ASSESSMENT OF HYDROCHEMICAL PROPERTIES AND ANNUAL VARIATION IN MELTWATER OF GANGOTRI GLACIER SYSTEM

S. Sah*, H. Bisht, K. Kumar, A. Tiwari, M. Tewari and H. Joshi

G.B Pant National Institute of Himalayan Environment and Sustainable Development Kosi-Katarmal, Almora, Uttarakhand, India

***Correspondence:** saurabhsah289@gmail.com

ABSTRACT

The aim of this study is to analyze the physicochemical parameters of melt water draining from Gangotri glacier along Baghirathi River during May-October, 2014 and 2015. A total 312 samples were collected each fortnightly in both the years. Results showed that cations and anions were found in the order Ca^{2+}> Mg^{2+}> Na^{+}> K^{+} and $SO4^{2-}$> $HCO3^{-}$>Cl^{-}>$NO3^{-}$>F^{-}> $PO4^{-}$, respectively. The ratio of (Ca+Mg)/(TZ^{+}) varied from 0.49 to 0.79 with mean value(0.63±0.18) indicating that Ca and Mg have larger contribution to the total cations. Which the elemental ratio (C+Mg)/(Na+K) ratio was also high varied from 2.10 to 3.42 with mean value (2.35±0.04) shows the dominancy of carbonate weathering in the study area on the other hand the C-ratio shows that sulphide oxidation is the major proton producing mechanism. The low Na/Cl and K/Cl ratios indicated major contribution from atmospheric perception to the observed dissolved ions of melt waters finally, study showed an increase in the concentration of cations as compared to previous studies, which could be attributed to increasing weathering rates due to temperature increase. The concentration of NO_3 and PO_4 compared to previous studies show the effect of human impact in the region.

Keywords: Atmospheric perception, Glacier melts water, Gangotri glacier, Garhwal Himalayas, Geochemical hydro-chemistry, Physicochemical parameter, Carbonate weathering.

INTRODUCTION

Himalaya is one of the important glaciated region u\outside the ice sheet of polar region. The Himalayan glacier experiences various expansion and recession during the Quaternary period (Singh *et al.,* 2016). These glacier fluctuations are directly related to climatic changes. The Indian Himalaya Mountains are the factor for controlling the meteorological and hydrological characteristics of Indian peninsular region (Bhutiyani 1999). Glaciers are mainly playing an important role in buffering stream acting as a hydrological budget (Barry *et al.,* 2000). The glacierised areas are an ideal environment to study rock water interaction and their role in changing of solute dynamics of glacier melt water. The hydrochemistry of meltwater of different glaciers are varying with surrounding lithology (Collins 1979 a). The hydro geochemical investigations of melt water draining from the glaciers are helpful to identifying the concentration and nature of solute present in the basal lithology and atmospheric input (Ramanathan 2011). Therefore the study of surrounding rock and soil is also necessary during the study of hydro chemical properties of glacier melt water. The weathering of surrounding rocks is the primary source of concentration of ions in glacier meltwater. However the secondary source of ion concentration in glacier meltwater is atmospheric precipitation (Hallet 1976).

The growing demand for fresh water in downstream stretches and geological information has made the hydro-chemical study of Himalaya glaciers highly necessary (Singh *et al.,* 2012). Ganga, Indus and Brahmaputra are three major rivers of the north India together supply near 50% ($320km^3$) of the total utilizable surface water resources of the country (690 km^3) (Srivastava 2004). Therefore the melt water Chemistry of the glacier is very important to assess impact of weathering reactions, anthropogenic and climate change impact on the water chemistry. The hydrogeo chemical studies of the Himalayan glaciers are lagging behind when compared with Alpine and Arctic glaciers due to difficulty in collection of data at higher altitudes. Despite this there are numbers of studies on hydro chemical aspect of Garhwal Himalaya glacier melt water (Haisnain *et al.*, 1996, 1999; Ahamad *et al.*, 2000; Kumar *et al.*, 2009; Trivedi *et al.*, 2010; Singh *et al.*, 2012). But no comparative study is available on dissolve ion Chemistry of the Gangotri glacier. So in this paper we have attempted to provide a preliminary hydro-chemical data for Gangotri glacier of two different years 2014 and 2015 during the whole ablation season. The present Study is aimed to determine the ion Chemistry of the glacier and evaluation of the geochemical process controlling the dissolve ion chemistry of the Gangotri glacier meltwater.

