed to the River Indus. Phuche stream (named after the Phuche glacier) at the sub-catchment outlet is an intermittent stream which flows only during the period of May to October. Meltwater samples for

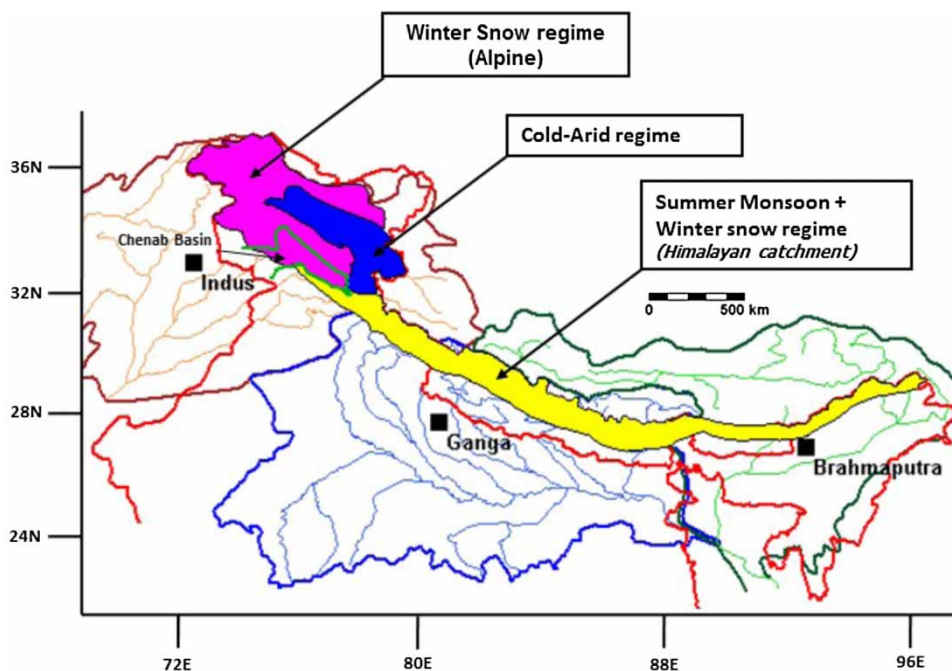


Figure 1 | Glacio-hydrological regimes of Himalaya depicting the cold-arid regime of the study area (after Thayyen & Gergan 2010).

the study were collected from the stream at South Pullu station at an elevation of 4,700 m a.s.l. (Figure 2). Geologically, the study area is part of Ladakh Batholith, which is composed of quartz bearing rocks such as quartz diorite, granodiorite, monzodiorite, monzonite and granite. Based on their SiO₂ and total alkalis portion, these rocks are classified as subalkaline granites (Upadhyay *et al.* 2008); the granites are calc-alkaline and belong to one type (Sharma & Choubey 1983; Chappell & White 2000; Jowhar 2001). A large number of basic (metavolcanics, dioritic and amphibolitic) and sedimentary (quartzite, marble, etc.) xenoliths forms the marginal part of the batholiths (Sharma & Choubey 1983).

MATERIAL AND METHODS

Sample collection and analytical techniques

Meltwater samples were collected from South Pullu station of Ganglass catchment during the period of May–September 2010. The samples were collected once daily at high flow period (1,700 h) in a 300 ml prewashed polyethylene bottle. After being taken to the laboratory in cold conditions,

electrical conductivity (EC) and pH of the water samples were measured using a portable multi-parameter meter (HACH-Sension 156). Suspended matter from the sample was removed through a filtration process using 0.45 µm Millipore membrane filters. Bicarbonate was measured by acid titration method with a semi-auto titrator (877 Titrino-plus) using 0.01M HCl as titrant and 4.6 pH as the end point. Major cations (Ca, Mg, Na and K) were analysed using atomic absorption spectroscopy (Thermal Scientific M series). The other analysis used different standard methods such as mercury (II) thiocyanate method (Florence & Farrar 1971) for chloride, brucine-sulphanilic acid method for nitrate, molybdosilicate method (APHA 2005) for dissolved silica, turbidimetric method for sulphate and ascorbic acid method (APHA 2005) for phosphate, respectively. Discharge was measured at South Pullu using the area–velocity method. Charge balance error, calculated using the formula $\{(TZ^+ - TZ^-)/(TZ^+ + TZ^-)\} \times 100$ is <10%, confirming reliability of the data.

Data analysis

The snow melt period is segregated into early snow melt (May–June), peak snow melt (July–August) and late snow melt (September) periods to evaluate the seasonal variations in the meltwater chemistry. To identify the sources and processes controlling meltwater chemistry, the data have been plotted against each other in different ways. C-ratio is the ratio of HCO₃ to (HCO₃ + SO₄), which is used to identify the major proton producing reactions, i.e., carbonation and sulphide oxidation (Brown *et al.* 1996). A ratio of 1.0 indicates weathering by carbonation reactions (Reynolds & Johnson 1972) and a ratio of 0.5 represents coupled reaction of both with proton derived from pyrite oxidation. To identify the main water types, major ion compositions were plotted on piper plot (Piper 1944) using AquaChem software. Further, the use of statistical tools like Carl Pearson correlation (significant level 0.01 and 0.05) and factor analysis have provided better understanding of the solute acquisition process in the system. R mode factor analysis has been used considering factors with eigen values >1 and indicating association between variables and factor by its loading. TDS flux has been calculated using the discharge and TDS data of meltwater, while cation weathering rate for

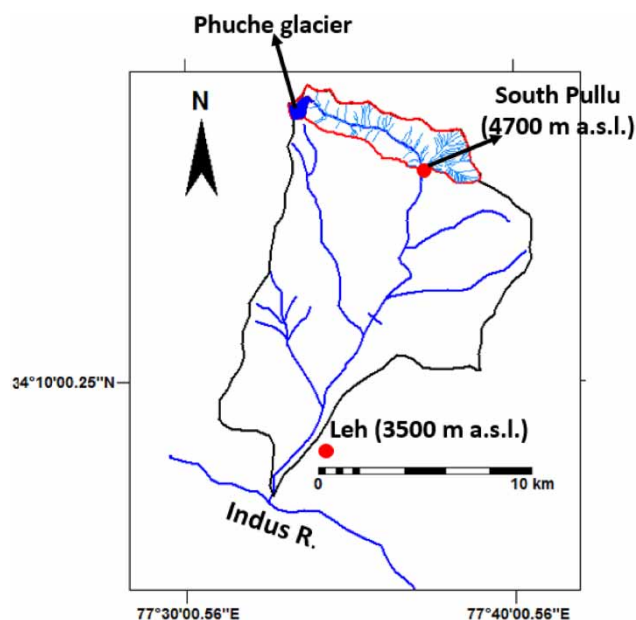


Figure 2 | Study area map showing location of sampling site at South Pullu station (Source: Thayyen & Dimri 2014).

the catchment has been calculated using dissolved cations concentration (Ca, Mg, Na and K), discharge data and catchment area (Singh & Hasnain 1998; Singh et al. 2014).

