

High Altitude Lake and Hydrochemistry: A Study of Lam Dal and Six Consecutive Lakes of Dhauladhar, Himachal Himalaya, India

Riju¹, Harminder Pal Singh¹ and Anurag Linda^{2*}

¹Department of Environment Studies, Panjab University, Chandigarh, India

²Department of Environmental Sciences, Central University of Himachal Pradesh, Dharamshala, India

✉ anuraglinda.cuhp@hpcu.ac.in

Received August 16, 2021; revised and accepted November 19, 2021

Abstract: Increased human influence has warmed the atmosphere, ocean and land thereby resulting in widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere (IPCC, 2021). High altitude lakes are generally small and quite sensitive to natural and anthropogenic perturbations. The present work is a preliminary work to investigate different hydro chemical processes and factors that controls the geochemistry of a high altitude lake, Lam Lake (*dal*) and its consecutive six lakes flowing through the Chamba district, Himachal Pradesh. Two hundred and eighty ($n=280$) water samples were collected in the year 2017 during the pre-monsoon and post-monsoon season. The anion concentration for all the seven lakes followed the trend $\text{HCO}_3^- > \text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{PO}_4^{3-}$ whereas the order of cation concentrations was $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ for both the seasons. Less EC of the water samples shows its serene nature. Components of bicarbonate (HCO_3^-) were found to be the major anion whereas calcium (Ca^{2+}) was found to be the major cation present in the lakes. Piper Plot and Durov plot indicated $\text{Ca}^{2+} - \text{HCO}_3^-$ as the major hydrogeochemical facies with comparatively less contribution from $\text{Mg}^{2+} - \text{HCO}_3^-$ type. The dominance of $\text{Ca}^{2+} - \text{HCO}_3^-$ over $\text{Mg}^{2+} - \text{HCO}_3^-$ reflects the possibility of the natural order of dominance in the geology of the catchment area. The low $\text{Na}^+ + \text{K}^+/\text{TZ}^+$ (total cations) ratios and the high $\text{Ca}^{2+} + \text{Mg}^{2+}/\text{TZ}^+$ (total cations) and $(\text{Ca}^{2+} + \text{Mg}^{2+})/(\text{Na}^+ + \text{K}^+)$ ratios showed dominance of carbonate weathering. The average carbon ratios during pre-monsoon and post-monsoon were found to be 0.97 and 0.98, respectively, suggesting that proton is primarily derived from the oxidation of sulphide involving carbonate dissolution. The baseline data generated for a high-altitude lake shows that weathering and erosion during monsoonal precipitation and snow melt runoff during ablation season are the main sources of the chemical composition of lake water. Further to trace the imprints of climate change and seasonal variations in the high-altitude lakes, long term monitoring is recommended along with isotopic tracer techniques.

Keywords: High-altitude lake; Hydrochemistry; Geochemistry; Weathering; Major ions.

Introduction

Water, the one most indispensable element in the earth's atmosphere that makes life possible, occupies nearly 75% of the earth's surface, most of it, however, is saline, found in the biggest water bodies like the oceans and

the seas (Clarke et al., 1924; Thompson, 1999). Fresh water covers less than 1% of the Earth's surface and one of the major sources of fresh water is lakes (Dudgeon, 2014). Lakes are large water bodies surrounded by land and inhabited by various aquatic life forms and contain about 0.013% of total water in the hydrosphere

*Corresponding Author

(Gleick, 1993). Lakes serve as a laboratory in which many of our ideas on physical, chemical and biological processes can be refined which are relevant not only to lacustrine systems and deposits but also to their environments. The significance of lake water is much greater than this value. The status of lakes is dependent on various natural processes such as the hydrological cycle along with different elemental cycles operating in the environment. The Himalayas is home to some of the highest lakes of India, many of which are even untouched and are in serene condition. Indian Himalayas cover approximately 591,000 km² or 18% of India's land surface (NWIA, 2011). Geochemical analysis of lakes is undertaken to examine the distribution of chemical elements and the movement of these elements into sediment and water systems. The chemistry of lakes vary in terms of the solute, bio-geochemistry and mineralogy, which are governed by climate, vegetation, lithology, tectonics and type of intensity of erosion or weathering at source (NWIA, 2011). Thus, the ion chemistry of lake water is important for understanding the nature of the catchment lithology, soil erosion on the hill slope, rate of sedimentation, evaporation, precipitation and anthropogenic activity in the basin. Lake water chemistry in high altitude regions largely depends upon (snow) melted water quality as well as terrain through which the melted water has travelled (Deka et al., 2015). Compared to other lakes, the high altitude lakes are impacted faster by the climate changes in their environment, hence, they are in an ecologically marginalised situation.

The high altitude lakes are fed by precipitation, snow melt and spring water (Kumar et al., 2019). High altitude lakes are mostly oligotrophic unlike low altitude lakes, which are in various stages of trophic state due to strong anthropogenic influence, the high altitude lakes still have a pristine environment (NWIA, 2011). There are mostly fresh water lakes in the Himalayan region varying from low elevation to high elevation with or without inflow and out flow. Primarily physiochemical properties of Himalayan lakes depend upon altitude, which governs the vegetative cover, climate, tectonics, intensity of weathering and erosion and finally the bedrock type or lithology. Many large lakes of Lesser Himalaya are formed during the Holocene period; these are fault basins formed due to tectonic activities, transformed into lakes due to the blocking of rivers or streams (Raymo et al., 1988). These water bodies are fed by underground springs and precipitation, it is also different for different types of lakes. Elemental water in the globe is always in motion through the natural hydrological cycle which further delineates the constant movement of water

on, above and below the surface of the Earth. The concentration of major ions in a surface water system (Ca²⁺, Mg²⁺, Na⁺, K⁺, SO₄²⁻, Cl⁻, HCO₃⁻ etc.) up to a certain limit specifies water suitability for drinking as well as irrigation and enables to understand catchment weathering, precipitation, sedimentation, and influence of anthropogenic activities around the lake (Anshumali and Ramanathan, 2007; Khadka and Ramanathan, 2012; Das and Kaur, 2001). In water, Ca²⁺ and Mg²⁺ generally come from carbonate and evaporites (Doner et al., 1989; Gauray et al., 2018; Sun et al., 2020). The source of Na⁺ and K⁺ may contribute to silicate weathering, evaporites and anthropogenic activities, whereas HCO₃⁻, Cl⁻, SO₄²⁻ originates from carbonate source, weathering of silicate, evaporites, gypsum, pyrites (Meybeck, 1987; Yao et al., 2015), and anthropogenic activities (Gupta et al., 2012). The study conducted by several researchers (Singh et al., 2014; Gopal et al., 2002; Deka et al., 2015; Das and Dhiman, 2003; Zutshi, 1991; Singh et al., 2014; Bhagabati and Borkotoki, 2014; Sharma and Kumar, 2017; Singh et al., 2013; Naik et al., 2012; Kumar and Sharma, 2019; Kumar et al., 2018; Kumar et al., 2019) have evaluated chemical and physical and biological characteristics of some high-altitude lakes of Indian Himalayan region having different geological setups. However, no study has been documented on Lam Dal to date. Hence, it is of paramount importance to provide the baseline information and relevant data about hydrochemical characteristics of Lam Dal in order to evaluate the status in response to various hydrochemical processes regulating the major ion chemistry of Lam Dal and its consecutive six lakes along with human intervention and climate change. Also, this baseline data have great importance for the conservation and management of Lam Dal in the near future. This will also provide baseline data to future researchers working in the relevant field.

Study Area, Sampling and Analysis

The maximum area in district Chamba is underlain by the formation of hard rock which ranges from Paleozoic to Triassic (CGWB, 2012). The geology of this region comprises slates, quartzite, schist, gneisses, granites, phyllite, etc. There are a few water bodies namely Khajjiar Lake, Manimahesh Lake, Chamera Lake, Lam Dal, Gadasru Lake, Maha Kali Dal in the Chamba district. Some of the lakes have been studied in this region. Although, no work has been documented on Lam Dal and its consecutive six lakes to date. The groundwater quality of District Chamba generally is maintained by various physiochemical parameters which

are produced from anthropogenic and natural sources. Rock dominance due to groundwater flow and longtime rock-water interaction within aquifers is mainly found to be the source of ions in the water bodies of this region along with the impact of precipitation dominance which may be due to higher recharge and continuous outflow of groundwater with short time rock-water interaction (Kumar et al., 2019). Other studies have also affirmed rock dominance as the main factor for controlling ionic composition in water bodies of other Himalayan regions (Gaury et al., 2018; Bhat et al., 2014). Groundwater quality is influenced by weathering of the surrounding rocks to the major extent and evaporation to some extent (Lu et al., 2015; Aghazadeh et al., 2017). Carbonate weathering is found to be dominant over silicate weathering which may be due to carbonate minerals' rich lithology (Kumar et al., 2019).

Lam Dal is located ($32^{\circ} 20' 19''$ N, $76^{\circ} 19' 42''$ E) in the Chamba district of Himachal Pradesh at an altitude of 3900 masl Figure 1(a). En route to Lam Dal (258126 m^2), there are six small lakes with areas ranging from 2931 m^2 to 26810 m^2 . These clusters of lakes are called the *area of the seven lakes* locally. According to local residents and Hindu mythology, this lake is considered a sacred lake with the least human interference. The general features of Lam Dal are given in Table 1. The region is characterised by robust topography with

elevation variation from 2200 to 4500 m amsl (Figure 2a,b). The catchment area of the lake receives water from nearby tributaries owing to snow melt and liquid precipitation (Figure 2c). The study area experiences a monsoon-arid transition climate and any change in the precipitation pattern either winter, monsoonal or westerly can be reflected in the water chemistry of the lake (Bookhagen and Burbank, 2010). The prevailing climate in the study area is shown in Figure 3 (a,b). The mean temperature from 1981-2019 has been recorded as 11.8°C . The annual mean monthly maximum temperature (T_{Max}) varies as 8.38°C (January) and 32.87°C (June) and mean monthly minimum (T_{Min}) from -0.73°C (January) to 20.15°C (July), respectively (reference). The catchment area of Lam Dal in the north consists of metamorphic rocks like slate, quartzite, phyllite, carbonaceous slate whereas in the south it is generally mandi granites (Figure 4) (reference). The mean monthly data of mean temperature (T_{Mean}), maximum temperature (T_{Max}), minimum temperature (T_{Min}) and diurnal temperature range (DTR) were obtained from the website (<https://power.larc.nasa.gov/>) for the period of 39 years (1981-2019).

