Hydrogeochemical Analysis of Phewa Lake: A Lesser Himalayan Lake in the Pokhara Valley, Nepal

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ABSTRACT

Phewa Lake in Nepal is a lake of international importance providing crucial ecological and economic services. However, increased urbanization, population growth and anthropogenic activities have resulted in degradation of the lake. Thus, understanding the lake hydro-geochemistry is crucial for identifying sources of elements. Preceding studies have mostly covered limnological and physico-chemical assessments which are not sufficient to explain the lake catchment characteristics. This study has assessed the major ions in relation to their hydro-geochemical processes in the catchment. To evaluate monsoonal impact, the rainwater was also analyzed. The major ions were determined by using standard methods. The results revealed significant seasonal variations in temperature, pH, TDS, EC, and most of the major ions. There was domination of the total anions (Tz^-) over the total cations (Tz^+) indicating possible ionic contribution through decomposition of organic compounds. The domination of Ca^{2+}, Mg^{2+} and HCO_3^- elucidates influence of carbonate weathering. The high (>1) equivalent ratio for $(Ca^{2+}+Mg^{2+})/(Na^++K^+)$, and $(Ca^{2+}+Mg^{2+})/(Tz^+)$ ratio ≈1 also suggest abundance of $(Ca^{2+}+Mg^{2+})$ and prevalence of carbonate weathering. The low (<0.5) $(Na^++K^+)/Tz^+$ ratio suggests lesser contribution of cations via alumino-silicate weathering. The positive correlation between Ca^{2+} and Mg^{2+}, and SO_4^{2-} and Ca^{2+} indicate their common sources. Although the major ions were within the acceptable limits for irrigation, fish farming and recreation purposes, the increased trophic status of the lake suggests possibility of other processes making the limiting nutrients available for algal and macrophytes growth. Further studies incorporating sediment-water interaction is anticipated for the better management of the lake.

1. INTRODUCTION

Lakes and reservoirs play a vital role in the cycling of elements. However, the present increased urbanization and anthropogenic pressure has hastened the transport of lithogenic and anthropogenic elements to the lakes altering the lake characteristics (Das et al., 1995). The elements brought to the lake are not primarily fixed on the sediment, and can be released back to the water-column with the change in environmental conditions (Forstner and Wittmann, 1983; Håkanson, 2004; Singh et al., 2005). Hence, knowing lake water chemistry is important for determining its use in domestic, recreational, irrigational and industrial purposes and understanding the nature of the catchment lithology, soil erosion, precipitation and anthropogenic activity. Additionally, it is important for determining the source of elements to the lake and understanding seasonal changes (Anshumali and Ramanathan, 2007; Das and Kaur, 2001).

The lakes in the Pokhara Valley are threatened by siltation, urbanization, land-use change and agricultural activity in the catchment and degradation of water quality (Rai, 2000a; Ross and Gilbert, 1999). As the high altitude lakes react faster to the changes in their environment; these lakes are vulnerable (Vreca and Muri, 2006). The Pokhara Valley has nine lakes playing a key role in maintaining regional hydrological cycle by recharging water, controlling flood and trapping sediment along with their

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contribution in economy, tourism and biodiversity. Thus, the Lake Cluster of Pokhara Valley has been recognized as the Ramsar Site on 2nd February, 2016 (Ramsar, 2016). Phewa Lake is the largest lake of the cluster and second largest of Nepal with biologically rich watershed (Oli, 1997; Shrestha and Janauer, 2001). Giri and Chalise (2008) reported 39 species of water-birds including 15 winter visitors, 10 resident, 10 occasional visitors, and 4 rare winter visitors. Besides, this is a multipurpose lake used for irrigation, commercial fish farming and fishery research, cultural sites, and recreation. Thousands of people depend on the lake for their livelihood and income generation from tourism, fisheries, irrigation, power generation and water supply (Ramsar, 2016). According to CSUWN (2011), the lake catchment area provides annual economic benefits worth USD 43.6 million through various ecosystem services. The study has also reported the lake as one of the attractive tourist destinations accounting 203,527 international and 200,000 domestic tourist visitors in the fiscal year 2008/2009. MoFE (2018) and Poudyal et al. (2016) have enlisted 23 ecosystem services of the local, regional and global importance provided by Phewa Lake Watershed. Moreover, as a Ramsar site, Phewa Lake provides habitats for various aquatic lives including endemic and migratory water fowls. The lake watershed is mostly covered by forest (47%) followed by agriculture (39.6%), water body and wetland (4.9%), built-up land (4.8%), waste land (2.7%) and bush/scrub and grass (1%) (Regmi et al., 2017). The settlement in the catchment includes six villages of Pokhara Metropolitan City. The urban land includes a large number of hotels and restaurants on the north-eastern shore. The growing population and urbanization in the catchment are causing municipal discharge, discharge from hotels/restaurants and sub-surface flow from septic tanks leading to sedimentation and siltation, and water quality deterioration (Rai, 2000a; Ross and Gilbert, 1999). Based on the rate of areal decline and sediment influx, 80% storage capacity of Phewa Lake has been reported to be lost by the next 110-347 years (Watson et al., 2019).

Phewa Lake is one of the better-studied lakes in the Pokhara Valley (Adhikari and Khadka, 2017; Ferro and Swar, 1978; Gurung et al., 2006; Gurung et al., 2010; Hickel, 1973; Jones et al., 1989; Kato and Hayashi, 1982; Pradhan and Kim, 2017; Rai, 2000a; Rai, 2000b; Regmi et al., 2017; Ross and Gilbert, 1999; Rowbotham and Dudycha, 1998; Swar and Fernando, 1979a; Swar and Fernando, 1979b; Swar and Fernando, 1980; Watson et al., 2019). However, the preceding works have mostly covered limnology, land-use studies, slope stability assessment, morphological changes and geological studies indicating very scarce hydro-geochemical studies. Thus, the present study has attempted to assess the hydro-geochemical characteristics of Phewa Lake. Besides, the study has also focused on examining the monsoon rain water for understanding impact of monsoon on the lake water. Findings of the study could be useful in future sustainable management of the Phewa Lake as well as other lakes in the region.

2. METHODOLOGY

2.1 Study area

The Pokhara Valley is characterized by the presence of Annapurna Himalaya, many lakes, and turbulent Seti River with a deep gorge (Figure 1). Phewa Lake lies in Pokhara Metropolitan City, the provincial capital of Gandaki Province and the second tourist destination after Kathmandu. The lake watershed occupies about 123 km^2 areas at 28°11'39" N to 28°17'25" N latitudes, and 83°47'51" E to 83°59'17" E longitudes within an elevation range from 789 m.a.s.l. to 2,508 m.a.s.l. (Regmi et al., 2017). The main inflows are perennial spring-fed streams, Harpan River with several small seasonal streams mostly draining during the monsoon. The lake has an area of 4.43 km^2 with maximum depth of 23.5 m and an average depth of 8.6 m (Gurung et al., 2006; Gurung et al., 2010) and a single outflow towards the southeast (Figure 1).

Geologically, the Pokhara Valley is an intermontane fluvial basin spread around the midstream of Seti River filled by a large volume of layered clastic deposits brought from the Annapurna Mountain (Yamanaka et al., 1982). The lake watershed constitutes weak, low-medium grade Pre-cambrian to early Cambrian grey phyllitic schists, talc-rich red phyllite schists (Ross and Gilbert, 1999; Rowbotham and Dudycha, 1998), quartzite schists inter-bedded with grey phyllite schists, carbonaceous conglomerate (Impat, 1980), and gneiss, granite, quartzite and schist (Gautam et al., 2000).