RESULTS AND DISCUSSION

Meltwater chemistry

Runoff in the upper Ganglass catchment is generated mainly from the snow melt. A summary of data during these periods is provided in Table 1. The slightly acidic to neutral pH

values (5.2–7.3) of the runoff resembles the snow meltwater from the Kashmir valley (Lone & Khan 2007). EC of the meltwater is highest during the late snow melt period ($50.99 \pm 23.18 \mu\text{S/cm}$), followed by early ($33.93 \pm 9.30 \mu\text{S/cm}$) and peak snow melt period ($26.15 \pm 6.19 \mu\text{S/cm}$). Ca and HCO_3 are the most dominant ions present throughout the melt period. Cation shows a similar trend of $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ for the whole melt period. The anions show a regular trend of $\text{HCO}_3 > \text{SO}_4 > \text{Cl} > \text{NO}_3 > \text{PO}_4$ for peak and late snow melt periods. A similar trend has been observed in surface water of SE Kashmir (Jeelani et al. 2011; Bhat et al. 2014). Deposition of alkaline dust causing alkalinity

Table 1 | Major ion composition of meltwater from the upper Ganglass catchment

	Early melt period 2010		Peak melt period 2010		Late melt period 2010	
	Range	Average \pm SD	Range	Average \pm SD	Range	Average \pm SD
Discharge	0.02–1.53	0.40 ± 0.49	0.93–8.46	2.15 ± 1.14	0.13–0.97	0.42 ± 0.24
EC	22.20–55.50	33.93 ± 9.30	17.60–37.0	26.15 ± 6.19	33.40–127.10	50.99 ± 23.18
pH	5.2–7.3	6.6 ± 0.29	5.3–7.0	6.2 ± 0.41	6.4–7.2	6.6 ± 0.21
Na	10–69.61	20.44 ± 13.54	8.09–52.13	19.43 ± 9.37	24.61–37.74	32.24 ± 3.75
K	6.82–25.54	12.84 ± 4.42	3.69–19.87	8.16 ± 2.84	9.69–14.97	11.73 ± 0.99
Ca	67.35–391	228 ± 75.70	94.45–243	157 ± 44.16	190–1,159	387 ± 246
Mg	25.83–72.83	42.07 ± 12.04	24.08–59.08	36.95 ± 10.52	49.33–282	82.25 ± 44.37
HCO_3	110–440	253 ± 79.29	80–290	170 ± 59.62	200–1,450	452 ± 295
PO_3	0–4.01	1.18 ± 0.74	0.44–4.36	1.36 ± 0.62	0.09–2.68	0.91 ± 0.75
SO_4	37.96–61.90	47.52 ± 7.34	41.73–60.94	49.73 ± 4.41	41.25–62.27	48.91 ± 4.56
NO_3	0.16–2.26	0.83 ± 0.47	0.16–14.52	1.37 ± 2.90	0.65–1.45	1.04 ± 0.27
Cl	8.18–14.10	10.98 ± 1.49	6.21–13.26	10.46 ± 1.55	9.59–13.26	11.45 ± 0.94
H_4SiO_4	7.96–19.09	12.94 ± 2.78	3.62–38.29	15.17 ± 7.04	2.42–43.22	27.35 ± 6.25
TZ^+	179–513	302 ± 90.63	135–340	222 ± 61.80	300–1,307	513 ± 274
TZ^-	180–494	314 ± 75.04	131–355	233 ± 61.26	261–1,506	514 ± 295
$(\text{Ca} + \text{Mg})/\text{TZ}^+$	0.60–0.92	0.88 ± 0.06	0.77–0.91	0.88 ± 0.03	0.84–0.96	0.9 ± 0.03
$(\text{Na} + \text{K})/\text{TZ}^+$	0.08–0.4	0.12 ± 0.06	0.09–0.23	0.12 ± 0.03	0.04–0.16	0.10 ± 0.03
$(\text{Ca} + \text{Mg})/(\text{Na} + \text{K})$	1.47–11.92	8.93 ± 2.50	3.33–10.70	7.56 ± 1.79	5.16–26.93	10.48 ± 5.46
Ca/Na	1.07–20.91	13.53 ± 4.45	2.91–13.66	9.07 ± 2.54	5.02–33.07	11.72 ± 6.55
Ca/Mg	1.7–6.56	5.39 ± 0.83	2.46–6.09	4.3 ± 0.65	1.69–11.42	4.71 ± 1.71
Mg/Na	0.6–3.29	2.43 ± 0.68	0.77–3.38	2.12 ± 0.58	1.60–8.78	2.53 ± 1.30
HCO_3/Na	2.15–25	15.07 ± 5.36	2.69–15.19	9.59 ± 2.81	5.30–41.38	13.71 ± 7.91
Na/Cl	1.01–5.71	1.87 ± 1.19	1.02–5.13	1.84 ± 0.84	1.98–3.56	2.83 ± 0.39
K/Cl	0.62–2.72	1.19 ± 0.44	0.41–3.20	0.80 ± 0.37	0.86–1.4	1.03 ± 0.12
C ratio	0.65–0.92	0.83 ± 0.06	0.59–0.86	0.76 ± 0.07	0.8–0.97	0.88 ± 0.04

Units: EC in $\mu\text{S/cm}$; H_4SiO_4 in $\mu\text{mol/l}$; dissolved ions, TZ^+ , TZ^- in $\mu\text{eq/l}$.

and high Ca values in the fresh snow samples of Kashmir valley has also been reported (Lone & Khan 2007).

Sources and processes controlling meltwater chemistry

Enrichment of ions in the snow meltwater has been observed within 3 m of overland flow with Ca, Mg and K showing the maximum increase of 178, 38 and 29 times, respectively (Quinton & Pomeroy 2006). Percolation, inter-flow movement and sub-surface drainage of meltwater causes its interaction with the land surface/sub-surface by the process of mineral weathering, cation exchange and biological processes, ultimately causing enrichment of base cations, silica and alkalinity. Similar processes seem to regulate the meltwater chemistry of the upper Ganglass catchment. The scatter plots of Ca + Mg v/s TZ, Ca + Mg v/s HCO_3^- , (most points falling along 1:1 line) and Na + K v/s TZ (most points falling below 1:1 line) indicate carbonate weathering in the basin as the major regulator of meltwater chemistry (Figures 3–5), as also supported by the high equivalent ratios of Ca + Mg/Na + K, Ca + Mg/TZ (Table 1). Higher average C-ratio (>0.7) throughout the melting season (Table 1) shows carbonic acid weathering as the dominant proton producer in the meltwater of the study area (Singh & Hasnain 2002). A Piper plot (Figure 6) clearly shows Ca, Mg and HCO_3^- as the major ions during all phases of melt period defining water to be Ca- HCO_3^- type. A Piper plot also shows that meltwater at the catchment outlet is Ca- HCO_3^- type throughout the melt period. Further, the high equivalent ratio of Ca/Mg (>4) throughout

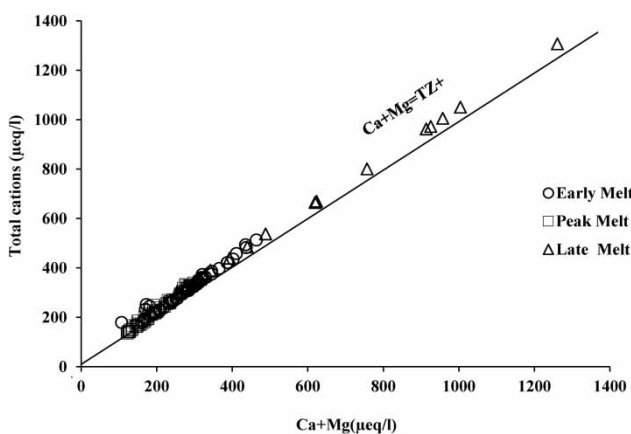


Figure 3 | Scatter plot between (Ca + Mg) and total cations (TZ^+).

