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RESEARCH ARTICLE - HYDROLOGY

Climate change-induced high-altitude lake: Hydrochemistry and area changes of a moraine-dammed lake in Leh-Ladakh

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Abstract

Himalayan glaciers are retreating, and glacial lakes are evolving and proliferating as a result of climate change. Glacier retreat marks in the formation and expansion, and sometimes outburst of moraine-dammed lakes. Lato Lake is one of the high-altitude and unexplored glacial lakes upstream of Gya-Miru village in the Leh-Ladakh region. This study is the first of its kind to assess hydrogeochemistry (HCO^{3-}, $SO_4{}^{2-}$, $NO_3{}^{-}$, Cl^-, F^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+) and studying the dynamics of a moraine-dammed lake in the Ladakh Himalayas. We observed substantial expansion of Lato Lake over the past 50 years between 1969 and 2019, and the areas of the lake have increased while the glacier area is reduced by 16.4% and 4.15%, respectively. The pH values ranging from 7.6 to 8.1 show slightly alkaline. $HCO_3{}^{-}$, Ca^{2+}, and $SO_4{}^{2-}$ were the most dominant ions during the study period 2018–19. The high ($Ca^{2+} + Mg^{2+}$) and a low ($Na^+ + K^+$) ratio to the total cations show that Lato Lake receives ions from rock weathering, primarily from carbonate rocks. Gibbs and Na-Mixing plot also support the hydrogeochemistry of lake water was primarily controlled by rock weathering. HYSPILT backward trajectory model suggested that atmospheric input mainly originated from the seawater vapor transported by the summer monsoonal and westerly circulation systems. Results show that the lake has a substantial impact on the long-range transport of ocean water relative to local interferences.

Keywords Moraine-dammed Lake · Major ions · Weathering · Hydrogeochemistry

Introduction

The Himalayan region has gained significant attention due to its large frozen freshwater reserve, some of its large Asian rivers and lakes and the associated glacio-hydrological hazards (Schild 2008; Prakash 2020; Azam et al. 2021; Shugar et al. 2021). Most studies in the Himalayan region showed a glacier mass loss in the past decades and which is predicted to continue with higher rates in the coming decades (Bolch et al. 2019; Rounce et al. 2020; Hugonnet et al. 2021). This will result in the shrinking of the glaciated areas and consequently the water availability in the region. Ladakh region holds many standing fresh and saline water lakes in their glaciated areas among the Himalayan regions. The glacier decline in the Ladakh region will adversely affect the food security and socioeconomic development in the region (Hock et al. 2019; Nüsser et al. 2019) as most of the villages, e.g., Stok, Lato, Gya and Mathoo (Nusser 2012; Schmidt et al. 2020), are considerably dependent on glacier meltwater during pre-monsoon and summer months especially in low precipitation and drought years (Pritchard 2019). Under rapid warming conditions, down-wasting and terminus retreat of glaciers has aggravated the evolution of new proglacial lakes and the growth of pre-existing lakes (Thakuri et al. 2016; Bolch et al. 2019; Shugar et al. 2020). The failure of moraine-dammed lakes can turn into the Glacial Lake Outburst Floods (GLOFs) and pose a severe threat to the downstream community and village infrastructure, like one catastrophe in August 2014 in Gya village of Ladakh region (Schmidt et al. 2020; Majeed et al. 2021). Numerous factors are responsible for triggering the GLOFs such as heavy rainfall, earthquake, rock avalanche and landslide (Allen et al.

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2016; Gurung et al. 2017; Hock et al. 2019; Nüsser et al. 2019). Such hazards related to GLOFs are most deceptive in the past few decades in the Himalayan region, where the number of GLOFs events has been increased significantly (Veh et al. 2019; Schmidt et al. 2020; Majeed et al. 2021; Shugar et al. 2021). Few studies have been conducted to account for the lake expansion in the Ladakh region regarding the impact of glacier recession and associated lake development due to climate change (Schmidt et al. 2020; Majeed et al. 2021). High-resolution satellite imagery is beneficial to account and monitor the evolution of glacial lakes and glacier changes in the Himalayan region (Schmidt et al. 2020; Pandey et al. 2021; Majeed et al. 2021; Allen et al. 2021) and gained considerable attention in the recent past decades.

Changing climate has also altered the general hydrogeochemistry of glacial lake water and shift in the biophysiochemical exchanges in the catchment area (Roberts et al. 2017; Woelders et al. 2018; Steingruber et al. 2020). It is predicted that the high-altitude lakes in the Himalayan region and Arctic are likely to respond to present climate instability, leading to variations in lake water chemical composition (Salerno et al. 2016; Kosek et al. 2021; Ruman et al. 2021). Lakes ecosystems are strongly coupled to the features of their different climatic regimes, neighboring landscapes, geomorphological characteristics, local vegetation, bedrock lithology, and accumulation of anthropogenic activity (Salerno et al. 2016; Gurung et al. 2018; Ruman et al. 2021; Kosek et al. 2021). Most of the glacial lakes are situated in a pristine environment high up in the Himalayan ranges and Arctic region, which are generally less impacted by the direct influence of anthropogenic activity (e.g., Samudra Tapu, Gepang Gath, Dehnasar, Satopanth Tal, Bhrigu Lakes in Himalayas and Hazen, Kongressvatn, Bungevatnet, and Revvatnet Lakes in high arctic regions). Climate change has also increased the moisture transport through the wind circulation from oceans to the high-mountains and polar regions and falling either as solid or liquid precipitation and brings a variety of pollutants (Kosek et al. 2021; Ruman et al. 2021). Any addition of these pollutants in the form of sulfur, nitrate-containing compounds, persistent organic pollutants (POPs) and trace elements to the glacial lake ecosystem via atmospheric deposition, there is a negligible chance for removal or uptake of such pollutants due to the limited buffering capacity of the lake (Li et al. 2014; Ruman et al. 2021). Therefore, high-altitude lake is identified as a sensitive indicator of changing climate in the global and regional environment (Karlsson et al. 2015; Salerno et al. 2016; Roberts et al. 2017; Woelders et al. 2018). Several studies are conducted on the impact of climate change through hydrochemistry on the glacial lakes of the Himalayas and High Arctic region (Karlsson et al. 2015; Dean et al. 2016; Roberts et al. 2017; Gurung et al. 2018; Woelders et al. 2018; Shukla et al. 2018; Slukovskii et al. 2020; Ruman et al. 2021; Khadka and Ramanathan 2021; Kaphle et al. 2021; Majeed et al. 2021). However, only a few Himalayan glacial lakes have been studied due to their inaccessibility, harsh climatic conditions, and challenging landscape.

Here, in this work, we study the evolution of Lato glacier lake in the Ladakh region with consideration to ongoing climate change and its impact. The Lato Lake is situated at the junction of two atmospheric circulation systems (mid-latitude westerlies and the Indian summer monsoon); thus, Lato Lake is a suitable site to understand the various environmental changes contributed from these circulations (Kumar et al. 2020). The current study focuses (a) to understand the sources of solute and factors controlling the hydrogeochemistry of the Lato Lake (b) to investigate the area change of Lato Glacier and lake under changing climate based on remote sensing datasets and (c) to understand the effect of long-range transport and atmospheric deposition in the hydrochemistry of lake water. This study provides a baseline dataset for further research work on the impact of climate change on hydrochemistry and area changes of the moraine-dammed lakes in the Ladakh and adjoining regions. This study will also help in policy and strategies to reduce the impact of GLOFs and adaptation practices on the forecasted changes in the region.

