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RESEARCH PAPER

Assessment of hydrogeochemistry, CO_2 consumption rate and suspended sediment fluxes in the catchment of Gaglu glacier, Western Himalaya, India

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Abstract

Hydrogeochemistry of meltwater along with chemical weathering and suspended sediment transport in the glacial environment plays an important role in the assessment of meltwater quality, dissolved load, chemical weathering rate, consumption of CO_2 from the atmosphere and suspended sediment flux in the glacierized area. HCO_3^- was the abundant anion in the Gaglu glacier meltwater constituting 67.6%, 74.9%, 77.6% and 74.6% of TZ^- (total anions) during the study period 2015, 2017, 2018 and 2019, respectively. While, Ca^{2+} was the dominant cation constituting 54.2% in 2015, 55% in 2017, 57.5% in 2018 and 56.8% in 2019 of TZ^+ (total cations) in the glacial stream meltwater. High equivalent (Ca + Mg) versus TZ^+ and (Ca + Mg) versus (Na + K) ratios and low (Na + K) versus TZ^+ ratio in the meltwater for all the four years of study shows that carbonate weathering regulates stream water hydrochemistry of the Gaglu glacier followed by silicate weathering. The mean dissolved load of the Gaglu glacier was estimated to be 25.5 t/day. Carbonate weathering rate (CWR) (78.7 t/km^2/year) in the Gaglu glacier basin shows higher value with respect to silicate weathering rate (SWR) (27.4 t/km^2/year). Total CO_2 consumption rate [φCO_2] via chemical weathering (contains both carbonate and silicate weathering) in the glacier basin has been calculated to be 17.6×10^5 mol/km^2/year during the observation period July 2019. The annual CO_2 drawdown by the Gaglu glacier basin (843×10^5 mol/year) is higher in comparison to the Batal glacier basin situated in the same region (i.e. Chandra basin), which might be due to high glacial stream discharge and bigger size of the Gaglu glacier as compared to the Batal glacier. The average value of suspended sediment load (SSL) and physical weathering rate of Gaglu glacier was calculated to be 841 t/day and 6402 t/km^2/year, respectively, which shows higher value with respect to the Chhota Shigri glacier situated near the Gaglu glacier.

Keywords Hydrogeochemical attributes · CO_2 consumption rate · Annual CO_2 drawdown · Suspended sediment fluxes · Gaglu glacier

Introduction

Glaciers are one of the unique geographical attributes found on the surface of earth at high altitude and high latitude cold climatic conditions (Yu et al. 2021). They are in the dynamic state and key indicators of climate change (Benn and Evans 2014; Pandey et al. 2021). Any changes occurring in the neighbouring environment of glacier shows direct or indirect relationship with the behavioural changes of glacier (Patel et al. 2018). Glaciers are natural reservoirs of freshwater and important part of global water cycle (IPCC 2007; Rai et al. 2017). Around 41000 glaciers are reported in the Himalaya-Karakoram region (Vishwakarma et al. 2022), while Indian portion of the Himalaya is the home of nearly 9,600 glaciers with area coverage of nearly 40000 km^2 (Raina and

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Srivastava 2008). The Himalayan region contains huge mountainous system and regulates regional and global climate (Negi et al. 2016). Precipitation in the mountainous region of Himalaya is largely regulated by Western Disturbance and Indian Summer Monsoon (Yadav et al. 2021). Seasonal and monsoonal precipitation along with meltwater of Himalayan glaciers supply the overall freshwater runoff to the various Himalayan rivers (Immerzeel et al. 2010), sustaining the livelihood of downstream population (Keser et al. 2010; Ménégoz et al. 2013).

Nowadays, hydrogeochemical assessment of Himalayan glacier meltwater is very imperative due to high need of freshwater in the downstream regions (Majeed et al. 2023). It is also very useful to evaluate the chemical, physical and biological status of water bodies (Steingruber and Colombo 2006). Hydrogeochemical investigation of glacial meltwater is very important to know about the effective utilization of water resources (Gibbs 1970; Collins 1979; Hodson et al. 2000). The concentration of numerous ions in the glacial stream water is mainly influenced by rock-water interaction, atmospheric sources and lithology of the catchment area (Singh et al. 2015a; Kumar et al. 2019a; Biswal et al. 2023; Sundriyal et al. 2024). Seasonal variations in the stream runoff of the glacier also influences the concentration of numerous ions in the glacial runoff (Singh et al. 2014, 2020). In addition, meltwater quality in the glacial environment is also affected by meltwater interaction with subglacial and englacial rock minerals in the glacierized area (Zhang et al. 2019).

Weathering in the glacierized area produces significant quantity of various ions and sediment into the main river ecosystem (Biswal et al. 2023). Chemical weathering inside the glacier occurs due to the integrated interaction processes between rock, meltwater and atmosphere (Bisht et al. 2018). Intense chemical weathering has been observed below the glaciers as compared to the other terrestrial ecosystems which play an important role in the regional biogeochemical cycles (Li et al. 2022). Huge quantity of fresh reactive surface of rock has been produced by the glacier due to physical erosion causing intense weathering in the glacial environment (Roy and Sen 2023). Silicate rock weathering converts CO_2 of the atmosphere into dissolved inorganic carbon (DIC) and gets deposited as carbonic sediment into the sea (Berner 1991). DIC flux from the glacial fed Himalayan meltwater stream links the global carbon cycle, glacier weathering and atmospheric CO_2 (Shukla et al. 2020). Approximately, 0.22–0.29 Gt C/year has been removed from the atmosphere due to rock mineral weathering which is very less with respect to the anthropogenic emission to the earth atmosphere (10 Gt C/year) (Gaillardet et al. 1999; Hartmann et al. 2009; Peters et al. 2012).

Rivers fed by glaciers produce more suspended sediment than that of non-glacial fed rivers, in which the quantity and quality of sediment is mainly depend on the intensity of glacial runoff (Collins 1998; Gardner 1986; Harbor and Warburton 1992; Singh et al. 2014; Singh and Ramanathan 2018; Bisht et al. 2020). Suspended sediment budget plays a significant role in the sediment delivery and mobilization processes along with implementation of management policies on the basin scale (Collins 1996; Liu et al. 2018a). Glaciers located in the different regions of the globe have different sediment yield due to the existence of numerous types of lithology and different thermal regimes in the different glacier environments (Hallet et al. 1996). Few hydrogeochemical, CO_2 consumption rate and suspended sediment transport studies are reported in the glaciers located in the Chandra basin (Western Himalaya) (Hasnain et al. 1989; Sharma et al. 2013; Singh et al. 2015a, b; Singh 2016; Singh et al. 2020, 2017; Singh and Ramanathan 2015, 2017, 2018; Kumar et al. 2019b; Shukla et al. 2018, 2020; Biswal et al. 2023). But there are no hydrogeochemical, CO_2 consumption rate and suspended sediment fluxes studies available on the Gaglu glacier located in the Chandra basin (Western Himalaya). Keeping it in view, this study has been carried out probably first time to determine the hydrogeochemistry, CO_2 consumption rate and suspended sediment fluxes in the catchment of Gaglu glacier. This specific study aims to focus on glacial stream water chemistry, hydrogeochemical attributes, dissolved load, chemical weathering rate of carbonates and silicates, consumption of atmospheric CO_2 by chemical weathering and suspended sediment fluxes in the catchment of Gaglu glacier.

Area of study

The Gaglu glacier is a south facing high altitude glacier situated in the Chandra basin of Lahaul and Spiti region, Himachal Pradesh (Western Himalaya, India). It is a type of valley glacier and geographically covered by the coordinates of 32° 21′ 40″–32° 28′ 10″ N and 77° 20′ 40″–77°26′ 40″ E (Kurien and Munshi 1959). Total 205 glaciers are reported in the high-altitude region of Chandra basin, extending over a geographical area of 703.6 km^2 (Sangewar and Shukla 2009). The Gaglu glacier snout is covered by rock debris and located at 32° 21′ 51.45″ N and 77° 23′ 36.79″ E having elevation of about 4200 m a.s.l. Meltwater stream originates from the centrally located ice cave of glacier, which flows in south direction along a narrow valley and finally merges with Chandra river at Chatru (Kurien and Munshi 1959). The gauging site (latitude 32° 19′ 06.74″ N and longitude 77° 22′ 45.11″ E) has been used for sampling of meltwater and discharge measurement situated on the stream of Gaglu glacier at about 6.0 km downward direction from the snout of this glacier (Fig. 1). The total catchment area of Gaglu glacier till gauging site is approximately 47.96 km^2.