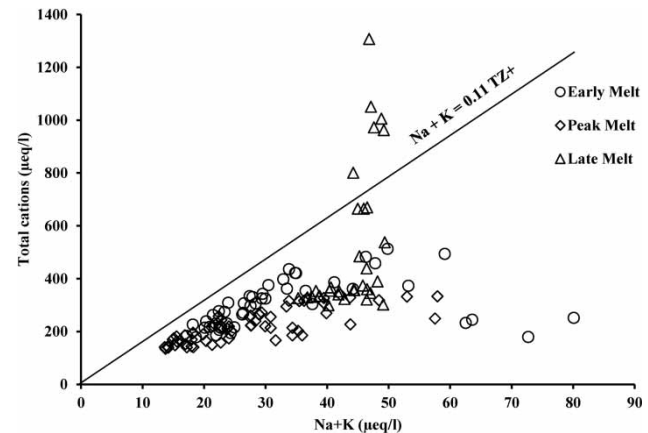


Figure 4 | Scatter plot between (Na + K) and total cations (TZ^+).

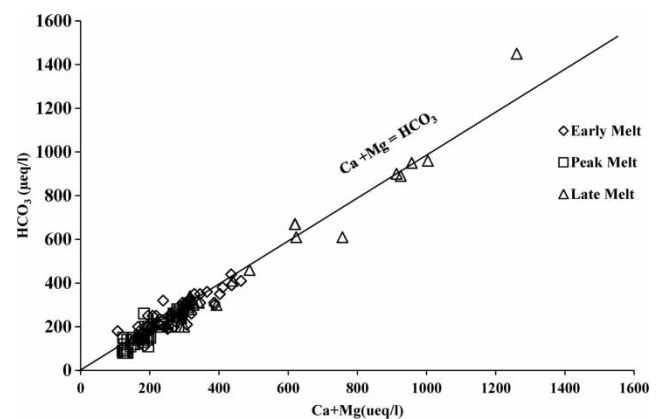


Figure 5 | Scatter plot between (Ca + Mg) and HCO_3^- .

the melt period indicates calcite weathering (Feng et al. 2012) as observed for the surface water in the SE Kashmir valley (Bhat et al. 2014). The high Ca/Na ratio can be explained as high physical weathering in steep un-vegetated slopes exposing intrinsic calcite with faster weathering potential (Clow & Sueker 2000).

In addition to weathering, atmospheric deposition in the form of alkaline dust, sea salt aerosol and SO_4/NO_3 aerosol may contribute to the solute load in snow-dominated basins (Holland 1978; Tranter et al. 1993; Quinton & Pomeroy 2006). Ratios of elements to Cl indicate the contribution of an atmospheric source to the dissolved ions in the meltwater (Pande et al. 1994; Sharma et al. 2012). The average ratio of Na/Cl and K/Cl in the present study varied from 1.8 to 2.8 and 0.8 to 1.2, respectively (Table 1). These values are

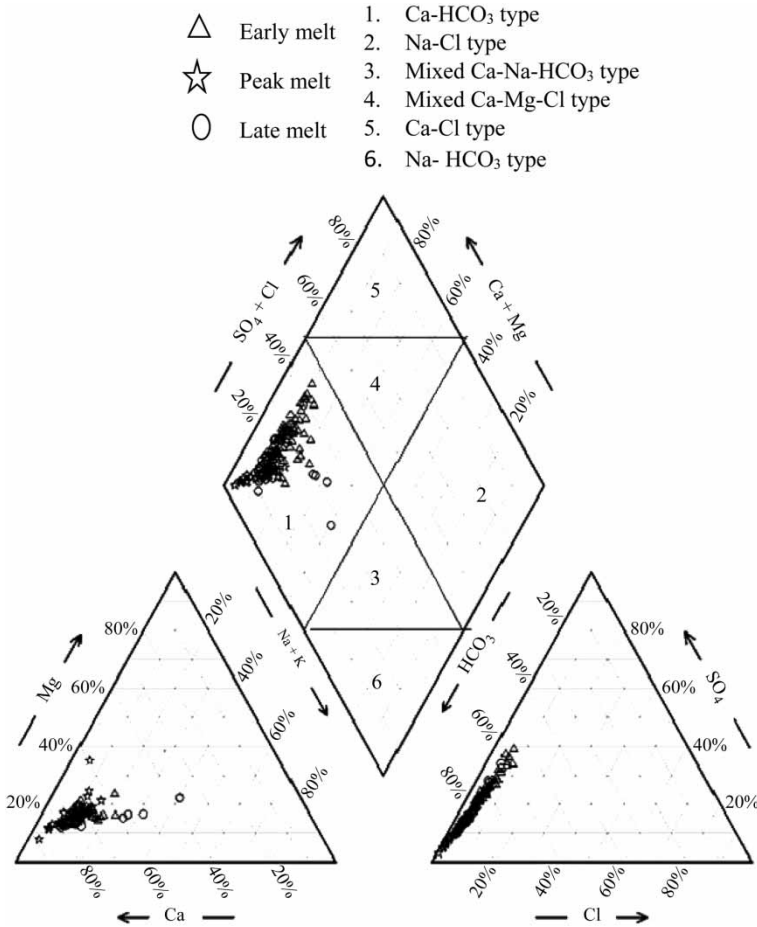


Figure 6 | Piper trilinear diagram showing hydrogeochemical characteristics of meltwater from the upper Ganglass catchment.

higher than the marine aerosol ($\text{Na}/\text{Cl} = 0.85$ and $\text{K}/\text{Cl} = 0.018$) indicating its negligible contribution to the dissolved solute budget of glacier meltwater (Kumar *et al.* 2009; Sharma *et al.* 2012). In contrast, high values of Cl have been reported in the snow samples from the Kashmir valley (Lone & Khan 2007) and low Cl in the meltwater runoff from the present study might be due to ion exchange process replacing Cl during overland flow (Quinton & Pomeroy 2006). Strong influence of alkaline dust has also been reported in some regions of the snow-covered basins of the Kashmir valley (Lone & Khan 2007). This deposition might be an additional source of solute (Ca, Na, Cl, and Mg) to the system. Stream discharge variations during the melt season also play an important role in the variation of ionic concentration in meltwater. The inverse relationship between EC and discharge (Figure 7) indicates that the

runoff in this catchment is strongly controlled by the snow and ice melting. This inverse relation is due to dilution from the snow melt as well as due to the conservative behaviour of these ions (Nagorski *et al.* 2003).