Climatically, the watershed is humid subtropical to temperate type with maximum monthly temperature ranging from 21.9±1.5°C (January) to 32.0±1.5°C (April); and minimum temperature ranging from 8.4±1.9°C (January) to 22.9±0.9°C (July) accounting more than 80% annual rainfall during June to September with humidity variation from 66.04±11.74% (April) to 94.06±2.43% (January) (Table 1).

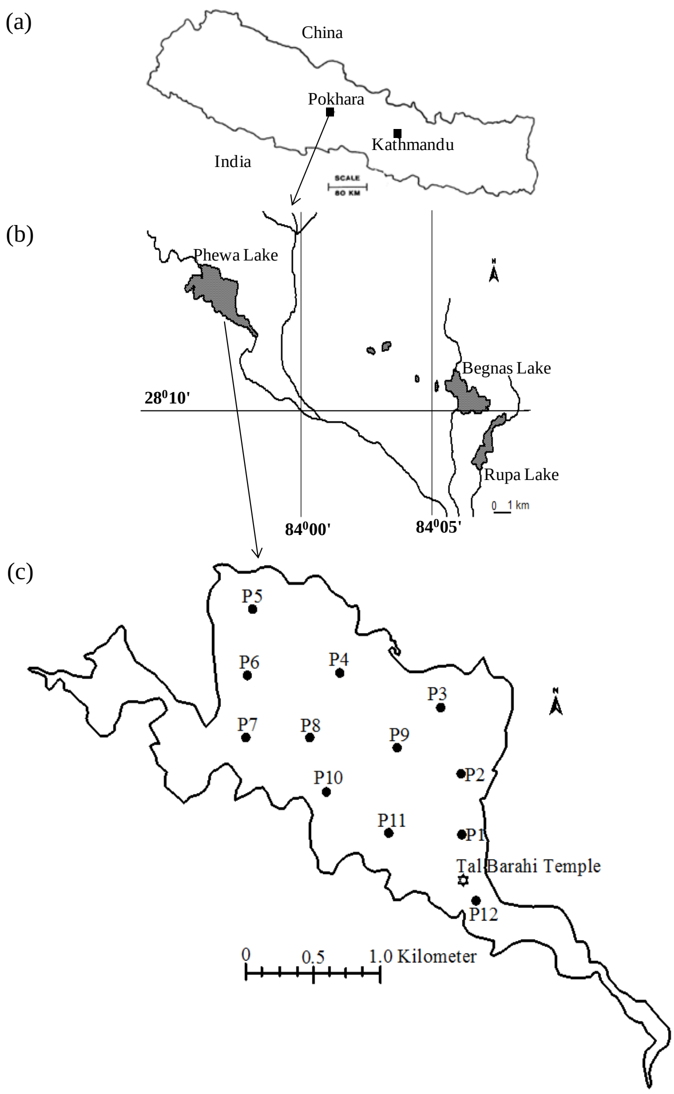

Figure 1. Location of the study area (a) showing distribution of lakes in the valley; (b) and sampling locations in Phewa Lake; (c) (Modified Hickel, 1973)

Table 1. The climatic condition of the study area during study period (2008-2009). Units: temperature in °C, humidity in %, and rainfall in mm

Season	Months	Max. Temp	Min. Temp	Humidity*	Humidity**	Rainfall
Post-monsoon	Oct	28.35±1.08	15.79±1.63	85.27±5.37	67.65±6.05	102.8
	Nov	25.37±1.52	11.95±1.75	86.89±5.83	60.75±8.03	-
	Dec	22.33±1.59	9.52±1.43	93.34±4.17	65.04±6.28	-
	Jan	21.89±1.49	8.42±1.86	94.06±2.43	57.96±6.51	-
Pre-monsoon	Feb	25.71±1.65	10.62±1.15	84.92±6.45	41.53±8.22	-
	Mar	28.65±1.78	12.62±1.45	69.09±7.50	41.74±9.52	25.3
	Apr	32.00±1.51	17.37±2.19	66.04±11.74	39.53±15.60	45.6
	May	30.78±2.10	19.14±1.56	75.91±11.98	58.30±14.87	260.2
Monsoon	Jun	31.52±2.01	21.43±1.53	81.30±10.79	68.50±11.53	609.3
	Jul	31.13±2.33	22.85±0.92	90.46±5.69	73.40±9.85	762.7
	Aug	30.51±1.98	22.57±1.01	91.41±3.88	78.03±9.38	1026.2
	Sept	30.28±1.72	21.03±0.88	86.82±6.02	73.71±7.54	302.5

Data source: Department of Hydrology and Meteorology, Government of Nepal (***** Humidity at 8:45 am and ** at 5:45 pm)

2.2 Sample collection and analysis

The 12 surficial water samples from Phewa Lake were collected during November 2008 (post-monsoon), April 2009 (pre-monsoon), and August 2009 (monsoon) from 12 locations, here referred as P1, P2, P3……P12 (Figure 1(c)), ensuring representation of the total lake area, traversing on a rowboat. The subsequent season's samples were carefully collected from the same locations. Two sets of water samples were collected for cation and anion analyses. For cation analysis, samples were preserved in nitric acid (HNO_3) to avoid precipitation or adsorption (APHA, 2005). All the samples were stored in properly cleaned plastic bottles, soaked overnight in HNO_3 (5% v/v), and rinsed with MilliQ water. The bottles were pre-washed with the water sample to be collected. Three rain water samples were collected from city area of Pokhara in a single rain event in August 2009 in properly cleaned and pre-washed plastic bags.

Water parameters like hydrogen ion concentration (pH), electrical conductivity (EC), bicarbonate (HCO_3^-), total dissolved solids (TDS) and dissolved oxygen (DO) were measured on-site using respective portable electrodes for pH, EC and TDS; acid titration method for HCO_3^- and Winkler's method for DO (APHA, 2005). The water samples were filtered through 0.45 µm cellulose filter paper and transported in an ice box and analyzed at the hydro-geochemistry laboratory of School of Environment Sciences, Jawaharlal Nehru University, New Delhi, India. Dissolved Cl^- was determined by colorimetric method, SO_4^{2-} by turbidimetric method, PO_4^{3-} by ascorbic acid method (APHA, 2005), NO_3^- by nitration of salicylic acid (Diatloff and Rengel, 2001) and dissolved H_4SiO_4 by molybdosilicate blue method (Strickland and Parsons, 1968). The major cations like Na^+, K^+, Mg^{2+}, and Ca^{2+} were determined by the Atomic Absorption Spectrophotometer (AAS-Thermo Scientific M Series). The high grade reagents and MilliQ water (Model Milli-Q, Biocell) were used during the analyses. In every analysis, controls were performed on appropriate blank solutions and precision was maintained by running known standard after every ten samples. The analytical precision was within ±10%. The data acquired were analyzed using Statistical Package for Social Sciences (SPSS) version 17.0.

3. RESULTS AND DISCUSSION

3.1 Physico-chemical characteristics of the lake water

The physico-chemical characteristics of the lake water show spatial and seasonal variations. Temperature is an important parameter regulating lake stratification. In Phewa Lake, the surface water temperature followed the pattern of the ambient temperature (Table 1) showing higher values during the monsoon (27.9±0.9°C) compared to pre-monsoon (26.3±0.5°C) and post-monsoon (23.5±0.8°C) with significant ($p<0.05$) seasonal variation (Table 2).