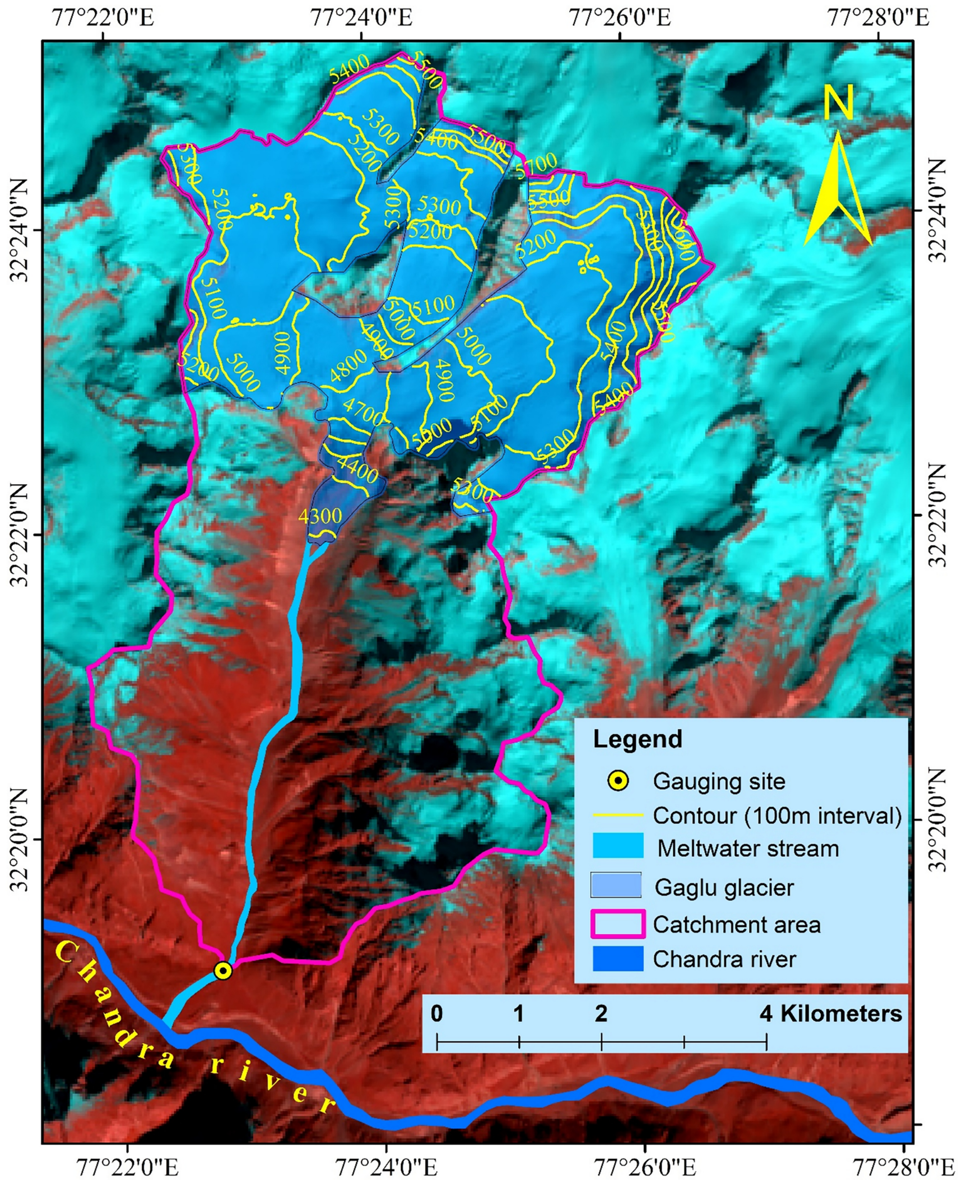

Fig. 1 Location map of the Gaglu glacier with gauging site

The climate of Chandra basin is influenced by monsoon circulation during the summer season and western disturbances during the winter season (Sharma et al. 2020). Various rock types like granite, schistose gneiss, muscovite-quartzite, augen gneiss, granite gneiss etc. have been observed in between the Chhota Shigri and nearby Bara Shigri glaciers situated in the Chandra basin near the Gaglu glacier (Kumar et al. 1987). Sutri Dhaka glacier situated near the Gaglu glacier contains several rock types such as sandstone, phyllite, limestone, shale, dolomite, quartzite etc. (Pandey and Parcha 2013; Singh et al. 2017).

Materials and methods

Meltwater samples have been collected manually in the high-density polyethylene (HDPE) sampling bottles from the gauging site of Gaglu glacier during the September month of 2015 and July month of 2017, 2018 and 2019. Before the collection of glacial meltwater samples, each HDPE bottle has been cleaned with nitric acid and then rinsed thrice with Milli-Q water. Apart from this, sampling bottles were rinsed thrice with the same glacial meltwater before the collection of stream water samples from the gauging site of Gaglu glacier (Pant et al. 2018). Portable electrical conductivity (EC) and pH meter has been used for the onsite analysis of EC and pH of glacial meltwater samples. Filtration unit with 0.45 µm Millipore membrane filter has been used for the filtration of stream water samples to separate the suspended sediment present in the meltwater samples. The collected glacial meltwater samples were stored at 4 °C in the refrigerator for the further analysis of cations and anions in the laboratory. Atomic absorption spectrophotometer (AAS) has been used for the analysis of various dissolved cations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}) in the glacial meltwater. Major dissolved anions (HCO_3^-, NO_3^- and SO_4^{2-}) have been analyzed by using standard analytical methods of APHA (2005) (acid titration method for HCO_3^-, brucine-sulphanilic acid method for NO_3^- and turbidimetric method for SO_4^{2-}). Whereas molybdo-silicate and mercury (II) thiocyanate methods have been used for the determination of dissolved silica and Cl^- in the meltwater runoff of Gaglu glacier, respectively (Florence and Farrar 1971; APHA 2005). The total dissolved solids (TDS) content in the glacial meltwater has been estimated by summation of the content of dissolved anions, cations and H_4SiO_4 measured in the meltwater. Discharge measurements of Gaglu glacier stream have been carried out only during July 2019 using velocity-area method (Singh et al. 2020). Suspended sediment concentration (SSC) in the glacial water has been calculated by drying and weighing of suspended glacier sediment gathered above the Millipore filter paper. Calculation of suspended sediment load (SSL) has been carried out by multiplying SSC and discharge of the study area, whereas computation of physical weathering rate has been carried out by dividing suspended sediment load with catchment area of the Gaglu glacier. Aquachem software has been used for plotting the Piper trilinear plot, whereas Statistical Package for Social Sciences (SPSS)-version 10.5 software has been used for statistical analysis of various hydrogeochemical parameters.