Spatial Method

Base map of the study area was prepared by using Survey of India Toposheet number I43W7 with a scale of

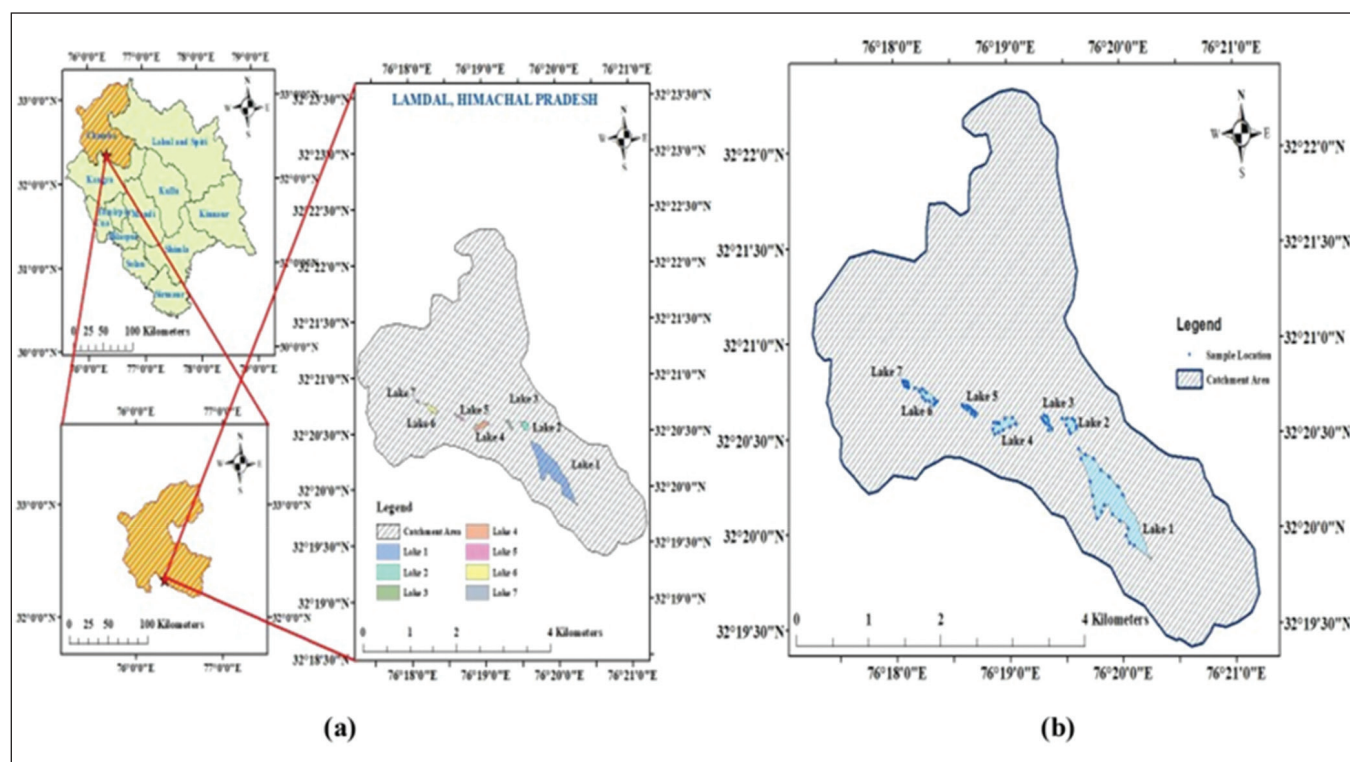


Figure 1: (a) Location map of study area and (b) sampling site.

Table 1: General features of Lam Dal, Chamba, Himachal Pradesh

Sites	Geographical coordinates	Altitude (masl)	Area (m ²)
Lake 1	32° 20' 19" N, 76° 19' 42" E	3972	258126
Lake 2	32° 20' 31" N, 76° 19' 34" E	3944	15821
Lake 3	32° 20' 34" N, 76° 19' 20" E	3918	8380
Lake 4	32° 20' 32" N, 76° 18' 53" E	3758	26810
Lake 5	32° 20' 28" N, 76° 18' 39" E	3738	8111
Lake 6	32° 20' 43" N, 76° 18' 16" E	3652	17727
Lake 7	32° 20' 47" N, 76° 18' 05" E	3648	2931
Country	India		
State	Himachal Pradesh		
District	Chamba		
Mountain Range	Dhauladhar		
Climate	Monsoon – Arid Transition Zone		

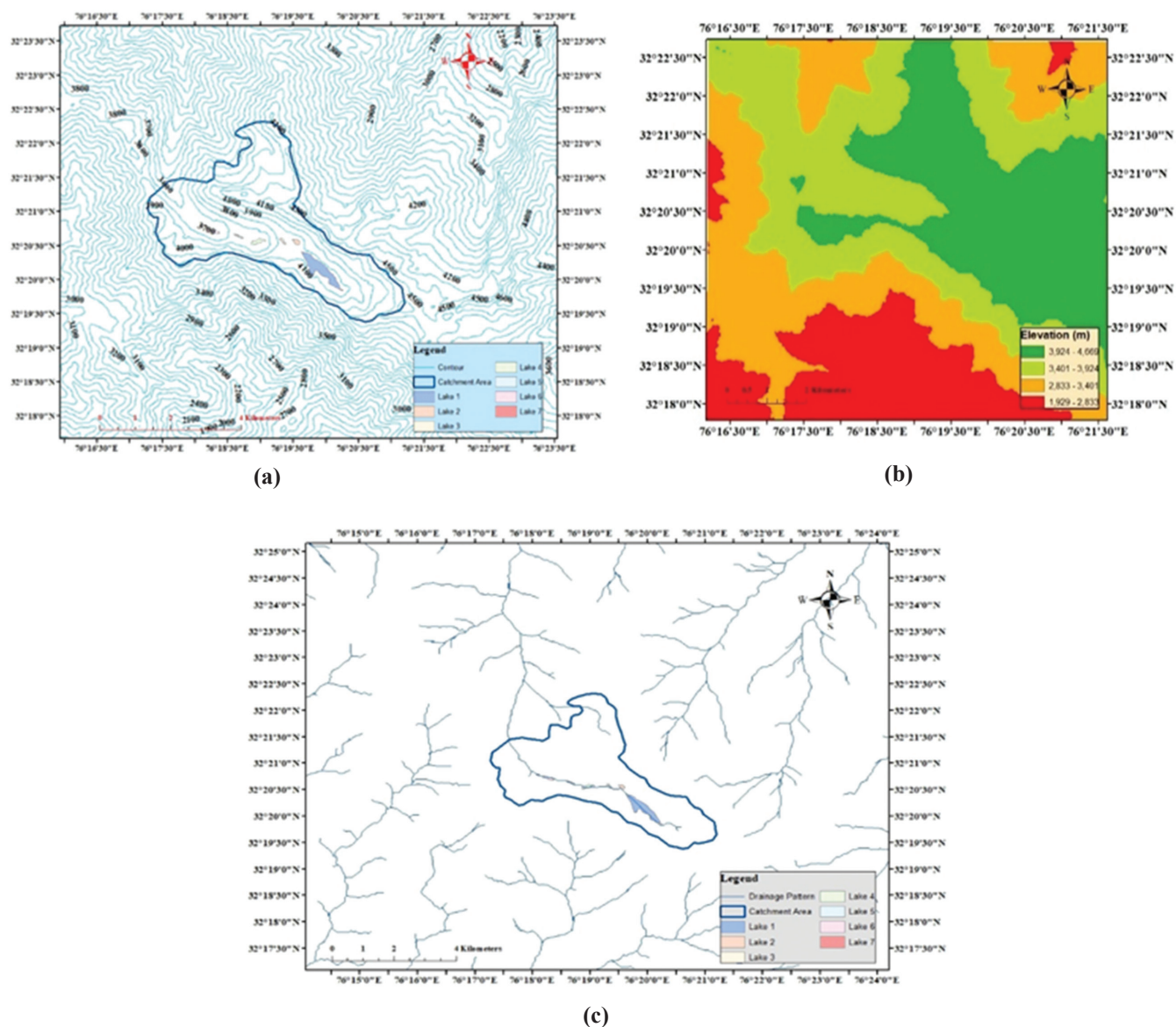


Figure 2: (a) Elevation map, (b) contour map and (c) drainage map of study area.

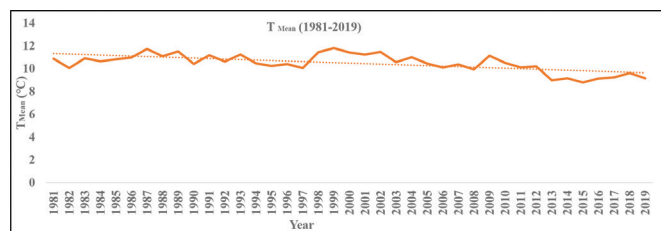


Figure 3(a): Annual mean temperature of study area from 1981-2019.

Source: <https://power.larc.nasa.gov/>

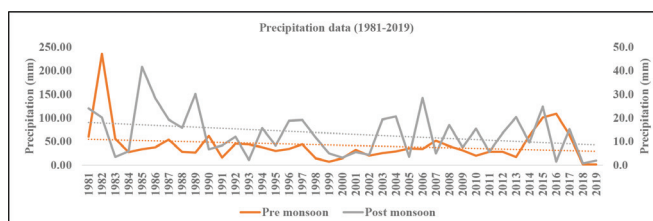


Figure 3(b): Precipitation data of study area from 1981-2019.

Source: <https://power.larc.nasa.gov/>

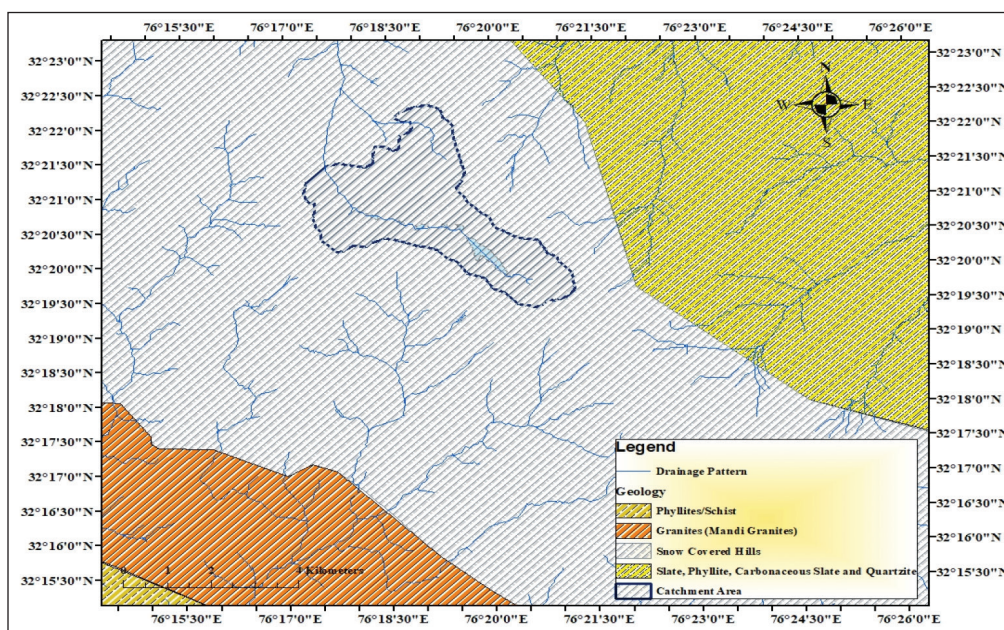


Figure 4: Geological map of study area.

