

Tracing the Imprints of Climate Change through Hydrogeochemical Studies on the Eastern Himalayan High Altitude Lakes

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Abstract: Four high altitude lakes i.e Sella Lake, Pangang Tang Tso Lake, Shungatser Lake and Tskyo Tso Lake located at an altitude of 3962 metres in the Eastern lesser Himalaya were monitored for seasonal variation in hydrogeochemical processes and effective CO₂ pressure in order to understand the imprints of climate change. A comparative scenario of water quality among high altitude Himalayan lakes has been also presented. In the post-monsoon season, all major cations increased whereas major anions except NO₃⁻ increased in the lake system. The results revealed that major cations in the lakes in post-monsoon increased whereas major anions except NO₃⁻ increased in post-monsoon. During pre-monsoon, Ca-HCO₃ type and Ca-Mg-SO₄ type were the major faces of lake water which changed to Na-SO₄ and Ca-Na-HCO₃ type in post-monsoon. It was found that wet precipitation of aerosols is the most important source of major ions followed by chemical weathering. The pCO₂ has increased in the post-monsoon probably due to higher atmospheric CO₂ during winter than that of rainy season. Factor analysis revealed that weathering, anthropogenic are the main governing process in the pre-monsoon whereas evaporative enrichment and geochemical inputs are the main process in the post-monsoon season. ANOVA analysis showed significant difference for pH, EC, SO₄²⁻, NO₃⁻, Na⁺, K⁺ indicating input from evaporative enrichment, weathering and long range transport of pollution to lake system.

Keywords: High altitude lake; Trace elements; Factor analyses; Weathering; Climate change.

Introduction

High altitude lake (HAL) research is of significant importance as changes in the lake chemistry can reflect global climate change (Thies et al., 2007). This is especially because these lakes are located in the pristine environment, in general lacking direct anthropogenic impacts. Further, if certain pollutants, such as major ions, trace elements, sulphur or nitrogen

containing compounds are being added to such system through dissolution atmospheric transport, there is minimal opportunity for neutralization or uptake of such compounds (Li et al., 2014). This is due to limited buffering capacity of lake attributed to the purity of water and weak soil-water interaction. Therefore, HALs are known as sensitive indicators of changes in local, regional or global environment (Talbot, 1996; Clow et al., 2001; Gopal, 2005; Zaharescu et al., 2009).

Being normally oligotrophic, and located on non-sedimentary basins ice-covered during the major portion of a year, the hydro-geochemistry of HALs is primarily influenced by the lithology, mineralogy, catchment area, weathering process operated in the vicinity of lakes and the weathering resistance (Lewin and Macklin, 1987; Zaharescu et al., 2009). Lake water chemistry infers the linkage between evaporation, chemical weathering, precipitation catchment characteristics and the seasonal changes in major ion behaviour (Patrick et al., 1998; Anshumali and Ramanathan, 2007). Mineral weathering contributes the majority of base cations and alkalinity to HALs, thus seasonal variations in such parameters along with trace elements can largely reflect differences in the dominant mineral weathering reactions and atmospheric inputs. In a monsoon dominated tropical country like India, seasonal variations can be dominating enough to understand the imprints of climate change. Numerous studies reported elevated trace element burden introduced to lake system due to long range transport of air pollutants (LRTAP) (Han et al., 2007).

Chemical weathering is a dominant natural process that consumes atmospheric CO_2 and converts it into alkalinity (HCO_3^- and CO_3^{2-}) of the water (Gaillardet et al., 1999; Horowitz et al., 1999; Grasby and Hutcheon, 2000; Millot et al., 2002). Both natural and anthropogenic sources are responsible for change in the lake water chemistry. Since the Cenozoic period, origin and evolution of the Himalaya contributes towards the enhanced silicate weathering and hence to increased CO_2 drawn from the atmosphere (Raymo et al., 1988). Thus, the estimation of partial pressure of CO_2 ($p\text{CO}_2$) in lakes can reflect both internal carbon dynamics and external biogeochemical processes like climate change.

Literature available pertaining to high altitude lakes of the world is still weak and need strengthening in the context of present environmental challenges. Especially, the Himalayan HALs have gained less attention so far in terms of studies carried, but they are becoming increasingly important under climate change scenario (Fort, 2015). Moreover, scientific information on the Eastern Himalayan high altitude lakes is rare. Thus we have chosen four unexplored high altitude lakes in eastern Himalaya for our study. The aims of this study were namely to: (a) understand the imprints of climate change through seasonal variation in hydrogeochemical processes occurring in the lake water; and (b) estimation of effective CO_2 pressure ($\log p\text{CO}_2$) for monsoon and post-monsoon samples.