Results and discussion

Glacial stream water hydrogeochemistry

The statistical results of various analysed physicochemical variables of Gaglu glacier stream water are given in the Table 1. The precision and quality of analysed hydrogeochemical data of glacial meltwater samples has been calculated by charge balance error and found to be < 10%. It is acceptable for hydrogeochemical interpretation based on analyzed data. EC value of the Gaglu glacier stream water varies from 24.9–34.1 µS/cm with an average value of 29.0 ± 2.76 µS/cm in 2015, 16.9–27.7 µS/cm with an average value of 21.2 ± 3.26 µS/cm in 2017, 19.5–28.2 µS/cm with an average value of 24.1 ± 2.39 µS/cm in 2018 and 18.4–29.6 µS/cm with an average value of 22.8 ± 2.54 µS/

Table 1 Physico-chemical parameters analysed in the Gaglu glacier stream water

Parameters	2015				2017				2018				2019			
	Max	Min	Avg	STDEV	Max	Min	Avg	STDEV	Max	Min	Avg	STDEV	Max	Min	Avg	STDEV
EC	34.1	24.9	29.0	2.76	27.7	16.9	21.2	3.26	28.2	19.5	24.1	2.39	29.6	18.4	22.8	2.54
pH	7.3	6.4	6.7	0.3	7.1	6.2	6.4	0.2	7.1	5.8	6.2	0.3	6.9	5.9	6.5	0.3
HCO_3^-	173	139	152	9.33	163	117	134	11.3	153	128	139	6.39	170	112	129	15.0
SO_4^{2-}	54.2	41.8	48.0	3.64	48.8	20.6	32.1	8.97	41.5	16.9	28.2	5.72	45.5	29.8	35.3	3.31
Cl^-	41.3	6.48	20.6	9.54	21.9	4.15	9.67	4.62	10.6	3.39	7.07	2.37	6.48	3.10	4.84	0.93
NO_3^-	6.79	2.63	4.33	1.35	4.85	1.61	3.24	0.77	7.45	2.24	4.61	1.34	5.97	2.47	3.92	1.02
Ca^{2+}	155	102	129	16.3	144	82.5	105	17.5	169	89.5	126	20.7	116	62.6	93.1	10.8
Na^+	71.8	38.0	53.0	12.2	61.8	24.0	40.8	9.75	61.2	21.2	43.4	10.0	41.3	24.4	31.8	4.27
Mg^{2+}	49.8	34.9	39.1	4.07	43.5	30.2	35.6	3.57	67.3	23.3	39.9	12.2	44.2	21.0	29.3	5.15
K^+	17.6	15.1	16.2	0.75	15.7	4.77	10.0	2.88	12.5	6.88	9.60	1.37	15.4	5.15	9.97	2.76
H_4SiO_4	29.9	12.9	20.7	5.54	13.7	6.65	9.56	1.72	18.2	9.84	14.4	2.09	8.44	2.60	4.61	1.58
TDS	21.5	17.4	19.5	1.43	19.5	12.2	15.0	1.95	19.2	13.7	16.1	1.41	17.8	11.6	13.8	1.49
Na/Cl	5.96	0.92	3.17	1.50	8.46	2.26	4.80	1.72	12.4	2.83	6.88	2.86	11.4	4.76	6.81	1.70
K/Cl	2.34	0.38	0.99	0.53	2.21	0.50	1.17	0.46	2.73	0.77	1.54	0.62	3.06	1.14	2.09	0.55
Ca + Mg vs TZ^+	0.77	0.64	0.71	0.04	0.80	0.69	0.74	0.03	0.84	0.67	0.76	0.05	0.80	0.69	0.75	0.03
Na + K vs TZ^+	0.36	0.23	0.29	0.04	0.31	0.20	0.26	0.03	0.33	0.16	0.24	0.05	0.31	0.20	0.25	0.03
Ca + Mg vs Na + K	3.38	1.75	2.49	0.46	3.91	2.22	2.86	0.52	5.36	2.01	3.26	0.90	3.92	2.25	2.98	0.47
C-ratio	0.78	0.74	0.76	0.01	0.86	0.76	0.81	0.03	0.89	0.79	0.83	0.02	0.80	0.77	0.79	0.01

Unit: EC in µS/cm; Major cations and anions concentrations in µeq/L, TDS concentration in mg/L and H_4SiO_4 concentration in µmole/L cm in 2019. While, pH value varies from 6.4–7.3 with an average value of 6.7 ± 0.3 in 2015, 6.2–7.1 with an average value of 6.4 ± 0.2 in 2017, 5.8–7.1 with an average value of 6.2 ± 0.3 in 2018 and 5.9–6.9 with an average value of 6.5 ± 0.3 in 2019. The average value of measured pH for all the four-year glacial meltwater samples shows slightly acidic nature of the Gaglu glacier stream water.

HCO_3^- was the dominant anion in the Gaglu glacier meltwater constituting 67.6% of the TZ^- in 2015, 74.9% of the TZ^- in 2017, 77.6% of the TZ^- in 2018 and 74.6% of the TZ^- in 2019 followed by SO_4^{2-} comprising 21.3% of the TZ^- in 2015, 17.9% of the TZ^- in 2017, 15.7% of the TZ^- in 2018 and 20.4% of the TZ^- in 2019. While, Ca^{2+} was the abundant cation among all the cations constituting 54.2% of the TZ^+ in 2015, 55% of the TZ^+ in 2017, 57.5% of the TZ^+ in 2018 and 56.8% of the TZ^+ in 2019 followed by Na^+ comprising 22.3% of the TZ^+ in 2015, 21.4% of the TZ^+ in 2017, 19.8% of the TZ^+ in 2018 and 19.4% of the TZ^+ in 2019. TDS content in the Gaglu glacier stream water varies from 17.4–21.5 mg/L with an average value of 19.5 ± 1.43 mg/L in 2015, 12.2–19.5 mg/L with an average value of 15.0 ± 1.95 mg/L in 2017, 13.7–19.2 mg/L with an average value of 16.1 ± 1.41 mg/L in 2018 and 11.6–17.8 mg/L with an average value of 13.8 ± 1.49 mg/L in 2019, showing lower value of TDS content of Gaglu glacier stream water in comparison to nearby Batal glacier (TDS = 48.5 mg/L) (Singh et al. 2020), Chhota Shigri glacier (TDS = 27.9 mg/L) (Singh and Ramanathan 2017) and Bara Shigri glacier (TDS = 33.7 mg/L) (Singh and Ramanathan 2015). In general, various ions content in the stream water of Gaglu glacier shows higher value during the year 2015 as compared to the years 2017–2019 because during the year 2015 sampling of meltwater was carried out in the low discharge period (i.e. September), whereas during the years 2017–2019 sampling of meltwater was carried out in the high discharge period (i.e. July). Hence, various ions concentration is high in the stream water of Gaglu glacier during 2015 as compared to the years 2017–2019.

Hydrogeochemical attributes

Glacial meltwater provides important information on the hydrochemical processes operational in the glacierized region (Singh et al. 2017). Various ions concentration in the glacial water are mainly depend on the intensity of weathering processes functional between the interface of bedrock and glacial water (Raiswell and Thomas 1984; Sharma et al. 2013). The X–Y scatter graph of (Ca + Mg) vs TZ^+ (Fig. 2) exhibit strong correlation among the sampling points. The (Ca + Mg)/TZ^+ ratio in the stream water of Gaglu glacier shows higher values having mean equivalent ratio of 0.71 ± 0.04 in 2015, 0.74 ± 0.03 in 2017, 0.76 ± 0.05 in 2018 and 0.75 ± 0.03 in 2019. Similarly, high ratios have also been found between (Ca + Mg) vs (Na + K) in the glacial runoff having mean equivalent ratio of 2.49 ± 0.46 in 2015, 2.86 ± 0.52 in 2017, 3.26 ± 0.90 in 2018 and 2.98 ± 0.47 in 2019. On the other hand, no strong relationship has been found in between (Na + K) vs TZ^+ (Fig. 3) and computed low mean equivalent (Na + K) vs TZ^+ ratios (0.29 ± 0.04 in 2015, 0.26 ± 0.03 in 2017, 0.24 ± 0.05 in 2018 and 0.25 ± 0.03 in 2019) in the meltwater. Higher equivalent (Ca + Mg) vs (Na + K) and (Ca + Mg) vs TZ^+ ratios as well as lower equivalent (Na + K) vs TZ^+ ratio for all the four years of study, shows that carbonate rock weathering