1:50000, surveyed in the year 1969 using Arc GIS 10.4.1. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) DEM was freely downloaded from <https://search.earthdata.nasa.gov/search/>, having a spatial resolution of 30mts, it was used to prepare thematic maps such as contour map and drainage map. Furthermore, geological and geomorphological maps were digitised and reproduced from the Ground Water Prospectus map, freely available on <https://bhuvan.nrsc.gov.in/>. DEM was used to extract, delineate and quantify the catchment of the study area. Hydrological tools in Arc GIS were used for delineating drainage networks, contours and catchment from DEM.

Analytical Method

Surface water samples were collected from Lam Dal and its consecutive six lakes in the year 2017 for two seasons i.e., pre-monsoon and post-monsoon. Figure 1(a,b) shows the location map of the study area and sampling

locations respectively. Samples were collected from 20 locations along the periphery from each lake. A total of 280 water samples were collected for both seasons from the periphery of each lake in polyethylene sampling bottles (500ml). Parameters like pH, EC and TDS were analysed in the field using hand held water analysis kit (Hanna-HI98130). Collected samples were stored at 4°C and were further transported to the laboratory for analysis. Samples were analysed as per the standard methods (APHA, 2012). GW Chart (Version 1.29) by United States Geological Survey (USGS) was used for Piper diagram plotting; Aquachem 2014 for Durov Plot; Statistical Package for Social Sciences (SPSS) (Version 16.0); and MS Excel, 2010 for statistical analysis. The Charge Balance Ratio was calculated using the following equation (Hounslow, 1995):

$$\text{CBE (\%)} = \frac{(1) \text{ meq (cations)} - \text{meq (anions)}}{\text{meq (cations)} + \text{meq (anions)}} \times 100$$

Results and Discussions

Preliminary Analysis of Primary Data

Eastern and Central Himalayas received 80% of the annual precipitation due to the Indian summer monsoon whereas the western Himalaya received ~30% due to western disturbances which, however, are embedded in the Indian winter monsoon (Dimri et al., 2021). In order to understand the variation in meteorological parameters and its impact on the water chemistry of lakes, interannual time series data of temperature (T_{Mean} , T_{Max} , T_{Min}), DTR, and precipitation were analysed for the entire period (1981–2019). The arithmetic mean and standard deviation, which are a measure of central tendency and dispersion, are employed for finding the significance of statistical data (Table 2). The coefficient of skewness, which is a measure of asymmetry in a frequency distribution around the mean, varied between -0.13 (T_{Min}) to 1.62 (rainfall). The negative value observed for T_{Max} , T_{Min} and T_{Mean} indicates that this is asymmetrically distributed and lies to the left of the mean. However, positive skewness was seen for DTR and rainfall. Kurtosis is a statistic describing the peakedness of a symmetrical frequency distribution, varying from -0.45 (DTR) to 2.56 (rainfall) within the lake region. The coefficient of variance (CV), a statistical measure of the dispersion of data points in a data series around the mean, was computed for studying variability in temperature (T_{Mean} , T_{Max} , T_{Min}), DTR, and rainfall over the study area. The CV varied between 19.21% (DTR) to 118.15% (rainfall).

The species of ion present in freshwater influences the water quality, determining its suitability for domestic, industrial and agricultural usage (Saleem et al., 2015). The important factors that control the water chemistry of surface natural water bodies are intensity and duration of precipitation, rate of evaporation, type of mineral weathering, relief features, vegetative cover and different biological activities (Kump et al., 2000). Depending upon the altitudinal location, the Himalayan lakes can be further categorised into high (>3000 m amsl), mid (1000-3000 m amsl) and low (<1000 m amsl) altitude

lakes (NWIA, 2011) which show heterogeneity in its physico-chemical properties due to different natural and anthropogenic inputs.

Geology

Himalayan evolution is mainly driven by the early Cenozoic collision of the Eurasian and Indian continents (Hu et al., 2016), which resulted in major crustal thickening and shortening (Yin and Harrison, 2000; Hodges, 2000). Himalaya is separated into four major litho tectonic units via a north-dipping fault system. These separations are from north to south, the Tethyan Sedimentary Series (TSS), the Higher Himalayan Crystalline Series (HHCS), the LHS Lesser Himalayan Series (LHS) and the Sub-Himalaya (SH). The main faults are from north to south, the South Tibetan Detachment System, which separates the TSS.

Chemical characterisation of Himalayan lakes greatly depends upon the weathering pattern of surrounding rocks, precipitation and evaporation-crystallisation process (Gibbs, 1970). In the Himalayan region, various rock types are found, in the eastern Himalaya major rock types are sedimentary, metamorphic as well as of igneous origin with the dominance of Limestone, sandstone, clay stone, arenite, diamictite, basalt, shale, mafic garnet-muscovite schist, phyllite, marble, quartzite conglomerate and gneiss (Yin et al., 2009; Sorkhabi, 2010; Chakrabati and Harris, 1995). Central and Western Himalayas also possess similar rock types i.e. sedimentary, metamorphic and igneous with the dominance of clay stone, sandstone conglomerate, schist, phyllite, quartzite, gneiss, slate, dolomite, limestone, arenite, conglomerate and shale (Bleam, 2017). Weathering of a particular rock type releases a specific set of ions in the water body,

Rock type, erosion rates and weathering fluxes in the Himalayan region seem to be relatively constant for the past 12 Ma (Derry and France-Lanord, 1996; Galy et al., 2010). Potential controls on these rates by tectonic parameters or monsoonal strength have not been fully understood yet, however, this has been a subject of postulation (Clift et al., 2008). The changes in weathering environment consequently derive from

Table 2: Climate data computed from 1981-2019

<i>Climate variables</i>	<i>Arithmetic mean</i>	<i>SD</i>	<i>Coefficient of skewness</i>	<i>Coefficient of kurtosis</i>	<i>CV%</i>
T_{Max}	21.45	21.45	-0.23	-1.17	30.80
T_{Min}	10.96	6.46	-0.13	-1.50	59.20
T_{Mean}	15.66	6.78	-0.21	-1.46	43.41
DTR	10.49	2.01	0.04	-0.45	19.21
Rainfall	68.03	81.50	1.62	2.46	118.15

climate change. Change in weathering is elusive, but it exists.

Amount of Precipitation and Atmospheric Fallout

The amount of precipitation and atmospheric fallout also is a factor that controls the physico-chemical properties of Himalayan lakes. Many water bodies in the central Asian region owe their source from the Himalayan drainage basins having a total area of around $6.7 \times 10^9 \text{ km}^2$. This supplies water to nearly more than 1.2 billion people (Revenga et al., 2003). The active source of precipitation in the Himalayan region is the monsoon. According to Burkbank and Bookhagen (2010), the monsoon is said to be accountable for more than 80% of rainfall (annually) on Tibetan Plateau and Central Himalayan regions, although, the monsoonal contribution is little in the eastern and western parts of the Himalaya, where mid-latitude low-pressure system and monsoon produces roughly the similar amount of precipitation. Glacier and snow are also major sources of water in the Indian Himalayan region (IHR), it releases water during the melting periods. Based on the study conducted by Ménégos et al. (2013), it was found that in the Himalayas, snow accumulation varies extensively along the mountain range. In western Himalaya, due to both mid-latitude low pressure systems and summer monsoons, snowfall may occur during all the seasons that bring moisture in the region making most of the lakes in the region perennial. The distribution of precipitation in time and space is erratic despite its being in huge quantity (Kumar et al., 2005). The maximum rainfall occurs during the monsoon which is a good producer of fresh water but is poorly distributed in the Indian subcontinent, whereas snow and glacier melt from the Indian Himalaya if compared with the water generated by rainfall constitute about 5% of the total fresh water which is a rich source of water in lakes of this region (Bahadur, 1998; Upadhyay, 1995).

In the High Altitude Himalayas, freshwater, as well as saline water lakes, exists (Bahadur, 1998). The high altitude lakes are located at altitudes ranging from 600 m to 5600 m and are exposed to different conditions of climate, varying from Ladakh (the cold desert) to Manipur (wet and humid). Also, the water chemistry of lakes depends upon the amount of precipitation and characteristics of atmospheric fallout. Precipitation is a good carrier and scavenger of other atmospheric components such as aerosols, gases and large particles like calcium carbonate and silicates. The process of precipitation involves condensation of atmospheric water vapour followed by gravitational deposition. The

large surface area of snow flakes, rain drops and certain physical properties of water, materials in the atmosphere move to terrestrial and aquatic ecosystems through precipitation along with adsorption of gases (SO_2 , CO_2) dry deposition and impaction of aerosols (Galloway and Cowling, 1978). Water also cycles from the atmosphere to the ground through precipitation which is a predominant process. The chemical composition resulting from these scavenging processes varies greatly from storm to storm and region to region.

Climate

The Himalayan range is greatly influenced by climate change in terms of amount of precipitation, melting of snow cover and glaciers. This mostly influences the runoff pattern of rivers that drain from glaciated catchments of the Himalayas (Tayal, 2019). Lakes in the Himalayan region are critical indicators of regional climate change and resultant glacier retreat (Ji et al., 2005; Yang et al., 2019). But these Himalayan lakes lack long-term systematic monitoring and therefore their responses to recent climatic change are still not fully understood. The change in climate has been projected throughout the twenty-first century, even at unequalled rates in recent human history (Solomon et al., 2007). There is much significance of climate change on high elevations due to its sensitivity to precipitation and temperature change (Barnett et al., 2005). The temperature in the Indian Himalayan region is estimated to exceed 2.5°C by the end of twenty-first century (Dimri et al., 2021). Expanding human interventions on the natural environment and land may increase the frequency of catastrophic events in the future (IPCC, 2021).

Anthropogenic Impacts

Increased population has a direct impact on various natural resources including lakes, streams, flora, fauna, etc. The impact of human activities on the Himalayan ecosystem can be linked to increase in the human population. Human pressure driven by an increase in population, technical changes, economic development and agricultural modifications has resulted in modifications of lake water chemistry. There are many such examples in high, mid and low altitude lakes in the Indian Himalayan region. The water quality of Dal lake and Khushalsar lake has been affected by agriculture intensification and municipal waste generation (Saleem et al., 2015; Najar and Khan, 2012). Likewise water quality deterioration of Patkai lake, a high altitude lake is reported due to acid mine drainage

in the vicinity (Bhagabati and Borkotoki, 2014). A study taken up by Chakrapani (2002); Saleem et al. (2015); Sheikh et al. (2014); Sarah et al. (2011); Malik et al. (2017) also strongly reflects the impact of human intervention on the water quality of lakes. According to Singh et al. (2010), intense pisciculture practices have also influenced the water quality of lakes. Cultural practices in sacred lakes of Himalaya are also one of the examples which were documented by Singh et al. (2010). Even the water chemistry of the streams that feed the lake can reflect changes in their watersheds, making streams as well as lakes, good indicators of land use pattern upstream in the watershed.