Materials and Methods

Study Area and Site Descriptions

Tawang district lies between North latitudes $27^\circ 52'$ and $27^\circ 28'$ and East longitudes between $91^\circ 32'$ and $92^\circ 23'$. The district is bounded by Lower Tibet in the north, Bhutan in the south and West Kameng district in the east. Annual rainfall in the district varies from 1500 to 2000 mm. The normal annual rainfall in Tawang area is nearly 1600 mm. Most of the rainfall is received during the monsoon period (May to September). Heavy rainfall is received during summer and occasional rainfall/snowfall during winter. January and February are the driest months. The rainfall received during summer is under the spell of South-West monsoon. The onset of South-West monsoon occurs by the end of May or the first week of June and it withdraws by late September or early October. The climate of the district is largely influenced by the nature of its terrain. The summer is moderate and extreme cold in winter. However, the mountain peaks are covered with perpetual snow. In winter, temperature falls below freezing point.

The nature and properties of soil vary with the area. The soils of the valleys are generally loamy or sandy loam mixed with coarser soil particles. Soil in greater part of the district is red sandy soils and skeletal soils. In the forested regions, the soil generally contains high humus and nitrogen due to extensive coverage of forests. Soils of the mountains are relatively lacking in organic materials. The soil of this category is reddish in colour and acidic in nature. The soil along the foothill areas is alluvial, loamy or sandy loam mixed with gravel and pebble brought down by rain waters from high altitudes. The soil in the valley is clayey alluvium and rich in organic content.

Surveyed four lakes (P.T. Tso, Sella, Shungatser and Tskyo Tso) are situated in the Tawang districts of Arunachal Pradesh and perched at an altitude of approximately 13,500 feet (Figure 1). While the other three lakes are natural lakes, Shungatser lake was originally a grazing field but took the lake shape due to massive earthquake in 1950's (Mathur, 2002).

Sella Lake

Sella Lake is situated in the Sella Pass which is the world's second highest pass, at an elevation of 4157 m (13,638 ft) above mean sea level at $92^\circ 06' 04.85''$ E and $27^\circ 30' 34.72''$ N latitude and longitude, respectively. The lake is mainly supplied by snow, ice-melt, and monsoon. The lithology of this region is highly

