Hydrogeochemistry of Two Major Mid-hill Lentic Water Bodies for Irrigation of the Central Himalaya, Nepal

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ABSTRACT

The concentration and composition of different salts in natural water bodies determine the water quality for various purposes. This study assesses the water quality of two mid-mountain lentic water bodies, Lake Phewa and Kulekhani Reservoir. For this purpose, selected physico-chemical parameters along with major ions such as HCO_3^-, SO_4^{2-}, PO_4^{3-}, NO_3^-, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, and NH_4^+ were analyzed. Major ions were analyzed using ion chromatography, anions by DX-600 and cations by Dionex ISC-2500 ion chromatographs. The sources of major ions were determined by using the Gibbs diagram, Piper plot, and Scatter plots. Dissolved oxygen, ammonia and phosphate showed seasonal variations in both lakes. The concentrations of cations are in the order of $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ in both water bodies. However the trend of anions had small variations for Cl^- and SO_4^{2-} in Lake Phewa ($HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$) and Kulekhani Reservoir ($HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$). The Piper plot and equiline plots indicated that the water chemistry is dominantly controlled by the dissolution of carbonate minerals and to a limited extent by weathering of silicate minerals. This is further supported by the Gibbs plot showing bedrock geology as the main source of major ions. The overall study indicates that the hydrogeochemistry of these water bodies is controlled by local geology and is suitable for irrigation purposes.

1. INTRODUCTION

Freshwater ecosystems serve multiple purposes and are widely used for domestic purposes, fisheries, recreation, irrigation, and hydroelectricity (Biswas, 2008). However, these ecosystems are undergoing deterioration (Wu and Sun, 2016) making water quality one of the growing environmental concerns (Juma et al., 2014). The quality of water in any ecosystem provides significant information about the available resources for supporting life in that ecosystem and its suitability for human use (Destouni et al., 2017). The importance of water quality to public health and aquatic life is a well-established fact and there is a great need to assess water quality (Gao et al., 2017) for various uses. Freshwater catchment areas and drainage basins are affected by natural processes including rainfall, erosion, and hydrological features (Bhat and Pandit, 2014). Furthermore, the quality of surface water is mainly governed by a range of anthropogenic activities including agricultural and industrial activities (Bhatnagar and Sillanpää, 2010; Gautam et al., 2019; Mayanglambam and Neelam, 2020). Accordingly, many freshwater bodies have become polluted in different parts of the world thereby making them unsuitable for various uses.

Nepal is endowed with rich freshwater resources in the form of rivers, lakes, glaciers, ice, and snow. Nevertheless, with a growing dependency on

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water for various uses, water availability and quality have become major concerns, particularly in urban and peri-urban areas. For instance, the Bagmati and other rivers in the heart of the capital Kathmandu are heavily polluted with organic and inorganic components (Sada, 2012; Paudyal et al., 2016; Tripathee et al., 2016; Prajapati et al., 2020). Likewise, lakes and wetlands are also facing similar problems (Gautam et al., 2019; Lamsal et al., 2019; Khatiwada et al., 2021). Therefore, water quality assessment is crucial in planning and developing sustainable management strategies for freshwater bodies.

The concentration of dissolved ions depends on water flow paths, and the interactions between rock and water (Nordstrom, 2011). The geochemical study of surface water allows us to obtain important information on the chemical weathering of rock/soil (Han and Liu, 2004). Chemical weathering processes would supply major ions to solution from all lithology to water sources. The ions in lake water are affected by rock characteristics such as porosity, lithology, hydro geomorphology, precipitation, and permeability of the topsoil (Ansari et al., 2015; Haque et al., 2020). Sediments of Tertiary age (mixed sandstone and shale) outcrop the length of southern Nepal in the Siwalik Range. Many mineral veins are present in those areas of the crystalline rocks. Veins of sulphide ores (including pyrite, chalcopyrite, arsenopyrite, and galena) occur in the Markhu-Kulekhani-Arkhaule area. Pyrite (iron sulphide) has also been recorded in black shale deposits in the Andhi Mohan Ghat area of the Gandaki region (Khan and Tater, 1969). For a trace element to be mobile in fresh water it must at least be present in the source rocks, it must be in sufficient quantities, it must be soluble, and it must be in the path of water flow (Nordstrom, 2011).

Comprehensive water quality assessments involve analyses of physical, chemical, and biological components (Bi et al., 2021). These components and parameters may vary depending upon the water use. Physico-chemical characterization, particularly an assessment of major ions, has long been accepted as an established practice to assess water quality. Major ions from aquatic ecosystems reflect the ionic contribution of bedrock geology, land use, and disturbances in the catchments (Feller, 2005). Furthermore, these ions form important cellular components of the biota (Kamunde and Wood, 2003). The concentrations of major ions present in water bodies thus have implications on productivity, the relative abundance of biota, and, accordingly, water use. This study assesses the water quality of lake Phewa and Kulekhani Reservoir two important freshwater lentic systems in Nepal especially focusing on their physico-chemical characterization and suitability of water for irrigation.

2. METHODOLOGY

2.1 Study area

Lake Phewa (Figure 1), located in the city of Pokhara in Gandaki Province, Nepal, has multiple uses. It is a stream-fed and dam-regulated semi-natural freshwater lake in the subtropical mountain area. It has a surface area of 5.23 km^2 with a mean depth of 8.6 m. The watershed area of the lake is 110 km^2 (Suwal, 2013). The main inlet in Phewa Lake is Harpan Khola (Khola means stream in Nepali) while the outlet is present at the dam and the water ultimately flows into the Seti River. Lake-dependent tourism, fishery, and irrigation form the basis of livelihoods for local communities (Pokharel, 2008; Shrestha and Aryal, 2011). In the year 2019 alone, nearly 1.2 million tourists visited the city (Joshi and Dahal, 2019). The common fishes found in the Phewa Lake are silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), grass carp (*Ctenopharyngodon idella*), Nile tilapia (*Oreochromis niloticus*) and common carp (*Cyprinus carpio*) (Gurung et al., 2005).

The Kulekhani Reservoir (Figure 1), located in Bagmati Province in Central Nepal, generates hydroelectricity and is also used for cage fishery (Gurung et al., 2010). The main source of water for the reservoir is the Chitlang Khola and other smaller streams. The reservoir, with a water storage capacity of 85.3 million m^3, produces 31 MW and 32 MW of electricity from Kulekhani I and Kulekhani II power stations, respectively (Kafle et al., 2019). The major fish species reared in cage culture are bighead carp (*Aristichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*) (Saund and Shrestha, 2007). However, the increasing number and volume of fish cages and the use of agrochemicals in the catchment area are the major causes of water pollution (Njiru et al., 2017) in the reservoir. Furthermore, in recent years, the number of domestic tourists visiting the reservoir and nearby areas has increased.