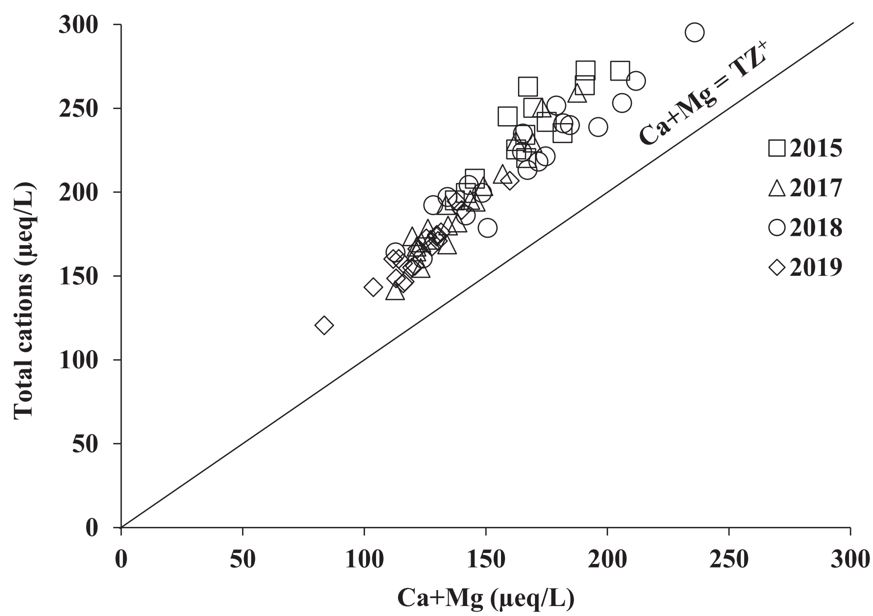

Fig. 2 Plot of total cations vs (Ca + Mg)

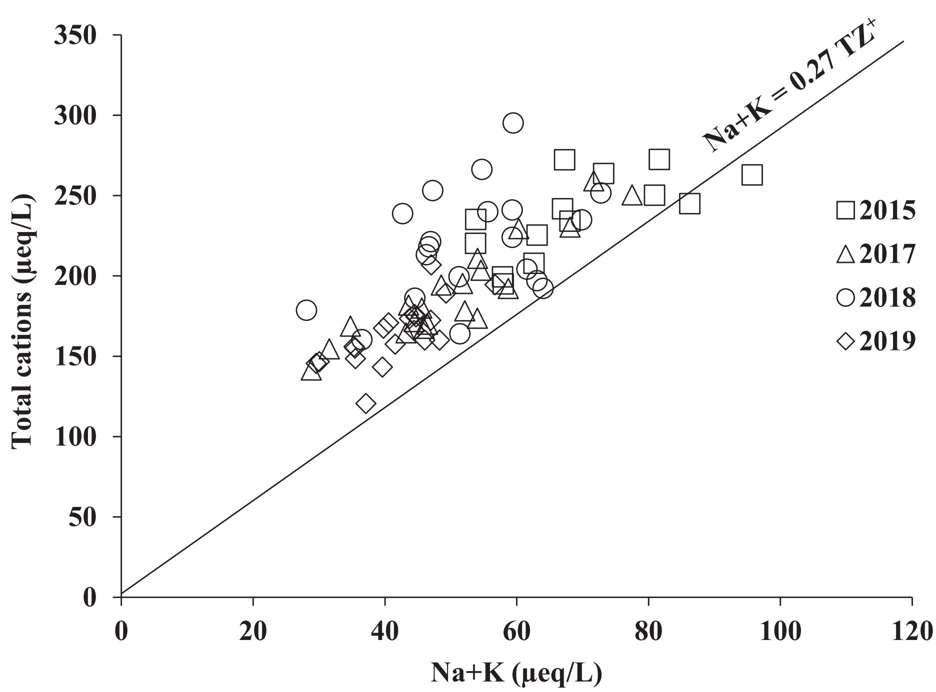

Fig. 3 Plot of total cations vs (Na + K)

regulates stream water chemistry of Gaglu glacier followed by silicate rock weathering (Singh et al. 2015a, 2020; Pant et al. 2023; Bishwakarma et al. 2024).

A source of proton (H^+) is needed for the hydrogeochemical weathering of carbonate containing lithology (Khadka and Ramanathan 2013). The C-ratio [$HCO_3/(HCO_3 + SO_4)$] provides an important information regarding relative significance of two dominant proton (H^+) generating mechanism such as carbonation and oxidation of sulphide (Brown et al. 1996). The mean value of C-ratio for the glacial runoff of study area was calculated to be 0.76 ± 0.01 in 2015, 0.81 ± 0.03 in 2017, 0.83 ± 0.02 in 2018 and 0.79 ± 0.01 in 2019. These C-ratios indicate that carbonic acid weathering is the main generator of aqueous H^+ in the Gaglu glacier (Brown et al. 1996; Singh and Hasnain 2002). The Piper diagram (Piper 1944) is a trilinear diagram commonly used to know about the hydrogeochemical regime of the glacial meltwater. The anionic and cationic triangles of Piper diagram for all the four years of study (Fig. 4) shows that most of the glacial meltwater samples fall in Ca^{2+} and HCO_3^- dominant zones, indicating predominance of Ca–HCO_3 hydrogeochemical facies and carbonate rock weathering in the Gaglu glacier (Singh and Ramanathan 2017; Kumar et al. 2019a; Awasthi et al. 2025).

The Raymahasay model (1986) used for the computation of HCO_3^- produced from weathering of carbonate and silicate rocks show that majority of HCO_3^- in the Gaglu glacier is derived from carbonate rock weathering (73.1% of HCO_3^- in 2015, 68.6% of HCO_3^- in 2017, 78.6% of HCO_3^- in 2018 and 62.5% of HCO_3^- in 2019), followed by weathering of silicate rock (26.9% of HCO_3^- in 2015, 31.4% of HCO_3^- in 2017, 21.4% of HCO_3^- in 2018 and 37.5% of HCO_3^- in 2019). On the other hand, carbonate weathering contributes 85% of HCO_3^-, while silicate weathering contributes 15% of HCO_3^- in the Gangotri glaciers (Kumar et al. 2009). The assessment of atmospheric input to the stream water chemistry has been carried out by the ratio of element to Cl^- because of the dominance of Cl^- in the water of ocean and relatively lesser availability of Cl^- in the different varieties of rock minerals (Dudeja et al. 2011). The plotted points in (Na + K) vs Cl^- plot (Fig. 5) describe the predominance of K^+ and Na^+ over Cl^-. The high mean Na/Cl ratio (3.17 ± 1.50 in 2015, 4.80 ± 1.72 in 2017, 6.88 ± 2.86 in 2018 and 6.81 ± 1.70 in 2019) and K/Cl ratio (0.99 ± 0.53 in 2015, 1.17 ± 0.46 in 2017, 1.54 ± 0.62 in 2018 and 2.09 ± 0.55 in 2019) have been calculated in the stream runoff of Gaglu glacier. These observed mean ratios of meltwater are much higher than those of oceanic water (K/Cl ratio = 0.02, Na/Cl ratio = 0.85), showing small atmospheric input to the total dissolved ions budget of Gaglu glacier meltwater (Kumar et al. 2009; Sharma et al. 2013; Singh and Ramanathan 2017; Tiwari et al. 2018; Bisht et al. 2018; Singh et al. 2020).

Assessment of hydrogeochemical attributes using statistical analysis

In general, statistical analysis is more useful with respect to geographical analysis for the assessment of solute acquisition processes because it contains limited number of variables (Srivastava and Ramanathan 2008). Principal component