Site description and geology of the study area

Lato Lake is one of the unexplored high-altitude lake near Lato and Gya-Miru Village in the Leh-Ladakh region (Fig. 1). The region is a core constituent of orthogenesis and granite, with late Cenozoic and Precambrian metasedimentary rocks surrounding it (Schlup et al. 2003). Meteorological data from Leh's weather station are considered to reflect the semi-arid climate of Zanskar's (Osmaston 2001). This lake is located 15 km away from Lato village and ~ 80 km from Leh city. The maximum length of the lake is about 900 m with 300 m width and located at an altitude of around 5200 m.a.s.l. Using a simple approach based on area-depth relationship, followed by several studies in the Himalayan region (Fujita et al. 2009; ICIMOD, 2011; Sakai, 2012; Fujita et al. 2013, Patel et al. 2017), the mean depth of Lato Lake is about 19 m. The present study focuses on the Lato Glacier and Lato village (altitude: ~ 3900 m.a.s.l) located in the Leh-Ladakh, Western Himalaya. At present, the glacier area is about 5.06 km^2 extending ~ 3.8 km, with the glacier snout located at an elevation of 5300 m.a.s.l. Glacial meltwater contributes to the various agricultural and domestic requirements in the downstream village. Lato Lake is connecting with a series of small lakes, and these small lakes are continuously expanding (according to our field observation of 2 years). There are no documented works available on the glacier/lake area change and hydrochemistry of the lake. In this region, the meltwater from the glacier is terminating in

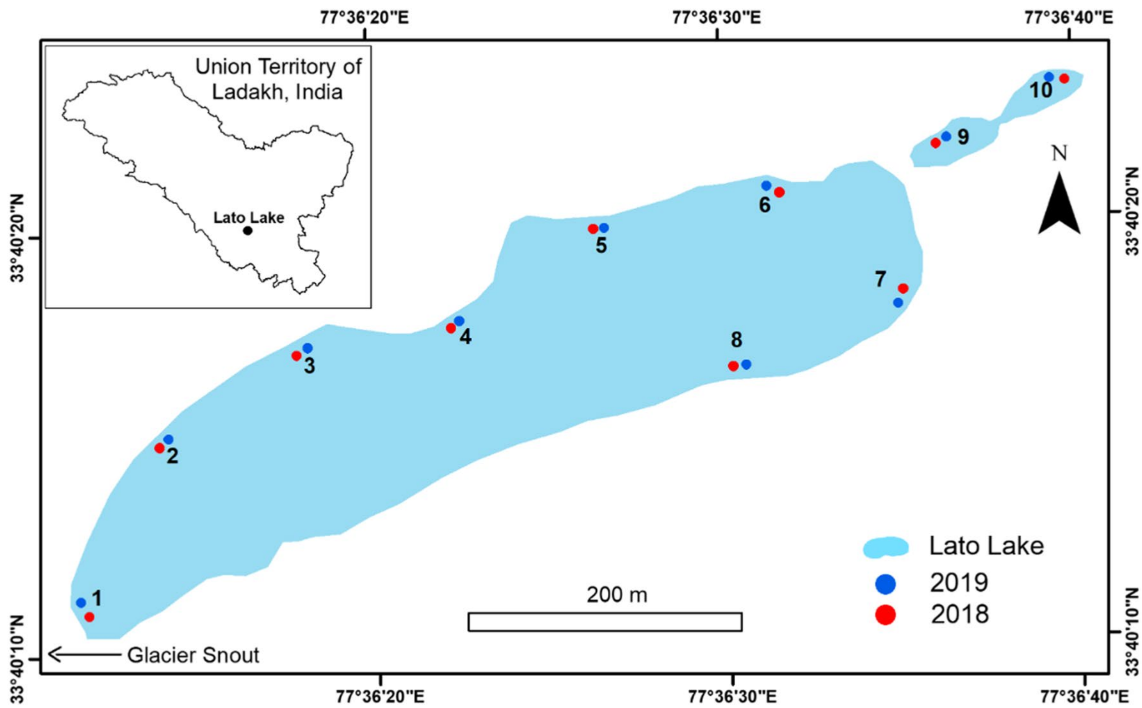

Fig. 1 Map showing sampling location of Lato Lake during 2018–19. The sampling location of 2019 (in blue color) and 2018 (in red color)

Lato Lake and finally drains downstream. The stream from the Lato catchment fed the Lato and Miru village (~100 households; ~500 individuals) before the confluence with the Chabe Nama stream and further with the Indus River.

Materials and methods

Sampling preparation and analytical procedure

Samples were collected from Lato Lake in the month of July during 2018–2019. The samples (n = 20) were gathered from different locations around the lake (Fig. 1). Samples were taken in pre-cleaned high-density plastic bottles (100 ml) around 10–15 cm beneath the surface water. The bottles were washed thrice with the lake water before the sample collection. *In situ* measurements of pH and EC were carried out using a portable Multiparameter kit (Thermo-STARA3250 series). For chemical analysis, the collected water samples were transported to the School of Environmental Science laboratory, Jawaharlal Nehru University, New Delhi. They were then filtered using 0.45 µm pore size syringe filters (Axiva SFNY25X Nylon) and refrigerated at 4 °C before analysis. Cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) were analyzed by ICP-OES (Thermo iCAP 76,000 Series), whereas anions (F^{-}, Cl^{-}, NO_3^{-} and SO_4^{2-}) were determined by ion chromatography (Metrhom 930 Compact IC Flex systems). HCO_3^{-} was analyzed by acid titration using the brucine-sulphanilic acid method (APHA 2005). In order to avoid contamination, masks and gloves were used during the sampling and analysis in the laboratory. Freshly prepared standards were used for the analysis, where blank standard and sample after analysis showed no cross-contamination. Limits of detection (LOD) and quantification (LOQ), precision and accuracy of major ions for 2018 and 2019 are presented in Table 1. Error and accuracy of the major ions data are calculated by using the formula $\{(TZ^{+}–TZ^{-})/(TZ^{+}–TZ)\} \times 100$ which represent < 10% error.

Statistical software

Aquachem software (Version 5.1)) was used for plotting the Piper diagram, whereas for statistical analysis, SPSS software (Version 10.5) was used for principal component analysis, and R-Studio software was used for correlation matrix.

HYSPLIT backward trajectory model

The backward trajectory model is a valuable technique for tracing the sources of atmospheric input in the high-altitude glacial lake (Diéguez et al. 2019; Deka et al. 2015a). In order to trace the atmospheric input into the lake environment, trajectories were computed from the HYSPLIT model using the open-source available at the Air Resources Laboratory website (http://www.arl.noaa.gov/ready.html) (Stein et al. 2015; Rolph et al. 2017). Archive data set from Global Data

Table 1 Limits of detection (LOD) and quantification (LOQ), precision and accuracy of major ions for 2018 and 2019

	F^-	Cl^-	NO_3^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
2018	IC	IC	IC	IC	ICP	ICP	ICP	ICP
Range of calibration (mg/L)	0.5–5	1.0–10	1.0–15	1.0–15	0.5–10	0.1–10	0.1–10	0.1–10
LOQ (mg/L)	0.55	0.33	3.77	6.17	1.06	0.38	1.06	0.75
LOD (mg/L)	0.05	0.03	0.37	0.61	0.10	0.04	0.10	0.07
Precision (%)	±2.02	±0.59	±0.73	±0.54	±1.67	±1.98	±5.36	±2.15
Accuracy (%)	2.40	0.48	0.89	0.82	2.48	4.40	9.80	6.20
2019								
Range of calibration (mg/L)	0.5–5	1.0–10	1.0–15	1.0–15	0.5–10	0.1–10	0.1–10	0.1–10
LOQ (mg/L)	0.14	0.07	0.74	0.90	0.24	0.07	0.27	0.22
LOD (mg/L)	0.05	0.03	0.33	0.61	0.09	0.03	0.11	0.09
Precision (%)	±2.23	±1.02	±0.56	±0.54	±1.89	±2.65	±3.98	±1.85
Accuracy (%)	4.7	1.7	1.0	0.8	1.6	4.8	5.8	5.6

Assimilation (GDS) was used as meteorological input. The trajectory's height was evaluated at three different altitudes of 5000, 5100, and 5200 above sea level and run for 120 h from the lake location.