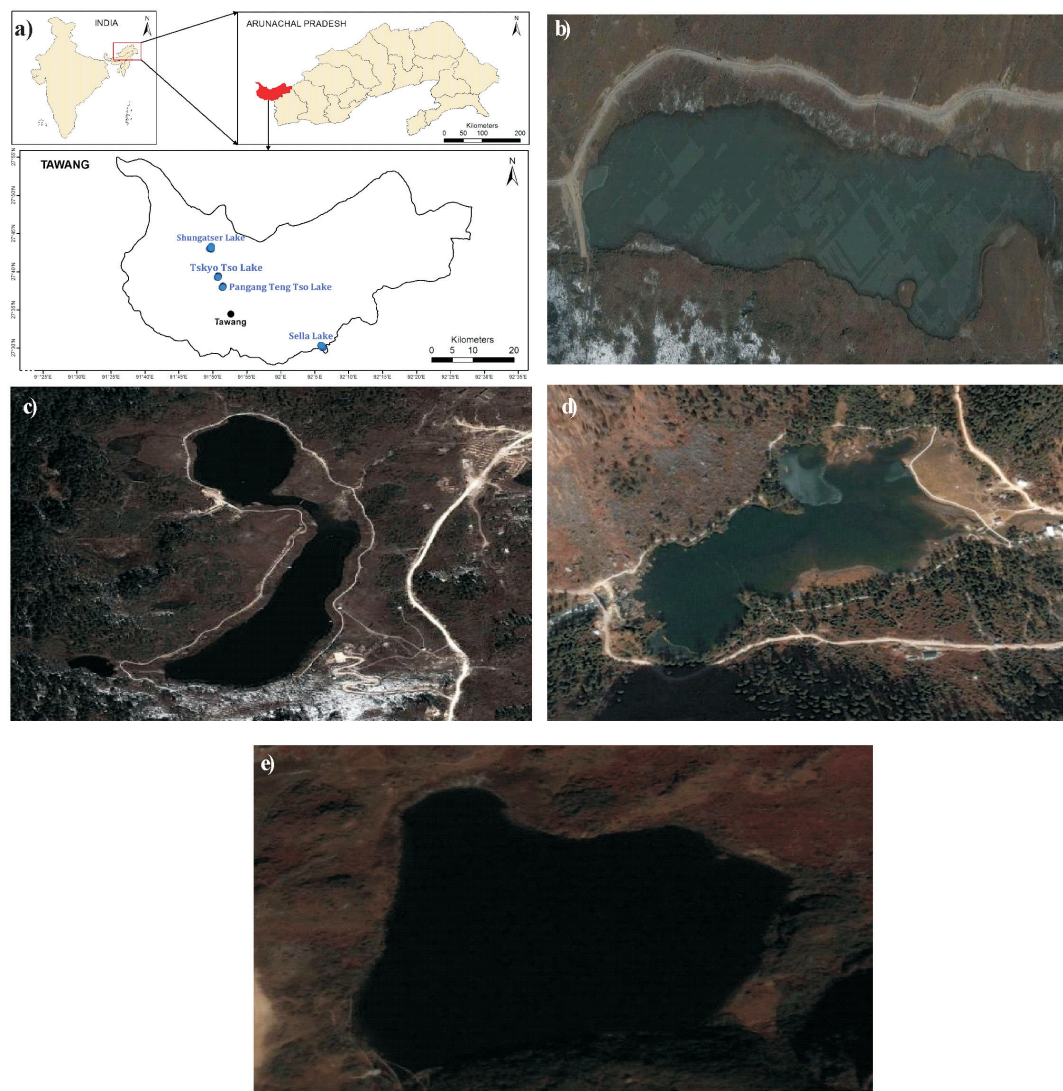


Figure 1: Map showing sampling site (a) Tawang district, Arunachal Pradesh with sampled, (b) Sella Lake, (c) Pangang Tso Lake, (d) Shungatser Lake and (e) Tskyo Tso Lake.

crumpled and undifferentiated. The region is hilly and sub-mountainous. Soil type is mainly silt and loam. It is rich in organic matter and acidic in nature. The soil is poor in nutrient availability (Kaushal et al., 2001).

Penga Teng Tso (P.T. Tso) Lake

Penga Teng Tso Lake, popularly known as P.T. Tso Lake, is located at around 12,000 ft in the eastern Himalayas. The lake is located at latitude and longitude of $27^{\circ} 36' 16.56''$ N and $91^{\circ} 51' 18.95''$ N. During the winter the lake remains entirely frozen. The soil is generally loamy or sandy loam mixed with coarser soil particles. In the forested regions, the soil generally contains high humus and nitrogen levels. The soil found along the foothill areas is alluvial, loamy or sandy loam mixed with gravel and pebble.

Shungatser Lake

Shungatser Lake is located at a distance of 42 kilometres from Tawang. This lake after the shooting of movie Koyla was named by tourists as Madhuri Lake. The Lake was formed in 1953, after an earthquake caused a mountain side to slide down and block the road of the stream flowing through it. There is a variation in climate around this area depending on the elevation. Here the temperature never rises above 20°C and remains much below freezing point during winter. Cold season starts from early part of November and continues upto late March. Winter season experiences snowfall. Weather remains pleasant from September to early part of November with little chill in the air.

Tskyo Tso Lake

Tskyo Tso Lake is situated at an altitude of 4123 m (13,526 ft) above mean sea level in the Eastern lesser Himalaya region. The latitude and longitude of the area are 91° 51' 52.43" E and 27° 39' 12.92" N, respectively. The circumference of the lake is 0.74 km.

Sampling

The sampling sites were selected in such a way so as to bear maximum representativeness for the lakes. The numbers of water samples were 39 and 36 in the pre-monsoon (May, 2011) and post-monsoon (November, 2011) seasons, respectively. Water samples were collected in two different poly propylene bottles of sizes 500 mL and 125 mL from the periphery of lakes at about 5 cm depth from the water surface. The water sample collected in the 125 mL bottles were filtered using 0.45 mm Millipore membrane filters with hand operated vacuum pump. The filtered samples were acidified with 2-3 drops of conc. HNO_3 in the field itself to bring pH less than two. Both acidified and raw samples were preserved at 4°C for further analyses. Unfiltered raw samples were used for major ion analyses whereas except magnesium (Mg^{2+}), calcium (Ca^{2+}) acidified samples were used for Mg^{2+} and Ca^{2+} trace metal analysis using inductively coupled plasma optical emission spectrometry (ICP-OES). On-site measurements included electrical conductivity (EC) and pH using portable Orion Thermo water analyzing kit (Model Beverly, MA, 01915). Alkalinity was also measured in the field using a titration method (APHA, 2005). For NO_3^- analysis, HBO_3 was used as preservative (Kumar et al., 2009).