The pH is an important parameter controlling weathering patterns and availability of the dissolved solids in lakes. In Phewa Lake, pH ranged from slightly acidic (6.5) to alkaline (8.0) during post-monsoon, neutral (7.0) to alkaline (9.1) during pre-monsoon and alkaline (7.5-7.9) during monsoon with significant variation ($p<0.05$) between post-monsoon and pre-monsoon, and pre-monsoon and monsoon (Table 2). Rai (2000a) observed pH variation from 6.3 (August-September) to 9.7 (May). The increase in pH during pre-monsoon can be attributed to the increased rate of photosynthesis by primary producers (Das et al., 2009). The peak value of phytoplankton cell numbers and abundance of phytoplankton species during pre-monsoon (Gurung et al., 2006) indicates the role of productivity in regulating the lake water pH.

The TDS is the sum of all the ions in aqueous solution which reflects magnitude of chemical weathering in the catchment (Singh and Hasnain, 1999). In Phewa Lake, TDS ranged from 54.2 to 97.73 mg/L with highest value during post-monsoon and lowest during monsoon with significant variation ($p<0.05$) between the seasons (Table 2). Likewise, EC is the ionic strength of solution that depends on concentration, volume and movement rate of ionic species (Das and Kaur, 2001). In Phewa Lake, EC showed a similar pattern as the TDS (Table 2). The lower TDS and EC during monsoon may be due to the dilution effect (Ross, 1998) and uptake of calcium by phytoplankton (Ross and Gilbert, 1999). Ross and Gilbert (1999) even observed increase in conductivity with the increase in distance from the river mouth, probably due to cumulative effect of dissolution of carbonaceous conglomerates, the input of contaminated runoff from the city and diversion of water to the lake through the Seti Canal, relatively carbonate-rich watershed of the Seti River.

Table 2. Physico-chemical composition of the surface water in Phewa Lake. Units: Temperature in °C, pH, EC in µS/cm, TDS, ions and ionic compounds in mg/L, and Tz^+ and Tz^- in µeq/L

Parameter	Post-monsoon		Pre-monsoon		Monsoon	
	Range	Average±SD	Range	Average±SD	Range	Average±SD
Temperature	22.5-25.0	23.54±0.81[a]	26.0-27.0	26.25±0.45[b]	26.75-29.0	27.92±0.89[c]
pH	6.5-8.0	7.5±0.50[a]	7.0-9.1	8.6±0.6[b]	7.5-7.9	7.7±0.1[a]
EC	116.92-125.69	120.48±2.52[a]	66.67-86.38	80.64±4.93[b]	52.16-65.73	58.23±4.04[c]
TDS	94.12-102.7	97.73±2.97[a]	63.41-77.18	72.76±3.73[b]	50.38-58.51	54.18±2.8[c]
DO	7.0-11.0	8.42±1.0[a]	10.0- 10.8	10.25±0.24[b]	12.0-13.2	12.52±0.39[c]
HCO_3^-	38.77-42.51	40.91±1.02[a]	20.14-33.88	26.95±4.27[b]	11.86-18.43	16.88±1.79[c]
Cl^-	0.76-2.5	1.29±0.47[a]	1.46-8.51	2.74±1.88[b]	0.33-2.21	0.69±0.60[a]
SO_4^{2-}	8.32-10.57	9.12±0.67[a]	6.97-8.6	7.62±0.51[b]	8.73-13.54	10.75±1.46[c]
PO_4^{3-}	0.0-0.14	0.09±0.04[a]	0.07-0.3	0.13±0.06[a]	0.01-0.07	0.03±0.02[b]
NO_3^-	3.26-5.38	4.32±0.87[a]	4.41-14.09	7.74±2.99[b]	3.23-4.36	3.82±0.4[a]
H_4SiO_4	9.47-15.34	11.02±2.21[a]	8.13-9.06	8.68±0.27[b]	7.48-8.42	7.89±0.26[b]
Na^+	1.76-3.62	2.82±0.61[a]	3.37-3.49	3.44±0.03[b]	3.26-4.36	3.72±0.35[b]
K^+	0.52-4.37	1.28±1.02	1.15-2.48	1.39±0.36	1.08-1.87	1.54±0.25
Mg^{2+}	2.15-2.44	2.29±0.08[a]	1.49-1.61	1.54±0.04[b]	1.12-2.67	1.7±0.38[b]
Ca^{2+}	14.0-17.87	16.7±1.07[a]	6.24-7.63	6.92±0.40[b]	2.08-2.75	2.44±0.19[c]
Tz^+	1,159-1,229	1,193±20.4[a]	627.2-706.8	665.5±23.4[b]	425.3-537	473.4±33.06[c]
Tz^-	950.4-999.1	969.3±14.0[a]	666.7-863.8	806.4±49.3[b]	521.6-657.3	582.3±40.4[c]

Different alphabets in superscript indicate significant difference in the mean values ($p<0.05$)

The DO reflects the organic pollution state of the water. In Phewa Lake, DO ranged from 8.4 to 12.5 mg/L with significant variation ($p<0.05$) between the seasons (Table 2). The higher DO during the monsoon indicates that water is well oxygenated and lower DO during post-monsoon is attributed to the beginning of water circulation due to change in temperature (Gurung et al., 2006; Rai, 2000a). The higher Biological Oxygen Demand during post-monsoon (January and December) (PSMC, 2007) suggests the high discharge and decomposition of organic matter which is also evident from low DO (Rai, 2000a; Gurung et al., 2006).

Among the major ions, HCO_3^-, PO_4^{3-}, H_4SiO_4, Mg^{2+}, Ca^{2+}, and both total cations (Tz^+) and total anions (Tz^-) are higher in the post-monsoon; Cl^-, NO_3^-, and Na^+ are higher in the pre-monsoon and SO_4^{2-} is higher in the monsoon season. Among the anions, HCO_3^- is mainly contributed from weathering and decomposition of organic matter in the catchment (Chakrapani et al., 2009; Jha et al., 2009). In Phewa Lake, HCO_3^- was the dominant anion which ranged from 16.9 to 40.9 mg/L (Table 2). The HCO_3^- dominance suggests intense chemical weathering. Chloride is a conservative anion generally originating either from sea spray via monsoon or from anthropogenic sources (Meybeck, 1983). In Phewa Lake, Cl^- varied from 0.69 to 2.74 mg/L (Table 2). The lower value of HCO_3^- and Cl^- during monsoon could be attributed to the dilution effect of the monsoon (Table 3).

Sulfur is a widespread element in the earth and is among the ten most abundant elements in the biological system. Thus, it is an essential element for organisms. In lakes, it is usually derived from oxidative weathering of sulfide bearing minerals, atmospheric deposition, dissolution of gypsum ($CaSO_4·2H_2O$), pyrite (FeS_2) rocks and/or by mineralization of organic sulfur in humus present in the bottom soil and sediments at the interface between aerobic and anaerobic environment. Such processes are common at the surface of reduced sediment which is covered by oxygenated water (Anshumali and Ramanathan, 2007; Jones, 1982). In Phewa Lake, SO_4^{2-} ranged from 7.6 to 10.8 mg/L with significant variation between the seasons (Table 2). The higher value during post-monsoon and monsoon may be due to the monsoonal runoff from agriculture and/or due to the combined effect of weathering and mineralization of autochthonous or allochthonous organic humus brought by the monsoonal runoff from agriculture. The results show SO_4^{2-} is substantially higher than the background value, 0.2 mg/L (Jones et al., 1989) demonstrating considerable increase over the period.