STUDY AREA

The Ganga river basin has two sub basin first one Alaknanda basin which have 407 glaciers covering an area around (1,229 km^2) and second one Bhagirathi basin which have approximately 238 glaciers covering an area around 755 km^2 (Dutt 1961; Raina *et al.,* 2011). The Bhagirathi river basin, lies in the Gangotri national park, Uttarkashi, India. The Gangotri glacier is one of the largest glacier of Indian Himalaya region covered an area around (86.32 km^2) and length approximately (30.2 km) (Singh *et al.,* 2011). It extends from ($30^0$43'10" to $30^0$55'50" N, $79^0$17'18" to $79^0$4'55" E) (Fig. 1). The Bagirathi River originates from Gaumukh, the snout of the Gangotri glacier. It is located at an elevation of about 4000 m asl. The Gangotri catchment area falls in the higher Himalayan region northern side of the Main Central Thrust. The Gangotri granite is exposed all along the upper reaches of the Bhagirathi river around the Gangotri glacier area and is the largest body of the high Himalayan Leucogranite (HHL) with an estimated age, based on geochemistry and geochronology study, of early Miocene period (~21 Ma) (Jain *et al.,* 2002). The highly sheared and crushed rocks are present nearby areas of Gangotri and Chaturangi glacier. The nearby areas of Gangotri glacier are neotectonically very active because many neo-tectonic evidences are present in that area likes deep gorges, tectonic depressions and triangular fault facets. The surface of the glacier is full of debris cover which contains fine sediment to boulder and pebble of granitic rocks. The numbers of debris cones are present both side of the Bhagirathi River formed due to slide, debris fall, rockfall and small avalanche in tributary glacier. A series of lateral moraines are present up to 2 km. downstream from the present position of snout, which indicates the various stage of recession during the historical past. The terminal moraines are also present all along the Bhagirathi valley which is now fully covered with grass also show the past position of glacier up to that height. The glacial striations in the Bhagirathi valley up to 2-3 km downstream from the snout of the glacier indicate that the retreat has been consistent in the past. In Gangotri glacier several temporary supraglacial lakes ranging from few centimeters to several meters in length were observed in the middle part of the glacier formed as a result of meeting and widening of underground glacial caves which has been induced to shrink of the glacier by allowing the ice to calve into them. The longitudinal and transverse crevasses are present on the glacier surface and also near the snout of the glacier, which are formed mainly due to unequal velocity of the glacier in the middle and marginal part. The marking on the valley walls and truncated spurs shows that once the glacier height was much higher than the present one showing that there is a tremendous thinning of the glacier.

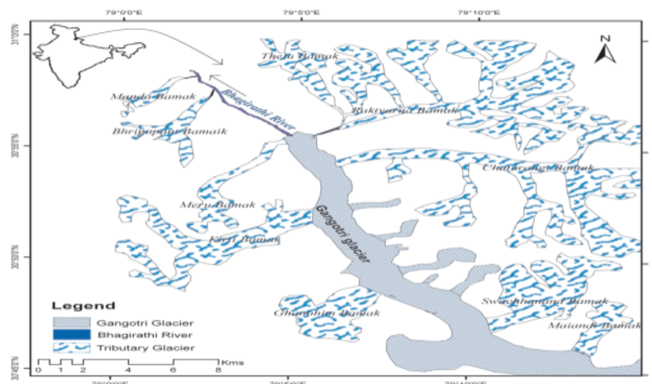

Fig.1. Location map of the study area

METHODOLOGY

Sampling technique

Gangotri melt water sampling was carried out during the monsoon (1 July-31 August), pre monsoon (1 May- 30 June) and Post Monsoon (1 September - 31 October) for two consecutive years (2014 and 2015). A total 312 samples were collected in a clean 1000 ml narrow necked polyethylene bottle following the Osterm (1975) method and analyzed for 18 physico-chemical parameters at GBPNIHESD Central