Correlation matrix (Table 2) and factor analysis (Table 3) add further insights to these results as they identify other processes in addition to carbonate weathering which are regulating the meltwater chemistry of the upper Ganglass catchment. The strong correlation between Ca, Mg, K, HCO_3 and EC with each other during the early melt period indicates the role of ion exchange process as well. Most of the catchment experiences seasonal freezing in winter with very low winter temperatures up to -27.4°C . Hence, meltwater infiltrations to the surface soil also help in seasonal thawing and enhance the residence time of snow meltwater in the catchment, which help it to acquire

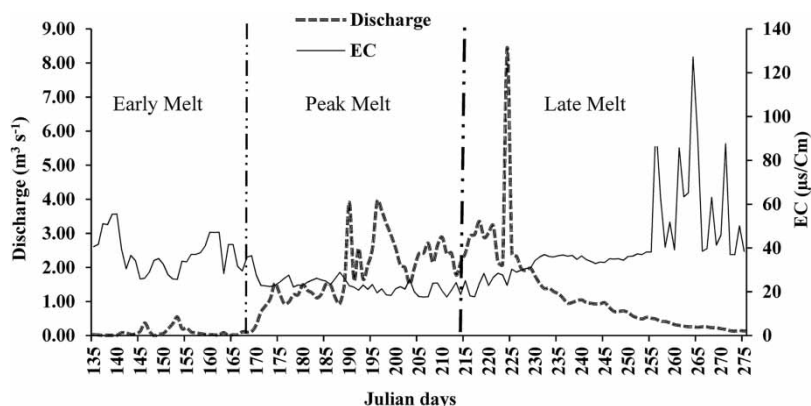


Figure 7 | Variation of EC with discharge during different melt periods.

more ions. The significant negative correlation of SO_4 with EC, cations and HCO_3 suggests inputs from multiple sources (Khadka & Ramanathan 2013). Atmospheric deposition of SO_4 from burning of coal and oil for winter-time heating might be the other possible source. During the peak melt period, all the major cations were showing significant correlation with each other suggesting input from combined carbonate/silicate weathering and ion exchange process (Oinam et al. 2012). Significant correlation of silica with all major cations and HCO_3 indicates weathering of aluminosilicate minerals (Singh et al. 2011). The correlation matrix shows the dominance of carbonate weathering during the late melt period. In the factor analysis, the early melt period explains 76% of the total variance with four major factors showing an eigen value >1 . Factor 1 with very high loading (>0.8) of K, Ca, Mg, HCO_3 and EC explains about 43% of variance indicating carbonate weathering followed by ion exchange processes. Factor 2 (12% of variance) shows high loading of silica and PO_4 indicating silicate weathering along with phosphorite leaching or anthropogenic contribution (Singh et al. 2014). Factor 3 (10.6% variance) with high loading of Na and Cl suggests deposition of sea salt aerosol. For the peak melt period, a total of three factors explaining 68% of the total variance have been identified. Factor 1 (47.5% variance) has high loading of Na, K, Ca, Mg, silica, Cl, HCO_3 and EC explaining carbonate and silicate weathering along with some atmospheric deposition. Factor 2 (11.3% variance) with high loading of NO_3 and pH shows atmospheric deposition (Singh et al. 2014), while factor 3 (9.4%) with high loading of PO_4 and SO_4 shows

an anthropogenic contribution (Anshumali & Ramanathan 2007). The late melt period identifies four factors explaining 66% of the total variance. Factor 1 (33% of variance) shows high loading of Na, Ca, Mg, HCO_3 and EC indicating the contribution from carbonate weathering and ion exchange process. Factor 2 (13% of variance) with high loading of Na, silica and SO_4 suggests sulphide oxidation coupled with silicate weathering. Factor 3 (10.9% of variance) with a high loading of K and silica indicates silicate weathering. Factor 4 (9% of variance) with a strong loading of PO_4 and Cl shows the anthropogenic and atmospheric contribution. Thus, the overall factors for the melt period can be grouped as carbonate and silicate weathering, ion exchange process and atmospheric deposition (alkaline dust, anthropogenic pollutants and sea salt aerosol). The atmospheric deposition can be linked to significant snow fall (which persisted until June 22, 2010) observed in the basin causing a higher accumulation of snow.

Seasonal variation of major ions

There was a pronounced intra-annual variation in the meltwater chemistry with maximum ionic concentration observed during the late snow melt period, while the peak melt period was recorded with minimum ion concentration (Table 1, Figure 8). Higher storage during the early and late ablation causes water to interact with rock, thus becoming chemically enriched (Singh et al. 2006). A within stream process during the late stage might be the other reason for ion enrichment due to increased exposure of stream water to

Table 2 | Correlation matrix of measured parameters for the upper Gangglass catchment during early melt period, peak melt period and late melt period of 2010

	EC	pH	Na	K	Ca	Mg	H ₄ SiO ₄	PO ₄	SO ₄	NO ₃	Cl	HCO ₃
Early melt period												
EC	1.00											
pH	0.07	1.00										
Na	0.02	-0.01	1.00									
K	0.75**	0.13	0.17	1.00								
Ca	0.98**	0.04	-0.09	0.73**	1.00							
Mg	0.95**	0.06	0.31*	0.75**	0.90**	1.00						
H ₄ SiO ₄	0.37**	0.06	0.01	0.07	0.36*	0.39**	1.00					
PO ₄	0.23	-0.12	0.24	0.20	0.14	0.30*	0.28	1.00				
SO ₄	- 0.62**	0.19	0.22	- 0.51**	- 0.65**	- 0.51**	-0.12	-0.04	1.00			
NO ₃	0.26	-0.12	-0.04	0.22	0.28	0.23	0.18	0.08	-0.38*	1.00		
Cl	0.16	-0.21	0.19	0.09	0.17	0.24	0.04	-0.15	0.01	-0.11	1.00	
HCO ₃	0.91**	0.00	-0.02	0.70**	0.88**	0.84**	0.36*	0.27	- 0.66**	0.32*	0.04	1.00
Peak melt period												
EC	1.00											
pH	-0.08	1.00										
Na	0.75**	-0.11	1.00									
K	0.61**	-0.02	0.49**	1.00								
Ca	0.93**	-0.10	0.63**	0.50**	1.00							
Mg	0.93**	-0.23	0.73**	0.55**	0.87**	1.00						
H ₄ SiO ₄	0.76**	-0.02	0.60**	0.50**	0.65**	0.77**	1.00					
PO ₄	-0.28*	0.10	-0.13	-0.02	-0.38**	-0.36**	-0.20	1.00				
SO ₄	0.12	0.02	0.17	0.09	0.14	0.06	0.03	0.04	1.00			
NO ₃	0.07	0.27*	-0.06	0.01	0.13	-0.01	-0.09	0.06	0.01	1.00		
Cl	0.51**	0.07	0.39**	0.18	0.48**	0.50**	0.39**	-0.23	0.04	0.16	1.00	
HCO ₃	0.91**	-0.11	0.63**	0.59**	0.90**	0.85**	0.64**	-0.33**	0.18	0.02	0.47**	1.00
Late melt period												
EC	1.00											
pH	0.33	1.00										
Na	0.53**	-0.01	1.00									
K	0.12	0.01	0.17	1.00								
Ca	0.99**	0.33	0.50**	0.11	1.00							

(continued)