Elemental Analysis

pH, conductivity and bicarbonate were measured in the field by using the sampling kit (Microprocessor water and soil analysis kit). Collected water samples were brought to the laboratory and stored in cold condition in order to avoid any major alteration for various physiochemical analyses (APHA, 2005). Sulphate (SO_4^{2-}) was measured by turbidimetric method. Nitrate (NO_3^-) was analyzed by using ultraviolet spectrophotometer screening method (APHA, 2005). The analysis was carried out in Lambda EZ-201 UV/VIS spectrophotometer. Phosphate (PO_4^{3-}) was measured by stannous chloride method. Reactive silica (SiO_2) was measured by molybdosilicate method. Chloride (Cl^-) was measured by silver nitrate test. The major cations like sodium (Na^+), potassium (K^+) and magnesium were determined by using Flame

Photometer. Magnesium (Mg^{2+}) and calcium (Ca^{2+}) were measured using inductively coupled plasma optical emission spectrometry (ICP-OES) (Perkin Elmer Optima 2100 DV). HBO_3 acid was used as preservative for NO_3^- analysis (Kumar et al., 2009).

Statistical Analysis

Pearson's correlation matrix was obtained to display linear relationship between the different physico-chemical parameters of both seasons. A correlation analysis is a bivariate method, applied to describe the degree of relationship between two hydrogeochemical parameters. The result of correlation analysis is considered in the subsequent interpretation. Both correlation and factor analysis was performed using Statistical Package for Social Sciences (SPSS) software (Version 21.0). Factor analysis aims to explain observed relation between numerous variables in terms of simpler relation for which the data have been standardized and presented using standard statistical procedures (Usunoff and Guzman-Guzman 1989). With the help of linear combinations, an originally large number of variables are reduced to a few factors. These factors can be interpreted in terms of new variables. One-way ANOVA was used to determine significant seasonal variations of chemical parameters in the Lake system.

Result and Discussion

Hydro-geochemistry of the Lake Water

The average chemical composition of the lakes is given in Table 1. The results reveal that major cations in the lake increased in post-monsoon season, major anions except NO_3^- also increased in post-monsoon season, though the variation was not too high. Such trends are an indicative of the addition of ions during monsoon period whether directly from the rain or runoff water of the catchment area. Decrease of NO_3^- is attributed to its consumption in biological processes and mineralization of the N, P-containing compounds by microorganism. Increase of other anion is the result of enrichment due to evapo-transpiration processes. Not much variation is observed among the different locations as evident from low standard deviation. This is also because water characteristics remain relatively uniform which are mixed by winds (Kaushal et al., 2001). Other factors responsible for the abundance and variation in major cations (Na^+ , Ca^{2+} , Mg^{2+} and K^+) and anions (Cl^- , SO_4^{2-} , NO_3^- , HCO_3^- and PO_4^{3-}) in surface water are weathering, atmospheric precipitation and possible atmospheric activities (Anshumali and Ramanathan, 2007).

Table 1: Statistical summary of the hydro-geochemical parameters of the lake water in monsoon and post-monsoon seasons

<i>Parameter</i>	<i>Pre to monsoon (N = 39)</i>		<i>Post to monsoon (N = 36)</i>	
	<i>Range</i>	<i>Avg±SD</i>	<i>Range</i>	<i>Avg±SD</i>
pH	3.5 to 7.9	6.57±1.09	4.41 to 6.66	6.0±0.49
EC	6 to 125	19.88±20.57	1.40 to 7.0	4.18±1.48
HCO ₃ ⁻	8 to 120	36.59±32.04	20 to 120	51.22±28.21
SO ₄ ²⁻	2.75 to 6.67	4.73±1.16	3.84 to 9.86	5.91±1.98
Cl ⁻	0.56 to 39.76	19.52±17.03	0.28 to 71	26.83±24.71
NO ₃ ⁻	0.00 to 6.34	1.26±1.21	0.08 to 1.25	0.45±0.21
PO ₄ ³⁻	0.00 to 0.021	0.06±0.05	0.02 to 0.41	0.08±0.07
Na ⁺	0.00 to 0.8	0.40±0.20	0.1 to 14.7	4.16±3.18
K ⁺	0.12 to 9.01	0.52±1.40	0.3 to 0.9	0.52±0.21
Ca ²⁺	0.002 to 6.24	1.46±0.97	0.05 to 2.49	1.48±0.60
Mg ²⁺	0.003 to 1.60	0.38 ±0.24	0.20 to 0.67	0.42±0.15
SiO ₂	0.77 to 3.33	1.75±0.55	1.36 to 32.99	3.40±5.26
logmHCO ₃ ⁻	-3.88 to -2.71	-3.41±0.43	-3.48 to -2.71	-3.15±0.26
pCO ₂	-3.68 to 1.12	-2.18±1.28	-1.93 to -0.05	-1.35±0.51

[All units are in mgL⁻¹, except EC (μS/cm), pH, logm HCO₃⁻ and pCO₂.]