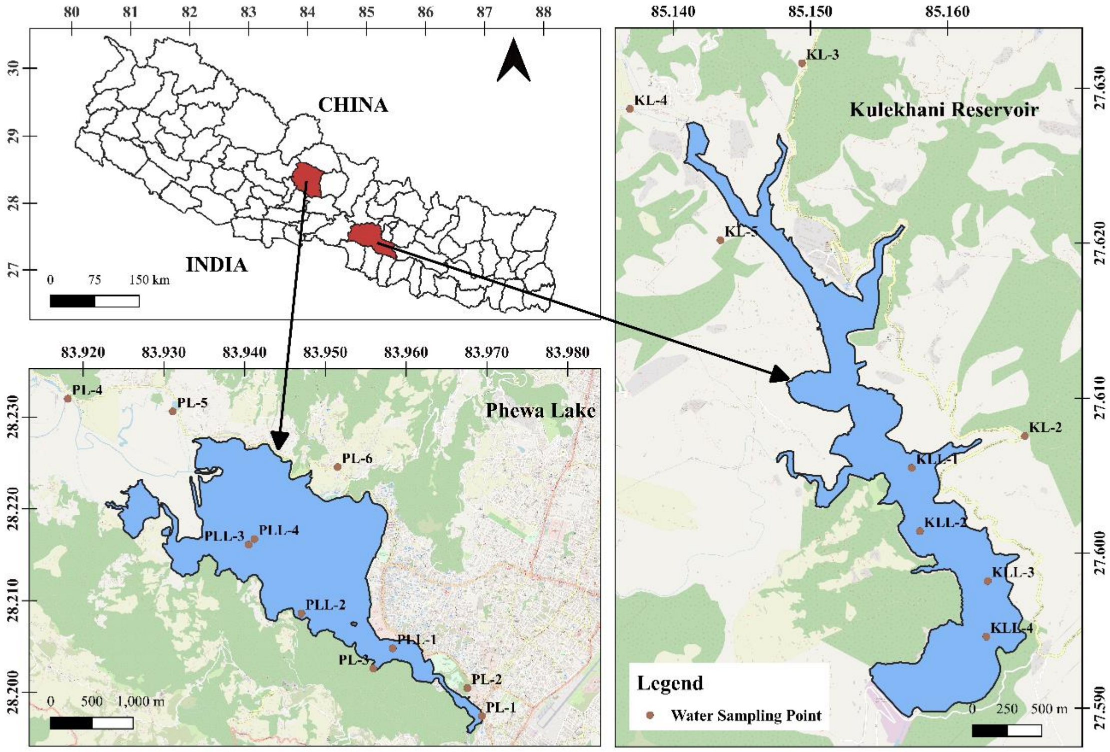

Figure 1. Location map of the study area showing sampling sites in Phewa Lake and Kulekhani Reservoir

2.2 Sampling and analysis

Sampling was conducted during October 2017 (autumn); February 2018 (winter); April 2018 (spring); and July 2018 (summer) encompassing four different seasons. Water samples were collected from nine sites (five from inlets and four from the reservoir) from the Kulekhani Reservoir and 10 sites (six from inlets and four from the main lake) from Phewa Lake (Figure 1). The sampling sites were selected based on accessibility but were representatives of inlets, outlets, and interiors of lakes.

The physico-chemical parameters such as dissolved oxygen (DO), pH, electrical conductivity (EC), temperature, turbidity, and total dissolved solids (TDS) were measured on-site with portable probes (Wagtech and LUTRON). From each site, 1,000 mL water samples were collected in high-density polyethylene (HDPE) bottles for the analysis of the major ions, viz. HCO_3^-, SO_4^{2-}, PO_4^{3-}, NO_3^-, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, and NH_4^+. The sampling bottles were rinsed with the lake water in the respective sampling sites before sample collection. The samples were immediately stored in an icebox until they were transported to the laboratory for further analysis.

The samples for major ions were analyzed using ion chromatography. The cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, and NH_4^+) were analyzed using an ion chromatograph (DX-600) with an IonPac CS12A analytical column, IonPac CG12A guard column, 20 mmol//L methane sulfonic acid (MSA) eluent, and CSRS 300 continuous self-regeneration cation suppressor. Similarly, anions (Cl^-, SO_4^{2-}, NO_3^-, and NO_2^-) were analyzed by Dionex ISC-2500 ion chromatograph using an IonPac AS11-HC analytical column, IonPac AG11-HC guard column, 20 mmol/L potassium hydroxide (KOH) eluent, and ASRS 300 continuous self-regeneration anion suppressor. Bicarbonate concentration was calculated using the ion balance of total cations and anions (Tripathee et al., 2014).

The sources of major ions were determined by using the Gibbs diagram, Piper plot, and Scatter plots. Important irrigation water quality parameters such as sodium absorption ratio (SAR), sodium percentage (%Na), and Kelley's ratio (KR) were estimated by following Ayers and Westcot (1985), Richards (1954), and Nagaraju et al. (2014) respectively (Table 1). Furthermore, the United States Salinity Laboratory (USSL) diagram (USSL, 1954) and the Wilcox diagrams were used for the further interpretation of irrigation water quality.

Kruskal-Wallis and One Way Analysis of Variance methods were used for comparing nonparametric and parametric data, respectively.

Table 1. Irrigation water quality parameters

Parameters	Equations	References
Sodium absorption ratio (SAR)	$SAR = \frac{Na^+}{\left(\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}\right)}$	Ayers and Westcot (1985)
Sodium percentage (%Na)	$(Na^+)\% = \frac{(Na^+ + K^+)}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \times 100$	Richards (1954)
Kelley's ratio (KR)	$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \times 100$	Kelley (1963)

3. RESULTS AND DISCUSSION

3.1 Physico-chemistry of water

The mean concentrations of different physico-chemical parameters of water samples from Phewa Lake and Kulekhani Reservoir are summarized in Tables 2 and 3, respectively. The average concentration of DO in Phewa Lake (7.36±2.32 mg/L) and Kulekhani Reservoir (10.98±3.50 mg/L) are consistent with previous studies in other subtropical lakes in Nepal such as Ghodaghodi Lake, Begnas Lake, and Phewa Lake (Table 4). Slight variations in DO concentrations in the water bodies may be due to differences in temperature and timing of samplings (Gurung et al., 2018). DO is a parameter that is often ignored in water quality studies and yet it can have a significant impact on plant health, root development, fertilizer, and water uptake as well as yield.

Phewa Lake water is slightly alkaline (7.51±0.87 pH value) in spring whereas Kulekhani Reservoir is alkaline (8.30±0.73 pH value) in spring and monsoon seasons. The pH value is proportional to the concentration of carbon dioxide, carbonate, and bicarbonate equilibrium and it is more affected due to the change in the physico-chemical condition of a water body (Sarkar et al., 2020). pH correlates with electric conductivity and total alkalinity (Kothari et al., 2021). Most of the water bodies in Nepal have been reported to be alkaline, possibly, at least in part, due to anthropogenic sources such as the use of detergents (Kannel et al., 2007). The pH values in the present study are within the range of Nepal quality guidelines for irrigation (CBS, 2012). High pH (>7.0) may reduce the availability of various metals and micronutrients to plants causing deficiency symptoms. High pH is often accompanied by high alkalinity whereas low pH (<5.0) may result in toxic high levels of metals like iron and manganese (He et al., 2005). Based on the pH values, the water from Phewa Lake is more suitable for irrigation in the spring season than in other seasons, whereas in Kulekhani Reservoir the water is relatively more suitable for irrigation in spring and summer seasons.