Table 2 | continued

	EC	pH	Na	K	Ca	Mg	H ₄ SiO ₄	PO ₄	SO ₄	NO ₃	Cl	HCO ₃
Mg	0.55**	0.02	0.35*	0.14	0.52**	1.00						
H ₄ SiO ₄	0.19	-0.03	0.35*	0.21	0.17	0.16	1.00					
PO ₄	-0.08	0.07	-0.13	0.01	-0.09	-0.06	0.00	1.00				
SO ₄	0.04	-0.19	0.31	-0.01	0.04	0.16	0.19	0.02	1.00			
NO ₃	-0.03	-0.14	-0.01	-0.13	-0.02	-0.26	-0.02	-0.08	0.24	1.00		
Cl	0.31	0.07	0.06	0.01	0.32	0.15	0.08	0.08	0.01	0.09	1.00	
HCO ₃	0.99**	0.34	0.47**	0.12	0.99**	0.54*	0.13	-0.11	0.01	0.02	0.32	1.00

**Correlation is significant at the 0.01 level.

*Correlation is significant at the 0.05 level.

calcareous sediment during low flow (Teare 1998; Quinton & Pomeroy 2006). Low EC during peak melt period reflects its dilution from high snow melting (Marsh & Pomeroy 1999). During the peak snow melt period, the snow line receded to higher altitudes and a large snow cover area contributed to the peak catchment runoff. During 2010, the discharge from the upper Ganglass catchment varied from 0.4 to 2.15 m³s⁻¹ with 81.5% of the annual discharge occurring in the months of July and August alone. Consequently, snowmelt water had a lesser residence time in the catchment leading to the dilution of stream flow chemistry. There seems to be significant ground ice melt contribution in the Ganglass catchment discharge, sourced from the periglacial zones located close to the glacier. During the late melt season, snow cover over this periglacial zone decreases, exposing the ground ice for melting which contributes to the significantly higher ionic pulses during this period (Figure 7). This has been reflected in distinctly different meltwater chemistry during the late melt period, as evident in Figures 3–5, showing significant increases in the concentration of Ca, Mg and HCO₃. However, a similar increase is not observed in Na + K (Figure 4), suggesting dominant carbonate weathering and prolonged residence time of water in the ground, underlining the contributions from ground ice melt in the catchment.

Total dissolved solids flux and cationic denudation rate

The average TDS flux calculated for the early, peak and late melt period for the upper Ganglass catchment is 0.64 t day⁻¹, 3.02 t day⁻¹ and 1.31 t day⁻¹, respectively. This is much lower when compared with TDS flux from glaciers in the monsoon regime. For example, Gangotri glacier has TDS flux of 310.9 t day⁻¹, 325.3 t day⁻¹ and 113.4 t day⁻¹ for the pre-monsoon, monsoon and post-monsoon season, respectively, and the value ranges from 2.77 to 31.32 t day⁻¹ for Dokirani glacier (Hasnain & Thayyen 1999; Singh et al. 2014). This significant difference between the monsoon and cold-arid regime (present study) is due to the smaller glacial area as well as very low precipitation in the latter system, resulting in low discharge (0.4–2.15 m³s⁻¹), and hence, lower TDS flux. Compared to this, monsoon systems experience much higher discharge ranging between 23.3 and 82.5 m³s⁻¹ for Gangotri glacier

Table 3 | Factor analysis of meltwater from the upper Ganglass catchment for the melt periods of 2010

Variables	Early melt period					Peak melt period					Late melt period				
	Factor 1	Factor 2	Factor 3	Factor 4	Communalities	Factor 1	Factor 2	Factor 3	Communalities	Factor 1	Factor 2	Factor 3	Factor 4	Communalities	
EC	0.97	0.16	0.01	0.01	0.96	0.98	0.04	-0.03	0.95	0.98	0.01	0.05	0.06	0.97	
pH	0.10	-0.04	-0.07	0.93	0.87	-0.11	0.74	0.16	0.59	0.38	-0.53	0.04	0.20	0.47	
Na	0.00	0.37	0.76	0.03	0.71	0.80	-0.10	0.16	0.67	0.55	0.51	0.21	-0.18	0.64	
K	0.82	0.08	0.10	0.10	0.70	0.67	-0.03	0.34	0.56	0.09	0.16	0.62	0.07	0.42	
Ca	0.97	0.07	-0.07	-0.03	0.94	0.92	0.07	-0.15	0.87	0.98	-0.01	0.02	0.06	0.96	
Mg	0.91	0.26	0.25	0.01	0.97	0.94	-0.10	-0.15	0.92	0.59	0.14	0.37	-0.09	0.51	
H ₄ SiO ₄	0.29	0.54	-0.06	0.02	0.38	0.80	-0.06	0.00	0.64	0.17	0.54	0.40	0.13	0.49	
PO ₄	0.09	0.84	0.12	-0.09	0.74	-0.31	0.09	0.73	0.63	-0.18	-0.03	0.18	0.83	0.75	
SO ₄	- 0.70	0.06	0.39	0.34	0.76	0.19	0.03	0.57	0.37	0.05	0.76	-0.13	0.05	0.60	
NO ₃	0.27	0.28	-0.43	-0.37	0.47	0.03	0.80	-0.05	0.64	0.01	0.38	-0.74	0.08	0.70	
Cl	0.23	-0.38	0.66	-0.35	0.75	0.55	0.34	-0.30	0.51	0.37	0.04	-0.22	0.57	0.51	
HCO ₃	0.90	0.23	-0.12	-0.07	0.89	0.92	0.01	-0.05	0.85	0.98	-0.04	0.01	0.04	0.96	
Eigen value	5.16	1.48	1.27	1.22		5.70	1.36	1.13		3.99	1.60	1.31	1.09		
% of variance	43.01	12.34	10.60	10.13		47.51	11.33	9.44		33.28	13.32	10.92	9.12		
% of cumulative variance	43.01	55.35	65.95	76.08		47.51	58.84	68.28		33.28	46.60	57.52	66.63		

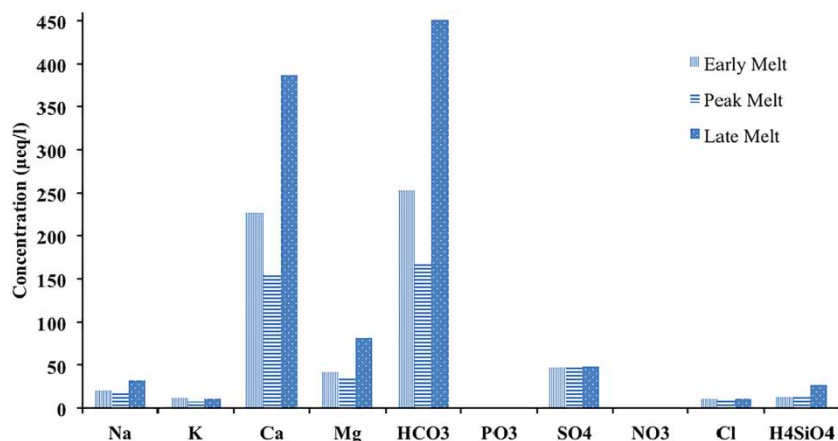


Figure 8 | Bar diagram showing variation of dissolved solutes during different phases of melting period 2010 in the upper Ganglass catchment.