The pH of lake water ranged from slightly acidic to acidic i.e. 3–7.9 with the average of 6.57±0.109 in the pre-monsoon season and 4.41–6.66 with an average of 6.0±0.49 in the post-monsoon season. This may be due to increase in SO₄²⁻ and Cl⁻ in the post-monsoon. Seasonal variations in the pH control the weathering pattern and availability of dissolved solids in lake water (Anshumali and Ramanathan, 2007). Electrical conductivity (EC) is a measure of the ionic strength and is dependent on the concentration, volume and rate of movement of ionic species (Das and Kaur, 2001). The conductivity of the lake was very less with an average of 19.88±20.57 μS/cm in the pre-monsoon season and an average of 4.18±1.48 μS/cm in the post-monsoon season, i.e. the lake is very dilute. Such low EC indicates that the lake had very little dissolved ions, i.e. the lake is very pure. However, higher EC in monsoon is another indication of addition of dissolved ion through rain and runoff. The order of the concentration of major cations was Ca²⁺>K⁺>Na⁺>Mg²⁺ in the pre-monsoon and Na⁺>Ca²⁺>K⁺>Mg²⁺ in the post-monsoon. Higher concentration of Na⁺ is probably due to silicate weathering that leads to addition of more Na⁺ in the system after monsoon. The order of the concentration of major anions in the lake water was HCO₃⁻>Cl⁻>SO₄²⁻>NO₃⁻>PO₄³⁻ for both seasons.

Graphical Representation of the Hydro-geochemical Data

The hydro-geochemical characterization lake water system is presented through Piper tri-linear diagram (Piper, 1944) (Figure 2). During the pre-monsoon season, the lake water facies were mainly of Ca²⁺-HCO₃⁻, Ca²⁺-Mg²⁺-SO₄²⁻ and Na⁺-HCO₃⁻ type whereas during the post-monsoon season water chemistry shifts to Na⁺-SO₄²⁻ and Ca²⁺-Na⁺-HCO₃⁻ type. Dominance of Ca²⁺ and SO₄²⁻ during both seasons suggested that alkaline earths exceed alkali metals and weak acidic anions exceed strong acidic anions in the studied lake system.

Low salinity water chemistry is controlled by the amount of dissolved salts furnished by atmospheric precipitation and chemical weathering (Gibbs, 1970). During rainy season, the major cations and anions are the result of atmospheric precipitation, but during dry season, they are consequence of atmospheric precipitation and chemical weathering processes (Anshumali and Ramanathan, 2007; Deka et al., 2015). Due to very low TDS and ion concentration in the lakes water discussed above, Gibbs plot can be used to evaluate the equilibrium state of the lake water with respect to the possible reactants and product minerals.

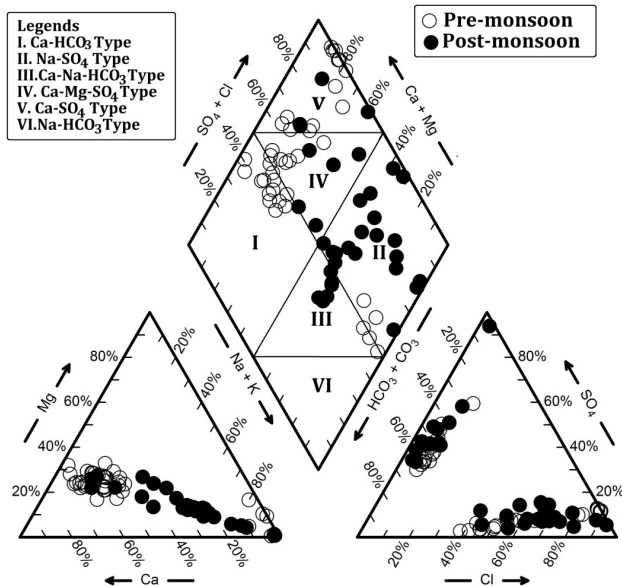


Figure 2: Piper plot showing the types of water of lakes in pre-monsoon and post-monsoon season.