Laboratory as standard Procedures (APHA 2005). Parameters with low stability such as Electrical Conductivity (EC) and Potential of hydrogen (pH) were measured on the spot using Conductivity meter and Potentiometer respectively and the other parameter were measured in the laboratory. The turbidity (NTU) is measured by Nephelometric. Magnesium (Mg), Calcium (Ca) and Nitrate (NO_3), Fluoride (F) were measured by EDTA (0.05N) titrimetric method and Ion electrode method respectively. Bicarbonate (HCO_3) and Chloride (Cl) were measured by titration with (0.01N H_2SO_4 and 0.05N $AgNO_3$) respectively. The Sodium (Na), Potassium (K) and Sulphate (SO_4), Phosphate (PO_4) were measured through the help of flame photometer and Photometric method respectively. The total dissolved solids (TDS), Total hardness (TH) and percentage balance error (%E) were determined through the help of formula given by Dinka 2010; Raghunath 1987; Fetter 2000 respectively. Filtration of melt water samples was carried out in the field by using Whatman filter paper no 42 to determine the Total Suspended Sediment (TSS). Statistical Software SPSS 15.0 was performed to find out the weathering and geochemical processes by elemental ratio, controlling melt water chemistry and Aquachem is used for plotting piper diagram for identification of water type.

RESULTS AND DISCUSSION

The hydro-chemical characteristics of meltwater draining from Gangotri glacier (Table 1). The values of charge balance errors for Gangotri glacier melt water samples varied from 3.03-3.42 % and 2.07-5.74 % for year 2014 & 2015 respectively showing the eminence of analytical precision and results. The average ratio of EC/TDS 0.64±0.14 and (0.62±0.12) in 2014, 2015 respectively showing the reliability and quality of the analytical result. EC values of meltwater of year 2014 fluctuated from (49–62) µs/cm with mean 57.66±8.26 µs/cm similarly it lies between (50.32-79.05) µs/cm with mean 68.2±8.49 µs/cm in 2015.Whereas, pH values of 2014 contrasted between (7.42-7.89) with mean 6.65±0.7 and (3.97-6.08) with mean 4.5±0.6 in 2015, indicating acidic nature of meltwater. These value are comparable to the report (Singh *et al.,* 2012) Salinity of melt water in year 2014 varied from 55-98 ppm with mean 63.2±9.23 ppm and (110-130) ppm mean 73.2±12.36 ppm in 2015 it indicates that in year 2015 the melt water is more saline comparison to last year. The Turbidity of melt water in 2014, (165 – 275) ntu with mean 215±14.36 ntu and it ranged between (235 – 512) ntu with mean 259±23.92 ntu in 2015. Other physical parameter like TH of melt water ranged from (22 – 56) meq/l mean 48±11.3 meq/l and (29 – 100) mean (52.44±14.32) meq/l in 2014, 2015 respectively. TSS (1.45-8.49)g/l mean 5.86±3.5 g/l and (0.2- 2.35) g/l mean 0.78±0.44 g/l.

Table 1. Chemical characteristics of Gangotri glacier meltwate**r**

Parameters	Year 2014 (May-October)				Year 2015 (May-October)			
	Max	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**
EC (µs/cm)	62	49	57.66	8.26	79.05	50.32	68.2	8.49
pH	7.89	7.42	6.65	0.7	6.08	3.97	4.5	0.6
TSS (g/l)	8.49	1.45	5.864	3.5	2.35	0.2	0.78	0.44
TDS (ppm)	39.68	31.36	36.48	10	50.56	32	43.52	8
TH (mg/l)	56	22	48	11.3	100	29	52.44	14.32
Turbidity (Ntu)	375	165	215	14.36	512	235	259	23.92
Salinity	98	55	63.2	9.23	130	110	73.2	12.36
Ca^{2+} (meq/l)	0.54	0.13	0.25	0.16	2.10	0.12	0.47	0.4
Mg^{2+} (meq/l)	0.49	0.10	0.09	0.13	1.13	0.06	0.33	0.25
Na^{+} (meq/l)	0.15	0.05	0.08	0.04	0.46	0.03	0.2	0.23
K^{+} (meq/l)	0.14	0.04	0.09	0.02	0.16	0.01	0.06	0.04
SO_4^{2-} (meq/l)	0.96	0.35	0.46	0.13	5.09	1.96	3.09	1.03
HCO_3^{-} (meq/l)	0.54	0.28	0.33	0.24	1.04	0.5	0.72	0.13
Cl^{-} (meq/l)	0.12	0.004	0.03	0.07	0.30	0.10	0.25	0.04
F^{-} (meq/l)	0.02	0.005	0.01	0.03	0.03	0.008	0.014	0.003
NO_3^{-} (meq/l)	0.008	0.001	0.002	0.08	0.28	0.05	0.12	0.05
PO_4^{-} (meq/l)	0.02	0.01	0.008	0.03	0.05	0.02	0.03	0.12
TZ^{+} (meq/l)	1.55	0.48	0.65	0.19	3.20	1.65	1.76	0.22
TZ^{-} (meq/l)	1.66	0.51	0.74	0.14	3.59	1.72	1.43	0.12
(Ca+Mg)/ TZ^{+}	0.68	0.47	0.67	0.09	0.81	0.52	0.63	0.18
(Na+K)/ TZ^{+}	0.24	0.18	0.20	0.03	0.74	0.42	0.39	0.21
(Ca+Mg)/Na+K	3.65	2.65	2.10	0.06	1.19	0.69	1.12	0.08
Na/Cl	1.35	1.20	1.21	0.21	3.42	2.41	3.25	0.34
K/Cl	1.26	1.09	1.05	0.16	2.42	1.19	2.25	0.18
TDS/Ec	0.64	0.47	0.63	0.14	0.66	0.48	0.62	0.12
Ca/Na	1.82	1.13	1.54	0.36	0.76	0.41	0.69	0.12
Mg/Na	1.63	1.05	1.21	0.19	3.21	1.42	1.93	0.24
C-ratio	0.83	0.67	0.73	0.01	0.42	0.28	0.33	0.02