Satellite data

The study uses easily accessible satellite images to define the glacier and lake boundaries of different years (Fig. 2).

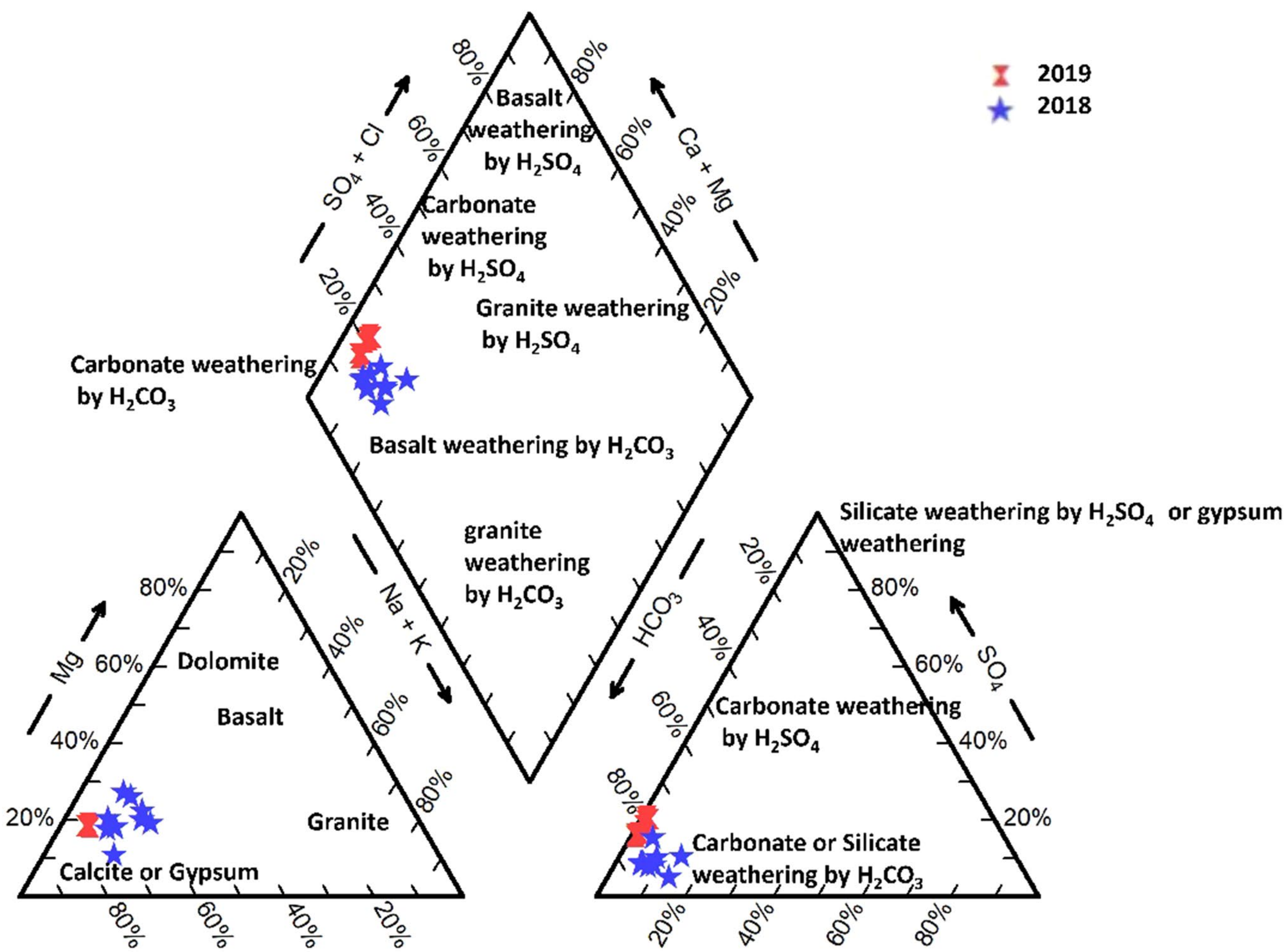

Fig. 2 Piper trilinear diagram showing the hydrogeochemical facies in the Lato Lake

We use images of the Landsat series from 1991, 1998, 2001, 2010, and 2019 (TM, ETM+, and OLI) to delineate glacier and lake boundaries. We use the semi-automatic method of shortwave infrared and red band ratio with other manual modifications (Racoviteanu et al. 2009). Followed by then, we also use declassified aerial corona images from 1969 to 1993 to find out the lake and glacier area (detailed in the paper of Soheb et al. 2020).

Results and discussion

Hydrochemistry of the lake

Hydrogeochemical characteristics of lake water provide vital information about the solutes sources and weathering processes in the glacial lake environment. The average chemical configuration of lake water is presented in Table 2. The lake is mostly alkaline, with pH ranging between 7.6 and 8.1, whereas the electrical conductivity ranges between 29 and 61 µS/cm during the study period. Lake water chemistry shows anionic abundance: $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^- > F^-$ in 2018, while in 2019, $HCO_3^- > SO_4^{2-} > NO_3^- > Cl^- > F^-$, whereas phosphorus was below detection limit in both the years. Cationic abundance varied as follows: $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ in 2018, while in 2019, $Ca^{2+} > Mg^{2+} > K^+ > Na^+$. However, Na^+ prevailing over K^+ due to its greater mobility and weathering of silicate minerals from the metamorphic and igneous rocks. (Sharma et al. 2013). HCO_3^- is the most predominant ion followed by Ca^{2+} and SO_4^{2-} as in other Himalayan glacial lakes presented in Table 3. Among the cations, Ca^{2+} and Mg^{2+} are the major constituents and produce 68 and 18% of the total cations, whereas for the anions, HCO_3^- and SO_4^{2-} are the major constituent and produce 76 and 13% of the total anions.

Ionic Ratio and Effective CO_2 pressure

Ionic ratios of Lato Lake during the period 2018–19 are presented in Table 2. Ionic ratios were $Na^+/Cl^- > 1$ in 2018 and > 2 in 2019, while $K^+/Cl^- > 0.9$ in 2018 and > 2 in 2019. All the ratios were greater than the resultant seawater ratios ($K^+/Cl^- = 0.02$ and $Na^+/Cl^- = 0.86$) (Pant et al. 2018). These ratios revealed the influence of atmospheric contributions in lake water (Singh et al. 2014b). The comparatively high $(Mg^{2+} + Ca^{2+})/TZ^+$ (> 0.75) and the low of $(Na^+ + K^+)/TZ^+$ (< 0.15) ratio revealed that the hydrochemistry is mainly dominated by carbonate weathering afterward silicate weathering (Singh et al. 2016). The cationic ratio of $[Mg^{2+} + Ca^{2+})/ Na^+ + K^+]$ is generally used to estimate the comparative influence of different rock types in the

Table 2 Summary of the chemical concentrations and ionic ratios of Lato Lake for 2018–19. (Unit: EC in µS/cm; dissolved ions, TZ^+ and TZ^- in µeq/L)