Hydro-chemical Properties of the Lakes Water

Table 3 represents the comparative summary of the water chemistry of all the seven lakes for the year 2017 in different seasons i.e., pre-monsoon and post-monsoon seasons, respectively. The average charge balance error between cations and anions is found to be $< \pm 10\%$. Low ionic strength samples are prone to charge balance errors even more than 10% (Fritz, 1994). The pH describes the acidic and basic properties of water. The average pH of Lam Dal and its consecutive 6 lakes ranged between 6.87-7.19 during pre-monsoon and 6.46-6.69 during post-monsoon season for the year 2017. These values indicated slightly acidic conditions during the post-monsoon season and almost neutral pH in the pre-monsoon season. It might be attributed to the difference in the wet and dry deposition in the catchment area (Deka et al., 2015). Total ions in the aqueous medium are represented by total dissolved solids (TDS) whereas electrical conductivity (EC) measures the strength of ions that depends upon the concentrations, volume and the rate of movement of ions that reflects the extent of the type of chemical weathering in the area (Das and Kaur, 2001; Walton, 1989). EC also measures the analysed ionic strength and mineralisation of natural water (Chidambaram et al., 2011). During the study period, the average EC and TDS of water samples from all the seven lakes were 11.4-14 $\mu\text{S}/\text{cm}$, 7.4-8 ppm and 16-20 $\mu\text{S}/\text{cm}$, 8-13 ppm, respectively. The most dominant anion was found to be bicarbonate, which accounted for more than 80% of the whole anionic budget in all seven lakes. The average concentration of bicarbonate for all the seven lakes varied between 54-99 mg/L and 180-200 mg/L during pre-monsoon and post-monsoon seasons, respectively. Increased concentrations of bicarbonate could be due to high chemical weathering in the catchment basin during the post-monsoon season (Khadka and Ramanathan,

2012). Among cations, calcium was found to be the major cation, whose average value varied between 7.6-13.6 mg/L during pre-monsoon season and 8-17 mg/L during the post-monsoon season for all the seven lakes. It accounted for 70% of the total cationic budget whereas magnesium accounted for more than 25% and the average value varied between 1.68-6.15 mg/L during pre-monsoon and 3.41-6.14 mg/L for the post-monsoon season. The order of cation concentrations was $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ for all the studied seven lakes. The average concentration of phosphate varied from 1.14-1.85 mg/L during pre-monsoon to 2.84-3.55 mg/L during post-monsoon season. The source could be from runoff around the catchment area. Cl^- concentration varied from 1.14-1.85 mg/L during pre-monsoon and 2.84-3.55 during post-monsoon season. Chloride enrichment during winters might be due to anthropogenic inputs. The order of anion concentration for all the seven lakes for the study period had a trend of $\text{HCO}_3^- > \text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{PO}_4^{3-}$.

Sources of Major Dissolved Ions

The main sources of dissolved ions evaluation were based on the relationship between ions and their ionic ratios (Singh et al., 2014). Precipitation (both solid and liquid), atmospheric fallout and rock weathering are the main sources of dissolved ions present in the water body. The $\text{Ca}^{2+} + \text{Mg}^{2+}$ versus TZ^+ plot (Figure 5a) showed a positive correlation among the data sets. The average equivalent ratio for all the seven lakes was measured to be 0.95 ± 0.004 during pre-monsoon season. For the post-monsoon season, the value was 0.92 ± 0.01 . Whereas the average $(\text{Ca}^{2+} + \text{Mg}^{2+})/(\text{Na}^+ + \text{K}^+)$ ratios were 22.3 ± 2.55 during pre-monsoon season and 12.95 ± 2.29 during post-monsoon season, respectively. The high ratios of $(\text{Ca}^{2+} + \text{Mg}^{2+})/(\text{Na}^+ + \text{K}^+)$ and $\text{Ca}^{2+} + \text{Mg}^{2+}/\text{TZ}^+$ and low ratios of $\text{Na}^+ + \text{K}^+/\text{TZ}^+$ had been observed in the study areas, it shows the dominance of carbonate weathering, which is the main mechanism controlling major ion chemistry of studied lakes with a minor contribution from silicate weathering. The water chemistry of most of the Indian high-altitude lakes and glaciers melt water was being dominated by carbonate weathering (Anshumali and Ramanathan, 2007; Jeelani and Shah, 2006; Singh et al., 2014). The observed average ratios of $\text{Ca}^{2+}/\text{Na}^+$ in the water samples from Lake 1 to Lake 7 were found to be 24.2 ± 3.1 during pre-monsoon and 14.4 ± 2.7 during post-monsoon season. The average ratio of $\text{Mg}^{2+}/\text{Na}^+$ was 6.99 ± 1.5 , and 6.32 ± 1.99 for pre and post-monsoon seasons, respectively. Also, the average

Table 3: Physico-chemical parameters of study areas (pre-monsoon and post-monsoon season)

Physico-chemical parameters	L1 (Mean $\pm$ SD)	L2 (Mean $\pm$ SD)	L3 (Mean $\pm$ SD)	L4 (Mean $\pm$ SD)	L5 (Mean $\pm$ SD)	L6 (Mean $\pm$ SD)	L7 (Mean $\pm$ SD)
Pre-monsoon							
pH	7.01 $\pm$ 0.08	7 $\pm$ 0.01	6.87 $\pm$ 0.01	7.01 $\pm$ 0.007	7.02 $\pm$ 0.007	7.19 $\pm$ 0.004	7.01 $\pm$ 0.007
EC (μ S/cm)	12.6 $\pm$ 0.8	14 $\pm$ 1.01	11.4 $\pm$ 1.01	12.4 $\pm$ 0.8	13 $\pm$ 0.8	13 $\pm$ 1.01	11.4 $\pm$ 1.01
TDS (ppm)	8 $\pm$ 0.63	8 $\pm$ 0.63	7.4 $\pm$ 0.48	8 $\pm$ 0.74	7.8 $\pm$ 0.74	8 $\pm$ 0.63	7.8 $\pm$ 0.74
HCO ₃ ⁻ (mg/l)	74 $\pm$ 0.58	71 $\pm$ 0.57	54 $\pm$ 0.55	56 $\pm$ 0.58	79 $\pm$ 0.48	69 $\pm$ 0.63	99 $\pm$ 0.58
PO ₄ ³⁻ (mg/l)	0.37 $\pm$ 0.004	0.27 $\pm$ 0.003	0.33 $\pm$ 0.005	0.43 $\pm$ 0.002	0.19 $\pm$ 0.006	0.33 $\pm$ 0.007	0.19 $\pm$ 0.006
SO ₄ ²⁻ (mg/l)	2.62 $\pm$ 0.01	1.69 $\pm$ 0.01	1.52 $\pm$ 0.01	2.05 $\pm$ 0.01	1.99 $\pm$ 0.01	1.93 $\pm$ 0.01	1.99 $\pm$ 0.01
Cl ⁻ (mg/l)	1.56 $\pm$ 0.28	1.85 $\pm$ 0.55	1.56 $\pm$ 0.53	1.28 $\pm$ 0.53	1.42 $\pm$ 0.44	1.14 $\pm$ 0.56	1.42 $\pm$ 0.44
NO ₃ ⁻ (mg/l)	2.83 $\pm$ 1.23	3.19 $\pm$ 0.51	2.86 $\pm$ 1.08	2.79 $\pm$ 0.88	3.01 $\pm$ 1.14	2.79 $\pm$ 0.37	2.92 $\pm$ 0.33
Ca ²⁺ (mg/l)	8 $\pm$ 1.26	10.8 $\pm$ 0.97	8.8 $\pm$ 0.97	7.6 $\pm$ 1.49	9.2 $\pm$ 0.97	9.2 $\pm$ 0.97	9.2 $\pm$ 0.97
Mg ²⁺ (mg/l)	2.73 $\pm$ 0.49	1.68 $\pm$ 0.23	2.58 $\pm$ 0.19	2.56 $\pm$ 0.36	2.36 $\pm$ 0.47	2.58 $\pm$ 0.19	3.36 $\pm$ 0.47
Na ⁺ (mg/l)	0.34 $\pm$ 0.06	0.46 $\pm$ 0.04	0.3 $\pm$ 0.04	0.34 $\pm$ 0.04	0.32 $\pm$ 0.04	0.44 $\pm$ 0.1	0.42 $\pm$ 0.04
K ⁺ (mg/l)	0.14 $\pm$ 0.04	0.1 $\pm$ 0.04	0.12 $\pm$ 0.04	0.12 $\pm$ 0.04	0.22 $\pm$ 0.32	0.2 $\pm$ 0.4	0.14 $\pm$ 0.3
Post-monsoon							
pH	6.53 $\pm$ 0.01	6.63 $\pm$ 0.03	6.67 $\pm$ 0.01	6.69 $\pm$ 0.01	6.57 $\pm$ 0.02	6.46 $\pm$ 0.01	6.59 $\pm$ 0.02
EC (μ S/cm)	19 $\pm$ 0.98	19 $\pm$ 0.75	20 $\pm$ 0.49	16 $\pm$ 0.4	19 $\pm$ 1.2	19 $\pm$ 0.98	20 $\pm$ 0.75
TDS (ppm)	10 $\pm$ 0.4	13 $\pm$ 0.49	13 $\pm$ 0.03	8 $\pm$ 0.20	11 $\pm$ 0.01	13 $\pm$ 0.12	11 $\pm$ 0.03
HCO ₃ ⁻ (mg/l)	180 $\pm$ 2	190 $\pm$ 6.53	190 $\pm$ 4.89	200 $\pm$ 4.89	190 $\pm$ 6.63	200 $\pm$ 6.73	190 $\pm$ 6.5
PO ₄ ³⁻ (mg/l)	0.04 $\pm$ 0.05	0.07 $\pm$ 0.02	0.06 $\pm$ 0.23	0.03 $\pm$ 0.05	0.0 $\pm$ 0.05	0.03 $\pm$ 0.02	0.05 $\pm$ 0.01
SO ₄ ²⁻ (mg/l)	3.27 $\pm$ 0.12	4.67 $\pm$ 0.11	2.67 $\pm$ 0.16	4.77 $\pm$ 0.13	3.2 $\pm$ 0.18	3.67 $\pm$ 0.06	3.67 $\pm$ 0.08
Cl ⁻ (mg/l)	3.55 $\pm$ 0.28	2.84 $\pm$ 0.28	2.84 $\pm$ 0.44	3.55 $\pm$ 0.34	2.84 $\pm$ 0.34	3.55 $\pm$ 0.44	2.84 $\pm$ 0.53
NO ₃ ⁻ (mg/l)	2.27 $\pm$ 0.12	2.45 $\pm$ 0.78	1.94 $\pm$ 0.14	2.45 $\pm$ 0.16	1.94 $\pm$ 0.12	2.45 $\pm$ 0.10	2.45 $\pm$ 0.12
Ca ²⁺ (mg/l)	10 $\pm$ 2.65	8 $\pm$ 2.4	8 $\pm$ 1.49	12 $\pm$ 1.26	10 $\pm$ 2.04	12 $\pm$ 1.6	10 $\pm$ 2.65
Mg ²⁺ (mg/l)	3.41 $\pm$ 1.29	3.41 $\pm$ 2.06	3.97 $\pm$ 1.60	3.9 $\pm$ 0.85	5.8 $\pm$ 1.13	3.9 $\pm$ 1.77	5.85 $\pm$ 1.09
Na ⁺ (mg/l)	0.8 $\pm$ 0.05	0.6 $\pm$ 0.05	0.4 $\pm$ 0.14	0.8 $\pm$ 0.15	0.8 $\pm$ 0.15	0.8 $\pm$ 0.10	0.8 $\pm$ 0.13
K ⁺ (mg/l)	0.56 $\pm$ 0.05	0.54 $\pm$ 0.06	0.34 $\pm$ 0.07	0.4 $\pm$ 0.12	0.32 $\pm$ 0.07	0.42 $\pm$ 0.09	0.32 $\pm$ 0.23

*Data of study sites represented as mean $\pm$ standard deviation

$\text{HCO}_3^-/\text{Na}^+$ ratios were observed to be the maximum with an average value of 193.72 ± 20.3 for pre-monsoon season and 284.5 ± 17.5 during the post-monsoon season for all the seven lakes (L1 to L7). The high ratio of $\text{Ca}^{2+}/\text{Na}^+$ nearly 50, $\text{Mg}^{2+}/\text{Na}^+$ nearly 10 and $\text{HCO}_3^-/\text{Na}^+$ nearly 120 showed that the water drains through carbonate dominant lithology, whereas the low ratios of $\text{Ca}^{2+}/\text{Na}^+$ is 0.35 ± 0.12 , $\text{Mg}^{2+}/\text{Na}^+ = 0.24 \pm 0.12$ and $\text{HCO}_3^-/\text{Na}^+ = 2 \pm 1$ showed that the water drain was from silicate weathering (Stallard, 1980). The observed ratios of $\text{Ca}^{2+}/\text{Na}^+$, $\text{Mg}^{2+}/\text{Na}^+$ and $\text{HCO}_3^-/\text{Na}^+$ in the study areas were near to the values of that of water draining from carbonate prevailing lithology unlike the water draining from the silicate prevailing lithology.