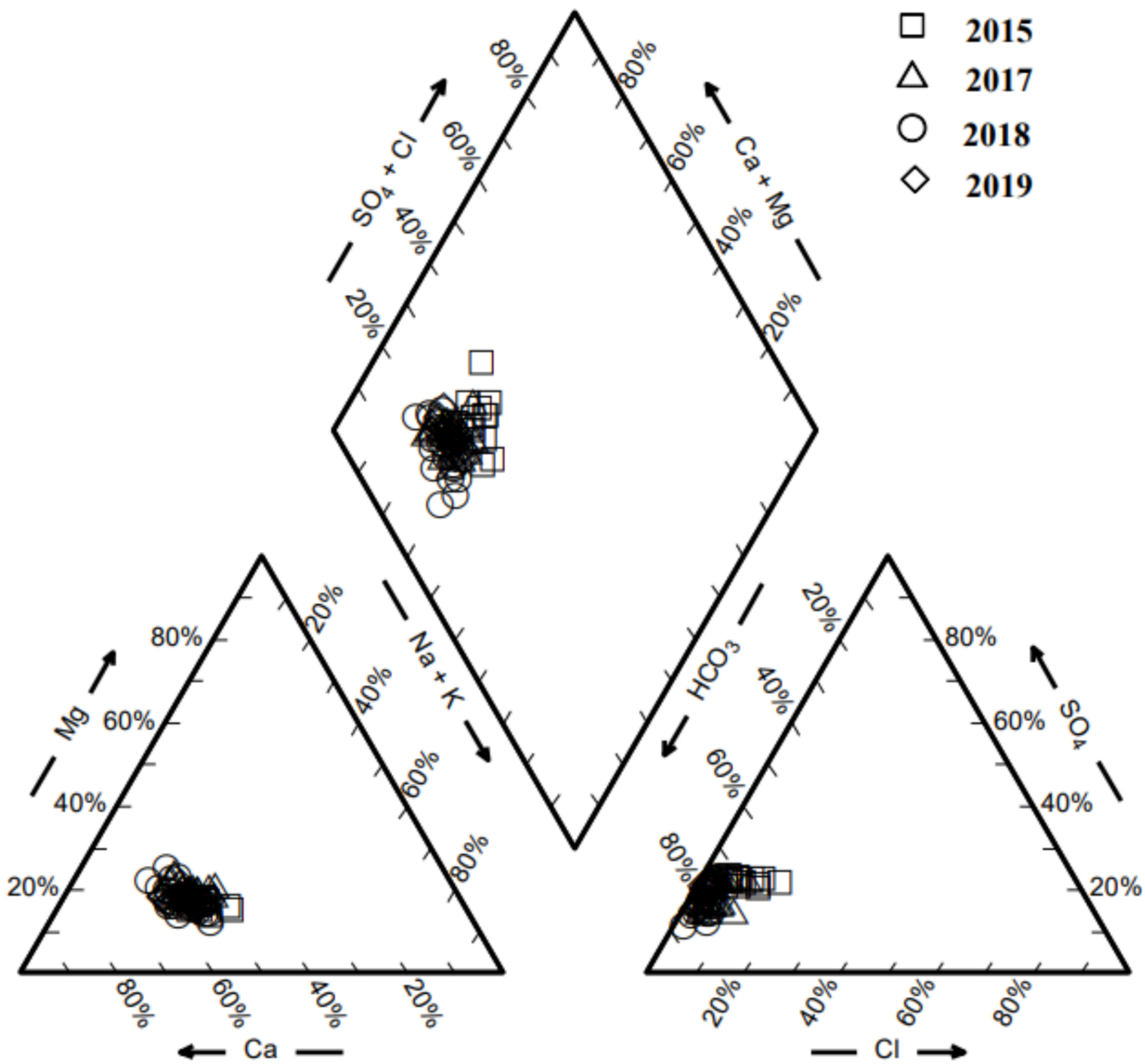

Fig. 4 Piper trilinear plot of Gaglu glacier stream water

analysis (PCA) and correlation matrix has been used in the present study for the assessment of hydrogeochemical attributes of stream water in the glacier environment.

Correlation matrix

Correlation matrix measures the interrelationship between two variables (Edet et al. 2003; Taoufik et al. 2017). Direct correlation has been observed between the two data sets when decrease or increase in the value of one data set is connected with the corresponding decrease or increase in the value of other data set (Behera and Das 2018). A multi-parametric correlation matrix between various analyzed hydrochemical variables in the stream runoff of Gaglu glacier is described in the Table 2 and 3. Strong positive correlation exists between Mg^{2+} and Ca^{2+} ($r^2 = 0.73$ in 2015, $r^2 = 0.82$ in 2017, $r^2 = 0.85$ in 2018 and $r^2 = 0.85$ in 2019), HCO_3^- and Ca^{2+} ($r^2 = 0.73$ in 2015, $r^2 = 0.94$ in 2017, $r^2 = 0.85$ in 2018 and $r^2 = 0.76$ in 2019) and HCO_3^- and Mg^{2+} ($r^2 = 0.76$ in 2015, $r^2 = 0.89$ in 2017, $r^2 = 0.76$ in 2018 and $r^2 = 0.78$ in 2019). These strong associations show common source of these hydrogeochemical species i.e. carbonate weathering (Lone et al. 2019; Singh et al. 2020). Ca^{2+} is linked strongly with SO_4^{2-} ($r^2 = 0.77$ in 2015, $r^2 = 0.97$ in 2017, $r^2 = 0.92$ in 2018 and $r^2 = 0.84$ in 2019), whereas Mg^{2+} is also linked very positively with SO_4^{2-} ($r^2 = 0.71$ in 2015, $r^2 = 0.79$ in 2017, $r^2 = 0.85$ in 2018 and $r^2 = 0.89$ in 2019), indicating that dissolution of sulphate containing minerals is the source of these anions and cations in the stream water (Tiwari et al. 2018). Good correlation exists between Na^+ and K^+ ($r^2 = 0.81$ in 2015, $r^2 = 0.95$ in 2017, $r^2 = 0.74$ in 2018 and $r^2 = 0.82$ in 2019), Na^+ and H_4SiO_4 ($r^2 = 0.61$ in 2015, $r^2 = 0.85$ in

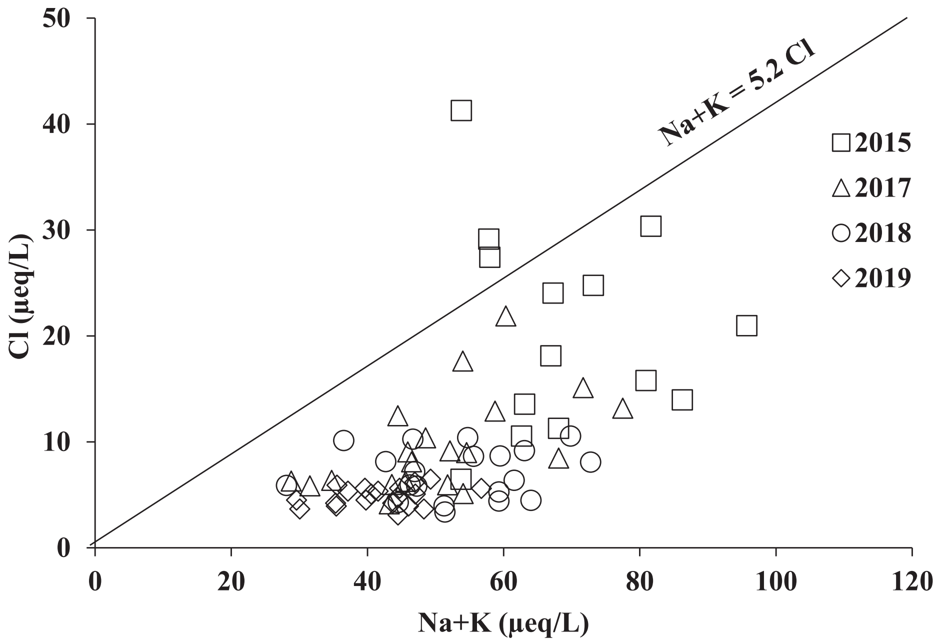

Fig. 5 Plot of (Na + K) vs Cl^-

Table 2 Correlation matrix of analysed physico-chemical variables of Gaglu glacier stream water for (a) 2015 (b) 2017

	EC	pH	HCO_3	SO_4	Cl	NO_3	Ca	Na	Mg	K	H_4SiO_4
(a)											
EC	1.00										
pH	− 0.32	1.00									
HCO_3	0.55	− 0.58	1.00								
SO_4	0.69	− 0.46	0.57	1.00							
Cl	0.56	− 0.13	0.16	0.57	1.00						
NO_3	0.10	0.09	− 0.11	− 0.10	0.30	1.00					
Ca	0.78	− 0.43	0.73	0.77	0.21	− 0.05	1.00				
Na	0.27	− 0.58	0.56	0.00	− 0.12	− 0.31	0.26	1.00			
Mg	0.71	− 0.38	0.76	0.71	0.39	0.22	0.73	0.09	1.00		
K	0.45	− 0.37	0.46	0.08	− 0.04	− 0.45	0.32	0.81	0.17	1.00	
H_4SiO_4	0.16	− 0.20	0.19	− 0.22	− 0.35	− 0.43	0.08	0.61	− 0.13	0.79	1.00
(b)											
EC	1.00										
pH	0.49	1.00									
HCO_3	0.91	0.59	1.00								
SO_4	0.88	0.42	0.91	1.00							
Cl	0.38	0.10	0.26	0.28	1.00						
NO_3	0.14	-0.31	0.17	0.12	0.19	1.00					
Ca	0.93	0.46	0.94	0.97	0.42	0.12	1.00				
Na	0.85	0.42	0.75	0.72	0.58	0.13	0.82	1.00			
Mg	0.80	0.38	0.89	0.79	0.30	0.17	0.82	0.66	1.00		
K	0.81	0.40	0.69	0.65	0.44	0.08	0.73	0.95	0.63	1.00	
H_4SiO_4	0.78	0.60	0.77	0.67	0.54	− 0.07	0.78	0.85	0.70	0.79	1.00