Table 2. Physico-chemical composition (average±SD) of the surface water in Phewa Lake

Parameters (average±SD)	Autumn	Spring	Summer	Winter
Temp (°C)	23.28±2.03^{ca}	22.59±2.95^{ab}	22.51±5.73^{a}	19.92±6.77^{b}
DO (mg/L)	6.76±0.88^{a}	9.01±1.58^{bd}	6.91±2.70^{c}	7.53±2.89^{d}
pH	6.86±0.31^{ac}	8.77±0.76^{b}	7.76±1.91^{cd}	7.40±1.90^{ad}
TDS (mg/L)	48.00±41.41^{a}	40.57±27.09^{a}	36.56±23.73^{a}	39.05±25.62^{a}
Conductivity (µS/cm)	96.33±82.96^{a}	85.57±50.94^{a}	76.67±45.36^{a}	85.56±59.80^{a}
Turbidity (NTU)	2.73±1.45^{a}	2.96±0.74^{a}	2.38±1.05^{a}	2.38±1.08^{a}
Hardness (mg/L)	20.25±21.29^{a}	20.40±8.16^{a}	13.65±9.64^{a}	19.05±20.89^{a}
Sulphate (mg/L)	0.01±0.00^{a}	0.46±0.39^{b}	0.33±0.35^{ba}	0.32±0.33^{bc}
Bicarbonate (mg/L)	31.01±33.95^{bc}	32.32±36.45^{ab}	25.94±32.23^{ac}	37.11±49.25^{b}
Ammonia (mg/L)	0.35±0.28^{ac}	0.73±0.17^{b}	0.42±0.35^{c}	0.46±0.34^{ab}
Chloride (mg/L)	1.12±1.93^{ac}	0.32±0.16^{bc}	0.26±0.16^{ab}	0.98±3.61^{c}
Nitrate (mg/L)	0.34±10.24^{a}	0.03±0.02^{ab}	0.02±0.02^{b}	0.06±0.12^{ac}
Phosphorus (mg/L)	1.44±0.89^{a}	0.16±0.02^{bc}	0.17±0.05^{ac}	0.16±0.12^{c}
Sodium (mg/L)	2.56±3.17^{a}	0.86±0.39^{a}	0.79±0.37^{a}	2.30 ±7.76^{a}
Potassium (mg/L)	0.90±1.12^{a}	0.37±0.19^{a}	0.32±0.19^{a}	0.65±1.59^{a}
Calcium (mg/L)	5.84±5.26^{c}	7.20±2.69^{bc}	4.68±3.38^{d}	6.28±6.07^{c}
Magnesium (mg/L)	1.38±2.01^{ab}	0.59±0.41^{bc}	0.48±0.36^{b}	0.81±1.49^{c}

*Different alphabets in superscript indicate a significant difference in the mean values (p<0.05).

Table 3. Physico-chemical composition (average±SD)of the surface water in Kulekhani Reservoir

Parameters (average±SD)	Autumn	Spring	Summer	winter
Temp (°C)	16.98±3.33^{c}	20.06±1.94^{dc}	16.48±1.94^{ac}	9.10±1.75^{b}
DO (mg/L)	7.15±2.82^{da}	9.88±1.68^{bc}	11.89±1.73^{b}	14.99±1.73^{cd}
pH	7.74±0.66^{ac}	8.77±0.53^{bd}	8.85±0.50^{b}	7.84±0.50^{cd}
TDS (mg/L)	95.07±28.99^{a}	114.75±63.87^{a}	114.57±63.13^{a}	117.12±63.94^{a}
Conductivity (µS/cm)	190.21±59.06^{a}	187.27±62.50^{bc}	185.19±62.85^{c}	192.15±58.71^{ac}
Turbidity (NTU)	2.48±1.58^{a}	3.37±1.07^{a}	9.07±20.64^{a}	2.57±1.05^{a}
Hardness (mg/L)	38.34±12.29^{abc}	29.94±19.79^{ac}	39.80±11.42^{ad}	54.08±18.45^{bd}
Sulphate (mg/L)	1.13±0.45^{a}	0.63±0.48^{a}	1.07±0.96^{a}	1.16±0.45^{a}
Bicarbonate (mg/L)	56.81±17.96^{cb}	40.67±25.60^{ac}	56.81±17.96^{ba}	94.01±47.90^{b}
Ammonia (mg/L)	0.14±0.23^{c}	0.10±0.13^{ac}	1.47±1.64^{b}	1.42±1.64^{ba}
Chloride (mg/L)	0.87±0.49^{a}	0.48±0.35^{a}	0.85±0.81^{a}	0.88±0.66^{a}
Nitrate (mg/L)	0.42±0.24^{a}	0.01±0.02^{a}	0.38±0.86^{a}	0.46±0.43^{a}
Phosphorus (mg/L)	1.59±0.91^{a}	0.22±0.01^{ac}	0.16±0.04^{cb}	0.07±0.04^{b}
Sodium (mg/L)	4.34±1.57^{a}	1.59±0.91^{b}	2.99±2.43^{ab}	8.88±14.58^{ca}
Potassium (mg/L)	1.52±0.50^{a}	0.64±0.43^{bc}	1.07±1.00^{ab}	1.43±0.53^{ca}
Calcium (mg/L)	11.60±3.20^{bc}	10.11±5.99^{ac}	13.92±4.18^{ab}	17.08±4.67^{b}
Magnesium (mg/L)	2.20±1.19^{a}	1.14±1.20^{a}	1.22±0.79^{a}	2.78±1.95^{a}

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

Table 4. Comparisons of the present study with the results from previous studies on different lakes from Nepal

Lakes	Begnas Lake	Phewa Lake	Rara Lake	Ghodaghodi Lake	Phewa Lake	Kulekhani Reservoir
References	Khadka and Ramanathan (2013)	Khadka and Ramanathan (2021)	Gurung et al. (2018)	Pant et al. (2020)	Present study	Present Study
DO (mg/L)	8.82	10.41	NA	5.54	7.58	10.98
pH	7.27	7.94	7.34	7.96	7.48	8.30
Conductivity (µS/cm)	90.51	86.45	193.85	142.00	86.73	188.70
Sulphate (mg/L)	7.26	9.16	2.15	4.80	0.18	1.00
Bicarbonate (mg/L)	25.31	28.25	122.15	49.00	33.09	62.00
Chloride (mg/L)	2.57	1.57	0.46	6.60	1.20	0.70
Nitrate (mg/L)	5.34	5.29	0.55	2.10	0.14	0.31
Phosphorus (mg/L)	0.09	0.08	NA	NA	0.50	0.56
Sodium (mg/L)	3.89	3.33	0.74	5.50	2.81	4.44
Potassium (mg/L)	1.42	1.40	1.48	2.10	0.80	1.16
Calcium (mg/L)	7.03	8.69	20.64	16.00	6.39	13.17
Magnesium (mg/L)	1.97	1.84	11.78	2.40	1.02	1.83

There was no significant seasonal variation in TDS values for both water bodies. The average TDS value for the Kulekhani Reservoir was 108.13± 53.19 mg/L and that of Phewa Lake was 41.20±28.77 mg/L. The TDS values in natural waters are generally in the range of 50 to 250 mg/L, despite areas of especially hard water or high salinity, its value may be as high as 500 mg/L (Omer, 2019). TDS levels should be below 640 mg/L to avoid problems in plugs and below 960 mg/L to avoid problems with other plant growing conditions. TDS levels above 2,000 mg/L are very likely to cause plant growth problems (Samuel et al., 2021).