Dissolved Ionic Contribution

The $(\text{Ca}^{2+} + \text{Mg}^{2+})$ versus total cations (TZ^+) plot for all the seven lakes during both seasons showed a linear trend indicating that Ca^{2+} and Mg^{2+} accounted for most of the cations (Figure 5a). The average ratio of $\text{Ca}^{2+} + \text{Mg}^{2+}$ to $\text{Na}^+ + \text{K}^+$ was 22.3 ± 2.55 during pre-monsoon season and 12.95 ± 2.29 during post-monsoon season. The plot between alkali metals and total cations, shown in Figure 5b revealed the average ratio values to be much below the equiline which strengthened the dominance of

alkaline earth over alkali metals. A plot of $(\text{Na}^+ + \text{K}^+)$ versus $(\text{Ca}^{2+} + \text{Mg}^{2+})$ showed the higher contribution of alkali earth metals over alkali metals (Figure 5c). The average ratio was observed for Na^+/Cl^- and K^+/Cl^- in the water body and was found to be 0.26 ± 0.06 and 0.22 ± 0.04 for pre-monsoon and post-monsoon respectively. Cl^- versus $(\text{Na}^+ + \text{K}^+)$ scatter plot indicated that Cl^- was abundant over alkali metals (Figure 5d). It further shows that silicate weathering is less dominant in the catchment area but has a relative ionic contribution from atmospheric fallout. Scatter plot of $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs $(\text{HCO}_3^- + \text{SO}_4^{2-})$, Figure 5e, defined the role of the ion exchange process. Plot with samples falling below the equiline indicated silicate weathering with the process of ion exchange. And the samples falling above the equiline indicated the dominance of reverse ion exchange and carbonate weathering. The pattern showed in the plots resulted that the lake water is dominated by Ca^{2+} , Mg^{2+} (alkali earth metals) and HCO_3^- (weak acids). The plot also indicated that Ca^{2+} - HCO_3^- was the major hydrogeochemical facies in the lake water for all the seven lakes with comparatively less contribution from Mg^{2+} - HCO_3^- type. To trace the source of aerosols into the lake system, trajectories were computed from HYSPLIT model (Figure 6). This illustrates the possible

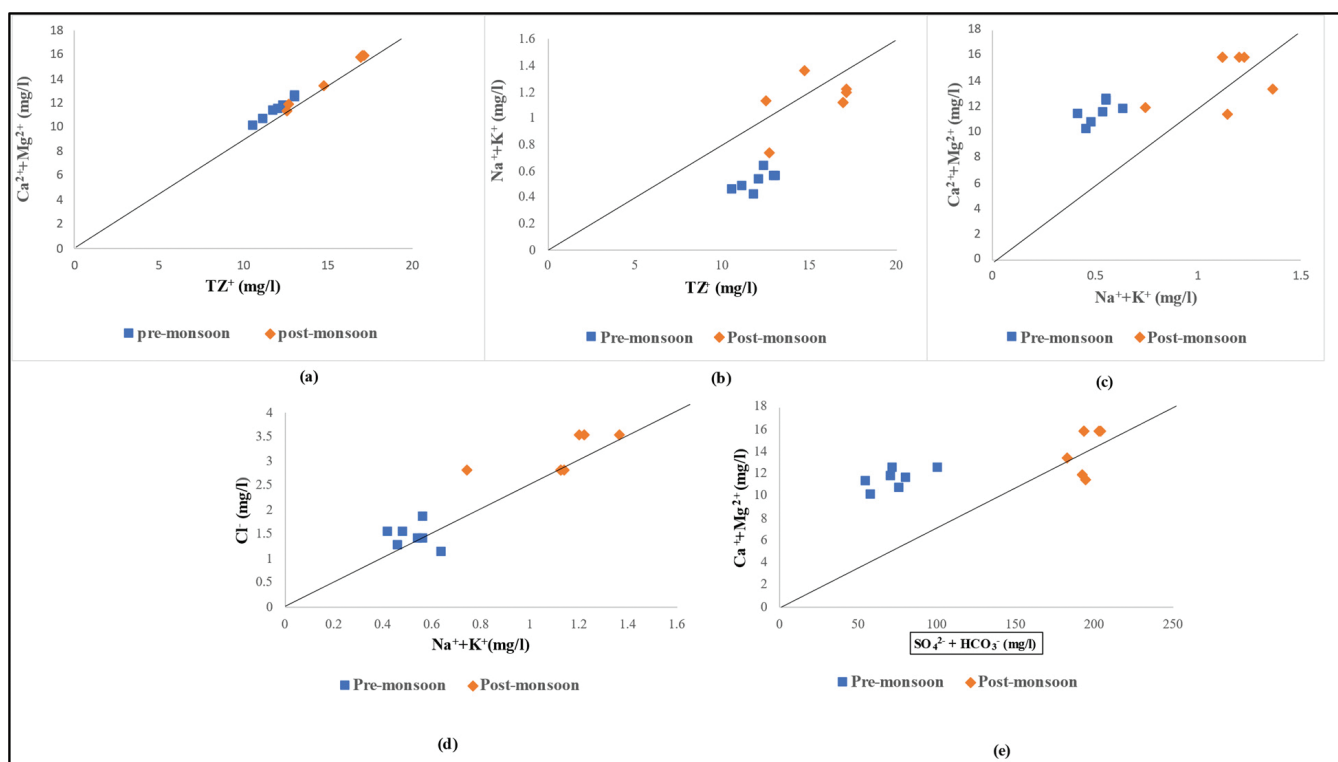


Figure 5: Scatter plot between (a) $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and TZ^+ , (b) $(\text{Na}^+ + \text{K}^+)$ and TZ^+ , (c) $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and $(\text{Na}^+ + \text{K}^+)$, (d) Cl^- and $(\text{Na}^+ + \text{K}^+)$ and (e) $(\text{SO}_4^{2-} + \text{HCO}_3^-)$ and $(\text{Ca}^{2+} + \text{Mg}^{2+})$.

source of aerosols in pre-monsoon and post-monsoon reaching the lakes. The computed trajectories suggest that air arriving at the vicinity of the lake has an origin mostly from the Middle East region. The results also show that all the studied lakes have significant impacts due to long-range transport of air pollutants rather than local interferences. Long-term monitoring is important to further analyse the fluctuations in the result. The Durov diagram provided a better display of hydro-chemical facies along with pH and TDS, which is used

to understand the hydro-chemical process controlling the water system (Durov, 1949). The Durov diagram in Figure 7 (a,b) for pre-monsoon and post-monsoon season respectively showed that the samples had bicarbonate and calcium in higher concentration and water samples with pH varied from 6.6 to 7.19 in pre-monsoon season and 6.46-6.69 in the post-monsoon season. It was further characterised that the water was rich in Ca-HCO_3 . Gibbs (1970) discussed the processes that significantly control the dissolved ions composition

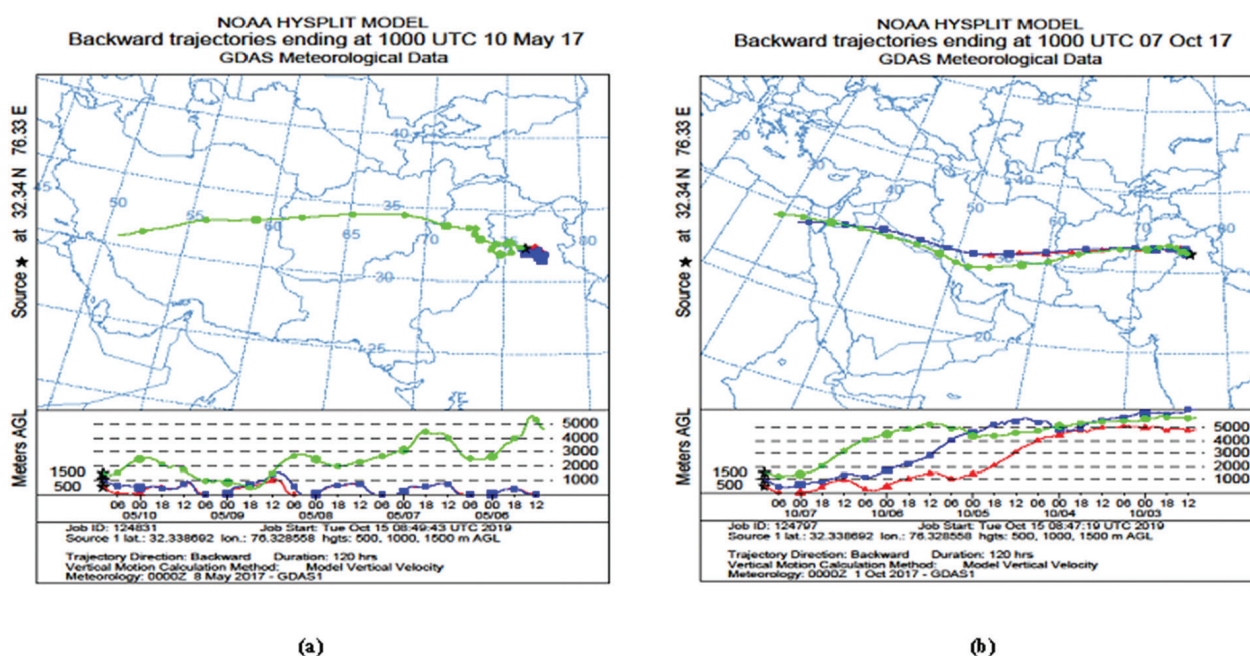


Figure 6: HYSPILT backward trajectories arriving at study area (a) pre-monsoon 2017 and (b) post-monsoon 2017.