In dissolve chemistry, Cationic Percentage of total cation (TZ^{+}) and anionic percentage of total anion (TZ^{-}) of both year is shown in Table 2. Cationic chemistry of Gangotri glacier melt water shows Ca^{2+} major cation constituting (38.25) % of TZ^{+} and (45.33) % of TZ^{+} in 2014, 2015 respectively. Followed by Mg^{2+} (26.25%) and (33.29%) in 2014, 2015 respectively. In both year the abundances sequence of cat ion are $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$. The concentration of Ca^{2+} in melt water varied from (0.13-0.54) meq/l mean 0.25±0.16 meq/l and (0.12-2.10) meq/l with mean 0.47±0.4 meq/l in 2014, 2015 respectively. Whereas the concentration of Mg^{2+} ranged from (0.10-0.49) meq/l mean 0.19±0.13 meq/l and (0.06-1.13) meq/l mean 0.33±0.25 meq/l. Ca^{2+} concentration are increases due to carbonate weathering compare to those report (Pandey *et al.*,1999; Singh *et al.*,2012).

Table 2. Cationic and anionic percentage of Gangotri glacier melts water

S. N.	Anion Name	Anionic % of Total Anion (TZ^-)		Cation Name	Cationic % of Total Cation (TZ^+)	
		2014	**2015**		**2014**	**2015**
1	Sulphate	48.32	50.63	Calcium	38.25	45.33
2	Bi Carbonate	22.18	19.37	Magnesium	26.25	33.29
3	Chloride	12.20	10.65	Sodium	24.30	12.71
4	Nitrate	10	9.75	Potassium	12.45	9.67
5	Fluoride	5.10	7.45	-	-	-
6	Phosphate	2.20	2.35	-	-	-

Anionic chemistry of Gangotri glacier melt water shows that SO_4^{2-} major Anion constituting (48.32%) of (TZ^-) and (50.63%) of (TZ^-) in 2014, 2015 respectively, followed by HCO_3^- (22.18%) and (19.37%) in 2014, 2015 respectively. In both year the dominant sequence of anion are $SO_4^{2-} > HCO_3^- > Cl^- > NO_3^- > F^- > PO_4^-$. The concentration of SO_4^{2-} in the melt water ranged from (0.35 - 0.96) meq/l mean 0.46±0.13 meq/l. and (1.96-5.09) meq/l mean 3.09±1.03 meq/l in 2014, 2015 respectively, whereas the concentration of HCO_3^- ranged from (0.28 - 0.54) meq/l mean 0.33+0.24 meq/l and (0.05 -1.04) meq/l mean 0.72±0.13 meq/l. These values are increased due to silicate weathering compare to the report (Singh *et al.*, 2012).