Gibbs plot showed that precipitation is the most dominating geochemical processes that govern the water chemistry in all four lakes with certain insignificant variations (Figure 3). Moreover, TDS is lower than the average Indian rain water which indicates that lake water originally receives majority of the water through snow melting.

Multivariate Statistical Analyses to Identify Governing Processes

Correlation Matrix

The correlation matrices are given in Table 2 exhibiting the correlation among different hydrogeochemical parameters of lake water samples. In the pre-monsoon season, significant relationships were observed between pH-EC, EC-NO₃⁻, HCO₃⁻-Cl⁻, SO₄²⁻-Cl⁻, SO₄²⁻-PO₄³⁻, Cl⁻-PO₄³⁻ and Ca²⁺-Mg²⁺. Such inter-relationships between pH⁻, EC, NO₃⁻, SO₄²⁻, PO₄³⁻ and HCO₃⁻ is attributed to rainfall contribution and the effect of long range transport of pollution. During the post-monsoon season, significant and positive relationships were observed between pH-PO₄³⁻, EC-SO₄²⁻, EC-Cl⁻, EC-K⁺, EC-Ca²⁺, EC-Mg²⁺, HCO₃⁻-Cl⁻, HCO₃⁻-SiO₂, HCO₃⁻-K⁺, SO₄²⁻-Cl⁻, SO₄²⁻-K⁺, Cl⁻-K⁺ and Ca²⁺-Mg²⁺. In this season geochemical processes like chemical weathering and the local environment govern the water chemistry. Strong correlations were found between EC and K⁺, Ca²⁺, Mg²⁺ suggesting that the Ca²⁺ and Mg²⁺ cations contribute mainly to the EC of the lake water.

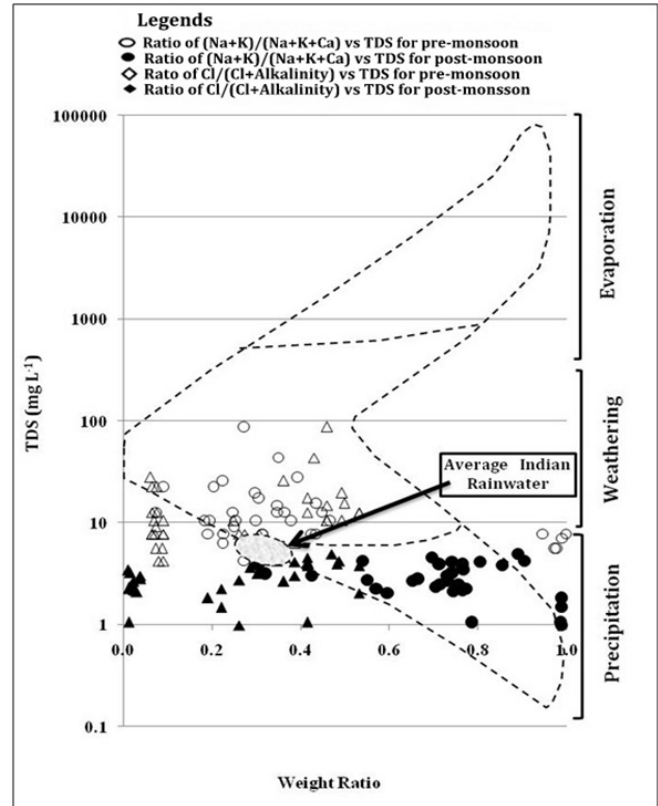


Figure 3: Gibbs Plot showing the mechanisms controlling the water quality lakes in pre-monsoon and post-monsoon season.

Factor Analysis

Factor analysis, which is also known as principal component analysis (PCA), is an efficient way of displaying complex relationships among many variables and their roles (Dalton and Upchurch, 1978; Fovell and Fovell, 1993; Guler et al., 2002). Eigen values greater than 1.0 were only considered to establish significant factors. In the monsoon season (Figure 4a), factor 1 accounted for 26.46% of variance in the data and it shows a strong geochemical association between EC, TDS and NO₃⁻ which indicates anthropogenic influence from long range transport of pollution in Lake water chemistry. Factor 2 represents association between SO₄²⁻ and Cl⁻ which indicates weathering contribution being induced due to rainwater alkalinity. This factor attributes to 18.34% of the variation of data. Factor 3 is accounted for 17.21% variation with high positive loading for Ca²⁺ and Mg²⁺ indicating prevalence of carbonate weathering in pre-monsoon season.