	2018				2019			
Parameters	Max	Min	Avg	STDEV	Max	Min	Avg	STDEV
EC	38	29	32	2.50	61	38	46.20	6.0
pH	8.10	7.60	7.80	0.14	8.10	7.60	7.90	0.20
HCO_3^-	435.90	299.90	375.50	44.80	399.90	299.90	330.0	48.20
SO_4^{2-}	57.60	24.40	41	10.50	106.10	60.70	77.70	11.50
Cl^-	75.10	19.70	39.20	19.40	8.90	3.70	5.50	1.50
NO_3^-	16.30	7.20	12.10	2.80	23.0	18.90	21.70	1.30
F^-	9.0	2.0	3.80	2.0	6.20	2.70	4.50	0.90
Ca^{2+}	421.70	273	363.90	52.50	400.70	247.50	301.40	39.90
Mg^{2+}	152.20	40.30	111.20	33.10	102.80	59.20	73.60	11.40
Na^+	75.40	30.40	44.80	13.90	14.40	8.70	10.80	1.60
K^+	67.40	16.90	31.30	14.40	17.10	12.30	13.80	1.50
TZ^+	669.80	372.90	551.10	87.50	535.0	330.0	399.60	53.80
TZ^-	548.40	366.80	471.60	60.40	535.70	388.0	439.40	54.70
$Ca+Mg/TZ^+$	0.90	0.80	0.86	0.03	0.94	0.93	0.94	0.00
$Na+K/TZ^+$	0.20	0.10	0.14	0.03	0.07	0.06	0.06	0.00
Ca + Mg/Na + K	9.09	3.99	6.66	1.83	16.67	13.21	15.31	1.22
Ca^{2+}/Na^+	12.81	5.44	8.62	2.29	31.26	23.71	28.13	2.78
Mg^{2+}/Na^+	4.38	0.94	2.63	0.99	7.57	5.67	6.86	0.70
Na^+/Cl^+	2.16	0.62	1.30	0.47	3.88	1.36	2.09	0.70
K^+/Cl^+	1.52	0.24	0.90	0.35	4.64	1.66	2.67	0.82
C-ratio	0.94	0.84	0.92	0.03	0.84	0.79	0.81	0.02
pCO_2	−3.92	−4.38	−4.16	0.12	−3.88	−4.50	−4.26	0.21

Table 3 Comparison of hydrochemistry of Lato Lake with other Himalayan lakes (Unit: EC in µS/cm; dissolved ions in mg/L)

Lakes	EC	pH	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	References
Chandratal	212	8.10	118	12.50	0.50	0.50	22.40	13.20	0.90	1.40	Singh et al. 2016
Pandoh	80.80	7.10	49.20	2.70	2.40	10.3	18	3.30	3.80	2.10	Anshumali and Ramanathan 2007
Suraj Tal	140	9.10	130	22	5.0	0.10	32.10	10.50	2.60	0.30	Singh et al. 2014a
Deepak Tal	130	8.80	120	20	4.30	0.10	30.50	8.80	2.80	0.30	Singh et al. 2014a
Begnas	90.50	7.30	25.30	7.30	2.60	5.30	7.0	2.0	3.90	1.40	Khadka and Ramanathan 2013
Pehwa	58	7.70	16.88	10.70	0.69	3.80	2.44	1.70	1.54	3.20	Khadka and Ramanathan 2021
Rara	189	8.30	54	0.14	0.10	-	9.17	5.89	0.80	0.35	Gurung et al. 2018
Sella	5.20	6.50	11.30	3.70	0.50	0.70	0.90	0.30	2.20	0.30	Deka et al. 2015b
Lato	24.40	7.61	21	3.0	0.72	1.11	6.56	1.03	0.84	0.58	Present Study

catchment (Ahmad et al. 1998; Zhang et al. 2007). The high molar ratio (> 6 in 2018 and > 15 in 2019) signifying the relative weakness of silicate dissolution and suggested the dominance of dolomite and calcite rich-weathering (Singh et al. 2014b).

C-ratio and pCO_2 variations in Lato Lake were presented for two years of 2018–19. pCO_2 was calculated using pH and HCO_3^- based on Wadham et al. (2001). The average pCO_2 values for Lato Lake were $10^{-4.16}$ atm during 2018 and $10^{-4.26}$ atm during 2019, respectively. The lower value of atmospheric pCO_2 during 2018–19 signified the dissolution of CO_2 into the lake water. If the adequate pressure of CO_2 in the solution is not equal to $10^{-3.5}$, then it is considered as an imbalance concerning the atmosphere. The low value of pCO_2 in the lake supported the coupling of carbonate dissolution and sulfide oxidation (Wadham et al. 1998). High-altitude glacial lakes are extremely cold, while CO_2 has a comparatively higher solubility rate associated with the release of surplus CO_2 to the atmosphere (Stumm and Morgan 1981). The average value of C-ratios is 0.92 ± 0.03 and 0.81 ± 0.02 during 2018–19. According to the earlier study, C-ratio indicates a huge massive source of atmospheric CO_2 increasing carbonate weathering when it is > 0.5 (Brown et al. 1996), the C-ratio in Lato Lake is quite high (0.81–0.92) hence suggests protons are resultant primarily from the dissociation and dissolution of atmospheric CO_2.

Hydrogeochemical features

We used a piper diagram (Piper 1944) for representing the association between water and rock types present in the lake (Fig. 2). In the piper plot, the cation triangle showed that maximum samples lie on the bottom-left side, suggesting the domination of Ca^{2+} in the lake water, whereas anion triangle presented that most meltwater samples are located in the bottom-left side close to the HCO_3-apex, indicating the domination of carbonate-rich lithology. The piper diagram showed the chemical facies of Lato Lake lied in the Ca–HCO_3 type for both years. Lake water composition is mostly mainly influenced by the bedrock lithology of the catchment area (carbonates, sulfide minerals, and silicates), which play a crucial role in varying the hydrochemical facies in the formation of Ca–HCO_3 type (Zang et al. 2020). The Piper diagram also suggested the dominance of alkaline earth metals (Ca^{2+} + Mg^{2+}) over alkalis earth metals (Na^+ + K^+) and weak acid (HCO_3^-) dominance over strong acid (SO_4^{2-} + Cl^-). There were no significant changes seen in the hydrochemical facies in the lake in 2018–19, which suggested that major ions primarily originated from the chemical weathering of carbonate rock from the lake catchment area.

Gibbs plot

The climatic parameters, mainly precipitation and temperature, have a large impact on the concentration of ions in the lake and glacial catchments. Lake hydrochemistry and its governing mechanism in a glacial environment can be qualitatively studied with Gibb's semi-logarithmic coordinates (Gibbs 1970). The ratios of $Cl^-/(Cl^- + HCO_3^-)$ and $Na^+/(Na^+ + Ca^{2+})$ in lake are < 0.5 and the distribution of water samples lies in the middle of the left side (Fig. 3). A lower concentration of Cl^- and Na^+ and a higher concentration of HCO_3^- and Ca^{2+} reflect that all the sites are mainly influenced by rock weathering of carbonate type. The results of these Gibbs plots revealed that the chemical characteristic of water is primarily governed by the geology of the area, which is consistent with the piper plot described above. Our outcomes are comparable with past studies of other Himalayan lakes and show rock weathering plays a significant role in glacial and river runoffs (Kumar et al. 2019; Singh et al. 2016).