Table 3. Characteristics of rainwater collected from the Pokhara City. Units: Temperature in °C, pH, EC in μS/cm, TDS, ions and ionic compounds in mg/L

Parameter	Monsoon Rainwater	
	Range	Average±SD
Temperature	21.5-23.0	22.25±0.69
pH	6.7-6.8	6.73±0.1
EC	26.13-29.1	27.64±2.58
TDS	21.38-24.0	22.65±0.96
DO	11.5-13.46	12.75±1.35
HCO_3^-	10.41-11.86	11.35±0.57
Cl^-	<0.25	<0.25
SO_4^{2-}	3.2-4.5	3.67±0.58
PO_4^{3-}	0.01-0.01	0.01±0.0
NO_3^-	3.0-4.36	3.81±0.64
H_4SiO_4	0.19-0.23	0.22±0.01
Na^+	0.15-0.88	0.52±0.4
K^+	0.09-0.33	0.21±0.13
Mg^{2+}	0.04-0.04	0.04±0.0
Ca^{2+}	0.53-0.88	0.70±0.19

Phosphorus is one of the most important limiting elements, thus its abundance is the major reason for lakes eutrophication. In Phewa Lake, PO_4^{3-} ranged from 0.03 to 0.13 mg/L showing significant variation ($p<0.05$) between post-monsoon and monsoon, and pre-monsoon and monsoon (Table 2). The higher value during the pre-monsoon may be due to evaporation effect. The distribution map reveals that during post-monsoon PO_4^{3-} concentrated towards the western, eastern, northern and south-eastern parts (Figure 2(a)) which is associated with agriculture, settlement and urban land-uses. During the pre-monsoon, PO_4^{3-} concentrated mostly towards the east (near temple) indicating anthropogenic contribution (Figure 2(b)), and during monsoon, it concentrated towards the eastern part (Figure 2(c)) which is mainly associated with urban activities. The PO_4^{3-} values of >0.05 mg/L during pre-monsoon and post-monsoon indicate anthropogenic input (Subramanian, 1984). Rai (2000a) reported PO_4^{3-} concentration up to 0.06 mg/L suggesting increase in PO_4^{3-} over the years.

The total nitrate nitrogen in water is derived either from atmospheric precipitation, biological conversion or anthropogenic inputs. In Phewa Lake, NO_3^- varied from 3.8 to 7.7 mg/L with significant variation between the post-monsoon and pre-monsoon, and pre-monsoon and monsoon (Table 2). The higher value during pre-monsoon may be due to the combined effect of evaporation and mineralization of N-containing compounds by microorganisms (Anshumali and Ramanathan, 2007; Håkanson, 1984). The NO_3^- in the monsoon possibly indicates the influence of leaching of fertilizers from agriculture. With respect to its spatial distribution, during post-monsoon, NO_3^- concentrated towards the north-western and south-western parts (Figure 2(d)) which is associated with settlement, agriculture and urban land-uses; during pre-monsoon, it concentrated towards the south-western part (Figure 2(e)) which is associated with anthropogenic inputs, and during monsoon, it spread towards the north-western, north-eastern and eastern parts (Figure 2(f)) which is associated with agriculture, settlement and urban land-uses. Rai (2000a) reported $(NO_2^-+NO_3^-)$-nitrogen upto 0.45 mg/L indicating increase in NO_3^- over the time.

Silicon is the second most abundant element in the earth's crust and is essential for life. In lakes, it is available for phytoplankton and algae as H_4SiO_4. In Phewa Lake, H_4SiO_4 ranged from 7.9 to 11.0 mg/L with significant variation between post-monsoon and pre-monsoon, and post-monsoon and monsoon (Table 2). The higher value during the post-monsoon might be due to the mixing which develops a vertical gradient of temperature that promotes death and decomposition of diatoms, besides weathering of the silicate minerals (Anshumali and Ramanathan, 2007; Håkanson, 1984). This is also supported by the high H_4SiO_4/Na^++K^+ ratio (Table 4). Similar finding has been reported by Anshumali and Ramanathan (2007) in Pandoh Lake of India. The dissolved silica in the pre-monsoon (8.68±0.27 mg/L) and monsoon (7.89±0.26 mg/L) are comparable to the Indian Himalayan River average, 9.6 mg/L; however the post-monsoon concentration (11.02±2.21 mg/L) is comparable to the world average, 12.0 mg/L (Subramanian, 1979). The present results show H_4SiO_4 value is substantially higher than the findings of Jones et al. (1989) (<1 mg/L SiO_2). The lower value of silica in Phewa Lake compared to the global average indicates silicate minerals are resistant to the prevailing weathering conditions. The silica may also be contributed by the dissolution of concrete in streets and sidewalks (Ravindra and Garg, 2007). The low pH supports a lower rate of silicate weathering which is evident from the positive correlation between H_4SiO_4 and pH during post-monsoon and pre-monsoon periods (Table 5 and Table 6). The negative correlation between silica, and bicarbonate and nitrate indicates their different sources (Table 7).