(Ramanathan 2010) and $2.4\text{--}8.4\text{ m}^3\text{s}^{-1}$ for Dokirani glacier (Kumar et al. 2014). In the Ganglass catchment, the high TDS flux despite the low TDS during the peak melt period is attributed to high discharge during this period (Singh et al. 2014; Yde et al. 2014).

Cation weathering rate in the upper Ganglass catchment is $778\text{ meq m}^{-2}\text{ a}^{-1}$, which is within the range of reported values ($660\text{--}4,200\text{ meq m}^{-2}\text{ a}^{-1}$) for the Himalayan glacial basin (Hodson et al. 2002). The significantly higher values of cation weathering rate in glaciers like Dokirani (Table 4) are the result of higher discharge from the monsoonal effect (Hodson et al. 2002). It has been reported that there is more intense weathering in a glaciated catchment compared to a non-glaciated one (Reynolds & Johnson

1972; Collins 1979). The lower glacierized area (Table 4) leads to lower weathering in the present study. The geology of the basin is composed of quartz bearing rocks (quartz, diorite, granodiorite, monzodiorite, monzonite, granite) adding further resistance to weathering.

Snow versus glaciated catchment

Not much research has been done to distinguish between glacier and snow cover contribution to the discharge and ion concentration in the runoff of Himalayan basins, leading to misrepresentation of snow melt contribution as glacier melt (Jeelani et al. 2012). In this context, the present study represents the hydrochemical comparison of a snow-

Table 4 | Cation denudation rates of the upper Ganglass catchment and comparison with other glacier basins

Glacier	Study period	Catchment area (km ²)	Glacierized area (%)	Cation denudation rate (meq m ⁻² a ⁻¹)	Solute flux (t day ⁻¹)	Reference
Chhota Shigri	1987	40	25	660	17 July to 17 August	Hasnain et al. (1989)
Dokirani	1994	15.7	44.6	4,160	2.77–31.32	Hasnain & Thayyen (1999)
Batura	1999		48	1,600		Hodson et al. (2002)
Haut	1990	11.7	54	640–685		Sharp et al. (1995)
Glacier de Tsijiore Nouve				508		Souchez & Lemmens (1987)
Gornergletscher	1978–1979			454		Collins (1983)
Upper Ganglass catchment	2010	15.8	1.6	778	0.64–3.02	Present study

dominated basin with a glacier-dominated basin, as shown in Table 5. The biggest difference observed here is the lower ionic concentration of the meltwater from the snow-fed catchment during the major period of the melting season. Second is the higher ionic concentration of snow meltwater reported during the late melt period. In monsoon glacial systems, this occurred either during the early melt period or during the peak melt period (Table 5). A comparison of major cation (Ca) and anion (HCO_3) reveals this characteristic difference. It is also noted that the lowest elemental concentration of the snow-dominated system is lower than the glacier system except for a few exceptions. However, other hydrochemical characteristics of both systems look very similar. Both the systems have a dominance of Ca, HCO_3 and SO_4 as the dominant ion (Singh *et al.* 1998; Hasnain & Thayyen 1999; Ahmad & Hasnain 2009; Kumar *et al.* 2009) and equivalent ratios of $\text{Ca} + \text{Mg}/\text{TZ}^+$ (0.8–0.9) and $\text{Na} + \text{K}/\text{TZ}^+$ (0.1–0.12) are similar to different glaciers (Singh & Hasnain 1998; Kumar *et al.* 2009). A Piper plot also indicates similar results for snow and glacier dominant systems. The glacier as well as the snow system produces dilute waters but the glacier system has a higher component of subglacial flows, which is chemically enriched due to higher residence time and close contact with high sediment load, resulting in higher ionic concentration of glacier waters.

CONCLUSIONS

The present study has been conducted in the Ladakh cryospheric system (cold-arid glacio-hydrologic regime of Himalaya), making the study unique in its kind as very few studies are reported from this system. The entire catchment experiences snowfall in winter and snow melt acts as the major water source in the catchment in summer months. Meltwater is slightly acidic to neutral with Ca and HCO_3 as the major ions throughout the melt period. The high ionic ratios of $(\text{Ca} + \text{Mg})/\text{TZ}^+$ and $(\text{Ca} + \text{Mg})/(\text{Na} + \text{K})$ with low ratio of $(\text{Na} + \text{K})/\text{TZ}^+$ indicates solute enrichment of snow meltwater by interacting with rock through the process of carbonate weathering followed by silicate weathering. Further dominance of carbonate weathering over silicate weathering in this catchment has been suggested by a correlation matrix

Table 5 | Comparison of major ions chemistry of the upper Ganglax catchment with other glaciers

	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Reference
Dokirani Glacier								
Pre-monsoon	262–608	40–117	23–65	45–73	159–397	160–418	2–24	Hasnain & Thayyen (1999)
Monsoon	236–1,941	31–80	12–36	41–128	128–1,053	85–1,140	1–12	
Post-monsoon	234–593	37–107	20–57	40–68	168–384	137–431	1–7	
Gangotri Glacier								
Pre-monsoon	153–478	160–368	26.2–98.8	36.9–80.7	169–300	300–698	0.34–32.9	Singh <i>et al.</i> (2014)
Monsoon	58–470	57.1–360	21.3–91.7	8.21–96.4	100–296	110–901	0.56–40.6	
Post-monsoon	170–429	164–336	32.2–88.3	32.8–81.8	150–283	323–239	2.54–32.4	
Ganglax catchment								
Early melt period	67.35–391	25.83–72.83	10–69.61	6.82–25.54	110–440	37.96–61.90	8.18–14.10	Present study
Peak melt period	94.45–243	24.08–59.08	8.09–52.13	3.69–19.87	80–290	41.73–60.94	6.21–13.26	
Late melt period	190–1,159	49.33–282	24.61–37.74	9.69–14.97	200–1,450	41.25–62.27	9.59–13.26	

Units are in $\mu\text{eq/l}$.

(very strong correlation ($r > 0.7$)) between Ca and HCO_3^- , factor analysis and Piper diagram. Low NO_3^- and Cl concentrations in the meltwater runoff from the cold-arid catchment of Ladakh suggest either a minor contribution from atmospheric sources or its retention in the watershed. Variation in the concentration of most of the dissolved solutes has been noted during early, peak and late melt periods. The discharge–EC relationship clearly shows their inverse relationship for all phases of melt period. The EC along with other dissolved solutes are lowest for the peak melt period suggesting the overwhelming contribution of snowmelt with lower residence time in contact with the rock/sediment. Significantly higher EC during the late melt period indicates higher rock water interaction and probable ground ice melt contribution during this period. The marked variation in EC throughout the melt period highlights the significance of data generation during the whole melting season even in the cold-arid system. The cation denudation rate of the cold-arid regime is found to be $778 \text{ meq m}^{-2} \text{ Yr}^{-1}$ which is significantly lower than the values reported from the monsoon regime, with values as high as $4,160 \text{ meq m}^{-2} \text{ Yr}^{-1}$. Intra-annual variation in the TDS flux ($0.64\text{--}3.12 \text{ ton day}^{-1}$) is mainly controlled by discharge. The low denudation rate and TDS flux in the upper Ganglax catchment as compared to other glacial basins shows a significant difference between snow–glacial processes. Indications of the contribution of ground ice melt in the cold-arid system runoff that emerged in this study requires in-depth study in the future.