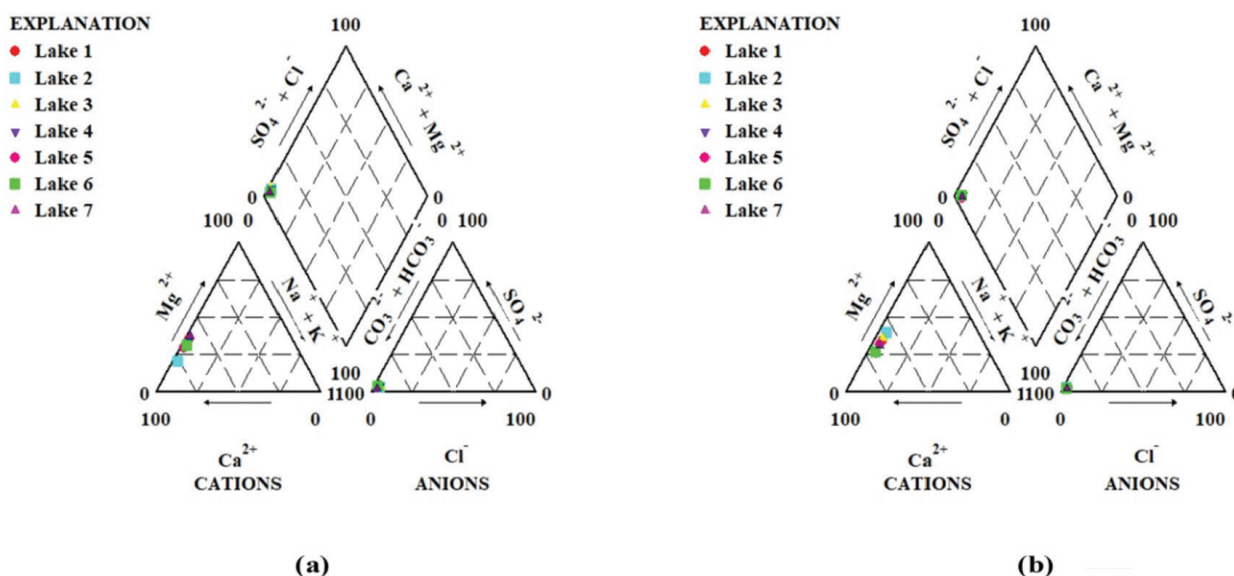


Figure 7: Piper plot showing water ion concentrations of study areas for (a) pre-monsoon and (b) post-monsoon.

of the water body. Gibb plots had the graph of ratio of cations [$(\text{Na}^+ + \text{K}^+)$ and $(\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+})$] and anions [Cl^- and $(\text{Cl}^- + \text{HCO}_3^-)$] against total dissolved solids (TDS). The proposed diagrams gave a better insight into the three major controlling mechanisms and factors such as atmospheric precipitation, rock dominance and evaporation-crystallisation that had clearly been demarcated to know the chemical components of a water body. Figure 8 shows the Gibbs diagram of Lam Dal and its consecutive six lakes altogether. Precipitation dominance was seen for all the seven lakes which shows that the lake water body is recharged by atmospheric precipitation. Also, low TDS average indicates that the snow melting was the major source of water in the lakes and dissolved salts purveyed by precipitation,

which controls the chemical composition of low salinity waters.

Correlation Matrix

Various physicochemical parameters in the correlation coefficient all together for Lam Dal and its consecutive lakes are given in Tables 4 and 5 for pre- and post-monsoon seasons, respectively. Correlation analysis was used to study the interrelationship of two or more chemical variables (Edet et al., 2003). The matrix displayed a positive correlation between EC and TDS in all the seasons for all the years in the study areas showing that EC is a function of TDS (Rusydi, 2018). A positive correlation between Cl^- and SO_4^{2-} was observed during the post-monsoon season which

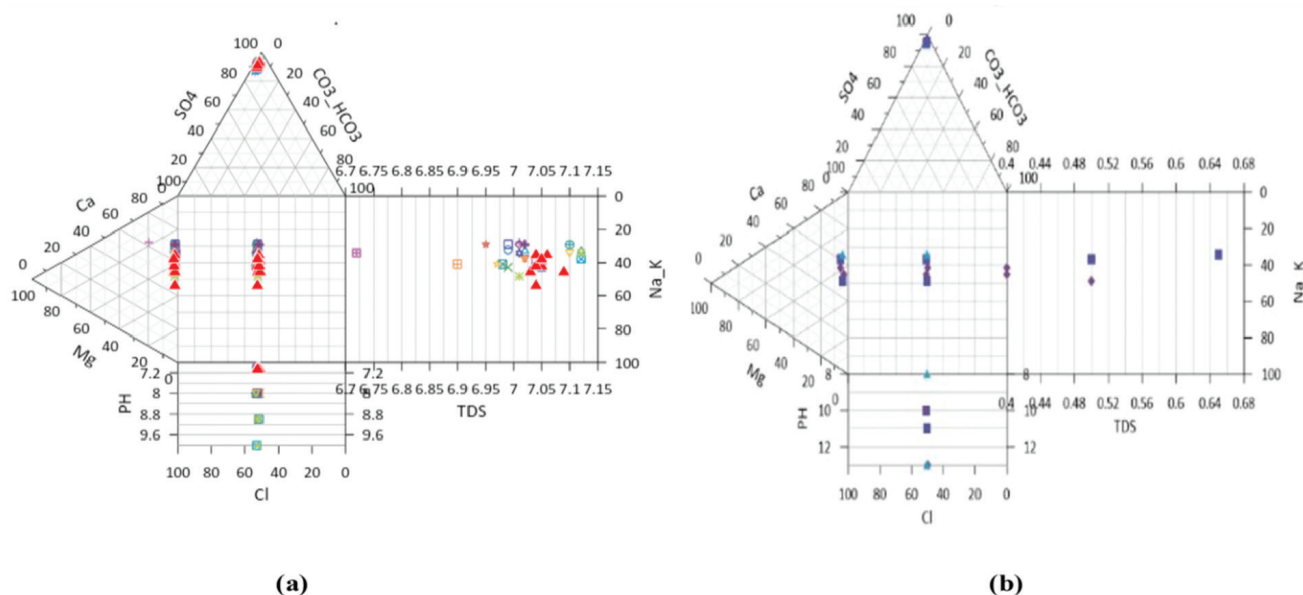


Figure 8: Durov diagram of surface water of the study areas for (a) pre-monsoon and (b) post-monsoon.

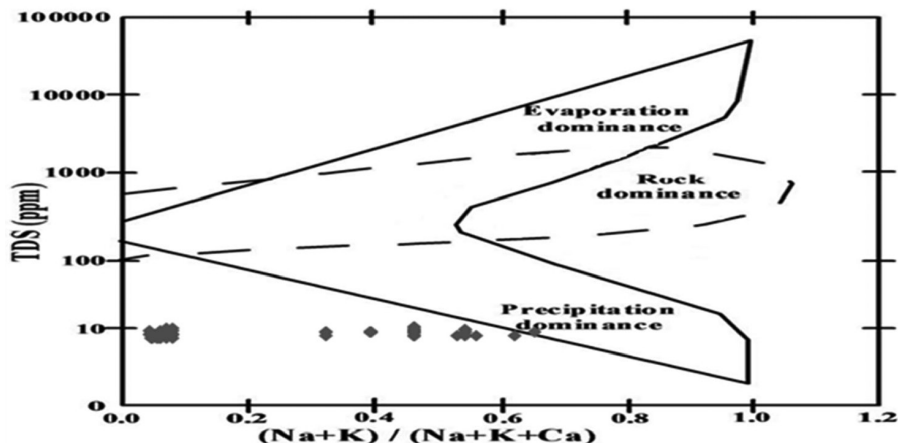


Figure 9: Gibbs Plot showing the mechanisms controlling the water quality of study area.

Table 4: Correlation coefficient matrix (pre-monsoon 2017)

	<i>pH</i>	<i>EC</i>	<i>TDS</i>	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
<i>pH</i>	1											
<i>EC</i>	.195	1										
<i>TDS</i>	.108	.663	1									
HCO_3^-	.764*	.327	.256	1								
SO_4^{2-}	.291	.429	.581	.796*	1							
Cl^-	-.470	.281	-.147	-.242	-.143	1						
NO_3^-	.287	.253	.737	.253	.345	-.150	1					
PO_4^{3-}	-.297	-.021	.201	-.742	-.628	-.187	.210	1				
Ca^{2+}	.395	.514	.008	.618	.394	.531	.098	-.628	1			
Mg^{2+}	-.743	-.096	.362	-.435	.153	.013	.032	.228	-.610	1		
Na^+	.183	.116	.132	.435	.369	.517	.487	-.538	.683	-.217	1	
K^+	-.549	.346	.436	-.332	.050	.573	.465	.303	.175	.342	.347	1

*Correlation is significant at the 0.05 level

Table 5: Correlation coefficient matrix (post-monsoon 2017)

	<i>pH</i>	<i>EC</i>	<i>TDS</i>	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+
<i>pH</i>	1										
<i>EC</i>	-0.336	1									
<i>TDS</i>	-0.582	0.549	1								
HCO_3^-	0.086	-0.513	0.019	1							
SO_4^{2-}	0.223	-0.478	-0.753	-0.256	1						
Cl^-	-0.365	-0.596	-0.276	0.258	0.624	1					
NO_3^-	0.201	0.275	0.527	-0.264	-0.562	-0.71	1				
PO_4^{3-}	0.352	0.6	0.345	-0.495	-0.464	-.904**	.832*	1			
Ca^{2+}	-0.38	-0.607	-0.23	0.592	0.27	.764*	-0.666	-.939**	1		
Mg^{2+}	-0.054	0.285	-0.012	0.013	-0.412	-0.519	0.108	0.172	0.08	1	
Na^+	-0.515	-0.382	-0.051	0.132	0.204	0.51	-0.262	-0.609	.778*	0.324	1
K^+	-0.205	-0.155	0.219	-0.371	0.373	0.426	0.202	-0.011	-0.122	-.787*	0.048

* Correlation is significant at the 0.05 level

** Correlation is significant at the 0.01 level

might be due to mineral dissolution whereas, in the pre-monsoon season, it showed a negative correlation. Ca^{2+} was positively correlated with HCO_3^- in both seasons. Positive correlation might be due to carbonate weathering whereas negative correlation suggested multiple sources. Ca^{2+} was positively correlated with SO_4^{2-} which might due to the dissolution of sulphate minerals. C ratio ($HCO_3^- / HCO_3^- + SO_4^{2-}$) was utilised to evaluate carbonation and oxidation of sulphides to evaluate the overall significance of two noteworthy proton producing reactions (Pandey et al., 1999). C ratio of 1 signifies carbonation reaction weathering whereas dissociation and dissolution of atmospheric CO_2 derive protons also have a carbon ratio of 0.5 which signifies

carbonate dissolution reactions with proton got from the oxidation of pyrite and coupled sulphide oxidation. The average C ratio during the pre-monsoon season of all the seven studied lakes (L1-L7) was around 0.97 and during the post-monsoon season, it was 0.98, suggesting proton is primarily derived from the oxidation of sulphide and coupled reactions involving carbonate dissolution.