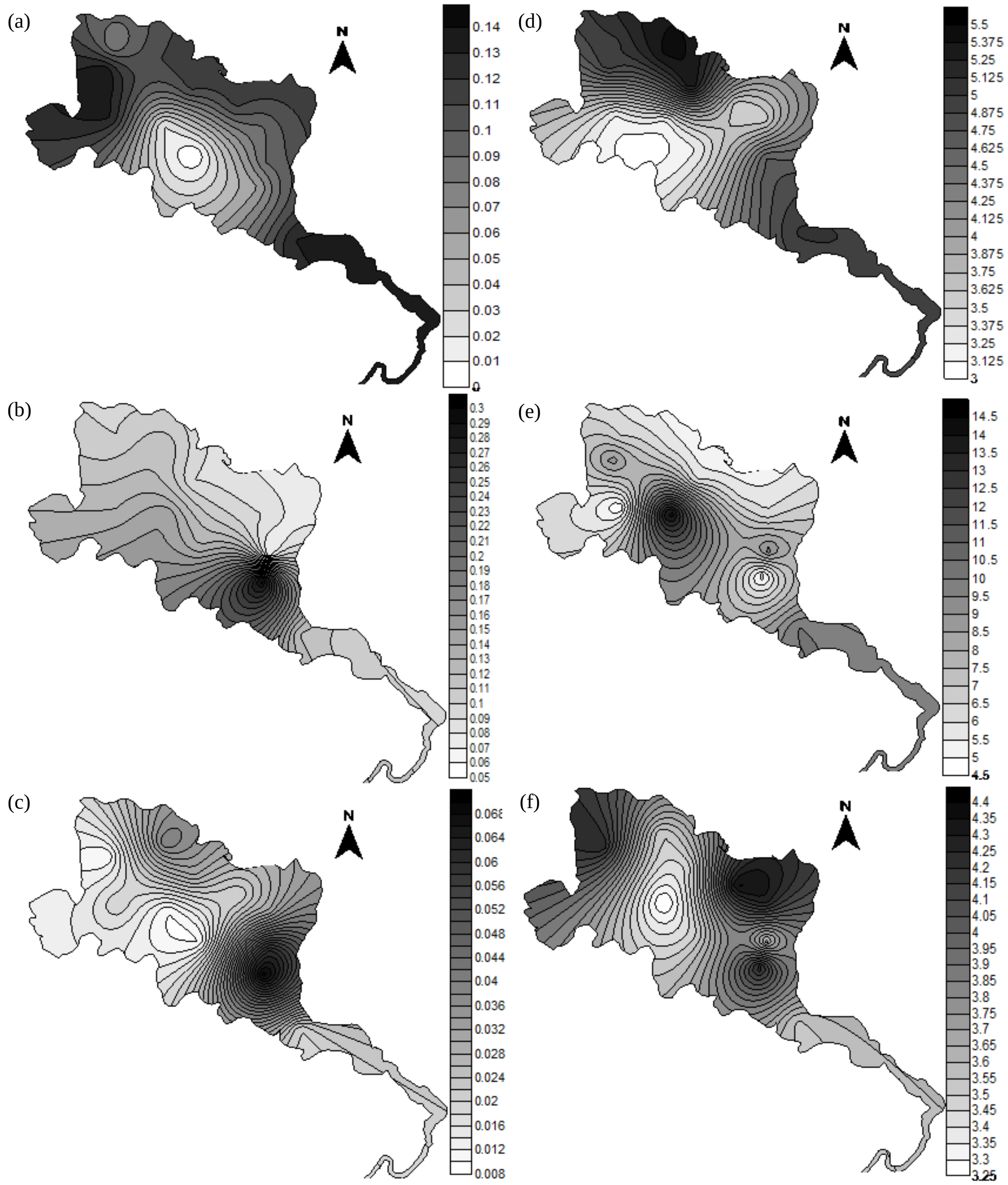

Figure 2. Isoline map showing surficial distribution of PO_4^{3-} (a=post-monsoon, b=pre-monsoon, c=monsoon) and NO_3^- (d=post-monsoon, e=pre-monsoon, f=monsoon)

Among the cations, Na^+ varied from 2.8 to 3.7 mg/L with significant variation between the post-monsoon and pre-monsoon, and post-monsoon and monsoon (Table 2). The higher value during monsoon could be due to rock weathering and continental runoff. Likewise, K^+ varied from 1.2 to 1.5 mg/L showing no significant variation between the seasons (Table 2). The higher value during monsoon may be due to silicate weathering. The surficial Mg^{2+} varied from 1.5 to 2.3 mg/L with significant variation between the post-monsoon and pre-monsoon, and post-monsoon and monsoon (Table 2). The surficial Ca^{2+} ranged from 2.4 to 16.7 mg/L with significant variation ($p<0.05$) between the seasons (Table 2). The lower Ca^{2+} during monsoon could be attributed to the dilution effect and uptake of Ca^{2+} by phytoplankton (Ross and Gilbert, 1999). The higher Ca^{2+} during post-monsoon is attributed to the release of additional Ca^{2+} by the decaying phytoplankton (Ross, 1998), in addition to the weathering processes. This is supported

Table 4. Ionic ratios of Phewa Lake in different seasons

Parameters	Post-monsoon		Pre-monsoon		Monsoon	
	Min-Max	Average±SD	Min-Max	Average±SD	Min-Max	Average±SD
$(Ca^{2+}+Mg^{2+})/(Tz^+)$	0.77-0.9	0.86±0.04	0.69-0.72	0.71±0.01	0.46-0.65	0.55±0.05
$(Na^++K^+)/(Tz^+)$	0.09-0.22	0.13±0.04	0.27-0.3	0.28±0.01	0.002-0.004	0.003±0.0
$H_4SiO_4/(Na^++K^+)$	0.4-1.48	0.8±0.33	0.4-0.52	0.49±0.03	0.34-0.47	0.41±0.041
$(Ca^{2+}+Mg^{2+})/(Na^++K^+)$	3.58-10.26	7.04±2.04	2.3-2.7	2.55±0.13	0.91-1.96	1.32±0.27
$HCO_3^-/(Ca^{2+}+Mg^{2+})$	0.59-0.76	0.66±0.04	0.68-1.16	0.93±0.14	0.8-1.35	1.07±0.14
$HCO_3^-/HCO_3^-+SO_4^{2-}$	0.75-0.8	0.78±0.01	0.69-0.79	0.73±0.03	0.41-0.61	0.55±0.05
$HCO_3^-/(Tz^-)$	0.66-0.72	0.69±0.02	0.41-0.67	0.55±0.08	0.36-0.51	0.47±0.04

Table 5. Correlation matrix for the post-monsoon

Parameters	pH	TDS	EC	DO	HCO_3^-	Cl^-	SO_4^{2-}	PO_4^{3-}	NO_3^-	H_4SiO_4	Na^+	K^+	Mg^{2+}	Ca^{2+}
pH	1.00													
TDS	0.74**	1.00												
EC	0.45	0.46	1.00											
DO	-0.31	-0.03	-0.13	1.00										
HCO_3^-	0.36	0.75*	0.38	0.07	1.00									
Cl^-	0.09	-0.41	-0.02	-0.18	-0.77**	1.00								
SO_4^{2-}	0.13	0.30	0.37	-0.23	0.01	0.29	1.00							
PO_4^{3-}	-0.33	-0.49	-0.01	-0.07	-0.42	0.23	-0.14	1.00						
NO_3^-	-0.34	-0.27	-0.07	0.40	-0.11	-0.29	-0.66*	0.48	1.00					
H_4SiO_4	0.62*	0.88**	0.44	-0.02	0.63*	-0.45	0.19	-0.65*	-0.38	1.00				
Na^+	-0.26	-0.22	0.01	-0.04	0.25	-0.39	-0.39	0.63*	0.58*	-0.46	1.00			
K^+	0.24	0.00	0.20	-0.14	0.09	0.14	-0.25	-0.22	0.03	-0.21	0.18	1.00		
Mg^{2+}	-0.30	-0.54	-0.41	0.47	-0.29	0.17	-0.54	0.18	0.26	-0.42	0.13	0.17	1.00	
Ca^{2+}	0.12	0.32	0.17	0.04	-0.11	0.17	0.66*	-0.11	-0.39	0.43	-0.63*	-0.76*	-0.46	1.00

* Correlation significant at $p<0.05$ (2 tailed)

** Correlation significant at $p<0.01$ (2 tailed)

Table 6. Correlation matrix for the pre-monsoon

Parameters	pH	TDS	EC	DO	HCO_3^-	Cl^-	SO_4^{2-}	PO_4^{3-}	NO_3^-	H_4SiO_4	Na^+	K^+	Mg^{2+}	Ca^{2+}
pH	1.00													
TDS	0.30	1.00												
EC	0.04	0.95**	1.00											
DO	0.30	0.28	0.17	1.00										
HCO_3^-	0.45	0.63*	0.46	0.40	1.00									
Cl^-	-0.85**	-0.25	0.06	-0.33	-0.57	1.00								
SO_4^{2-}	0.17	0.16	0.07	0.22	0.21	-0.38	1.00							
PO_4^{3-}	-0.63*	-0.24	0.05	-0.24	-0.50	0.91**	-0.56	1.00						
NO_3^-	0.32	0.30	0.27	-0.08	-0.37	-0.16	-0.01	-0.14	1.00					
H_4SiO_4	0.63*	0.34	0.12	0.56	0.38	-0.60*	0.37	-0.48	0.18	1.00				
Na^+	0.62*	-0.08	-0.24	0.41	0.13	-0.39	0.01	-0.27	0.01	0.50	1.00			
K^+	-0.94**	-0.29	0.01	-0.42	-0.51	0.96**	-0.36	0.81**	-0.26	-0.70*	-0.52	1.00		
Mg^{2+}	0.13	0.05	0.12	-0.05	-0.07	0.10	-0.09	0.34	0.13	0.09	-0.11	-0.08	1.00	
Ca^{2+}	-0.23	0.73**	0.82**	0.09	0.34	0.29	-0.07	0.17	0.03	-0.07	-0.10	0.26	-0.17	1.00

* Correlation significant at $p<0.05$ (2 tailed)
** Correlation significant at $p<0.01$ (2 tailed)