In the post-monsoon season (Figure 4b), factor 1 accounted for 33.25% of the variance and shows a strong positive loading between EC, HCO₃⁻, SO₄²⁻, Cl⁻ and K⁺ illustrating evaporative enrichment. Factor 2 explains

Table 2: Correlation matrix of the hydro-geochemical parameters of lake water in the pre-monsoon season and post monsoon season

	<i>pH</i>	<i>EC</i>	<i>HCO₃⁻</i>	<i>SO₄²⁻</i>	<i>Cl⁻</i>	<i>NO₃⁻</i>	<i>PO₄³⁻</i>	<i>SiO₂</i>	<i>Na⁺</i>	<i>K⁺</i>	<i>Ca²⁺</i>
<i>Pre-Monsoon (n = 39)</i>											
EC	-0.59**	1									
HCO ₃ ⁻	-0.14	-0.05	1								
SO ₄ ²⁻	-0.41**	0.29	0.11	1							
Cl ⁻	-0.36*	0.17	0.81**	0.51**	1						
NO ₃ ⁻	-0.74**	0.79**	0.08	0.14	0.10	1					
PO ₄ ³⁻	0.27	-0.27	-0.32*	-0.51**	-0.64**	-0.13	1				
SiO ₂	-0.41**	0.43**	-0.37*	0.25	-0.05	0.24	-0.20	1			
Na ⁺	0.19	-0.23	0.09	-0.01	0.00	-0.19	0.02	-0.18	1		
K ⁺	0.03	-0.04	-0.09	0.01	-0.09	0.03	0.07	0.07	-0.01	1	
Ca ²⁺	0.02	0.19	-0.41*	-0.10	-0.22	-0.02	-0.01	0.23	-0.08	-0.17	1.0
Mg ²⁺	0.15	0.12	-0.38*	-0.27	-0.31	-0.05	0.13	0.14	-0.08	-0.17	0.96**
<i>Post-Monsoon (n = 36)</i>											
EC	0.39*	1									
HCO ₃ ⁻	0.20	0.34*	1								
SO ₄ ²⁻	0.17	0.63**	0.44*	1							
Cl ⁻	0.17	0.59*	0.81**	0.66*	1						
NO ₃ ⁻	0.13	0.27	-0.16	-0.04	-0.07	1					
PO ₄ ³⁻	-0.59**	-0.61**	-0.50**	-0.25	-0.58**	-0.11	1				
SiO ₂	0.11	-0.23	0.50**	-0.02	0.21	-0.19	-0.06	1			
Na ⁺	0.17	0.28	-0.10	0.26	0.16	0.00	-0.08	-0.03	1		
K ⁺	0.28	0.79**	0.67**	0.74**	0.87**	0.10	-0.59**	-0.07	0.13	1	
Ca ²⁺	0.23	0.61**	-0.13	0.40*	0.10	0.45**	-0.14	-0.38*	0.09	0.42*	1
Mg ²⁺	0.06	0.47**	-0.29	0.13	-0.09	0.49**	0.02	-0.46*	-0.02	0.20	0.88**

** Correlation is significant at 0.01; * Correlation is significant at 0.05

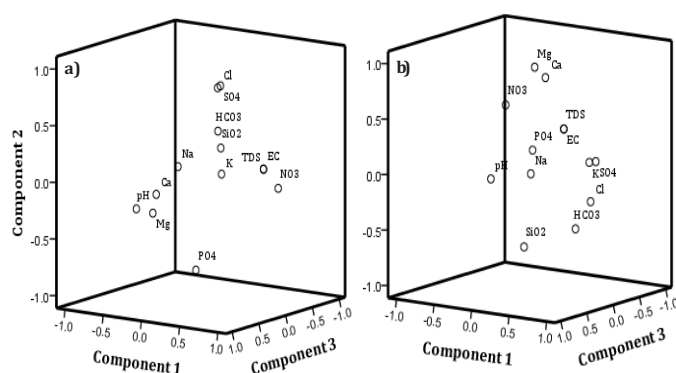


Figure 4: Three-dimensional representation of water quality parameters alignment obtained from multivariate factor analysis of lake water in (a) pre-monsoon and (b) post-monsoon.

24.71% of variation in the dataset showing positive loading for Ca^{2+} , Mg^{2+} and NO_3^- . This relationship aptly

explains the change in geochemical processes (Kumar et al., 2009) with input from anthropogenic sources. Factor 3 does not vouch for any specific process with showing positive loading only for pH with 14.50% of the variation. Positive loading may be due to the weathering pattern and availability of inorganic ions and dissolved solids in the lake systems. It can be said that the factor analyses have effectively established the operation of different processes in the lake system.