There is no significant seasonal variation in EC for either water body except in autumn in the Kulekhani Reservoir. The average level of EC in Phewa Lake (90.28±65.62 µS/cm) and Kulekhani Reservoir (188.70±58.21 µS/cm) are similar to other lakes of Nepal such as Begnas Lake, Phewa Lake (previous study), Rara Lake, and Ghodaghodi Lake

(Table 4). EC of lake water has a strong interrelationship with pollution levels (Das et al., 2006). These EC values are within the range of CBS (2012) guidelines, i.e., 400 µS/cm. Elevated EC levels in water can damage growth media and rooting function resulting in nutrient imbalances and water uptake issues. Similarly, turbidity also did not show seasonal variations in either water body. The average level of turbidity in Phewa Lake and Kulekhani Reservoir were 2.43±1.02 NTU and 4.37±10.30 NTU, respectively. Turbidity is caused by particles, suspended or dissolved, in water that scatter light making the water appear cloudy. Nutrients are the leading source of impairment to lakes, ponds, and reservoirs (USEPA, 2000).

The average concentration of sulphate (SO_4^{2-}) in Phewa Lake (0.20±0.25 mg/L) and Kulekhani Reservoir (1.00±0.63 mg/L) were relatively low in comparison with previous studies in Begnas Lake, Phewa Lake, Rara Lake, and Ghodaghodi Lake (Table 4). Sulfur is an essential plant nutrient and sulfur addition is often needed in fertilizer (Gilbert, 1951). The average concentration of bicarbonates (HCO_3^-) in Phewa Lake (32.88±46.50 mg/L) and Kulekhani Reservoir (62.087±34.870 mg/L) are within the range of previous studies in Begnas Lake, Phewa Lake, Rara Lake, and Ghodaghodi Lake (Table 4). The cumulative effect of carbonates (CO_3^{2-}), bicarbonates (HCO_3^-), and hydroxide ions is represented by the alkalinity. A high concentration of bicarbonates is problematic because it increases the pH of the growth media which can cause various nutrient problems, e.g., iron and manganese deficiency, calcium, and magnesium imbalance (Horneck et al., 2011).

There is a significant seasonal variation of ammonia (NH_4^+) ($p<0.05$) for both water bodies. It was significantly higher during summer and winter in Kulekhani (H=18.17, $p<0.001$) and during summer in Lake Phewa (F=12.61, $p<0.001$). The average concentration of NH_4^+ in Phewa Lake and Kulekhani Reservoir were 0.40±0.34 mg/L and 0.78±1.70 mg/L, respectively. Nitrogen is a critical plant nutrient, and it can be beneficial for irrigation when present in water but should be accounted for in the overall fertilization program considering the other form of Nitrogen (Fageria and Baligar, 2005).

Chloride did not differ seasonally in the Kulekhani Reservoir, but it showed a significantly higher concentration in winter compared to summer in Phewa Lake (H=12.11, $p<0.007$). Nevertheless, the average concentration of chloride in Phewa Lake (1.17±3.59 mg/L) and Kulekhani Reservoir (0.77 ±0.60 mg/L) were within the range of previous studies in Nepalese lentic water bodies (Table 4). Chloride can damage plants from excessive foliar absorption (with sprinkler systems) or excessive root uptake (with drip irrigation). Most plants can tolerate chloride up to 100 mg/L although as little as 30 mg/L can be problematic in a few sensitive plants (Fipps, 2003).

Nitrate did not show significant seasonal variation in the Kulekhani Reservoir, but it was significantly lower in summer compared to the winter and autumn seasons in Phewa Lake (H=19.45, $p<0.001$). The average concentration of nitrate in Phewa lake (0.14±0.20 mg/L) and Kulekhani Reservoir (0.32±0.51 mg/L) were relatively low compared to previous studies in other nearby lakes (Table 4). The level of nitrogen should be less than 300 mg/L according to Nepal quality guidelines for aquaculture and 5 mg/L for irrigation as per CBS (2012).

The average concentration of phosphate in Phewa Lake (0.48±0.71 mg/L) and Kulekhani Reservoir (0.51±0.77 mg/L) was relatively high compared to previous studies in other nearby lakes (Table 4), and it showed a significant seasonal variation in both water bodies, particularly it was higher in winter in Kulekhani (H=31.36, $p<0.05$) and autumn in Lake Phewa (H=22.01, $p<0.001$). Phosphorous levels above 5 mg/L may cause antagonism and deficiencies in other nutrients and its levels in water need to be considered in the overall fertilization program (Bindraban et al., 2020).

There is no seasonal variation of sodium in Phewa Lake, but it significantly varied seasonally in the Kulekhani Reservoir having the lowest concentration in spring (H=12.96, $p<0.005$). The average concentration of sodium in Phewa Lake (2.73±7.61 mg/L) and the Kulekhani Reservoir (4.45±7.64 mg/L) was consistent with previous studies in similar lakes in Nepal (Table 4). High sodium in the irrigation water can impact both the soil and the plant and can also be toxic to many plants (Safdar et al., 2019).

The average concentration of calcium in Phewa Lake (6.45±6.30 mg/L) and Kulekhani Reservoir (13.18± 50.16 mg/L) was relatively high compared to previous studies in other Nepalese lakes (Table 4). Calcium compounds occur naturally in surface water, and their concentrations are mainly determined by the carbonate balance (Potasznik and Szymczyk, 2015). Calcium enters the freshwater systems through weathering of rocks, especially limestone, and from the leaching and runoff of forest soils. Like calcium, magnesium is washed from rocks like dolomite [$CaMg(CO_3)_2$] and magnesite ($MgCO_3$) and subsequently enters the water bodies as runoff.

The average concentration of magnesium in Phewa Lake (1.02±1.73 mg/L) and Kulekhani Reservoir (1.83±1.47 mg/L) were relatively high compared with other lakes (Table 4). Anthropogenic sources of magnesium include fertilizer, cattle feed, and chemical industries (Potasznik and Szymczyk, 2015). Chemical industries add magnesium to plastics and other materials as a fire protection measure. Magnesium sulphate is applied in beer breweries, and magnesium hydroxide is applied as a flocculant in wastewater treatment plants. Magnesium is also a mild laxative.

There is no significant seasonal variation in hardness in Phewa Lake, but a significant seasonal variation was observed in the Kulekhani Reservoir ($p<0.05$). The average level of hardness in Phewa Lake and Kulekhani Reservoir were 20.28±22.36 mg/L and 40.54±17.58 mg/L, respectively. Since calcium and magnesium are essential plant nutrients, moderate levels of hardness of 100 to 150 mg/L are considered ideal for plant growth (Boman et al., 2002).

3.2 Ionic composition and hydro-geochemistry of the lake water

The concentrations of cations are in the order $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ for both water bodies whereas those of the anions are in the order $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ in Phewa Lake; and $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ in Kulekhani Reservoir. The dominance of Ca^{2+} and HCO_3^- in freshwater bodies has been frequently reported on global as well as regional scales (Wetzel, 2001). Previous studies on Nepalese lakes and rivers have also reported similar findings (Gurung et al., 2018; Sharma et al., 2021; Khadka and Ramanathan, 2021; Bhatta et al., 2022).