Table 3 Correlation matrix of analysed physico-chemical variables of Gaglu glacier stream water for (a) 2018 (b) 2019

	EC	pH	HCO_3	SO_4	Cl	NO_3	Ca	Na	Mg	K	H_4SiO_4
(a)											
EC	1.00										
pH	0.18	1.00									
HCO_3	0.88	0.26	1.00								
SO_4	0.70	0.34	0.73	1.00							
Cl	0.48	− 0.13	0.47	0.24	1.00						
NO_3	0.42	− 0.25	0.27	0.15	0.43	1.00					
Ca	0.82	0.34	0.85	0.92	0.32	0.32	1.00				
Na	0.51	0.31	0.34	0.15	0.12	− 0.15	0.20	1.00			
Mg	0.75	0.13	0.76	0.85	0.43	0.46	0.85	0.02	1.00		
K	0.35	0.10	0.16	-0.06	− 0.02	− 0.23	0.01	0.74	− 0.24	1.00	
H_4SiO_4	0.52	0.12	0.35	0.14	0.04	− 0.05	0.23	0.89	0.04	0.62	1.00
(b)											
EC	1.00										
pH	− 0.23	1.00									
HCO_3	0.62	0.04	1.00								
SO4	0.66	0.04	0.90	1.00							
Cl	0.28	0.01	0.03	0.11	1.00						
NO_3	0.00	0.41	0.45	0.29	− 0.03	1.00					
Ca	0.79	− 0.06	0.76	0.84	0.03	0.13	1.00				
Na	0.44	− 0.32	0.50	0.41	0.15	0.45	0.45	1.00			
Mg	0.76	− 0.14	0.78	0.89	0.19	0.16	0.85	0.38	1.00		
K	0.58	− 0.33	0.47	0.45	0.46	0.28	0.50	0.82	0.47	1.00	
H_4SiO_4	0.33	− 0.30	0.20	0.19	0.30	0.17	0.32	0.63	0.25	0.82	1.00

2017, $r^2 = 0.89$ in 2018 and $r^2 = 0.63$ in 2019) and K^+ and H_4SiO_4 ($r^2 = 0.79$ in 2015, $r^2 = 0.79$ in 2017, $r^2 = 0.62$ in 2018 and $r^2 = 0.82$ in 2019), showing common source of these dissolved solutes i.e. silicate rock weathering (Singh and Ramanathan 2017).

Principal component analysis (PCA)

PCA is one of the important statistical techniques introduced by Pearson (1901) and improved by Hotelling (1933). It is a data reduction tool (Loska and Wiechula 2003) used for the

Table 4 Principal component analysis of the stream water samples of Gaglu glacier for 2015 and 2017

Variables	2015			2017			
	Factor 1	Factor 2	Communalities	Factor 1	Factor 2	Factor 3	Communalities
EC	0.861	0.116	0.755	0.890	0.355	0.060	0.922
pH	− 0.540	− 0.415	0.464	0.496	0.097	0.687	0.727
HCO_3	0.778	0.392	0.759	0.971	0.169	0.069	0.977
SO_4	0.883	− 0.132	0.798	0.926	0.167	0.080	0.886
Cl	0.582	− 0.401	0.500	0.090	0.907	− 0.127	0.868
NO_3	0.122	− 0.604	0.379	0.203	0.078	− 0.888	0.836
Ca	0.861	0.168	0.769	0.907	0.334	0.039	0.936
Na	0.231	0.854	0.783	0.666	0.686	0.074	0.919
Mg	0.888	− 0.830	0.795	0.876	0.184	− 0.035	0.803
K	0.268	0.878	0.842	0.636	0.614	0.113	0.793
H_4SiO_4	− 0.09	0.872	0.768	0.653	0.598	0.320	0.886
Eigen value	4.435	3.177		5.753	2.371	1.408	
% of variance	40.315	28.880		52.304	21.557	12.803	
% of cumulative variance	40.315	69.195		52.304	73.861	86.664	

Table 5 Principal component analysis of the stream water samples of Gaglu glacier for 2018 and 2019

Variables	2018				2019				
	Factor 1	Factor 2	Factor 3	Communalities	Factor 1	Factor 2	Factor 3	Factor 4	Communalities
EC	0.797	0.467	0.320	0.956	0.800	0.261	– 0.222	0.227	0.810
pH	0.438	0.129	– 0.681	0.673	– 0.029	– 0.447	0.793	0.184	0.864
HCO_3	0.862	0.274	0.189	0.854	0.859	0.220	0.299	– 0.105	0.886
SO_4	0.940	– 0.014	– 0.083	0.890	0.934	0.121	0.179	0.012	0.919
Cl	0.345	0.096	0.678	0.588	0.059	0.204	0.006	0.948	0.944
NO_3	0.282	– 0.150	0.765	0.688	0.125	0.357	0.864	– 0.152	0.912
Ca	0.963	0.078	0.057	0.936	0.914	0.204	– 0.031	– 0.027	0.878
Na	0.166	0.942	– 0.099	0.924	0.311	0.871	0.122	– 0.092	0.880
Mg	0.904	– 0.138	0.276	0.912	0.932	0.141	– 0.030	0.102	0.900
K	– 0.086	0.877	– 0.086	0.783	0.360	0.861	– 0.009	0.296	0.959
H_4SiO_4	0.147	0.898	0.013	0.828	0.094	0.853	– 0.066	0.208	0.783
Eigen value	4.452	2.829	1.752		4.209	2.790	1.567	1.169	
% of variance	40.476	25.715	15.926		38.264	25.367	14.244	10.628	
% of cumulative variance	40.476	66.191	82.116		38.264	63.631	77.874	88.502	

conversion of huge numeral of analyzed variables/parameters into small numeral of factors required for the analysis of interrelationship among the analyzed parameters (Yongming et al. 2006). The summary of PCA along with eigenvalues, total variance and communalities are given in Table 4 and 5. This PCA is accredited by Kaiser–Meyer–Olkin (KMO) test and Bartlett's sphericity test.

Two dominant contributing factors were identified with eigenvalues higher than one in the present hydrogeochemical study on the Gaglu glacier during the observation period 2015 which described about 69.2% of total data variance. Factor 1 is dominated by HCO_3^-, Ca^{2+}, Mg^{2+}, SO_4^{2-} and EC, seems to be related with carbonate weathering and dissolution of SO_4^{2-} bearding minerals in the Gaglu glacier (Singh et al. 2020; Patel et al. 2023). Factor 2 contains significantly highly positive loading for H_4SiO_4, K^+ and Na^+. Such significant factor seems to be associated with silicate rock weathering (Singh et al. 2014). In 2007, three significant factors were extracted with eigenvalues higher than one, which accounted for 86.7% of the total variability. The first factor is highly positively loaded with EC, SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+} and Na^+ and moderately loaded with K^+ and H_4SiO_4, explaining about the importance of weathering of sulphate, carbonate and silicate containing minerals and sulphide oxidation in the investigation area. Factor 2 is strongly loaded with Cl^- and Na^+ and moderately loaded with K^+ and H_4SiO_4, showing the important input of atmospheric sources and silicate rock weathering in the Gaglu glacier. Factor 3 is significantly positively loaded with pH and highly negatively loaded with NO_3^-, showing contribution from multiple sources.