Scatter diagram and mixing plot

SO_4^{2-} is the most abundant anion in both years after HCO_3^- in the Lato Lake. The possible sources of SO_4^{2-} in the Lato Lake could be from the natural origin, such as

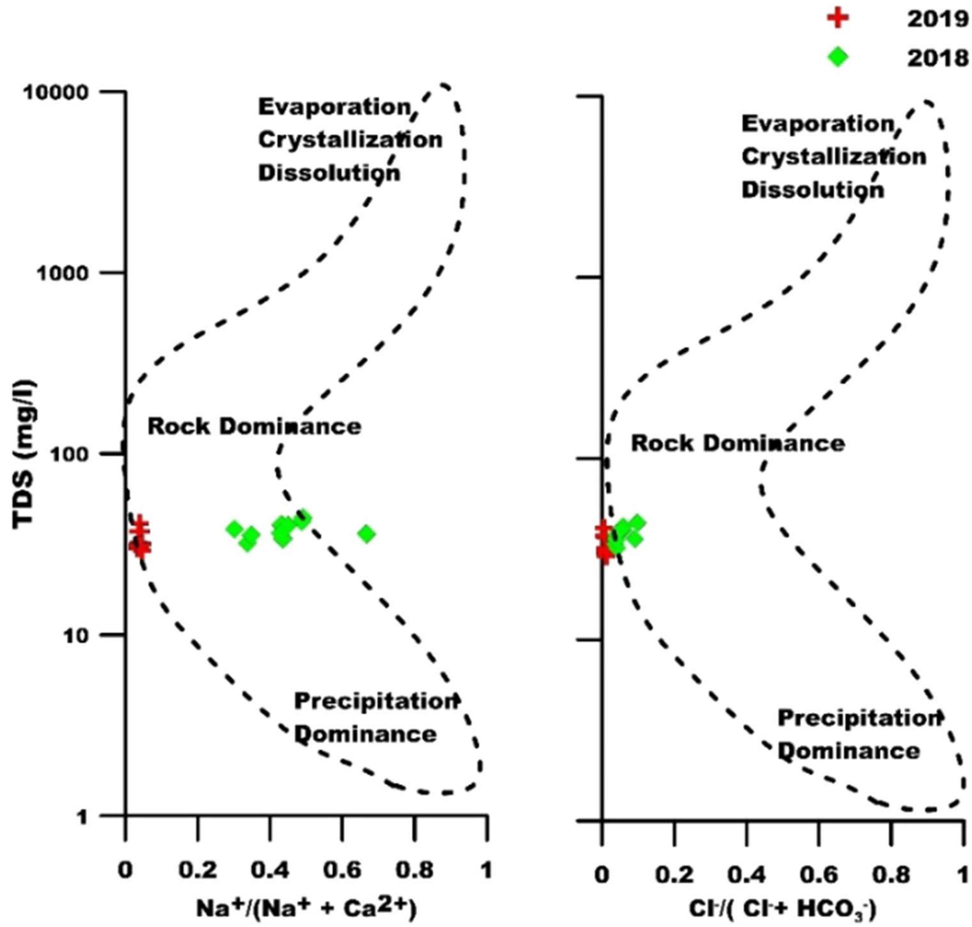

Fig. 3 Gibbs plots of Lato Lake in 2018–19. TDS versus Na^+/(Na^+ + Ca^{2+}) and TDS versus Cl^-/(Cl^- + HCO_3^-)

weathering of pyrite and gypsum (own mineralogy data, which are not shown here). In addition, anthropogenic (combustion of sulfur-containing fossil fuels and the smelting of nonferrous metals) and biological sources of SO_4^{2-} can also be contributing through atmospheric transport (Potapowicz et al. 2020). Overall rock-water interactions, atmospheric deposition, biological activity, morphology, and human activities are likely to affect the hydrogeochemistry in glacial lake environments (Singh et al. 2012). Sulfur dioxide in the atmosphere can further be reacted with water vapor to form H_2SO_4, and affecting the pristine lake environment (Zhang et al. 2020). The relationship between Ca^{2+} and SO_4^{2-} (Fig. 4) indicates that the samples in the Lato Lake for both years are found below the 1:1 gypsum dissolution line and below the 1:2 sulfide-carbonate weathering line. This implies that the majority of excess Ca^{2+} is coming from carbonate dissolution and silicate weathering. Hence, the contribution of sulfide dissolution from natural origin (like from evaporites sources) to the hydrochemistry in Lato Lake is insignificant. Therefore, the SO_4^{2-} contribution to the total anions 8.79% in 2018 and 17.73% in 2019, respectively, may be attributable to a weak influence from atmospheric acid deposition. Glacier mass loss is also considered a key factor for the rise of sulfate in lake water attributed to chemical variations, primarily to the sulfide oxidation that occurs in the subglacial catchment (Salerno et al. 2016).

Mixing end members among weathering products such as carbonates, silicates, and evaporates are widely used to study the rock weathering contribution to the primary element compositions in various hydrological regimes (Cao et al. 2016; Ollivier et al. 2010). The Na-standardized molar ratio of the Lato Lake for 2018 and 2019 is shown in Fig. 5. The plots show a high contribution of Ca^{2+} and HCO_3^-, corresponding to the shift of the water samples toward the carbonate weathering end member. It shows that the Lato Lake's major ion chemistry is contributed chiefly by the CO_3^- dissolution (~75%) and little contribution (~25%) from silicate and none from evaporates weathering. The dominance of carbonate dissolution over silicate weathering and the insignificant contribution from evaporates during the study suggest that Lato Lake functions predominantly as a temporary CO_2 sink. This observation is significant for the global carbon cycle since carbonate dissolution consumes CO_2 released into the atmosphere from oceans through carbonate precipitation over the time scale of thousands of years (Cao et al. 2015). The hydrochemistry in the lake is

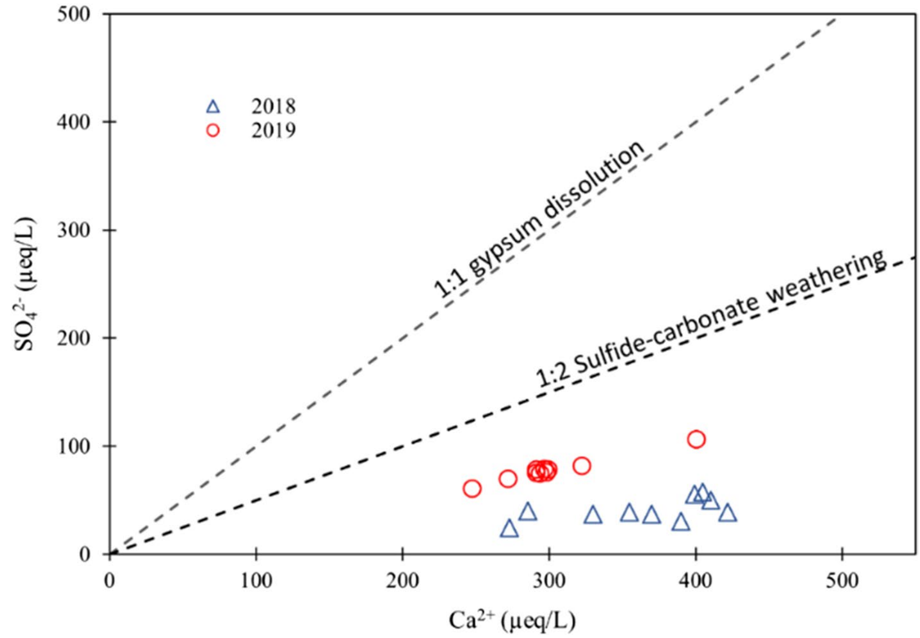

Fig. 4 Relationship between Ca^{2+} and SO_4^{2-} in 2018 and 2019 in the Lato Lake

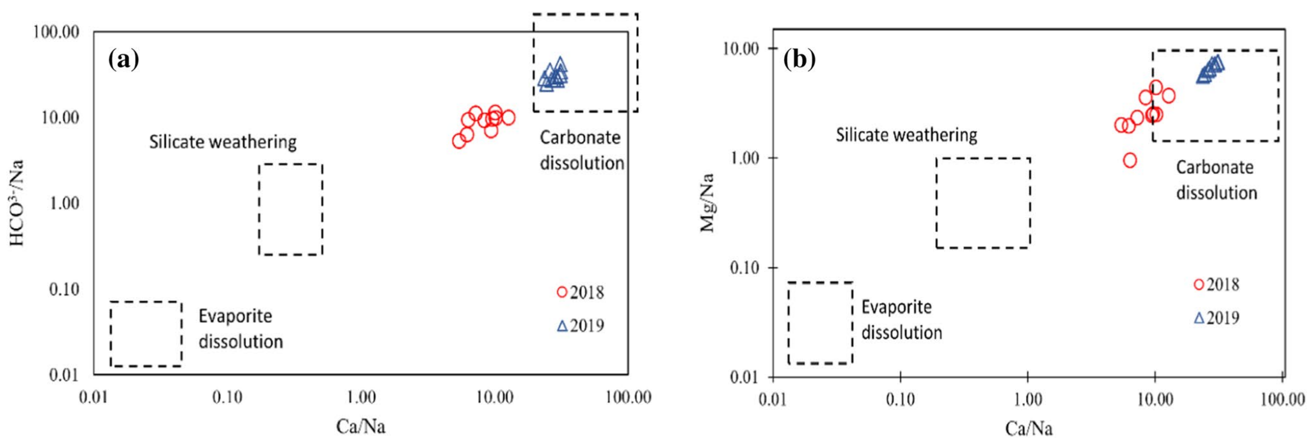

Fig. 5 End member mixing diagrams using Na-standardized molar ratios: **a** HCO_3^-/Na^+ vs Ca^{2+}/Na^+ and **b** Mg^{2+}/Na^+ vs Ca^{2+}/Na^+ in a log–log plot

likely influenced by atmospheric deposition inputs, chemical and mineral weathering of rocks.