Factor Analysis

It was a useful multivariate statistical tool commonly used to explain the transformation of a larger number of correlated variables called principal components (Shrestha et al., 2007). The intensity of the relationship between each factor and each variable is given by its

loading on that factor (Jha et al., 2009). An Eigenvalue greater than 1 was considered as a significant contributing factor within the data set (Ramanathan, 2007). Tables 6 and 7 summarise the principal component analysis of the study areas. Four factors were extracted having eigen value >1 for both the seasons which explained 89.3% of the total variability in the data set in the pre-monsoon season and 91.1%

in the post-monsoon season. First, second, third and fourth factors explained about 37.6%, 24.1%, 15.2% and 12.3% of the total variance in the data set during pre-monsoon season whereas for the post-monsoon season it explained about 44.1%, 21.9%, 15.2% and 9.7%, respectively. Factor 1 during pre-monsoon season shows a significant positive loading for pH, EC, HCO_3^- , SO_4^{2-} , Ca^{2+} , Na^+ in pre-monsoon season and

Table 6: Component Matrix (pre-monsoon 2017)

	<i>Component</i>				<i>Communalities</i>
	1	2	3	4	
pH	0.694	-0.585	0.143	0.38	0.99
EC	0.44	0.387	0.239	0.205	0.442
Cl	0.093	0.813	-0.555	0.018	0.978
NO₃	0.304	0.299	0.756	0.349	0.875
PO₄	-0.745	0.069	0.344	0.557	0.987
SO₄	0.693	0.08	0.461	-0.522	0.971
HCO₃	0.928	-0.279	0.17	-0.167	0.997
Na	0.666	0.506	-0.082	0.014	0.707
K	-0.108	0.921	0.236	0.148	0.937
Ca	0.847	0.325	-0.353	0.161	0.974
Mg	-0.545	0.345	0.412	-0.623	0.975
Eigen value	4.144	2.661	1.672	1.356	
% of variance	37.669	24.189	15.201	12.326	
Cumulative %	37.669	61.857	77.058	89.383	

Table 7: Component Matrix (Post-Monsoon 2017)

	<i>Component</i>				<i>Communalities</i>
	1	2	3	4	
pH	-.298	-.194	-.886	-.192	.948
EC	-.688	.128	.537	-.212	.823
Cl	.943	-.286	.119	.046	.988
NO₃	-.763	-.093	.059	.467	.812
PO₄	-.981	-.128	-.008	.028	.980
SO₄	.561	-.562	-.147	-.552	.956
HCO₃	.436	.472	-.507	.512	.932
Na	.650	.339	.420	.022	.714
K	.154	-.854	.340	.322	.971
Ca	.921	.370	.037	.087	.995
Mg	-.255	.857	.103	-.310	.906
Eigen value	4.861	2.415	1.674	1.077	
% of variance	44.190	21.950	15.218	9.791	
Cumulative %	44.190	66.141	81.358	91.149	

HCO_3^- , SO_4^{2-} , Ca^{2+} , Na^+ , Cl^- in post-monsoon season indicated contribution from carbonate weathering with the dissolution of sulphide oxidation, gypsum and contribution from atmospheric precipitation. Factor 2 showed strong loading for Cl^- , K^+ , Na^+ and Mg^{2+} in pre-monsoon season which explained contribution from silicate weathering and atmospheric precipitation. HCO_3^- , Ca^{2+} , K^+ , Na^+ and Mg^{2+} in post-monsoon season also indicated contribution from carbonate weathering taking place in the study area. Factor 3 had high positive loading for NO_3^- and SO_4^{2-} in the pre-monsoon season and a high positive load of NO_3^- in the post-monsoon season. These factors might explain the contribution from the dissolution of gypsum and the contribution from atmospheric dissolution. Factor 4 showed positive loading for PO_4^{2-} and NO_3^- in pre-monsoon season and HCO_3^- , NO_3^- , PO_4^{2-} in the post-monsoon season.

Conclusion

The physico-chemical parameters studied during pre-monsoon and post-monsoon seasons in the year 2017 showed slight variations in water chemistry. Studies showed that the lake water system possessed very little EC that meant water had a low ionic strength due to the least perturbation by anthropogenic activities. The anion concentration for all the seven lakes showed a trend of $\text{HCO}_3^- > \text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{PO}_4^{3-}$ whereas the order of cation concentrations was $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ for all the studied seven lakes for both seasons. The difference in values could be due to increased chemical weathering in the catchment area during the post-monsoon season and snow melt runoff during the pre-monsoon season. Along with trekkers, thousands of pilgrims mostly from the Dharamshala and Chamba regions visit this sacred lake during *Janmashtami* festival every year during the months from April to August. This might be the reason for some anthropogenic perturbation in the catchment area. The high ratios of $\text{Ca}^{2+} + \text{Mg}^{2+}/\text{Na}^+ + \text{K}^+$ and $\text{Ca}^{2+} + \text{Mg}^{2+}/\text{TZ}^+$ and low ratios of $\text{Na}^+ + \text{K}^+/\text{TZ}^+$ had been observed in the study areas indicating that carbonate weathering is the dominant mechanism controlling the major ion chemistry of Lam Dal and its consecutive six lakes with minor contribution by silicate weathering. Carbon ratio suggests that proton is primarily derived from the oxidation of sulphide and coupled reactions involving carbonate dissolution. Correlation and factor analysis show that the hydrochemistry of all the seven lakes is mainly due to carbonate dominant lithology and dissolution of sulphate minerals. Geology of the area plays a very important role in the ionic concentration

of the water system of Lam Dal catchment, ions are released due to monsoonal precipitation as well as due to seasonal snow melt runoff. The study area remains snow covered during the winter months. Streams coming from the north and other directions intersect with different geological setups. The variation in ions during pre-monsoon and post-monsoon season could be due to change in atmospheric precipitation over the period along with limited anthropogenic inputs. The global water cycle will continue to intensify as global temperatures rise, with precipitation and surface water flows projected to become more variable over most land regions within seasons and from year to year. Monsoon precipitation is projected to increase from mid- to long term at a global scale, particularly over South and Southeast Asia, East Asia and West Africa apart from the far west Sahel (IPCC, 2021). Most of the high altitude lakes are under serene conditions; thus, water quality can be the indicator of not only weathering processes but can also be an indicator for various other processes like atmospheric fallout along with different precipitation dynamics that can change the water quality of a high altitude Himalayan lakes due to climate change. The role of high-altitude lakes as water towers is that they can sustainably be used for supplying fresh water downstream among the hill communities, under gravity. This can be a promising approach in the Himalayas with the least energy consumption (Liniger and Weingartner, 1998). This approach can be proved to be a sustainable approach for water availability in the hilly region without changing the energy balance of high altitude Himalayan regions that can be the main reason for the increased rate of flash floods in the higher Himalayas. The Himalayas have many marsh, peat and lake wetlands, which make it a unique ecosystem that fulfils important functions in the overall water cycle of the basins, and provides habitats for wildlife. The high altitude lakes are important sources of water for many rivers and have cultural and spiritual values for local people. However, these wetlands have received little attention so far in terms of their conservation and management, but they are increasingly becoming important due to the possible consequences of global climate change, and globalisation in economic development. Conservation of these unique spaces needs special effort by the whole society. They need technical support, innovative partnership and networking, which mobilises political wills, stakeholder involvement, financial resources as the pre-requisite conditions.

Acknowledgement

The authors are thankful to the Chairperson, Department of Environment Studies, Panjab University Chandigarh, Chairperson, Department of Geology, Panjab University Chandigarh and Dean, Department of Environmental Sciences CUHP for providing laboratory and other facilities. We also are grateful to Mr. Kuldeep Bisht and Shikha Rawal for their contribution towards laboratory and GIS work, respectively.

Conflict of Interest

The authors declare that there are no conflict of interest.

References

- Aghazadeh, N., Chitsazan, M. and Golestan, Y., 2017. Hydrochemistry and quality assessment of groundwater in the Ardabil area, Iran. *Applied Water Science*, **7(7)**: 3599-3616.
- APHA, 2012. Standard Method for the Examination of Water and Wastewater. 22nd ed. American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF). Washington DC, USA.
- Bahadur, J. and Prasar, V., 1998. Himalayan glaciers. *Vigyan Prasar*, New Delhi.
- Barnett, T.P., Adam, J.C. and Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, **438(7066)**: 303-309.
- Bhagabati, R. and Borkotoki, A., 2014. Status of Patkai lake near tikak open cast mine, Assam: A hydro-biological approach. *Biolife*, **2(2)**: 615-626.
- Bhat, N.A., Jeelani, G. and Bhat, M.Y., 2014. Hydrogeochemical assessment of groundwater in karst environments, Bringi watershed, Kashmir Himalayas, India. *Current Science*, 1000-1007.
- Bleam, W., 2017. Water chemistry. *Soil and Environmental Chemistry*, **5**: 189-251.
- Bookhagen, B. and Burbank, D.W., 2010. Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research: Earth Surface*, **115(F3)**.
- CGWB, G.Y.B.I., 2012. Central Ground Water Board. Ministry of Water Resources Government of India, Faridabad.
- Chakrapani, G., 2002. Water and sediment geochemistry of major Kumaun Himalayan lakes, India. *Environmental Geology*, **43(1-2)**: 99-107.
- Chidambaram, S., Karmegam, U., Prasanna, M.V., Sasidhar, P. and Vasanthavigar, M., 2011. A study on hydrochemical elucidation of coastal groundwater in and around Kalpakkam region, Southern India. *Environmental Earth Sciences*, **64(5)**, 1419-1431.
- Clift, P.D., Hodges, K.V., Heslop, D., Hannigan, R., Van Long, H. and Calves, G., 2008. Correlation of Himalayan exhumation rates and Asian monsoon intensity. *Nature Geosciences*, **1(12)**: 875-880.
- Climate data <https://power.larc.nasa.gov/data-access-viewer/>. Accessed on 15th March 2021.
- Das, B.K. and Kaur, P., 2001. Major ion chemistry of Renuka lake and weathering processes, Sirmour district, Himachal Pradesh, India. *Environmental Geology*, **40(7)**: 908-917.
- Deka, J.P., Tayeng, G., Singh, S., Hoque, R.R., Prakash, A., and Kumar, M., 2015. Source and seasonal variation in the major ion chemistry of two eastern Himalayan high altitude lakes, India. *Arabian Journal of Geosciences*, **8(12)**: 10597-10610.
- Derry, L.A. and France-Lanord, C., 1996. Neogene Himalayan weathering history and river: Impact on the marine Sr record. *Earth and Planetary Science Letters*, **142(1-2)**: 59-74.
- Dimri, A.P., Simon, A., Huggel, C. and Mal, S., Ballesteros-Canovas, J., Rohrer, M., Shukla, A., Tiwari, P., Maharana, P., Bolch, T., Thayyen, R. and Pandey, A., 2021. Climate change, cryosphere and impacts in the Indian Himalayan Region. *Current Science*, **120**: 775-790. 10.18520/cs/v120/i5/774-790.
- Dudgeon, D., 2014. Threats to freshwater biodiversity in a changing world. *Global Environmental Change*, pp. 243-253.
- Durov, S.A., 1949. Treugolnaja forma graficeskogo vyrazenija rezultatov vodnyh analizov I primenenije jejo k klassifikaciji prirodnyh vod. *Gidrochem. materialy*, **16**: 54.
- Edet, A.E., Merkel, B.J. and Offiong, O.E., 2003. Trace element hydrochemical assessment of the Calabar Coastal Plain Aquifer, southeastern Nigeria using statistical methods. *Environmental Geology*, **44(2)**: 137-149.
- Fritz, S.J., 1994. A survey of charge-balance errors on published analyses of potable ground and surface waters. *Groundwater*, **32(4)**: 539-546.
- Gaillardet, J., Dupré, B., Louvat, P. and Allegre, C.J., 1999. Global silicate weathering and CO₂ consumption rates deduced from the chemistry of large rivers. *Chemical Geology*, **159(1-4)**: 3-30.
- Galloway, J.N. and Cowling, E.B., 1978. The effects of precipitation on aquatic and terrestrial ecosystems: A proposed precipitation chemistry network. *Journal of the Air Pollution Control Association*, **28(3)**: 229-235.
- Galy, V., France-Lanord, C., Peucker-Ehrenbrink, B. and Huyghe, P., 2010. Sr-Nd-Os evidence for a stable erosion regime in the Himalaya during the past 12 Myr. *Earth and Planetary Science Letters*, **290(3-4)**: 474-480.
- Gaury, P.K., Meena, N.K. and Mahajan, A.K., 2018. Hydrochemistry and water quality of Rewalsar Lake of