Table 7. Correlation matrix for the monsoon

Parameters	pH	TDS	EC	DO	HCO_3^-	Cl^-	SO_4^{2-}	PO_4^{3-}	NO_3^-	H_4SiO_4	Na^+	K^+	Mg^{2+}	Ca^{2+}
pH	1.00													
TDS	0.12	1.00												
EC	0.13	0.98**	1.00											
DO	-0.26	0.27	0.17	1.00										
HCO_3^-	0.31	0.72**	0.66*	0.06	1.00									
Cl^-	0.54	0.27	0.41	-0.59*	0.22	1.00								
SO_4^{2-}	-0.52	0.33	0.33	0.47	-0.36	-0.29	1.00							
PO_4^{3-}	0.41	0.20	0.35	-0.63*	0.27	0.90**	-0.35	1.00						
NO_3^-	0.34	0.62*	0.60*	0.21	0.69*	0.23	-0.21	0.14	1.00					
H_4SiO_4	-0.09	-0.32	-0.29	-0.10	-0.70*	0.02	0.41	-0.09	-0.62*	1.00				
Na^+	-0.36	0.25	0.15	0.32	-0.02	-0.45	0.51	-0.62*	-0.15	0.06	1.00			
K^+	0.18	0.14	-0.03	0.58*	0.37	-0.62*	-0.08	-0.60*	0.19	-0.38	0.41	1.00		
Mg^{2+}	0.22	0.77**	0.87**	-0.03	0.48	0.68*	0.20	0.65*	0.50	-0.17	-0.27	-0.39	1.00	
Ca^{2+}	0.22	0.39	0.42	-0.13	0.45	0.36	-0.22	0.43	0.58*	-0.15	-0.56	-0.21	0.48	1.00

* Correlation significant at $p<0.05$ (2 tailed)
** Correlation significant at $p<0.01$ (2 tailed)

by a remarkable decrease in phytoplankton numbers and primary productivity during the post-monsoon (Gurung et al., 2006). Besides, the increase in Ca^{2+} could also be due to contribution from the dissolution of concrete in streets and sidewalks (Ravindra and Garg, 2007).

The surficial Tz^- (total anions) ranged from 582 to 969 µeq/L and the Tz^+ (total cations) ranged from 473 to 1193 µeq/L with significant ($p<0.05$) seasonal variations (Table 2). The higher Tz^- values during pre-monsoon and monsoon indicates possible contribution through decomposition of organic compounds (Dalai et al., 2002). The major ions composition of the lake water is within the range of the National Drinking Water Quality Standards and Directive 2005, thus lake water quality is acceptable for irrigation, fish farming and recreation (MoPPW, 2005). However, increasing trophic state of the lake over the period of time, as evident from massive growth of algae and water hyacinth, indicates possibility of other autochthonous processes making limiting nutrients available for the growth of algae and macrophytes. This suggests possibility of nutrients release from the lake sediments. Thus, in order to evaluate the possible internal source of nutrients, further studies incorporating sediment-water interaction need to be carried out.

3.2. Source of the major dissolved ions

The major dissolved ions are assessed to evaluate their sources and illustrate their relation to the regional geology and weathering processes. In Phewa Lake, among the cations, Ca^{2+} and Mg^{2+} were dominant over Na^+ and K^+ suggesting the dominant role of carbonate weathering (Table 2). The positive correlation between Ca^{2+} and Mg^{2+} ($r^2=0.48$) during monsoon suggests their common sources (Table 7). Likewise, the positive correlation between SO_4^{2-} and Ca^{2+} ($r^2=0.66$) during post-monsoon (Table 5) suggests their common origin like gypsum, oxidation of pyrite, dissolution of sulphate minerals and oxidation of sulfur compounds in the bottom sediment at the transition zone between aerobic and anaerobic environment (Ansumali and Ramanathan, 2007; Singh et al., 2016).

The ratios between different ions were modeled to explain their sources. In Phewa Lake, $(Ca^{2+}+Mg^{2+})/(Na^++K^+)$ ratio varied between 7.04±2.04 during post-monsoon, 2.55±0.13 during pre-monsoon, and 1.32±0.27 during monsoon, further supporting dominance of carbonate weathering (Table 4) corresponding with many Indian mountain lakes (Anshumali and Ramanathan, 2007; Das and Kaur, 2001; Jeelani and Shah, 2006; Singh et al. 2012; Singh et al., 2014; Singh et al., 2015a; Singh et al., 2015b; Singh et al., 2016). The $(Ca^{2+}+Mg^{2+})/(Tz^+)$ ratio varied from 0.77 to 0.90 during post-monsoon, 0.69 to 0.72 during pre-monsoon and 0.46 to 0.65 during monsoon suggesting domination of $Ca^{2+}+Mg^{2+}$ (Table 4). The $Ca^{2+}+Mg^{2+}$ vs. Tz^+ scatter plot (Figure 3) shows linear spread a little below the 1:1 line reflecting an increasing contribution of sodium and potassium with increase in TDS. This result suggests the major contribution of $Ca^{2+}+Mg^{2+}$ with a certain contribution of alkali derived possibly from silicate weathering (Das and Kaur, 2001). A similar trend has been reported by Bartarya (1993) in the Lesser Himalayan River Basin of Kumaun, India.

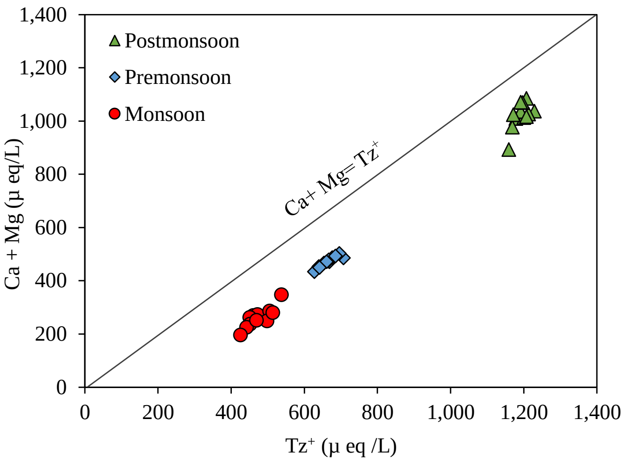

Figure 3. Scatter diagram of $Ca^{2+}+Mg^{2+}$ versus total cations (Tz^+) for Phewa Lake

The $(Na^++K^+)/(Tz^+)$ ratio is an index used for assessing contribution of cations via silicate weathering (Stallard and Edmund, 1983). In Phewa Lake, $(Na^++K^+)/Tz^+$ ratio varied between 0.13±0.04 during post-monsoon, 0.28±0.01 during pre-monsoon and 0.003±0.0 during monsoon indicating shortage of Na^+ and K^+ (Table 4). The low $(Na^++K^+)/Tz^+$ ratio suggests lower contribution of cations via alumino-silicate weathering compared to carbonate weathering. The Na^++K^+ vs. Tz^+ plot (Figure 4) further indicates that water is relatively deficient in Na^+ and K^+.

The scatter plot of $Ca^{2+}+Mg^{2+}$ vs. HCO_3^- (Figure 5) shows that pre-monsoon and monsoon samples mostly fall on or near 1:1 equiline suggesting HCO_3^- is balanced by Ca^{2+} and Mg^{2+}. However, the post-monsoon samples fall above the equiline requiring other anions to balance. The scatter plot of

Ca^{2+}+Mg^{2+} vs. HCO_3^-+SO_4^{2-} (Figure 6) shows the pre-monsoon and monsoon samples mostly fall below 1:1 equiline requiring a portion of HCO_3^- and SO_4^{2-} to be balanced by Na^++K^+ from silicate weathering. However, during post-monsoon, Ca^{2+}+Mg^{2+} is still above the equiline requiring more neutralizing anions other than HCO_3^- and SO_4^{2-}.