Major sources and controlling factors of the hydrochemistry

Correlations Analysis

Correlation analysis can be useful for establishing the interrelationship among two variables and prophesying the degree of dependency of inter-elemental variables. In this present study, the correlation matrix is represented in the hydrochemical variables in Lato Lake (Fig. 6). In both years, we observed a strong positive association among Ca^{2+}–SO_4^{2-}, Mg^{2+}–SO_4^{2-}, Na^+–SO_4^{2-}. These positive associations suggested a similar source of these ions, and they might be coming from the pyrite oxidation, as well as and dissolution of sulfide minerals (Salerno et al. 2016; Singh et al. 2016). On the contrary, the relationship among HCO_3^-–Ca^{2+}, HCO_3^-–Mg^{2+}, HCO_3^-–Na^+ and HCO_3^-–K^+ is not significant. The relationship between SO_4^{2-} and HCO_3^- was not significant during the study period, whereas Na^+ and K^+ showed a strong positive association during 2019, indicating a similar origin of these two ions most possibly associated with the weathering silicate minerals. The negative correlation of Na^+–Cl^- in 2018–19 indicates halite's interface with meltwater and supported common lithogenic and marine inputs of these solutes (Jiang et al. 2015).

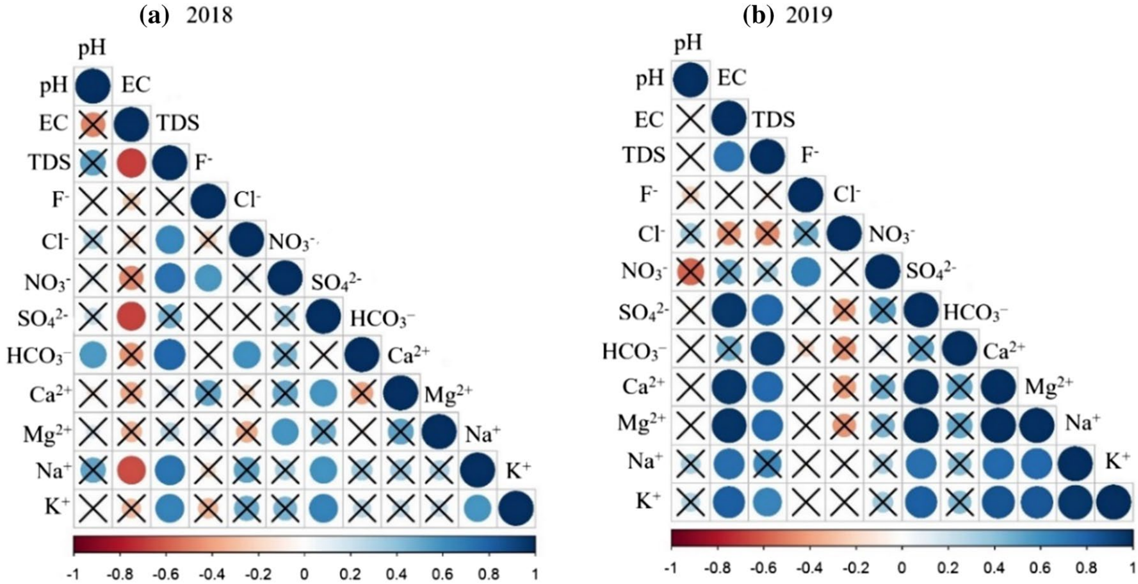

Fig. 6 The correlation matrix A and B showed the chemical parameters of Lato Lake in 2018–19. Cross indicate insignificant at 95% confidence ($p<0.05$) interval

Principal Component Analysis

PCA is a useful statistical technique applied to the hydrochemical parameter of lake water to reduce the dimensionality containing interrelated datasets (Singh et al. 2004). Factor analysis was applied to 12 parameters based on the 20 water samples. Factor analysis is categorized as strong and moderate loading equivalent to absolute values > 0.75 and 0.75–0.5 (Liu et al. 2003). It is indicated that three-factor loading with eigenvalues > 1, explained about 77.14% of the total variance in the dataset (Fig. 7). Factor 1 accounting for 35.54% of the total variance has strong positive loading of EC, NO_3^- and SO_4^{2-}, whereas moderate negative loading of Cl^-, K^+ and Na^+. The group of these hydrochemical parameters specifies diverse sources, for instance, atmospheric deposition, sulfide oxidation, and weathering of silicate mineral's might be the governing factor of these ions (Pant et al. 2018). Factor 2 accounted for 26.62% of the total variance, with strong positive Ca^{2+} and Mg^{2+} and moderate loading with TDS. These attributes specify that CO_3^- weathering is the primary source of these ions. Factor 3 accounts for 15.07% of the total variance while pH and HCO_3^- show moderate positive loading which reveals that the potential influences of rock–water interaction, as well as atmospheric deposition (Sun et al. 2010).

Cluster analysis (CA)

Hierarchical CA is a useful statistical tool applied to the hydrogeochemical dataset to group similar sampling sites (Pacheco Castro et al. 2018). Hierarchical cluster analysis

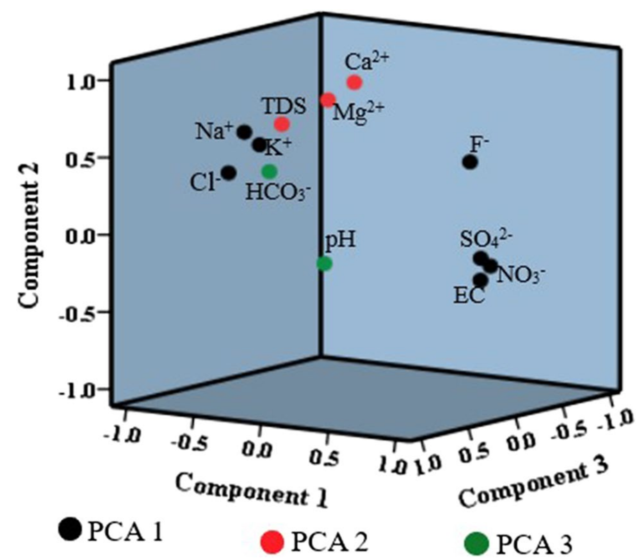

Fig. 7 Factor loading plot of the PCA for pH, EC, TDS, and major ions in Lato Lake during 2018–19

shows that lake water is divided into two principal cluster components presented through the dendrogram (Fig. 8). In both years, all sampling sites reflected low-to-moderate ionic strengths in the lake water. Meltwater samples from the similar sampling site reach were nearly classified into a similar cluster, indicating the similarity of geological background and hydrochemical characteristics with some minor changes over both years of the study. Present studies show a good agreement with previous studies conducted in other parts of the Himalayan Lake (Singh et al. 2016). Additionally,