From the Piper plot, it is seen that, in both water bodies, cations are found to be distributed in the calcium type and that of anions in the HCO_3^- zone (Figure 2). The plot also indicates that the majority of samples are located on the Ca^{2+}-Mg^{2+}-HCO_3^- hydro-geochemical facies. It indicates that the water chemistry is dominantly controlled by the congruent dissolution of carbonate minerals and to a limited extent by incongruent weathering of silicate minerals in the surface sediments. The dissolved salts in freshwater lakes are low as these are derived from atmospheric precipitation and chemical weathering (Kilham, 1990). The pattern of Ca^{2+}-Mg^{2+}-HCO_3^- is considered the source of water from carbonate dissolution and atmospheric precipitation (Asare-Donkor et al., 2018). Since the lake watersheds are held by both types of rock at the sources, they contribute to making both alkalinity and acidity in the water (Kafle et al., 2019).

The major mechanisms that control lake water chemistry can be interpreted with the help of the Gibbs diagram (Gibbs, 1970; Marandi and Shand, 2018) which shows bedrock geology as the source of major ions in both water bodies.

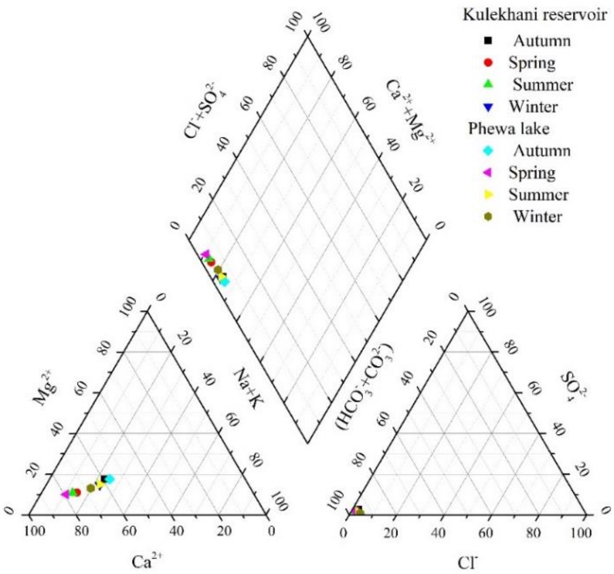

Figure 2. Piper plot of Kulekhani Reservoir and Phewa Lake

The (Ca^{2+} + Mg^{2+}) vs. (HCO_3^- + SO_4^{2-}) graph illustrates the processes of mineralization of ground water (Kumar et al., 2020). Several studies on Himalayan lakes revealed the dominance of Ca^{2+} and Mg^{2+} among the cations and HCO_3^- among the anions in lake waters (Mayanglambam and Neelam, 2020). The relatively higher concentration of HCO_3^- indicates an intense weathering catchment area rocks and organic matter decomposition in the area (Figure 3). Other factors responsible for the abundance and variation in major cations (Ca^{2+}, Na^+, Mg^{2+}, and K^+) and anions (HCO_3^-, SO_4^{2-}, PO_4^{3-}, NO_3^-, and Cl^-) in surface water are controlled by weathering, atmospheric precipitation, and possible atmospheric activities (Pollock, 2011).

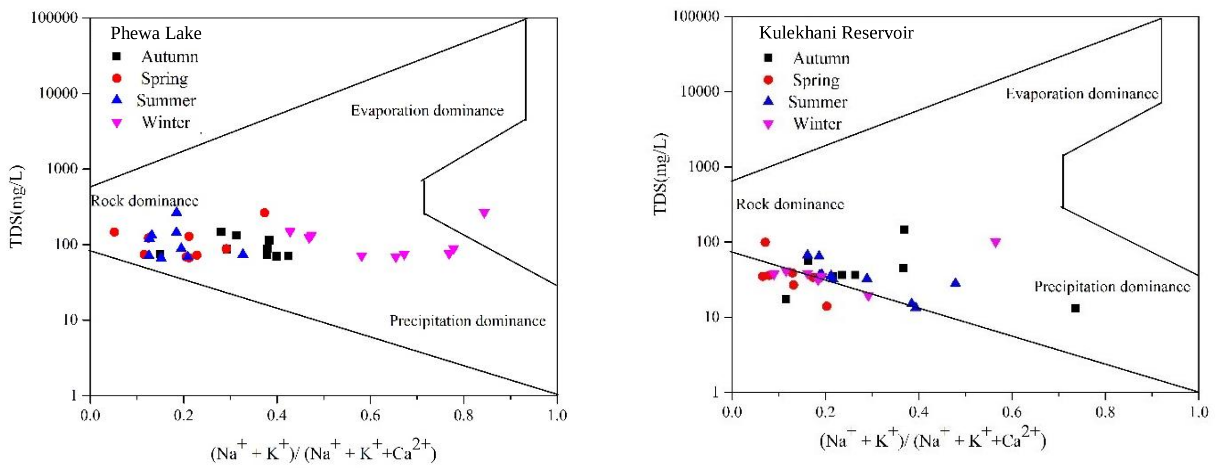

Figure 3. Gibbs diagram of Kulekhani Reservoir and Phewa Lake

Data points along or near the 1:1 line are attributed to carbonate and sulphate mineral weathering (Figure 4). Those that fall above the 1:1 line resulted from the effects of the reverse ion exchange processes in the system. Data points that fall below the equiline are deemed to have also resulted from the dissolution of carbonates. The points of the Scatter plot of alkali metals (Ca^{2+} + Mg^{2+}) vs TZ^+ (total cations) are slightly below 1:1 equiline (Figures 4(a) and 4(a')) indicating the dominance of alkaline earth metals over alkali metals suggesting carbonate weathering as the dominant control mechanism over silicate weathering. This fact is also verified by the similar information obtained in the Gibbs diagram (Figure 3). Furthermore, Ca^{2+} + Mg^{2+} vs. HCO_3^- + SO_4^{2-} (Figures 4(b) and 4(b')) points lying below the equiline further confirms carbonate weathering with only a minor contribution from silicate weathering along with the ion exchange process. Ca^{2+} + Mg^{2+} vs. HCO_3^- points also lie below the equiline indicating very low concentrations of SO_4^{2-} (Figures 4(d) and 4(d')). In general, the weathering of carbonate rocks is more effective (12 times) than that of silicate rocks (Gaillardet et al., 1999), and similar observations have been reported in many freshwater bodies across the lesser Himalayan region (Jeelani and Shah, 2006; Saini et al., 2008).

The Scatter plot of Na^+ + K^+ vs. TZ^+ in a 1:6 ratio indicates that water is relatively deficient in Na^+ + K^+ (Figures 4(c) and 4(c')). The samples mostly fall on or near the 1:1 equiline suggesting HCO_3^- is balanced by Ca^{2+} and Mg^{2+} while the monsoon samples fall below the equiline indicating HCO_3^- needs to be balanced also by Na^+ + K^+, in addition to Ca^{2+} + Mg^{2+}. The Scatter plot of Ca^{2+} + Mg^{2+} vs. HCO_3^- + SO_4^{2-} shows that the sampling points fall mostly below 1:1 equiline requiring a portion of HCO_3^- and SO_4^{2-} to be balanced by Na^+ + K^+ from weathering of silicate.