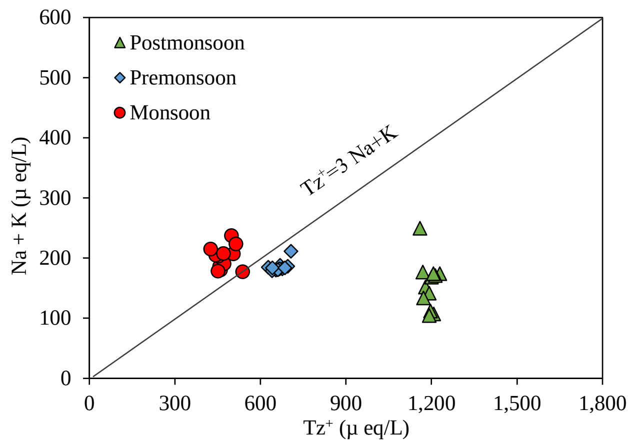

Figure 4. Scatter diagram of Na^++K^+ versus total cations (Tz^+) for Phewa Lake

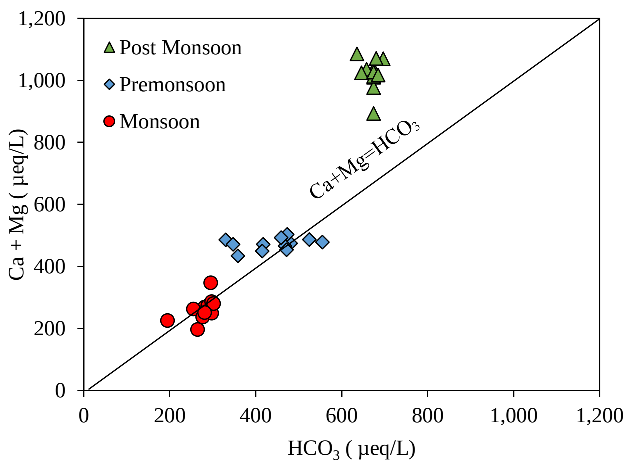

Figure 5. Scatter diagram of Ca^{2+}+Mg^{2+} versus HCO_3^- for Phewa Lake

For the weathering of carbonate rocks, proton sources are required. In order to evaluate the sources of proton whether from carbonation or oxidation of sulfides, the C-ratio (HCO_3^-/HCO_3^-+SO_4^{2-}) is used (Brown et al., 1996). In Phewa Lake, the C-ratio varied between 0.78±0.01 during post-monsoon, 0.73±0.03 during pre-monsoon and 0.55±0.05 during monsoon seasons suggesting coupled reactions involving carbonate dissolution and proton derived primarily from oxidation of sulfide (Table 4).

The main source of the major elements and ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, Cl^-, and Si) to the lake is weathering of the drainage basin lithology. A simple plot of TDS vs. weight ratio of Na^+/(Na^++Ca^{2+}) (Gibbs diagram) provides information about the relative importance of the major natural mechanisms controlling the surface water chemistry are whether from atmospheric precipitation, rock weathering or evaporation and fractional crystallization (Gibbs, 1970). The dashed 'boomerang' line represents composition of most of the world's surface water (Figure 7). The elliptical area within boomerang represents Indian rainwater average (Das and Kaur, 2001). In Phewa Lake, the Gibbs diagram demonstrates that weathering of rock primarily controls the major ion chemistry (Figure 7) as in many other high altitude lakes- Nainital, Bhimtal, Sattal, Naukuchiatal Lakes of Kumaun Himalaya (Das, 2005), Mansar Lake of Jammu, India (Al-Mikhlafi et al., 2003), Lake Pumayum Co, Southern Tibet (Zhu et al., 2010) and Begnas Lake of Nepal (Khadka and Ramanathan, 2013).

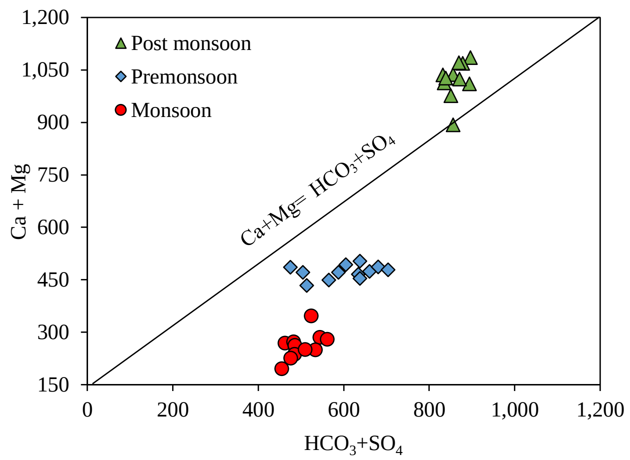

Figure 6. Scatter diagram of Ca^{2+}+Mg^{2+} versus HCO_3^-+SO_4^{2-} for Phewa Lake

The main water types are identified by plotting the major ion on a Piper trilinear diagram (Piper, 1944; Figure 8). The Piper diagram of Phewa Lake shows that Ca^{2+}+Mg^{2+} are the dominant cations and HCO_3^- is the dominant anion defining the water to be Ca-HCO_3 type (Figure 8). The Piper plotting pattern shows that the lake water is dominated by alkaline earth (Ca^{2+}, Mg^{2+}) and weak acids (HCO_3^-). This is also evident from the major ion compositions and ionic ratios (Tables 2 and Table 4). This finding is in agreement with the Manasbal Lake of Kashmir Himalaya (Sarah et al., 2011) and Begnas Lake of Nepal (Khadka and Ramanathan, 2013). However, the seasonal variations in hydrochemical facies in Phewa Lake indicate that water chemistry is also influenced by factors other than natural lithogenic processes.

3.3 Hydro-geochemical analysis of the Himalayan Lakes

The comparative analysis of the major ions of Phewa Lake and the other Himalayan Lakes show that many Lesser Himalayan Lakes are alkaline (Table 8). Among the Himalayan Lakes, Phewa Lake shows lower HCO_3^-, except for Begnas Lake (Khadka and Ramanathan, 2013). In Phewa Lake, SO_4^{2-} is higher than Renuka, Pandoh and Begnas Lakes, while other major cations and anions are lower than Renuka Lake (Das and Kaur, 2001), and Nainital, Bhimtal, Sattal and Naukuchiatal Lakes (Das, 2005). However, most of these values are comparable with Pandoh Lake (Anshumali and Ramanathan, 2007) and Begnas Lake (Khadka and Ramanathan, 2013). Furthermore, $(Ca^{2+}+Mg^{2+})/(Tz^+)$ ratio in Phewa Lake (0.71) is comparable with Pandoh Lake (0.79) and Begnas Lake (0.61). Similarly, $(Na^++K^+)/(Tz^+)$ ratio accounting 0.14, 0.18, and 0.22 for Phewa, Begnas and Pandoh Lakes, respectively, depicts deficiency of Na^++K^+ over the total cations. Likewise, $(Ca^{2+}+Mg^{2+})/(Tz^+)$ ratio >0.6 indicates dominance of $Ca^{2+}+Mg^{2+}$ (Table 8). These ratios suggest a dominant contribution of carbonate rock weathering in the Himalayan Lakes.