Three statistically significant factors were recognised (eigenvalues > 1) during the study period 2018 which elucidates about 82.1% of the whole variance in the physicochemical data. Factor 1 is dominated by EC, SO_4^{2-}, HCO_3^-, Mg^{2+} and Ca^{2+}. This factor described about the importance of sulphate mineral dissolution, carbonate type weathering and oxidation of pyrite controlling solute chemistry of glacial meltwater. Factor 2 is represented by H_4SiO_4, K^+ and Na^+, seems to be related with weathering of silicate containing minerals. Factor 3 is significantly positively loaded with Cl^- and NO_3^-, indicating input from atmospheric deposition. In 2019, four significantly dominant contributing factors were extracted with eigenvalues higher than one, which accounted for 88.5% of the whole data variance. Factor 1 is dominated by EC, SO_4^{2-}, HCO_3^-, Mg^{2+} and Ca^{2+}. This factor described about the important role of weathering of sulphate, carbonate and silicate containing minerals in the studied area. Factor 2 is dominantly loaded with H_4SiO_4, K^+ and Na^+, showing the importance of weathering of silicate bearing minerals in the Gaglu glacier. Factor 3 is represented by pH and NO_3^- and Factor 4 is represented by Cl^-, seems to be associated with atmospheric sources.

Dissolved load and chemical weathering rates of carbonates and silicates

Even though Himalayan region contains only 4% of total land area of the earth but this region contributes nearly 25% of the total global dissolved flux to the world's oceans (Raymo and Ruddiman 1992). In general, weathering of different types of rock minerals is the major source of dissolved load (Panwar et al. 2016). The content of dissolved flux is higher in the sedimentary environment as compared to the metamorphic and igneous environments (Meybeck 1979). Estimation of dissolved load of Gaglu glacier was carried out by stream runoff and TDS content of glacial meltwater. The mean value of stream runoff from the Gaglu glacier was computed to be 21.4 m^3/s during the investigation period July 2019. Since hydrological investigation of the study area has been carried out only during the month of July 2019, hence mean dissolved load of the Gaglu glacier was estimated to be 25.5 t/day during this time period. Dissolved load of the Gaglu glacier has higher value with respect to the other glaciers reported in the region of Western Himalayan such as Batal (12.4 t/day) (Singh et al. 2020), Patsio (7.12 t/day) (Singh et al. 2015c) and Chhota Shigri (8.06 t/day) glaciers (Singh and Ramanathan 2017), which might be associated with huge size along with higher stream discharge of the Gaglu glacier in comparison with these Western Himalayan glaciers.

Chemical weathering of different types of rock minerals is an important hydrogeochemical processes that interlink geochemical cycle of solid earth to the ocean and atmosphere (Liu et al. 2018b). It is also responsible for limiting the levels of CO_2 in the atmosphere on geological time scales (> 1 Ma) (Beaulieu et al. 2012). The silicate weathering rate (SWR) in the Gaglu glacier catchment has been estimated using the following equation (Roy et al. 1999; Li et al. 2014; Das et al. 2016; Bastia and Equeenuddin 2019).

$$\mathrm{SWR} = \frac{\mathrm{TDS_{sil}} \times \mathrm{discharge}}{\mathrm{drainage\ area}} \tag{1}$$

where $TDS_{sil} = [\Sigma(Ca_{sil} + Mg_{sil} + Na_{sil} + K_{sil}] + SiO_2$. Ca_{sil}, Mg_{sil}, Na_{sil} and K_{sil} refer to silicate component of Ca, Mg, Na and K in mg/L, respectively and they are estimated using the following equations (Galy and France-Lanord 1999; Dalai et al. 2002; Das et al. 2016).

$$\mathrm{Na_{sil}} = \mathrm{Na_r} - \mathrm{Cl_r} \tag{2}$$

$$\mathrm{K_{sil}} \approx \mathrm{K_r} \tag{3}$$

$$\mathrm{Ca_{sil}} = \mathrm{Na_{sil}} \times (\mathrm{Ca/Na})_{sol} \tag{4}$$

$$\mathrm{Mg_{sil}} = \mathrm{Na_{sil}} \times (\mathrm{Mg/Na})_{sol} \tag{5}$$

where subscript "r" represents river and "sil" refers to silicate contribution. $(Ca/Na)_{sol}$ and $(Mg/Na)_{sol}$ refer to molar ratios discharged into the riverine water from silicate containing rocks during the time of hydrochemical weathering in the drainage area. We used 0.3 ± 0.2 and 0.7 ± 0.3 values in this study for $(Mg/Na)_{sol}$ and $(Ca/Na)_{sol}$, respectively (Krishnaswami and Singh 1998; Krishnaswami et al. 1999).

The carbonate weathering rate (CWR) in the Gaglu glacier catchment has been estimated using the following equations (Roy et al. 1999; Sharma and Subramanian 2008; Das et al. 2016).

$$\mathrm{CWR} = \frac{\mathrm{TDS_{carb}} \times \mathrm{discharge}}{\mathrm{drainage\ area}} \tag{6}$$

where $TDS_{carb} = [Ca_{carb} + Mg_{carb} + 0.5(HCO_3)]$, all ions concentration in mg/L. Ca_{carb} and Mg_{carb} refer to carbonate component of calcium and magnesium, respectively and they are estimated using the following equations

$$\mathrm{Ca_{carb}} = \mathrm{Ca_r} - \mathrm{Ca_{sil}} \tag{7}$$

$$\mathrm{Mg_{carb}} = \mathrm{Mg_r} - \mathrm{Mg_{sil}} \tag{8}$$

where subscript "carb" represents carbonate, "r" refers to river and "sil" refers to silicate.

The mean value of SWR has been computed to be 27.4 t/km^2/year for the Gaglu glacier basin during the investigation period July 2019, whereas the mean value of CWR has been calculated to be 78.7 t/km^2/year for this glacier basin during the investigation period July 2019. Hence, CWR shows higher contribution with respect to SWR in the Gaglu glacier basin.

Consumption of atmospheric CO_2 by chemical weathering

Hydrogeochemical attributes of Himalayan glaciers meltwater are very useful to know about the acquisition processes of various types of solutes and CO_2 consumption rates in the glacier environment (Shukla et al. 2018, 2020; Singh et al. 2020; Biswal et al. 2023; Sundriyal et al. 2024). Two major rock types such as carbonates and silicates consume atmospheric CO_2 during the weathering processes (Moquet et al. 2011), but the effect of silicate rock weathering on the consumption of CO_2 from the atmosphere is slightly different as compared to the carbonate weathering (Mortatti and Probst 2003; Vinnarasi et al. 2021). CO_2 consumption rates associated with silicate rock weathering $[\varphi CO_2]_{sil}$ and carbonate rock weathering $[\varphi CO_2]_{carb}$ in the Gaglu glacier basin has been computed using the following equations (Wu et al. 2008; Jha et al. 2009).

$$[\varphi \mathrm{CO_2}]_{sil} = \frac{(2\mathrm{Ca_{sil}} + 2\mathrm{Mg_{sil}} + \mathrm{K_{sil}} + \mathrm{Na_{sil}}) \times \mathrm{discharge}}{\mathrm{drainage\ area}} \tag{9}$$

$$[\varphi \mathrm{CO_2}]_{carb} = \frac{(\mathrm{Ca_{carb}} + \mathrm{Mg_{carb}}) \times \mathrm{discharge}}{\mathrm{drainage\ area}} \tag{10}$$

where Ca_{sil}, Na_{sil}, Mg_{sil} and K_{sil} refer to silicate component of these cations, while Ca_{carb} and Mg_{carb} represent carbonate component of Ca and Mg.

The mean value of CO_2 consumption rates via silicate rock weathering $[\varphi CO_2]_{sil}$ and carbonate rock weathering $[\varphi CO_2]_{carb}$ in the Gaglu glacier basin has been computed as

12.8×10^5 and 4.8×10^5 mol/km^2/year, respectively during the investigation period July 2019. Total CO_2 consumption rate [φCO_2] via chemical weathering (contains both silicate and carbonate weathering) in this glacier catchment has been calculated to be 17.6×10^5 mol/km^2/year during the observation period July 2019. The mean annual CO_2 drawdown by the Gaglu glacier catchment (drainage area: 47.96 km^2) associated with consumption of CO_2 via chemical weathering has been computed as 843×10^5 mol/year. The annual CO_2 drawdown by this glacier catchment is higher in comparison to the Batal glacier (346×10^5 mol/year) situated in the same basin (Singh et al. 2020), which might be associated with high stream discharge and bigger size and area of the Gaglu glacier with respect to Batal glacier.