ACKNOWLEDGEMENTS

This work has been supported by the Department of Science and Technology (DST) and Council of Scientific and Industrial Research (CSIR). The authors are grateful to SES, Jawaharlal Nehru University for providing the required analytical facility. Thanks also to the Director NIH for his support and encouragement. Assistance by Shailesh for plotting the Piper diagram and help from Parmindra Ola and Naveen Pandey during analysis work is also acknowledged. The authors sincerely thank the two anonymous reviewers for their very constructive and useful comments.

REFERENCES

- Ahmad, S. & Hasnain, S. I. 2001 Chemical characteristics of stream draining from Dudu glacier: an Alpine meltwater stream in Ganga Headwater, Garhwal Himalaya. *J. China Univ. Geosci.* **12** (1), 75–83.
- Anshumali & Ramanathan, A. L. 2007 Seasonal variation in the major ion chemistry of Pandoh Lake, Mandi district, Himachal Pradesh, India. *Appl. Geochem.* **22** (8), 1736–1747.
- APHA 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. American Public Health Association, Washington, DC, USA.
- Arora, M., Kumar, R., Kumar, N. & Malhotra, J. 2014 Assessment of suspended sediment concentration and load from a large Himalayan glacier. *Hydrol. Res.* **45** (2), 292–306. DOI:10.2166/nh.2013.129.
- Bahadur, J., Murthy, A. S., Lal, V. B. & Das, M. C. 1978 Snow and glacier contribution in a western Himalayan catchment. In: *Proc. Int. Symp. on Computation of the Runoff from Glaciers and Glacierised Areas*, Tbilisi, USSR.
- Bhat, N. A., Jeelani, G. H. & Bhat, M. Y. 2014 Hydrogeochemical assessment of groundwater in karst environments, Bringi watershed, Kashmir Himalayas, India. *Curr. Sci.* **106** (7), 1000–1007.
- Brown, G. H., Tranter, M. & Sharp, M. 1996 Subglacial chemical erosion: seasonal variations in solute provenance, Haut Glacier d'Arolla, Valais, Switzerland. *Ann. Glaciol.* **22**, 25–31.
- Chappell, B. & White, A. J. R. 2001 Two contrasting granite types: 25 years later. *Aust. J. Earth Sci.* **48** (4), 489–499.
- Clow, D. W. & Mast, M. A. 1995 Composition of precipitation, bulk deposition, and runoff at a granitic bedrock catchment in the Loch Vale Watershed, Colorado, USA. In: *IAHS Publications-Series of Proceedings and Reports-Intern. Assoc. Hydrological Sciences* 228, 235–242.
- Clow, D. W. & Sueker, J. K. 2000 Relations between basin characteristics and stream water chemistry in alpine/subalpine basins in Rocky Mountain National Park, Colorado. *Water Resour. Res.* **36** (1), 49–61.
- Collins, D. N. 1979 Hydrochemistry of meltwaters draining from an alpine glacier. *Arct. Antarct. Alp. Res.* **11** (3), 307–324.
- Collins, D. N. 1983 Solute yield from a glacierised high mountain basin. In: *Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships* (B. W. Webb, ed.). International Association of Hydrological Sciences Publication 141. IAHS Press, Wallingford, UK, pp. 41–49.
- Feng, F., Li, Z., Jin, S., Dong, Z. & Feiteng, W. 2012 Hydrochemical characteristics and solute dynamics of meltwater runoff of Urumqi Glacier No. 1, eastern Tianshan, northwest China. *J. Mt. Sci.* **9** (4), 472–482.
- Florence, T. M. & Farrar, Y. J. 1971 Spectrophotometric determination of chloride at the parts-per-billion level by the Mercury (II) thiocyanate method. *Anal. Chim. Acta* **54** (2), 373–377.