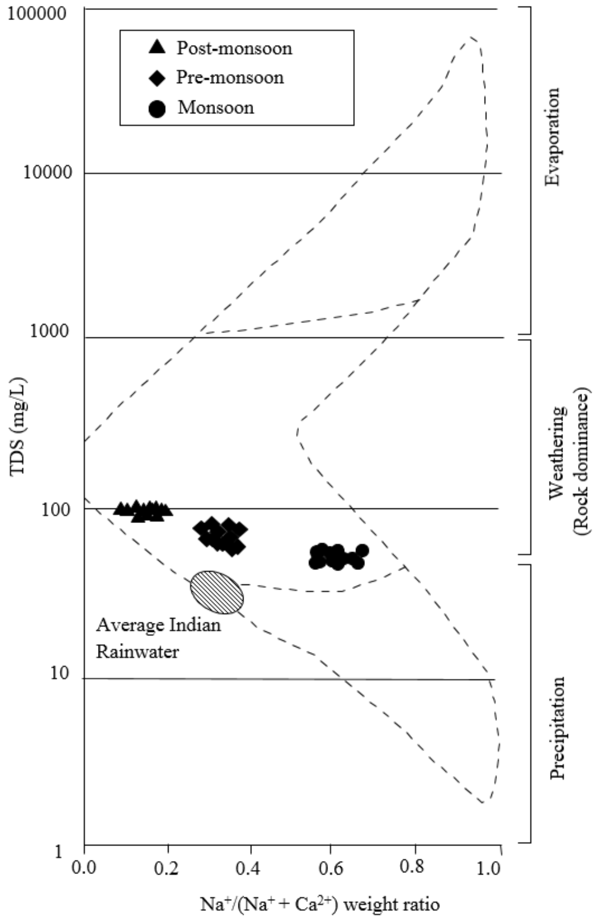

Figure 7. Gibbs diagram showing the major ions source of Phewa Lake in different seasons

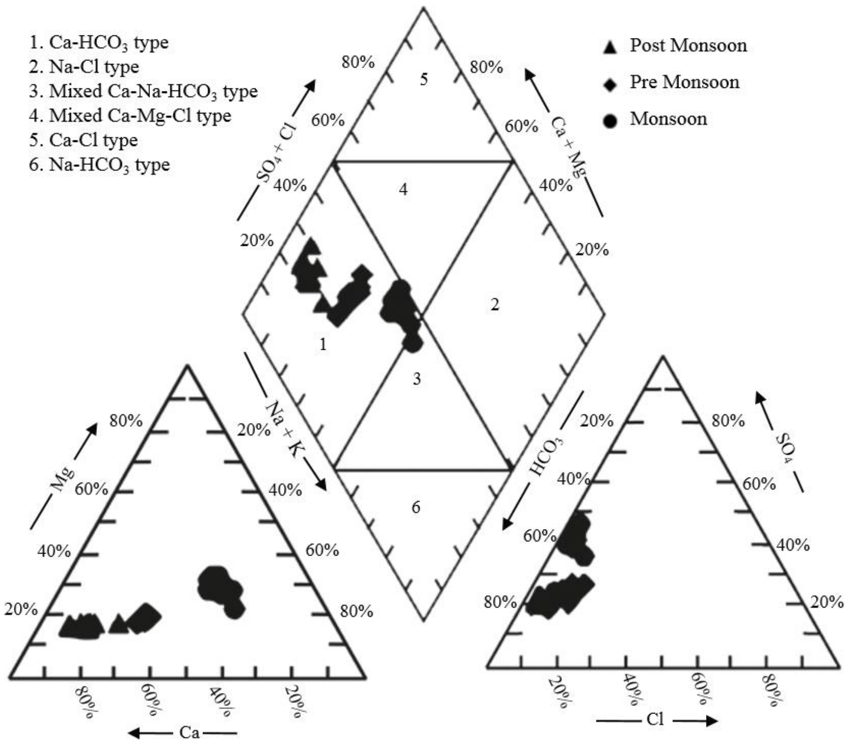

Figure 8. Piper trillinear diagram of the major ions in Phewa Lake

Table 8. Average chemical composition of water in the Lesser Himalayan Lakes (Units: ions and ionic compounds in mg/L, pH, EC in µS/cm, and ionic ratios in equivalent)

Parameters	Das and Kaur (2001)	Das (2005)				Anshumali and Ramanathan (2007)	Khadka and Ramanathan (2013)	Present Study
	Renuka Lake	Nainital	Bhimtal	Sattal	Naukuchiyatal	Pandoh Lake	Begnas Lake	Phewa Lake
pH	8.38	8.67	8.9	9.66	9.4	7.13	7.27	7.94
EC	590.25	706	180.9	119.2	147.55	80.8	90.51	86.45
DO	8.25	-	-	-	-	8.19	8.82	10.41
HCO_3^-	146.42	350.6	91.1	54.0	73.91	49.17	25.31	28.25
Cl^-	11.92	15.3	6.39	7.33	6.6	2.37	2.57	1.57
SO_4^{2-}	6.41	97.75	37.02	19.44	14.04	2.74	7.26	9.16
PO_4^{3-}	6.40	0.124	< 0.01	<0.01	<0.01	1.28	0.09	0.08
NO_3^-	-	-	-	-	-	10.33	5.34	5.29
Na^+	8.33	13.14	4.37	2.69	4.28	3.82	3.89	3.33
K^+	2.02	3.67	2.07	0.72	1.21	2.06	1.42	1.40
Mg^{2+}	38.30	59.3	6.69	5.41	5.49	3.31	1.97	1.84
Ca^{2+}	57.74	32.73	19.80	11.13	14.64	17.96	7.03	8.69
$(Ca^{2+}+Mg^{2+})/(Tz^+)$	-	-	-	-	-	0.79	0.61	0.71
$(Na^++K^+)/(Tz^+)$	-	-	-	-	-	0.22	0.18	0.14

4. CONCLUSION

The Phewa Lake is a fresh-water lake having both national and international importance. The lake is susceptible to the regional phenomena of chemical weathering, atmospheric precipitation and anthropogenic inputs. The surface water temperature of the lake is influenced by the ambient temperature. The lake water pH fluctuates from slightly acidic to alkaline with higher value during pre-monsoon. The EC and TDS value was minimum during monsoon and maximum during post-monsoon. The DO was minimum during post-monsoon and maximum during monsoon period. The overall physico-chemical parameters like temperature, pH, TDS, EC, DO, and major ions (Cl^-, SO_4^{2-}, PO_4^{3-}, HCO_3^-, NO_3^-, Na^+, K^+, Ca^{2+}, and Mg^{2+}) in the surficial water fluctuate with the seasons but remain within acceptable limits for fisheries and recreation. The increasing concentrations of dissolved phosphate, nitrate and sulphate over the period of time demonstrate the contribution of these nutrients from anthropogenic sources. The contribution of Ca^{2+}+Mg^{2+} to the total cations (Tz^+) was higher indicating dissolution of calcareous materials as the major sources. The dominance of total anions (Tz^-) over the total cations (Tz^+) indicates their possible contribution from decomposition of organic compounds further suggesting increased organic load in the lake. This information will be useful for the better management of the lake by controlling anthropogenic activities contributing organic load.

Moreover, although the major ions concentrations are within tolerable limits, the increasing trophic status of the lake, as manifested by massive growth of macrophytes, indicates that, along with external input, internal processes like internal loading of nutrient elements may be contributing to enhance the trophic status of the lake. Therefore, for understanding the autochthonous process releasing limiting element like phosphorus and for sustainable management and conservation of the lake, further studies on sediment-water interaction is anticipated.

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