Sodium ion is ubiquitous in water, owing to the high solubility of its salts and the abundance of sodium-containing mineral deposits (Arega, 2020). Potassium is an important element for aquatic animal and plant species, although the least abundant of four major elements (Ca^{2+} > Mg^{2+} > Na^+ > K^+) in natural waters based on esthetic considerations. World Health Organization has established a drinking water guideline of 200 mg/L of sodium. Sodium levels in drinking water are typically less than 20 mg/L but can vary in different countries.

In a freshwater system, chloride is generally a minor component of the total ionic composition. The mean concentration of chloride in river waters is about 8 mg/L (Wetzel, 1983). However, chloride from anthropogenic sources is increasingly identified as a significant pollutant of freshwater lakes and streams (Gillis, 2011). The concentration of chloride is within the range of the Nepal standard for drinking water i.e., 250 mg/L (CBS, 2012) because the average concentration of chloride was 1.20 mg/L in Phewa Lake and 0.70 mg/L in the Kulekhani Reservoir. In Phewa Lake, it is consistent with the previous study (1.57 mg/L) by Khadka and Ramanathan (2021). In the Kulekhani Reservoir, the concentration of chloride is relatively lower than in other lakes but slightly higher than in Rara Lake (Table 4).

From these results, it is evident that the main source of major ions in both the water bodies can be attributed to their geology. The Phewa Lake watershed predominantly lies on the Kuncha formation rocks that comprise phyllite and phyllitic quartize (Stöcklin and Bhattarai, 1977). The rock types indicate the contribution in the lake water with mild acidic anions in most of the seasons. The southwestern parts of the watershed are composed of quartzite rock named the Fagfog Quartzite Formation that has massive white and pinkish white quantize and the northwestern part has phyllite with quartz veins with little carbonate content. However, in the rainy season (monsoon), the nearby Ghachok and Tallakot Formation (Yamanaka et al., 1982) plays the main role in contributing to alkalinity in the water of its carbonate contents. This comparative result shows that Phewa Lake water is a little more acidic compared with the Kulekhani Reservoir water as also indicated by Kafle et al. (2019).

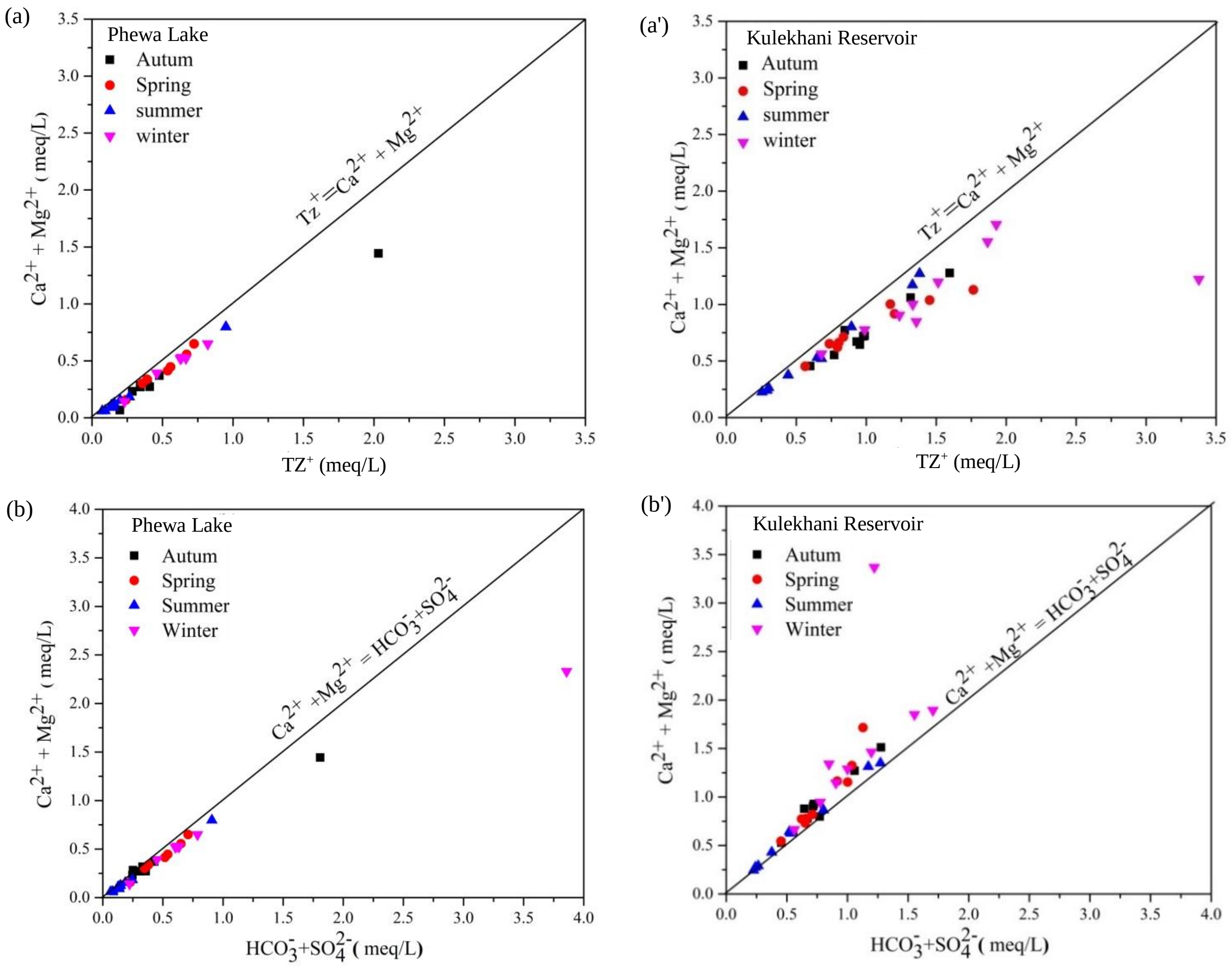

Figure 4. Scatter diagrams showing: (a),(a') $Ca^{2+} + Mg^{2+}$ vs. TZ^{+}; (b),(b') $Ca^{2+} + Mg^{2+}$ vs. $HCO_3^- + SO_4^{2-}$; (c),(c') $Na^+ + K^+$ vs. TZ^+ ; (d),(d') $Ca^{2+} + Mg^{2+}$ vs. HCO_3^- for Phewa Lake and Kulekhani Reservoir