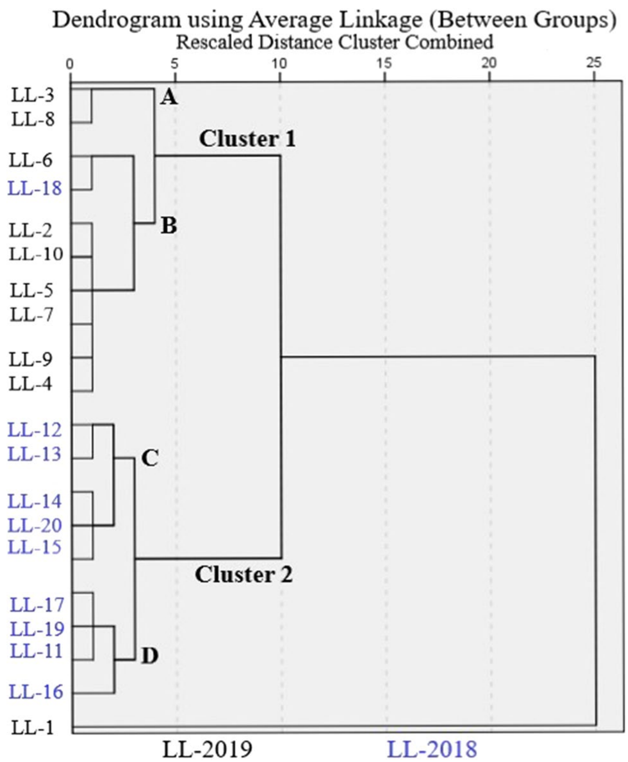

Fig. 8 Cluster analysis showing the linkage of water samples from 10 locations during 2018–19

rock–water interactions, atmospheric deposition, biological activity, and morphology may also have been altered the hydrogeochemistry (Singh et al. 2012; Szopińska et al. 2018).

Tracing the atmospheric sources through HYSPLIT backward trajectory

Using the HYSPLIT model, the air mass is tracked during the study time to trace the sources of atmospheric input in the lake environment. The black star represents the lake location, and HYSPLIT backward trajectory modeled the sources of water vapor. Figure 9a and b shows the possible source of atmospheric input reaching Lato Lake during the sampling period. The air mass trajectories (Fig. 9a) suggested that air inward at the locality of the lake had originated from the westward direction from the Gulf of Persian/Arabian in 2018, while during 2019 (Fig. 9b), it shows the eastward direction from the Bay of Bengal. In the lake, the primary source of water vapor came from the Gulf of Persian/Arabian in July 2018 due to the westerly circulation system, while in July 2019, it came from the Bay of Bengal due to the Indian summer monsoon. Although the atmospheric sources mainly come from the seawater vapor transported by the monsoonal and westerly circulation systems, the results show that Lato Lake has substantial impacts on long-range

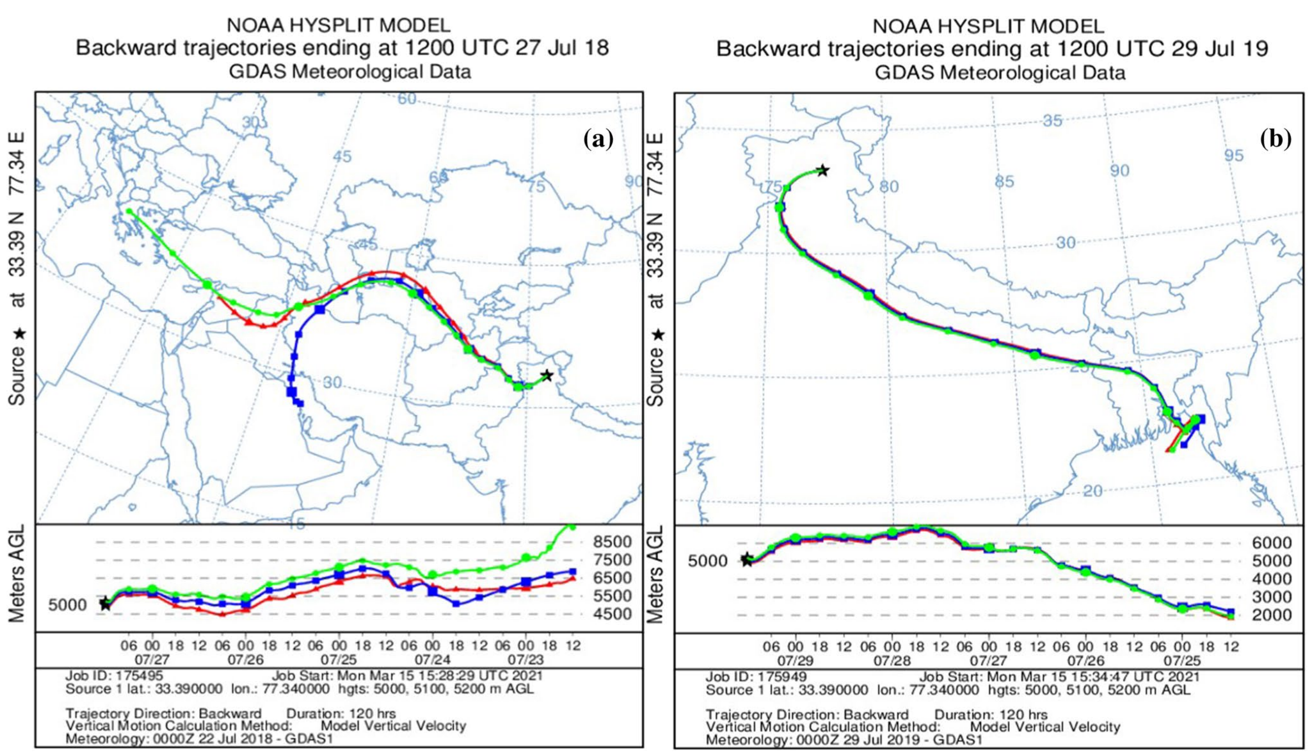

Fig. 9 The backward trajectory of the atmospheric source in the study area

transport rather than local interferences. Long-term monitoring can further verify the outcomes of this study.

Recession and expansion of Lato Lake and glacier

Lake, glacier, and snout changes between 1969 and 2019

Geospatial analysis carried out for Lato Lake shows substantial expansion in the lake area over the last five decades between 1969 and 2019. The glacier area is reduced by about 4%, while the lake area has increased by ~ 16%. The result shows that increased melting of the feeding Lato Glacier contributes to lake area expansion. The magnitude of the glacier retreat rate is 0.08%, while glacial lake increase rate is of 0.33% per year between 1969 and 2019. The lake area has increased about six times since 1969 (Figs. 10 and 11), which is quite significant in terms of GLOF hazards potential. Nüsser (2012) and Soheb et al. (2020) have reported a significant increase in the Ladakh region's air temperature and precipitation variability, which could be the primary cause of lake area expansion. Such expansion of lake area and water volume is a rising concern for the downstream villages, which could be vulnerable to catastrophic natural hazards like GLOF or avalanche break (Schmidt et al. 2020; Majeed et al. 2021). Such lake-related floods and catastrophic events are becoming more frequent in the Himalayan region, such as in 2014 adjacent to Gya village in the same catchment (Schmidt et al. 2020; Majeed et al. 2021).