The different dissolve ion in river or glacier melt water is produced by different weathering processes in parental rocks. The scatter diagrams of (Ca+Mg) versus (TZ^+) of Gangotri melt water in 2014 and 2015 (Fig. 2) shows that most of the points fall above 1:1 equiline with mean (0.67±0.09) and (0.63+0.18) in 2014,2015 respectively. The relatively high contribution of (Ca+Mg) to the (TZ^+) and high (Ca+Mg)/ (Na+K) ratio (2.10±0.6) and (1.12±0.8) in 2014, 2015 respectively, indicates that Carbonate Weathering is a major Source of dissolve ion in the melt water of Gangotri glacier. Other researchers also reported primacy of Carbonate Weathering in Garhwal Himalaya (Ahamad *et al.*, 2001; Singh *et al.*, 2012). The Scatter Plot Between (Na+k) versus TZ+ (Fig. 3) indicates that relatively small contribution of (Na+K) to the (TZ^+) and its ratio fluctuated between (0.18- 0.24) with mean (0.20±0.03) and (0.42- 0.74) mean (0.39±0.21) in 2014, 2015 respectively. Theses result shows that there is a small contribution of solutes from silicate weathering in the Gangotri glacier. These values are comparable to those reports (Singh *et al.*, 2014; Kumar *et al.*, 2009). The Scatter diagram between (Ca+Mg) versus (HCO_3+SO_4) (Fig. 4) shows that most of the points fall above 1:1 equiline. These diagram shows that Concentration of (HCO_3+SO_4) are higher than (Ca+Mg), Excess of (HCO_3+SO_4) to be balanced by Alakali Metal (Na+K) from silicate rock weathering (Khadka *et al.*, 2013; Bartarya 1993; Pandey *et al.*,1999). The scatter plot between (Ca+Mg) versus SO_4 (Fig. 5) Shows that the major samples fall above 1:1 equiline. It indicates that CaSo4 and $MgSO_4$ contribute SO_4 to the melt water of Gangotri glacier. There are two possible ways of source of SO_4 in Gangotri melt water. First dissolution of Sulphate minerals (gypsum and anhydrite) and second Sulphate ion derived from Sulphides Oxidation (Srivastava *et al.*, 2004).