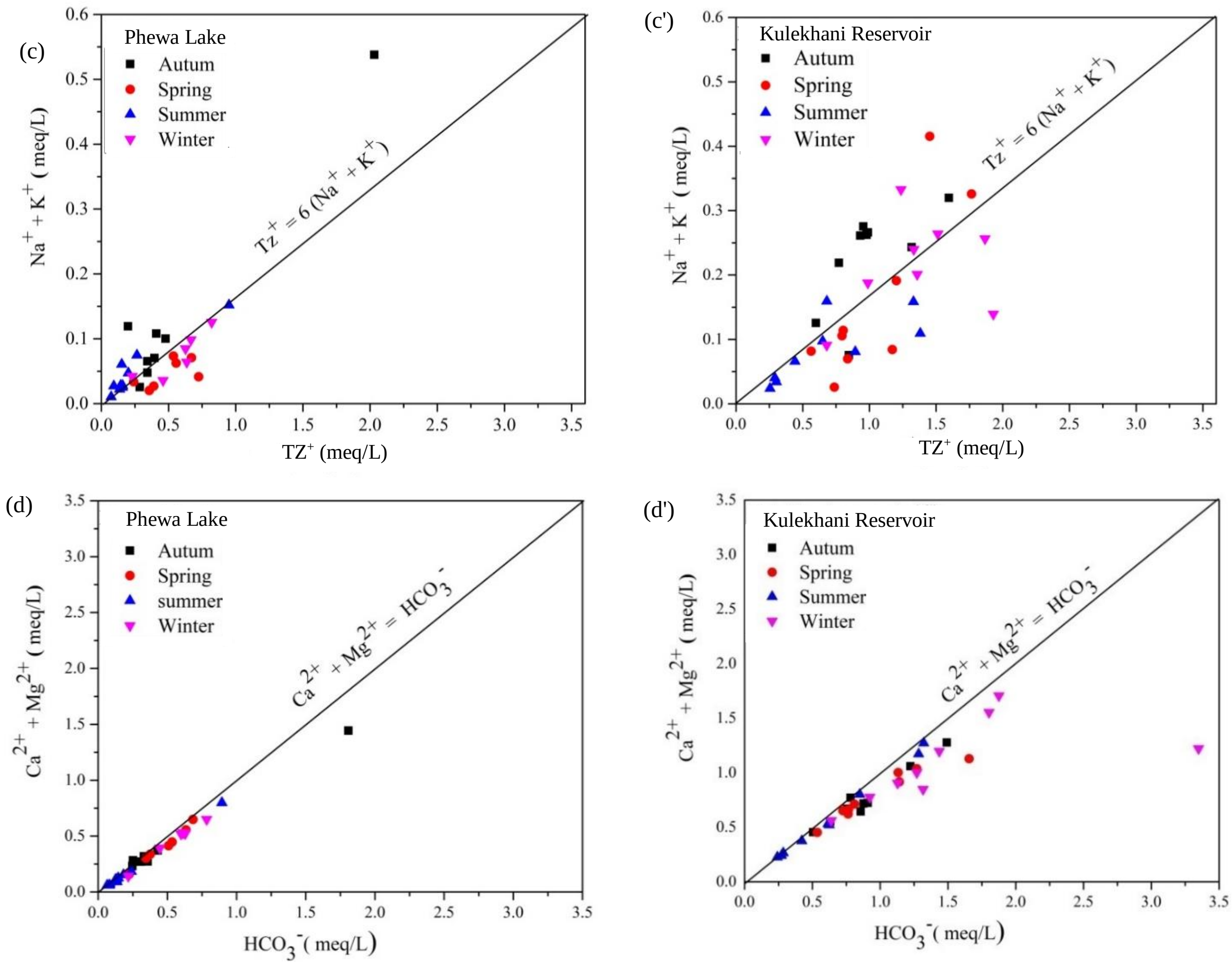

Figure 4. Scatter diagrams showing: (a),(a') Ca^{2+} + Mg^{2+} vs. TZ^+; (b),(b') Ca^{2+} + Mg^{2+} vs. HCO_3^- + SO_4^{2-}; (c),(c') Na^+ + K^+ vs. TZ^+ ; (d),(d') Ca^{2+} + Mg^{2+} vs. HCO_3^- for Phewa Lake and Kulekhani Reservoir (cont.)

In the Kulekhani watershed, the carbonate and silicate rocks are prominent. The reservoir water with cations (Ca^{2+} + Mg^{2+}) is contributed from the north side inlet streams, which flow from calcareous Markhu Formations (coarse crystalline marble) and Chandragiri limestone and Chitlang slate made of argillaceous limestone (Stöcklin and Bhattarai, 1977; Stöcklin, 1980). The reservoir itself is situated along a part of the Markhu formation which contributes to the alkalinity in the water. Similarly, the acidic rocks are situated in the western and southern part of the lake watershed that has silicate rocks with granite that contribute to a mild acidic anion (Neupane et al., 2017).

3.3 Water quality for irrigation

The water samples are classified for irrigation purposes as US Salinity Laboratory (USSL, 1954) classification shown in the USSL diagram (Figure 5). It is classified into four types - C1, C2, C3, and C4 based on salinity hazard and S1, S2, S3, and S4 based on sodium hazard. Based on the USSL diagram most of the samples fall under the C1S1 (low salinity and low sodium) category, which can be used for irrigation in most soil types. A few samples are in the C2S1 category indicating the suitability of the lake waters for irrigation (Figure 5).

Likewise, the Wilcox diagram (Wilcox, 1955) revealed good water quality (Figure 6) for irrigation. According to the categorization of the Wilcox diagram, the irrigation water quality falls mostly in the excellent to good category and only a few samples are in the good to permissible category.

Sodium is an important ion used for the classification of irrigation water because its reaction with soil reduces its permeability. Excessive amounts of EC and Na^+ content in agricultural water may also decrease the osmotic gradient and reduce the ingestion of nutrients from the soil by plants (Saleh et al., 1999).

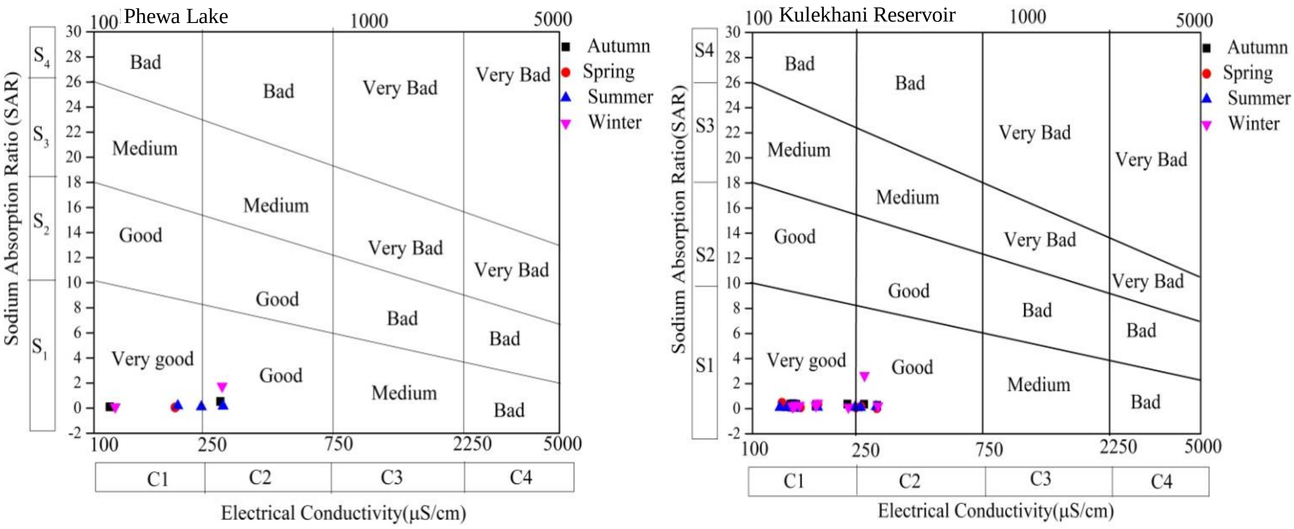

Figure 5. USSL diagram showing the relation between SAR and electrical conductivity