Comparison of hydrogeochemistry of Gaglu glacier meltwater with others glaciers situated in the Chandra basin, Western Himalaya, India

Table 6 shows hydrogeochemistry of the Gaglu glacier stream water and its comparison with other glaciers situated in the Chandra basin, Western Himalaya. Ca^{2+} is the predominant cation in the stream water of glaciers located in the Chandra basin. While, HCO_3^- is the most dominant anions among all the measured anions in the stream water of majority of the Chandra basin glaciers except Batal glacier, here SO_4^{2-} is the predominant anions. High equivalent (Ca + Mg) vs (Na + K) and (Ca + Mg) vs TZ^+ ratios along with low equivalent (Na + K) vs TZ^+ ratios have been observed in the stream water of Chandra basin glaciers, showing carbonate rock weathering regulates stream water chemistry of glaciers situated in the Chandra basin followed by silicate rock weathering (Singh et al. 2015b, 2020, 2017; Singh and Ramanathan 2017).

Suspended sediment fluxes

Himalayan glaciers are one of the important source of sediment for various rivers situated in the Asian continent. Transport of glacial sediment from the glacierized catchment is dependent on the quantity of runoff emerging from the glacier (Singh 2006). Assessment of SSC, SSL and physical weathering rate of the Himalayan glaciers play a key role in the water resources management in the lowland area. Daily mean SSC in the stream runoff of Gaglu glacier has been calculated to be 455 mg/L during the observation period July 2019. SSC in the Gaglu glacier meltwater shows lower value than that of Bara Shigri (887 mg/L) (Singh and Ramanathan 2015) and Gangotri (1815 mg/L) glaciers (Singh et al. 2014), which may be due to smaller size, lower coverage of debris along with lower stream runoff of Gaglu glacier in comparison with Bara Shigri and Gangotri glaciers. On the other hand, daily mean SSL of the investigation area has been computed to be 841 t/day in July 2019. SSL of the Gaglu glacier exhibits higher value as compared to the East Rathong, Chorabari, Dokriani, Dunagiri, Shaune Garang, Patsio and Chhota Shigri glaciers (Table 7), which might be due to high stream discharge, big size and high coverage of rock debris in the Gaglu glacier in comparison with these glaciers.

Glacial erosion is responsible for the generation of sediment mainly due to the abrasion and plucking processes below the glacier (Bogen 2008). Meltwater draining from glacierized area contains high sediment yield, which depends on the amount of suspended sediment and meltwater runoff (Drewry 1986; Harbor and Warburton 1992). Glaciers located in various regions of the world have different sediment yield due to the existence of different types of rocks and different thermal regimes in the different glacier environments (Hallet et al. 1996). The physical weathering rate or suspended sediment yield of the Gaglu glacier was estimated to be 6402 t/km^2/year in July 2019. Table 6 shows physical weathering rate of Gaglu glacier and other selected glaciers, indicating lower value of physical weathering rate of the Gaglu glacier with respect to Gangotri (Central Himalayan) glacier. This might be associated with smaller size, low stream discharge and low physical denudation of Gaglu glacier in comparison with the Gangotri glacier (Singh et al. 2015c).

Conclusions

The present dissolved ions chemistry, CO_2 consumption rate and suspended sediment flux studies provide a base line information about the identification of sources of driftnet solutes, estimation of chemical and physical weathering rates and consumption of CO_2 from the atmosphere by chemical weathering in the Gaglu glacier catchment. The average value of measured pH of glacial meltwater samples for all the four years show slightly acidic nature of meltwater in the study area. The high (Ca + Mg) vs TZ^+ and (Ca + Mg) vs (Na + K) ratios in the stream water shows that Gaglu glacier receives various dissolved ions mainly from carbonate rock weathering. The Piper diagram also support the dominancy of carbonate rock weathering in the Gaglu glacier. The high Na^+ to Cl^- and K^+ to Cl^- equivalent ratios in the stream runoff show smaller atmospheric input to the total dissolved ions budget of Gaglu glacier. CWR in the basin of Gaglu glacier shows higher value with respect to SWR in the study area. The annual CO_2 drawdown by the Gaglu glacier basin has higher value as compared to the Batal glacier situated in the same basin, which might be due to high stream discharge and bigger basin area of Gaglu glacier with respect to the Batal glacier. Conversely, SSL and physical weathering rate of Gaglu glacier geographically

Table 6 Hydrogeochemical comparison of Gaglu glacier meltwater with other glaciers situated in the Chandra basin, Western Himalaya, India

Glaciers	Latitude	Longitude	Basin area (km^2)	EC	pH	Ca^{2+}	Mg^{2+}	K^+	Na^+	SO_4^{2-}	HCO_3^-	Cl^-	NO_3^-	References
Gaglu (2015, 2017–2019)	32° 21′ 40″- 32°28′ 10″ N	77° 20′ 40″- 77° 26′ 40″ E	47.96	29.0/21.2/ 24.1/22.8	6.7/6.4/ 6.2/6.5	129/105/ 126/93.1	39.1/35.6/ 39.9/29.3	16.2/10.0/ 9.60/9.97	53.0/40.8/ 43.4/31.8	48.0/32.1/ 28.2/35.3	152/134/ 139/129	20.6/9.67/ 7.07/4.84	4.33/3.24/ 4.61/3.92	(Kurien and Munshi 1959); Present study)
Batal	32° 20′ 29″ N	77° 34′ 57″ E	16.0	74.1	6.6	559	101	30.0	50.2	441	168	16.3	5.50	(Sharma et al. 2016); (Singh et al. 2020)
Chhota Shigri	32.23° N	77.51° E	34.7	36.8	6.6	150	74.2	30.8	37.9	113	216	15.9	3.50	(Singh and Ramanathan 2017); (Mandal et al. 2020)
Bara Shigri	32.21° N	77.63° E	–	40.6	6.6	274	60.2	28.8	28.4	192	232	15.4	3.28	(Schauwecker et al. 2015); (Singh et al. 2015b)
Sutri Dhaka	32° 22′ 49″ N	77° 32′ 05″ E	42.0	59.9	8.2	242	43.6	14.7	5.00	71.6	221	0.30	3.30	(Sharma et al. 2016); (Singh et al. 2017)

Unit: EC in µS/cm; Major cations and anions concentrations in µeq/L

Table 7 Comparison of SSL and physical weathering rate of various Himalayan glaciers

Glacier	Region	Basin area (km^2)	SSL (t/day)	Physical weathering rate (t/km^2/year)	References
Chhota Shigri (2011–2014)	Himachal Pradesh, India	34.7*	76.9/523/398/143	809/5502/4187/1506	(Singh 2016; Singh and Ramanathan 2018)
Patsio (2011/2012)	Himachal Pradesh, India	7.82	1.70/3.96	79.3/185	(Singh et al. 2015c)
Shaune Garang	Himachal Pradesh, India	38.1	42.9	411	(Kumar et al. 2018a)
Gangotri	Uttarakhand, India	556**	11673	7663	(Singh et al. 2014)
Dunagiri	Uttarakhand, India	17.9	47.0	296	(Srivastava et al. 2014)
Dokriani	Uttarakhand, India	16.1	447	2800	(Singh and Ramasastri 1999); (Singh et al. 2003))
Chorabari	Uttarakhand, India	15.4	513.8	4064	(Kumar et al. 2016; 2018b)
East Rathong	Sikkim, India	19.8	54.2	281.9	(Sharma et al. 2022)
Gaglu	Himachal Pradesh, India	47.96	841	6402	Present study

*Source: (Wagnon et al. 2007); **Source: (Singh et al. 2006)

located in the Western Himalayan region shows lower value as compared to the Gangotri glacier geographically situated in the Central Himalayan region.

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Data availability The datasets will be accessible from the corresponding author of the manuscript upon proper region.

Declarations

Competing interests The authors of this research paper declare no competing interests.

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