- Hasnain, S. I. & Thayyen, R. J. 1999 Discharge and suspended-sediment concentration of meltwaters, draining from the Dokriani glacier, Garhwal Himalaya, India. *J. Hydrol.* **218**, 191–198.
- Hasnain, S. I., Subramanian, V. & Dhanpal, K. 1989 Chemical characteristics and suspended sediment load of meltwaters from a Himalayan glacier in India. *J. Hydrol.* **106** (1), 99–108.
- Hodson, A., Porter, P., Lowe, A. & Mumford, P. 2002 Chemical denudation and silicate weathering in Himalayan glacier basins: Batura Glacier, Pakistan. *J. Hydrol.* **262**, 193–208.
- Holland, H. D. 1978 *The Chemistry of Atmosphere and Ocean*. John Wiley, New York, USA.
- Jeelani, G. H., Bhat, N. A., Shivanna, K. & Bhat, M. Y. 2011 Geochemical characterization of surface water and spring water in SE Kashmir Valley, western Himalaya: implications to water–rock interaction. *J. Earth Syst. Sci.* **120** (5), 921–932.
- Jeelani, G., Feddema, J. J., Veen, C. J. & Stearns, L. 2012 Role of snow and glacier melt in controlling river hydrology in Liddar watershed (western Himalaya) under current and future climate. *Water Resour. Res.* **48**, W12508. DOI:10.1029/2011WR011590.
- Jones, N. & Parker, C. 2015 Water quality in two Icelandic rivers: the influence of impoundment, agriculture, glaciation and permafrost. *Hydrol. Res.* **46** (3), 429–445. DOI:10.2166/nh.2014.268.
- Jowhar, T. N. 2001 Geobarometric constraints on the depth of emplacement of granite from the Ladakh batholith, Northwest Himalaya, India. *J. Miner. Petrol. Sci.* **96**, 256–264.
- Kaser, G., Grobhauser, M. & Marzeion, B. 2010 Contribution potential of glaciers to water availability in different climate regimes. *Proc. Nat. Acad. Sci.* **107** (47), 20223–20227.
- Khadka, U. R. & Ramanathan, A. L. 2013 Major ion composition and seasonal variation in the Lesser Himalayan lake: case of Begnas Lake of the Pokhara Valley, Nepal. *Arab. J. Geosci.* **6** (11), 4191–4206.
- Kumar, K., Miral, M. S., Joshi, S., Pant, N., Joshi, V. & Joshi, L. M. 2009 Solute dynamics of meltwater of Gangotri glacier, Garhwal Himalaya, India. *Environ. Geol.* **58** (6), 1151–1159.
- Kumar, A., Verma, A., Dobhal, D. P., Mehta, M. & Kesarwani, K. 2014 Climatic control on extreme sediment transfer from Dokriani Glacier during monsoon, Garhwal Himalaya (India). *J. Earth Syst. Sci.* **123**, 109–120.
- Liu, Z. F. & Yao, Z. J. 2016 Contribution of glacial melt to river runoff as determined by stable isotopes at the source region of the Yangtze River, China. *Hydrol. Res.* **47** (2), 442–453. DOI:10.2166/nh.2015.089.
- Lone, F. A. & Khan, M. A. 2007 Himalayan snow chemistry: chemical composition of fresh snow samples from Kashmir valley. *Curr. World Environ.* **2** (1), 17–20.
- Marsh, P. & Pomeroy, J. W. 1999 Spatial and temporal variations in snowmelt runoff chemistry, Northwest Territories, Canada. *Water Resour. Res.* **35**, 1559–1567.
- Nagorski, S. A., Moore, J. N., Mckinnon, T. E. & Smith, D. B. 2003 Geochemical response to variable streamflow conditions in contaminated and uncontaminated streams. *Water Resour. Res.* **39** (2), 1044. DOI:10.1029/2001WR001247.
- Oinam, J. D., Ramanathan, A. L. & Singh, G. 2012 Geochemical and statistical evaluation of groundwater in Imphal and Thoubal district of Manipur, India. *J. Asian Earth Sci.* **48**, 136–149.
- Pande, K., Sarin, M. M., Trivedi, J. R., Krishnaswami, S. & Sharma, K. K. 1994 The Indus river system (India-Pakistan): Major-ion chemistry, uranium and strontium isotopes. *Chem. Geol.* **116** (3), 245–259.
- Pandey, S. K., Singh, A. K. & Hasnain, S. I. 1999 Weathering and geochemical processes controlling solute acquisition in Ganga headwater–Bhagirathi river, Garhwal Himalaya, India. *Aquat. Geochem.* **5**, 357–379.
- Piper, A. M. 1944 A graphic procedure in the geochemical interpretation of water-analyses. *Trans. Am. Geophys. Union* **25**, 914–928.
- Quinton, W. L. & Pomeroy, J. W. 2006 Transformations of runoff chemistry in the Arctic tundra, Northwest Territories, Canada. *Hydrol. Proc.* **20**, 2901–2919.
- Ramanathan, A. L. 2010 Study of Deglaciation and Associated Consequences in the Gangotri Glacier: Dye Tracer and Hydrochemical Approach. Project report submitted to Department of Science and Technology, Government of India.
- Ramanathan, A. L. 2011 *Status Report on Chhota Shigri Glacier (Himachal Pradesh)*. Himalayan Glaciology Technical Report No. 1. Department of Science and Technology, Ministry of Science and Technology, New Delhi, India.
- Reynolds, R. C. & Johnson, N. M. 1972 Chemical weathering in the temperate glacial environment of the Northern Cascade Mountains. *Geochim. Cosmochim. Acta* **36** (5), 537–554.
- Sharma, K. K. & Choubey, V. M. 1983 Petrology, geochemistry and geochronology of the southern margin of the Ladakh batholith between Upshi and Chumathang. In: *Geology of the Indus Suture Zone of Ladakh* (V. C. Thakur & K. K. Sharma, eds). Wadia Institute of Himalayan Geology, Dehra Dun, India, pp. 41–60.
- Sharma, A., Singh, A. K. & Kumar, K. 2012 Environmental geochemistry and quality assessment of surface and subsurface water of Mahi River basin, western India. *Environ. Earth Sci.* **65** (4), 1231–1250.
- Sharma, P., Ramanathan, A. L. & Pottakkal, J. G. 2013 Study of solute sources and evolution of hydrogeochemical processes of the Chhota Shigri Glacier meltwaters, Himachal Himalaya, India. *Hydro. Sci. J.* **58** (5), 1128–1143.
- Sharp, M., Brown, G. H., Tranter, M., Willis, I. C. & Hubbard, B. 1995 Comments on the use of chemically based mixing models in glacier hydrology. *J. Glaciol.* **41** (138), 241–246.
- Singh, A. K. & Hasnain, S. I. 1998 Major ion chemistry and weathering control in a high altitude basin: Alaknanda River, Garhwal Himalaya, India. *Hydrol. Process.* **43** (6), 825–843.
- Singh, A. K. & Hasnain, S. I. 2002 Aspects of weathering and solute acquisition processes controlling chemistry of sub-Alpine proglacial streams of Garhwal Himalaya, India. *Hydrol. Process.* **16** (4), 835–849.

- Singh, V. B. & Ramanathan, A. L. 2015 Assessment of solute and suspended sediments acquisition processes in the Bara Shigri Glacier meltwater (Western Himalaya, India). *Environ. Earth Sci.* DOI:10.1007/s12665-015-4584-3.
- Singh, P., Haritashya, U. K., Kumar, N. & Singh, Y. 2006 Hydrological characteristics of the Gangotri glacier, central Himalayas, India. *J. Hydrol.* **327** (1), 55–67.
- Singh, A. K., Tewary, B. & Sinha, A. 2011 Hydrochemistry and quality assessment of groundwater in part of NOIDA metropolitan city, Uttar Pradesh. *J. Geol. Soc. India* **78** (6), 523–540.
- Singh, V. B., Ramanathan, A. L., Pottakkal, J. G. & Kumar, M. 2014 Seasonal variation of the solute and suspended sediment load in Gangotri glacier meltwater, central Himalaya, India. *J. Asian Earth Sci.* **79**, 224–234.
- Singh, V. B., Ramanathan, A. L., Sharma, P. & Pottakkal, J. G. 2015a Dissolved ion chemistry and suspended sediment characteristics of meltwater draining from Chhota Shigri Glacier, western Himalaya, India. *Arab. J. Geosci.* **8**, 281–293.
- Singh, V. B., Ramanathan, A. L. & Sharma, P. 2015b Major ion chemistry and assessment of weathering processes of the Patsio Glacier meltwater, western Himalaya, India. *Environ. Earth Sci.* **73**, 387–397.
- Souchez, R. & Lemmens, M. 1987 Glacio-fluvial sediment transfer: an alpine perspective. In: *Solutes* (A. M. Gurnell & M. J. Clark eds). John Wiley and Sons, New York, USA, pp. 285–303.
- Teare, C. J. 1998 *Spatial and temporal patterns of chemical solute signals in sixteen small tundra streams of the Trail Valley Creek watershed in the western Canadian Arctic*. MSc Thesis, Department of Geography, Simon Fraser University, Burnaby, Canada.
- Thayyen, R. J. & Gergan, J. T. 2010 Role of glaciers in watershed hydrology: a preliminary study of a Himalayan catchment. *Cryosphere* **4**, 115–128.
- Thayyen, R. J. & Dimri, A. P. 2014 Factors controlling Slope Environmental Lapse Rate (SELR) of temperature in the monsoon and cold-arid glacio-hydrological regimes of the Himalaya. *The Cryosphere Discuss.* **8** (6), 5645–5686.
- Tranter, M., Brown, G. H., Raiswell, R., Sharp, M. & Gurnell, A. M. 1993 A conceptual model of solute acquisition by Alpine glacial meltwaters. *J. Glaciol.* **39**, 573–581.
- Upadhyay, R., Frisch, W. & Siebel, W. 2008 Tectonic implications of new U–Pb zircon ages of the Ladakh batholith, Indus suture zone, northwest Himalaya, India. *Terra Nova* **20**, 309–317.
- Wulf, H., Bookhagen, B. & Scherler, D. 2010 Seasonal precipitation gradients and their impact on fluvial sediment flux in the Northwest Himalaya. *Geomorphology* **118**, 13–21.
- Yde, J. C., Knudsen, N. T., Hasholt, B. & Mikkelsen, A. B. 2014 Meltwater chemistry and solute export from a Greenland Ice Sheet catchment, Watson River, West Greenland. *J. Hydrol.* **519**, 2165–2179.

First received 9 August 2015; accepted in revised form 3 December 2015. Available online 1 February 2016