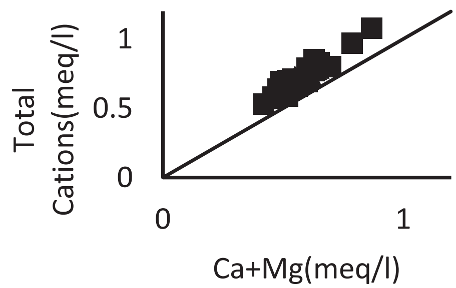

Fig. 2. Scatter plot between Ca+Mg and TZ^+

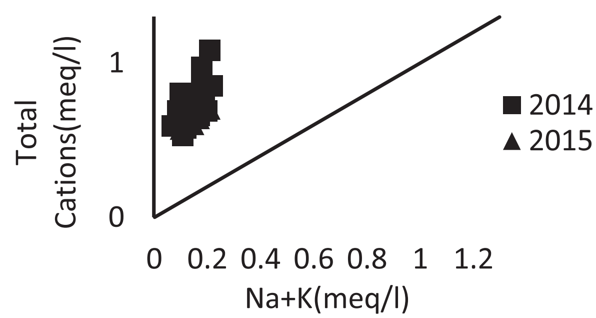

Fig. 3. Scatter plot between Na+K and TZ^+

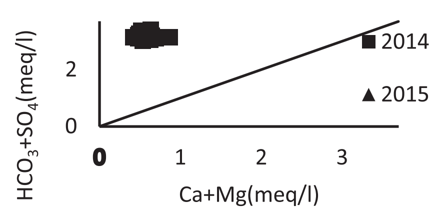

Fig. 4. Scatter plot between Ca+Mg and HCO3+SO4

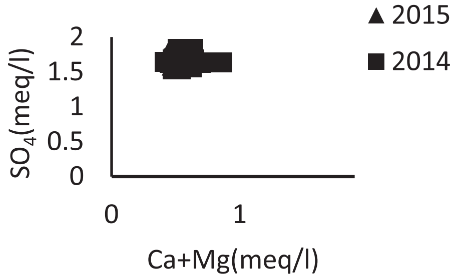

Fig. 5. Scatter plot between Ca+Mg and SO4

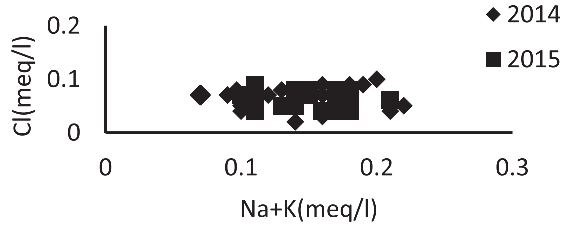

Fig. 6. Scatter plot between Na+K and Cl

In the weathering of rock-forming minerals hydrogen ion plays an important role which comes from different source (Kumar *et al.*, 2009). C-ratio is the ratio of HCO_3 to (HCO_3+SO4). It is used for evaluation of two major proton producing reaction which are oxidation of sulphides and second one is carbonation (Reynolds *et al.*, 1972). The C-ratio of value 1 indicate that reveal weathering by carbonation and if the value is 0.5 would signify coupled reaction i.e. oxidation of sulphides and carbonate dissolution and proton derived from sulphide oxidation (Brown *et al.*, 1996). The C-ratio of Gangotri melt water varied from (0.67-0.83) mean 0.73±0.01 (0.28-0.42) with mean 0.33±0.02.Which indicate that sulphide oxidation is the major Proton delivering mechanism in the Gangotri melt water.

Rock weathering and atmospheric precipitation are responsible for total dissolve ion in the glacier melt water. Rock weathering is major source but atmospheric precipitations have low contribution. The Scatter plot between (Na+K) versus Cl indicate that concentration of Na and K are too higher than cl. The Na/cl ratios ranged from (1.20-1.35) with mean 1.21±0.21 and (2.41-3.42) with mean 3.25±0.34, whereas K/Cl ratios (1.09 - 1.26) mean 1.05±0.16 and (1.19- 2.42) mean 2.25±0.18 (Fig. 6). These ratios are higher which indicates that the contributions of atmospheric precipitation are also high in the Gangotri glacier melt waters chemical characterization. The mean concentration of NO_3^- 0.11±0.08 meq/l and 0.12±0.05 meq/l in 2014, 2015 respectively. This is very low as compared to other ions indicating palatability of melt water of Gangotri glacier. Acidic No_3^- is mainly possible source of NO_3 (Tranter *et al.*, 1993). The study area is tourist places so many tourist and pilgrims come in this area so anthropogenic activities are the secondary source of No_3 in the Gangotri glacier.

Classification of hydro chemical facies based on the plotting of major ion concentration is done by piper diagram (Piper 1944).The piper trilinear diagram display that (Ca+Mg) was considerably higher than the alkali metal (Na+K), whereas on the other hand in acid, the percentage value of Strong acid (SO_4+Cl) was higher than weak acid (HCO_3) (Fig. 7). Such types of result are shown by chemical Composition of melt water draining from study area. These Piper diagram also indicate that melt water samples are of Ca-SO_4 type of water (Fig. 8).

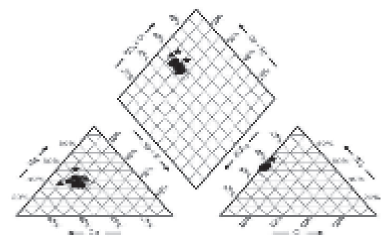

Fig. 7. Piper diagram to determine the water type in year 2014

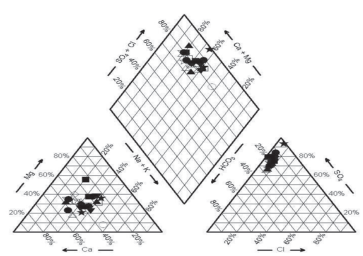

Fig. 8. Piper diagram to determine the water type in year 2015

The average chemical composition of meltwaters draining from Garhwal himalyan glaciers is given in Table 3. The Cationic chemistry of Garhwal Himalyan glaciers indicates that Ca^{2+} is major cation and Anionic chemistry indicate So_4^{2-} is the major anion in the meltwater of Dudu and Chaturangi glacier whereas, HCO_3^- is the major anion in the melt water of Stopanth–Bhagirathi Kharak and Dokrani Glaciers. Carbonate Weathering is the dominant mechanism controlling the melt water Chemistry of Garhwal Himalyan glaciers with minor contribution from silicate weathering (Ahmad *et al.*, 2000; Ahmad *et al.*, 2001; Singh *et al.*, 2012).