ANOVA Analysis

To determine an existence of a significant difference between any of the means, single factor ANOVA (Table 3) was used. For ANOVA analysis, we have chosen data from common sampling points, where samples were taken in both seasons. There will be a significant

Table 3: Single factor ANOVA analysis of lake water for significance mean variation

<i>Parameters</i>	<i>F-Critical</i>	<i>F-Calculated</i>
pH	3.99	5.66
EC	3.99	19.36
HCO₃⁻	3.99	2.39
Cl⁻	3.99	1.09
SO₄²⁻	3.99	8.71
NO₃⁻	3.99	13.49
PO₄³⁻	3.99	2.81
SiO₂	3.99	3.63
Na⁺	3.99	45.37
K⁺	3.99	22.22
Ca²⁺	3.99	0.01
Mg²⁺	3.99	0.43

difference between the means if the F-calculated value is more than the F-critical value. pH, EC, SO₄²⁻, NO₃⁻, Na⁺ and K⁺ showed significant difference i.e. F-calculated is more than the F-critical. Significant variance of pH, EC, Na⁺ and K⁺ showed evaporative enrichment. The ANOVA analysis showed significance variance of SO₄²⁻ indicating the dissolution of gypsum and anhydrite and the weathering of pyrite and iron sulphides due to after rain event. Significance variance of NO₃⁻ indicated the anthropogenic influence on the lake chemistry attributed due to rainfall contribution and the effect of long range transport of pollution.

Effective CO₂ Pressure

For both seasons, the 'effective CO₂ pressure' or 'internal CO₂ pressure' (log pCO₂) which indicates a global trend that natural water bodies are commonly out of equilibrium with the atmosphere (Raymahashay, 1986), was estimated from pH values and HCO₃⁻ concentration (Table 1). The long standing water bodies have a significant fraction of high-CO₂ and the re-equilibration occurs in the atmosphere by releasing the excess CO₂ though its rate is relatively slow (Stumm and Morgan, 1970; Holland, 1978; Anshumali and Ramanathan, 2007). The pCO₂ has increased in the post-monsoon season. High pCO₂ values are likely to arise from the coupling of sulphide oxidation and carbonate dissolution. Such increase in pCO₂ is an indication of higher atmospheric CO₂ during winter than that of rainy season during which atmospheric

CO₂ is being continuously removed through frequent rain events due to bicarbonate formation. In addition, people residing in the Himalayan range are highly dependent on biomass burning resulting in heavy metals associated carbonaceous aerosols which is likely to get transported to the lake water. Effective CO₂ pressure can also be changed by photosynthesis by algae or other organisms living in lakes. So, further long term monitoring of chlorophyll of content of the lake system is highly recommended to monitor the effective CO₂ pressure changes.

Conclusion

The study presents the first hand report to trace the effect of climate change in the pristine high altitude lakes of the Eastern lesser Himalaya through geochemical processes and effective CO₂ pressure. Hydro-geochemical processes like weathering, dissolution and precipitation seem to be playing vital role in governing the lake water chemistry. The pH of the lake remained slightly acidic in both the seasons. The results reveal that major cations in the lakes increased in post-monsoon season. Major anions except NO₃⁻ increased in post-monsoon season, though the variation was not too high. Decreased value of NO₃⁻ in post-monsoon season indicated that monsoon does not contribute any anthropogenic input in the lake systems. Carbonate weathering and atmospheric precipitation were strong factors controlling the lake water chemistry.

The overall hydro-geochemical evaluation of the lake water suggested that the lake is not influenced by direct anthropogenic input but long range transport induced contaminants. During the pre-monsoon season, the lake water facies were mainly of Ca²⁺-HCO₃⁻, Ca²⁺-Mg²⁺-SO₄²⁻ and Na⁺-HCO₃⁻ type which is changed to Na⁺-SO₄²⁻ and Ca²⁺-Na⁺-HCO₃⁻ type in the post monsoon. Lower TDS than the average Indian rain water indicated that lake water originally receives majority of the water through snow melt. The pCO₂ has increased in the post-monsoon season probably due to higher atmospheric CO₂ during winter than that of rainy season during which atmospheric CO₂ is being continuously removed through frequent rain events. Factor analysis showed that weathering and anthropogenic processes are the main governing factors in the pre-monsoon whereas evaporative enrichment and geochemical inputs are the main processes in the post-monsoon season. ANOVA

analysis showed significant difference for pH, EC, SO_4^{2-} , NO_3^- , Na^+ and K^+ i.e. indicating input from evaporative enrichment, weathering and long range transport of pollution to lake system. Long-term monitoring programmes are recommended for periodic evaluation of the high altitude lakes worldwide in order to trace climate change impacts.

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