- Lesser Himalaya, Himachal Pradesh, India. *Environmental Monitoring and Assessment*, **190**(2): 1-22.
- Gibbs, R.J., 1970. Mechanisms controlling world water chemistry. *Science*, **170**(3962): 1088-1090.
- Gleick, P.H., 1993. Water and conflict: Fresh water resources and international security. *International Security*, **18**(1): 79-112.
- Gupta, P., Roy, S. and Mahindrakar, A.B., 2012. Treatment of water using water hyacinth, water lettuce and vetiver grass—A review. *System*, **49**: 50.
- Harris, N., 1995. Significance of weathering of Himalayan meta sedimentary rocks and leucogranites for the strontium isotope evolution of seawater during early Miocene. *Geology*, **23**: 795-798.
- Hodges, K.V., 2000. Tectonics of the Himalaya and southern Tibet from two perspectives. *Geological Society of America Bulletin*, **112**(3): 324-350.
- Hu, X., Garzanti, E., Wang, J., Huang, W., An, W. and Webb, A., 2016. The timing of India-Asia collision onset—Facts, theories, controversies. *Earth-Science Reviews*, **160**: 264-299.
- IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.
- Jha, P.K., Tiwari, J., Singh, U.K., Kumar, M. and Subramanian, V., 2009. Chemical weathering and associated CO₂ consumption in the Godavari river basin, India. *Chemical Geology*, **264**(1-4): 364-374.
- Ji, J., Shen, J., Balsam, W., Chen, J., Liu, L. and Liu, X., 2005. Asian monsoon oscillations in the northeastern Qinghai–Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments. *Earth and Planetary Science Letters*, **233**(1-2): 61-70.
- Khadka, U.R. and Ramanathan, A.L., 2013. Major ion composition and seasonal variation in the Lesser Himalayan lake: Case of Begnas Lake of the Pokhara Valley, Nepal. *Arabian Journal of Geosciences*, **6**(11): 4191-4206.
- Krishna Kumar, K., Hoerling, M. and Rajagopalan, B., 2005. Advancing dynamical prediction of Indian monsoon rainfall. *Geophysical Research Letters*, **32**(8).
- Kumar, P., Mahajan, A.K. and Kumar, A., 2020. Groundwater geochemical facie: Implications of rock-water interaction at the Chamba city (HP), northwest Himalaya, India. *Environmental Science and Pollution Research*, **27**(9): 9012-9026.
- Kumar, P., Meena, N.K. and Mahajan, A.K., 2019. Major ion chemistry, catchment weathering and water quality of Renuka Lake, north-west Himalaya, India. *Environmental Earth Sciences*, **78**(10): 1-16.
- Kumar, R. and Sharma, R.C., 2019. Assessment of the water quality of Glacier-fed lake Neel Tal of Garhwal Himalaya, India. *Water Science*, **33**(1): 22-28.
- Kump, L.R., Brantley, S.L. and Arthur, M.A., 2000. Chemical weathering, atmospheric CO₂, and climate. *Annual Review of Earth and Planetary Sciences*, **28**(1): 611-667.
- Liniger, H. and Weingartner, R., 1998. Mountains and freshwater supply. Unasylva (FAO).
- Lu, Y., Tang, C., Chen, J. and Chen, J., 2015. Groundwater recharge and hydrogeochemical evolution in leizhou peninsula, China. *Journal of Chemistry*, 2015.
- Malik, M., Balkhi, M.H., Abubakr, A. and Bhat, F., 2017. Assessment of trophic state of Nagin Lake based on limnological and bacteriological studies. *Nature Environment & Pollution Technology*, **16**(2).
- Ménégoz, M., Gallée, H. and Jacoby, H.W., 2013. Precipitation and snow cover in the Himalaya: From reanalysis to regional climate simulations. *Hydrology and Earth System Sciences*, **17**(10): 3921-3936.
- Meybeck, M., 1987. Global chemical weathering of surficial rocks estimated from river dissolved loads. *American Journal of Science*, **287**(5): 401-428.
- Muri, G., Cermelj, B., Faganeli, J. and Brancelj, A., 2002. Black carbon in Slovenian alpine lacustrine sediments. *Chemosphere*, **46**(8): 1225-1234.
- Najar, A.I. and Khan, B.A., 2012. Assessment of water quality and identification of pollution sources of three lakes in Kashmir, India, using multivariate analysis. *Environmental Earth Sciences*, **66**: 2367-2378. Doi 10.1007/s12665-011-1458-1
- Pandey, S.K., Singh, A.K. and Hasnain, S.I., 1999. Weathering and geochemical processes controlling solute acquisition in Ganga headwater—Bhagirathi river, Garhwal Himalaya, India. *Aquatic Geochemistry*, **5**(4): 357-379.
- Panigrahy, S., Patel, J.G. and Parihar, J.S., 2012. National Wetland Atlas: High altitude lakes of India. Space Applications Centre, ISRO, Ahmedabad, India.
- Ramanathan, A.L., 2007. Seasonal variation in the major ion chemistry of Pandoh Lake, Mandi district, Himachal Pradesh, India. *Applied Geochemistry*, **22**(8): 1736-1747.
- Revenga, C., 2003. Status and trends of biodiversity of inland water ecosystems. *Secretariat of the Convention on Biological Diversity*.
- Rusydi, A.F., 2018, February. Correlation between conductivity and total dissolved solid in various type of water: A review. In: IOP conference series: earth and environmental science, **118**(1): 012019. IOP Publishing.
- Saleem, M., Jeelani, G. and Shah, R.A., 2015. Hydrogeochemistry of Dal Lake and the potential for present, future management by using facies, ionic ratios, and statistical analysis. *Environmental Earth Sciences*, **74**(4): 3301-3313.
- Sarah, S., Jeelani, G.H. and Ahmed, S., 2011. Assessing variability of water quality in a groundwater-fed perennial lake of Kashmir Himalayas using linear geostatistics. *Journal of Earth System Science*, **120**(3): 399-411.

- Sharma, R.C. and Kumar, R., 2017. Water quality assessment of sacred glacial Lake Satopanth of Garhwal Himalaya, India. *Applied Water Science*, **7(8)**: 4757-4764.
- Sheikh, J.A., Jeelani, G., Gavali, R.S. and Shah, R.A., 2014. Weathering and anthropogenic influences on the water and sediment chemistry of Wular Lake, Kashmir Himalaya. *Environmental Earth Sciences*, **71(6)**: 2837-2846.
- Shrestha, S., Kazama, F. and Nakamura, T., 2008. Use of principal component analysis, factor analysis and discriminant analysis to evaluate spatial and temporal variations in water quality of the Mekong River. *Journal of Hydroinformatics*, **10(1)**: 43-56.
- Singh, K.K., Sharma, B.M. and Usha, K.H., 2010. Ecology of Kharungpat lake, Thoubal, Manipur, India: part-I water quality status. *Ecoscan*, **4(2-3)**: 241-245.
- Singh, V.B., Ramanathan, A.L., Pottakkal, J.G. and Kumar, M., 2014. Seasonal variation of the solute and suspended sediment load in Gangotri glacier meltwater, central Himalaya, India. *Journal of Asian Earth Sciences*, **79**: 224-234.
- Solomon, S., Manning, M., Marquis, M. and Qin, D., 2007. Climate change 2007 – The physical science basis: Working group I contribution to the fourth assessment report of the IPCC (4). Cambridge University Press.
- Sorkhabi, R., 2010. Geologic formation of the Himalaya. *The Himalayan Journal*, **66**: 87-102.
- Stallard, R.F., 1980. Major element geochemistry of the Amazon River system (Doctoral dissertation, Massachusetts Institute of Technology).
- Subramanian, V., 2004. Water quality in south Asia. *Asian Journal of Water, Environment and Pollution*, **1(1,2)**: 41-54.
- Sun, M., Jin, H., Yao, X., Yan, L., Li, X. and Gao, Y., 2020. Hydrochemistry differences and causes of tectonic lakes and glacial lakes in Tibetan Plateau. *Water*, **12(11)**: 3165.
- Talbot, M.A., 1996. Lakes. Sedimentary environments: Processes, facies and stratigraphy, **4(83)**: 124.
- Tayal, S., 2019. Climate Change Impacts on Himalayan Glaciers and Implications on Energy Security of India, TERI Discussion Paper. New Delhi: The Energy and Resources Institute.
- Taylor, M. and Yin, A., 2009. Active structures of the Himalayan-Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism. *Geosphere*, **5(3)**: 199-214.
- Thompson, D.B., 1999. Beyond benefit-cost analysis: Institutional transaction costs and regulation of water quality. *Natural Resources Journal*, 517-541.
- Upadhyay, D.S., 1995. Cold Climate Hydrometeorology. New Age International Publication, New Delhi. 135.
- Walton, N.R.G., 1989. Electrical conductivity and total dissolved solids—what is their precise relationship? *Desalination*, **72(3)**: 275-292.
- Yang, X., Lu, X., Park, E. and Tarolli, P., 2019. Impacts of climate change on lake fluctuations in the Hindu Kush-Himalaya-Tibetan Plateau. *Remote Sensing*, **11(9)**: 1082.
- Yao, Z., Wang, R., Liu, Z., Wu, S. and Jiang, L., 2015. Spatial-temporal patterns of major ion chemistry and its controlling factors in the Manasarovar Basin, Tibet. *Journal of Geographical Sciences*, **25(6)**: 687-700.
- Yin, A., Dubey, C.S., Webb, A.A.G., Kelty, T.K., Grove, M., Gehrels, G.E. and Burgess, W.P., 2010. Geologic correlation of the Himalayan orogen and Indian craton: Part 1. Structural geology, U-Pb zircon geochronology, and tectonic evolution of the Shillong Plateau and its neighboring regions in NE India. *Bulletin*, **122(3-4)**: 336-359.
- Zutshi, D.P., 1991. Limnology of high altitude lakes of Himalayan region. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, **24(2)**: 1077-1080.