Environmental implication and concern

The Himalayas has steadily laid more than 5,000 moraine-dammed glacial lakes that are possibly unstable (Kumar and Murugesh 2012). Thinning of glaciers due to retreating/shrinking and melting has aggravated the evolution of proglacial lakes and the amplification of present ones behind loosely consolidated moraines (Kumar and Murugesh 2012). These moraine-dammed glacial lakes are potentially unstable, and when it breaches, GLOF can cause geomorphic and disastrous societal impact (Veh et al. 2020). Several catastrophic in this region, Gya village of Ladakh, witnessed a GLOF in 2014 while a flash flood in Leh city in 2010 (Majeed et al. 2021). GLOF and debris flow catastrophic event in Kedarnath, Uttarakhand in June 2013 and a massive rock and ice avalanches in 7th February 2021 were the destructive disasters in the Chamoli district Uttarakhand (Dash and Punia. 2019; Shugar et al.2021). Hence, the monitoring of glacial lakes and preparedness for disaster risk reduction are some of the prime objectives of this study. If future projected glaciers mass loss remains, there is a possibility of forming more unstable moraine-dammed lakes; eventually, GLOF events in these regions may increase in the future. The gradual intensification and significant fluctuation of temperature and precipitation patterns can further result in frequent flash floods, cloudbursts, landslides, and GLOF in a climate-sensitive region like Ladakh with much higher intensity than reported earlier (Schmidt et al. 2020; Majeed et al. 2021).

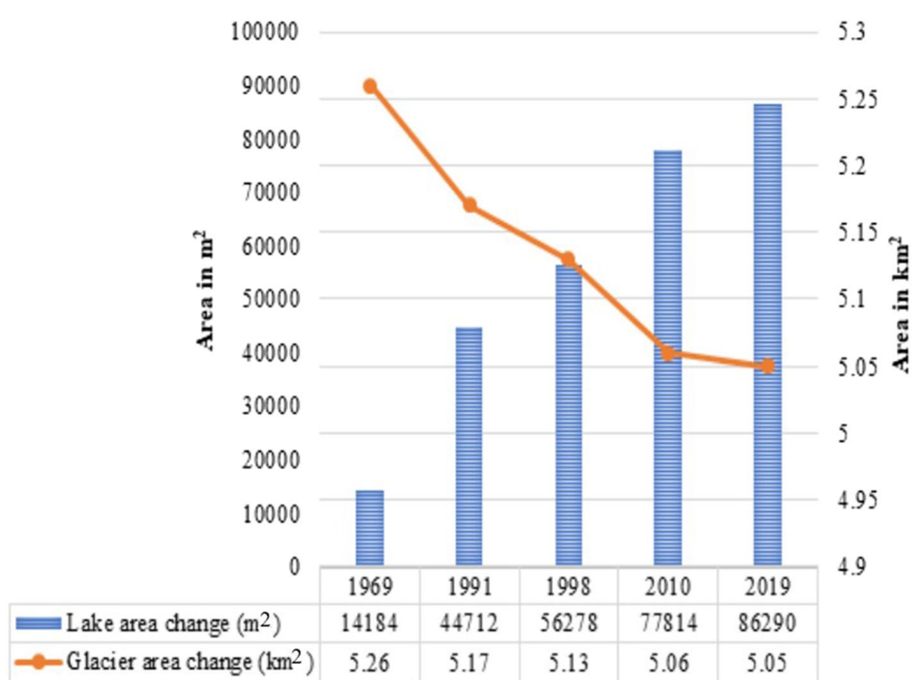

Fig. 10 Lato Glacier recession and lake expansion between 1969 and 2019

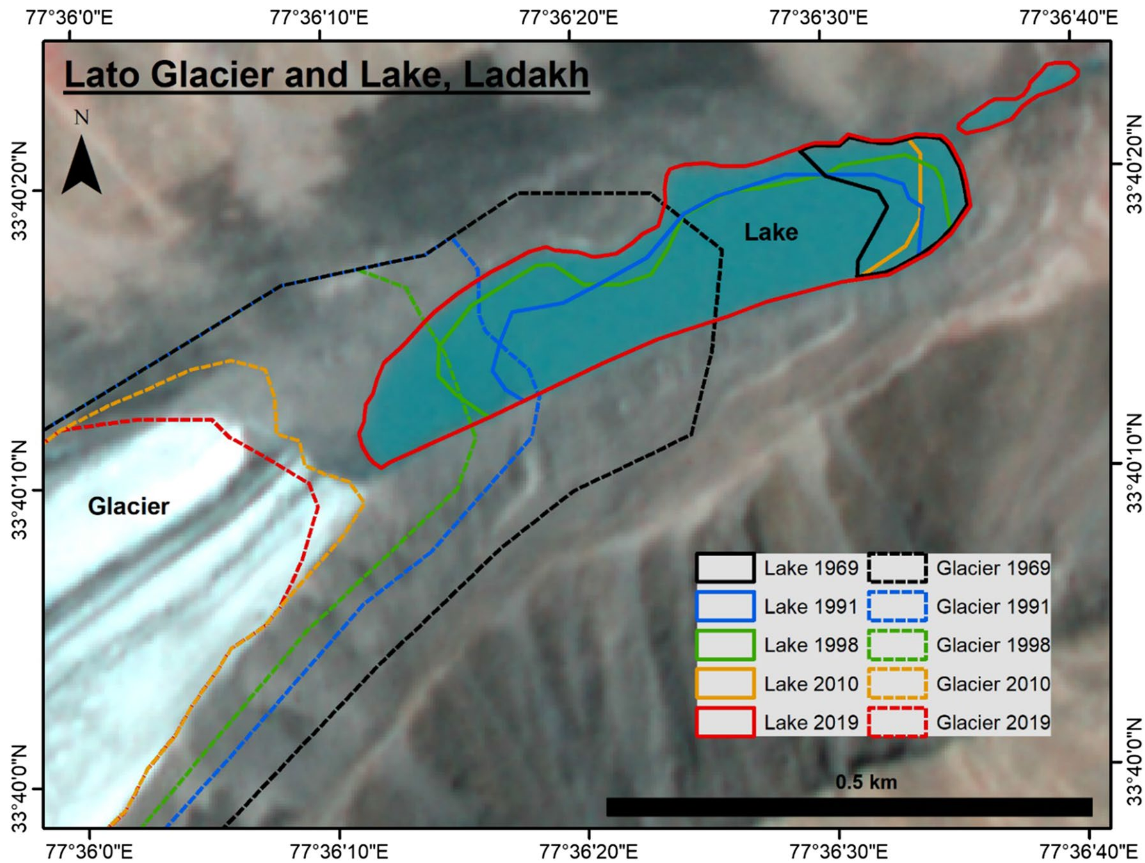

Fig. 11 Lato Glacier recession and lake expansion between 1969 and 2019

Conclusions

The study presents two years' primary dataset of the hydrogeochemistry and area change of moraine-dammed lake in the Ladakh region of western Himalaya. Our study covering 20 surface water samples reveals that the lake water is slightly alkaline with pH between 7.4 and 8.1. HCO_3^-, SO_4^{2-} and Ca^{2+} were the most dominant ions, respectively. CO_3^- weathering is the primary source of major ions, showing that the hydrochemistry of the lake water is primarily governed by local lithology and the high concentration of sulfate in the samples that are predominantly controlled by wet atmospheric deposition. We also hypothesize that glacier mass loss is another important factor for higher sulfate concentration in the lake water through subglacial sulfite oxidation. Such phenomena were previously reported in 20 Nepalese glacial lakes (Salerno et al. 2016). This study also explores the link between Lato Lake's area increase and Lato Glacier fluctuations under the influence of climate change. Between 1969 and 2019, Lato Lake expanded from 14,184 to 86,290 m^2 at the rate of 0.33% per year. Glacier area has reduced by about 4%, while the area of the lake area has increased by 16%, which is six times increased since 1969. This observation is quite significant in terms of GLOF hazards potential in the future with immediate impacts on the people of Lato village. Hereafter, the current study results build the baseline dataset, and continuous monitoring programs are suggested for the expansion and assessment of the lakes to trace the impact of climate change.

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Author contributions HK, ALR, MS, and MSS conceptualized the study. ALR supervised the study. HK, KB, CS, and AM performed the analysis, developed the figures, and wrote the paper. All authors contributed significantly in fieldwork and to improve the draft manuscript.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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