Table 3. Chemical characteristics of meltwater of some selected GarhwalHimalya glacier

Glacier	EC	pH	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	SO_4^{2-}	HCO_3^{-}	Cl^{-}	NO_3^{-}	References
Stopanth and BhagirathKharak	39.3	7	295	50.8	60.5	57.4	88.9	-	-	-	Chauhan *et al.*,1993
Dokriani	48.2	7	271	100	116	64	406	625	16	-	Ahmad *et al.*, 2000
Dudu	31.9	6.3	91.1	6.5	24.6	42.7	85.4	52.3	5	14.9	Ahmad *et al.*, 2001
Chaturangi	124	5.8	490	405	85.8	105	837	288	12.8	2.86	Singh *et al.*, 2014
Gangotri	62.93	5.57	360	210	70	50	1770	520	140	60	Present study

CONCLUSION

Hydro-chemistry of glacial melt waters of the Gangotri glacier was studied. The alkaline nature pH, variable TSS was seen typical of the head waters. Dissolved ion chemistry of the glacial meltwater Ca^{2+} and Mg^{2+} are dominant cation and So_4^{2-} are anion. (Ca+Mg)/TZ and (Ca+Mg)/(Na+K) ratios indicate that the carbonate weathering as a major source of dissolve ion in the Gangotri glacial melt water. There has been an increase in the concentration of cations from the past year,which may be due to increase in chemical weathering due to temperature increase in the basin. Elevated concentration of nitrates and phosphate are seen compared to previous year, the effect of human impact in the region.The scatter diagram between (Ca+Mg) versus (HCO_3+SO_4) shows that concentration of (HCO_3+SO_4) are higher than (Ca+Mg), indicating excess of (HCO_3+SO_4) to be balanced by alkali metals (Na+K) coming from silicate weathering. The elemental ratio of Na/Cl and K/Cl is very low indicating major contribution from atmospheric precipitation to the observed dissolve ion of glacial meltwaters. The c-ratio indicates that sulphide oxidation is the major proton delivering mechanism in the study area. The piper diagram (Fig. 7, 8) shows that the maximum water samples are of Ca-SO_4 type of water. These results display that carbonate and silicate weathering, dissolution of sulphate mineral and oxidation and atmospheric precipitation are the main process controlling meltwater chemistry of the study area with small contribution from anthropogenic activities.

REFRENCES

Ahmad S, Hasnain SI (2000). Meltwater Characteristics of Garhwal Himalayan glacier, *J. Geol. Soc. India*, 56: 431-439.

Ahmad S, Hasnain SI (2001). Chemical characteristics of stream draining from Duddy glacier, an Alpine meltwater stream in Ganga Headwater, Garhwal Himalaya. *J. China Univ. Geosci.*, 58: 1151-1159.

APHA (2005). Standard Methods for Examination of water and waste water. *American Public Health Association*, Washington DC, 1(1): 21-28.

Barry R, Seimon A (2000). Climatic Fluctuations in the Mountains of the Americas and Their Significance, Ambio. *Research for Mountain Area Development*, 364-370.

Bartarya SK (1993). Hydrochemistry and rock weathering in a Sub-tropical Lesser Himalaya river basin in Kumuan, *India. J. Hydrol.*, 146: 149-174.

Bhutiyani MR (1999). Mass-balance studies on Siachen glacier in the Nubra valley, Karakoram Himalaya. *India. J. Glaciol.*, 45(149): 112-118.

Brown GH, Trancer M, Sharp M (1996). Subglacial chemical erosion-seasonal variation in solute provenance, Haut glacier d'Arolla, Switzerland. *Ann. Glaciol.*, 22: 25-31

Chauhan DS, Hasnain SI (1993). Chemical, Charecterstics, solute and suspended sediments loads in meltwaters draining Satopanth and Bhagirath Kharak glaciers, Ganga Basin, India Snow and glacier Hydrology. *Proceedings of the Kathraandu Symposium*, *IAHS publication*, 218: 403-410.

Collins DN (1979a). Quantitative determination of the subglacial hydrology of two Alpine glaciers. *J. Glaciol*, 23: 347–362.

Collins DN (1979). Hydrochemistry of meltwater draining from an Alpine glacier. *Alp. Res.*, 11: 307-324.

Dinka MO (2010). Analyzing the extents of Basaka Lake Expansion, University of Natural. *Resources and Applied Life Sciences*, 1-9. Vienna, Austria.

Dutt GN (1961). The Bara Shigri glacier, Kangra District, East Punjab, India. *J Glaciol*, 3(30); 1007-1015.

Fetter CW (2000). Upper Saddle River, Prentice hall Inc., New Jersey. *Applied Hydrology*, 598.