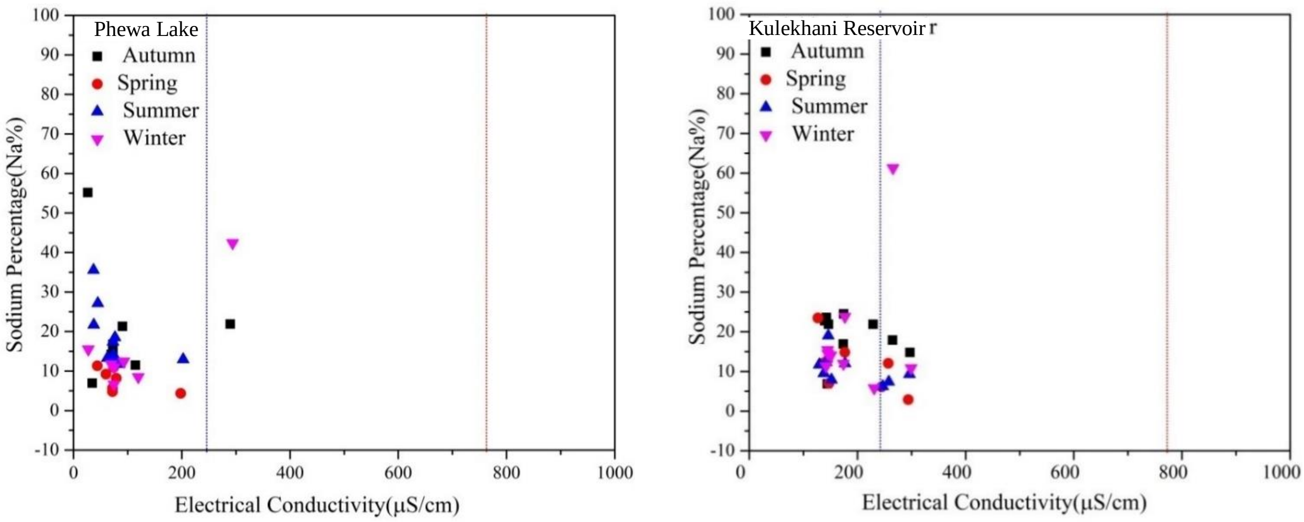

Figure 6. Wilcox diagram for Kulekhani Reservoir and Phewa Lake

The mean values of different irrigation water quality attributes are presented in Tables 5 and 6. All the values comply with Nepal's standard of irrigation water quality (CBS, 2012). Sodium values reflected that the water was under the category of good to excellent (20-40 Na%). As per Nepal water quality guidelines for irrigation, a sodium percentage of less than 70 mg/L is recommended for irrigation water (CBS, 2012), and up to 460 mg/L depending upon the sensitivity of crops. Furthermore, the Wilcox diagram showed that most of the samples were good for irrigation (Figure 6). SAR is used to measure the alkali/sodium level to determine the harmful level of crops. Na^+ replaces the exchangeable Ca^{2+} and Mg^{2+} ions; the high Na^+ content of irrigation water changes the soil characteristics and reduces crop yield.

The computed SAR values in the present study ranged between 0.04 to 2.64 (Table 5). The SAR values of the Phewa Lake ranged between 0.04 and 1.75 meq/L with an overall average value of 0.20 meq/L, whereas it ranged between 0.04 and 2.64 meq/L with an overall average value of 0.29 meq/L in the Kulekhani Reservoir (Table 5).

The value of Kelley's ratio less than one is suitable for irrigation and greater than one is unsuitable for irrigation purposes. In the Kulekhani Reservoir, the KR ranged from 0.03 to 1.69 in four different seasons, with an average of 0.22 (Table 6).

Table 5. Average sodium percentage and sodium absorption ratio (SAR) in lake waters during four seasons in Kulekhani Reservoir and Phewa Lake

Seasons	Sodium percentage (%Na)			Sodium absorption ratio (SAR)		
	Min	Max	Average±SD	Min	Max	Average±SD
Kulekhani Reservoir						
Autumn	6.67	24.50	19.00±5.60	0.09	0.39	0.31±0.01
Spring	2.99	23.48	11.46±5.90	0.04	0.47	0.20±0.13
Summer	6.27	19.02	10.61±3.81	0.06	0.25	0.13±0.06
Winter	5.78	61.26	18.76±16.64	0.12	2.64	0.51±0.80
Phewa Lake						
Autumn	11.48	55.16	20.38±14.88	0.05	0.61	0.25±0.20
Spring	4.36	11.33	7.78±2.88	0.04	0.13	0.08±0.03
Summer	11.75	35.54	18.54±7.66	0.05	0.25	0.13±0.06
Winter	6.63	42.39	15.44±12.22	0.07	1.75	0.36±0.61

Table 6. Kelley's ratio of water samples from Kulekhani Reservoir and Phewa Lake during four seasons

Rank	Kelley's ratio	Quality	Number of samples				Percentage of water samples
			Autumn	Spring	Summer	Winter	
Kulekhani Reservoir							
1	<1.0	Suitable	9	9	9	8	97.20
2	>1.0	Unsuitable	0	0	0	1	2.80
Phewa Lake							
1	<1.0	Suitable	7	7	10	7	96.90
2	>1.0	Unsuitable	1	0	0	0	3.10

According to Richards (1954) classification, a value of SAR less than 10 is excellent, 10 to 18 is good, 18 to 26 is doubtful, and greater than 26 is unsuitable for irrigation uses. Based on the classification, both water bodies are excellent for irrigation purposes. Based on Kelley's ratio, 97.20% of the water samples from the Kulekhani Reservoir are suitable for irrigation purposes having a KR ratio of less than 1. Similarly, the KR values from Phewa Lake varied from 0.05 to 1.63 and the average value was 0.25. The present study shows that 96.90% of water samples are found to be suitable for irrigation purposes.

4. CONCLUSION

The study focused on water quality assessments of two mid-hill lakes in Nepal; Phewa Lake and Kulekhani Reservoir. The suitability for irrigation of the water from the lakes was evaluated based on water physico-chemical parameters, SAR index, Wilcox plot, Kelley's ratio, and Sodium percentage. Samples from all four seasons were analyzed for dissolved oxygen, pH, conductivity, temperature, turbidity, total dissolved solids, major ions, and important salts. Dissolved oxygen, ammonia, and phosphate showed seasonal variations in both lakes. However, chloride and nitrate had seasonal variations in Lake Phewa only, and sodium had seasonal variations in Kulekhani only. The concentrations of cations are in the same order of abundance, namely Ca^{2+} > Na^{+} > Mg^{2+} > K^{+} in both water bodies. However, the trend of anions had small variations for Cl^{-} and SO_4^{2-} in Lake Phewa (HCO_3^{-} > Cl^{-} > SO_4^{2-} > NO_3^{-}) and Kulekhani Reservoir (HCO_3^{-} > SO_4^{2-} > Cl^{-} > NO_3^{-}). The water chemistry of both mid-hill lakes is dominantly controlled by the dissolution of carbonate minerals from watershed bedrock as the main source of major ions, which was clearly reflected by a Piper plot and Gibbs diagram. Based on the KR values and SAR index more than 96 percent of water samples were suitable for irrigation purposes. Although the water chemistry of the middle mountains of Nepal is substantially affected by local geology, the water is suitable for irrigation in all seasons.

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