Hallet B (1976). Deposits formed by subglacial precipitation of CaCO3, *Geol. Soc. Am. Bull.* 87: 1003–1015.

Haisnain SI, Thayyen RJ (1996). Sediment transport and solute variation in meltwaters of Dokriani Glacier (Bamak), Garhwal Himalaya, *Journal of the Geological Society of India*, 47: 731–739.

Haisnain SI, Thayyen RJ (1999). Controls of major-ion chemistry of the Dokriani glacier meltwaters, Ganga basin, Garhwal Himalaya, *Journal of Glaciology*, 45(149): 87–92.

Jain AK, Singh S, Manickavavasagam RM (2002). Himalayan Collision Tectonics, *Gondwana Research Group Memoirs*, 7: 1-14.

Khadka UR, Ramanthan AL (2013). Major ion compositon and seasonal variation in the Lesser Himalayan, lake, case of Begnas Lake of Pokhara Valley, Nepal. *Arab J. Geosci*, 6: 4191-4206.

Kumar K, Miral MS, Joshi S, Pant N, Joshi V, Joshi LM (2009). Solute dynamics of meltwater of Gangotri Glacier, GarhalHimalya, India. *Environ Geol*, 58: 1151-1159.

Osterm G (1975). Sediment transport in glacial melt water stream, Jopling AV, MC, Donald, BC (1975) Glacio-Fluvial and Glacio-lacustrine Sedimentation. *Society of Economic paleontologists and Mineralogists*, 23: 101-122.

Pandey SK, Singh AK, Hasnain SI (1999). Weathering and Geo-Chemical processes controlling Solute acquisition in Ganga Headwater-Bagirathi River, Garhwal Himaya, India, *Aquat Geo chem*, 5: 357-379.

Piper AM (1944). A graphical procedure in the geochemical interpretation of water analysis. *Trans Am Geophy union*, 25: 914-923.

Raghunath HM (1987). Groundwater. *Wiley Eastern Ltd*, New Delhi, 563-569.

Raina VK, Srivastava D (2011). Status Report on Gangotri Glacier, science and Engineering Research Board, Department of Science and Technology, New Delhi. *Himalyan Glaciology Techenical Report*, 3: 102.

Ramanathan AL (2011). Status Report on Chhota Shigri glacier (Himachal Pradesh). Department of Science and Technology, Ministry of Science and Technology, New Delhi, *Himalayan glaciology technical report no*, 1: 88.

Reynolds RC, Johnson NM (1972). Chemical weathering in the temperate glacial Environment of the Northern Cascade Mountains. *Geoc him Cosmochim Acta*, 36: 537-554.

Singh DS, Tangri AK, Kumar D, Dubey CA, Bali R (2016). Pattern of retreat and related morphological zones of Gangotri glacier, Garhwal Himalaya India. *Quaternary International Journal*, 1-10.

Singh P, Kumar A, Kishore N (2011). Meltwater Storage and dealying Characteristics of Gangotri glacier (Indian Himalayas) during ablation Season. *Hydol. Proc.*, 25: 159-166.

Singh VB, Ramanathan AL, Pottakkal JG, Kumar M (2014). Seasonal variation of the solute and suspended sediment load in Gangotri glacier meltwater, central Himalaya, India. *J Asian Earth, Syst Sci*, 79: 224-234.

Singh VB, Ramanathan AL, Pottakal JG, Sharma P, Linda A, Azam MF,Chatterjee, C (2012). Chemical Characterisation of Meltwater Draining From Gangotri Glacier, Garhwal Himalaya, India. *Journal of Earth System Science*, 121: 625-636.

Srivastava D, Absar A, Sangewar CV, Pandey SN, Obberoi LK, Siddiqui MA (2004). Chemical signatures of lithology on Gangotri Glacier meltwater and Gaumukh-Tehri dam section of Bagirathi river, proceeding of workshop on gangotri glacier, *Geological survey of india, special publ*, 80: 223-226.

Tranter M, Brown GH, Raisweii R, Sharp MJ, Gurnell AM (1993). A Conceptual model of solute acquisition by alpine glacier meltwaters. *J. Glaciol.*, 39(133): 573-581.

Trivedi S, Gopal K, Singh J (2010). Hydrogeochemical attributes of the meltwater emerging from Gangotri glacier, Uttaranchal, *Journal of the Geological Society of India*, 76: 105–110.