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Research Article

HYDROCHEMISTRY AND WATER QUALITY OF PHOKSUNDO LAKE (DOLPA): INSIGHTS FROM THE HIGHER HIMALAYA RAMSAR SITE OF NEPAL

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ABSTRACT

Phoksundo Lake, a distinctive 'Y' shaped Ramsar site located in the arid alpine region of the Nepal Himalayas, is a critical freshwater resource with significant ecological and cultural value. This study presents the first comprehensive hydrochemical assessment of the lake to determine its baseline water quality and suitability for drinking and irrigation. Thirteen surface water samples were collected in June 2024 from the lake's inlets, outlet, and main body. Physicochemical analysis revealed that the lake water is of the Ca^{2+}-HCO_3^- type, with ionic dominance orders of $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ and $HCO_3^- > SO_4^{2-} > Cl^-$. While most parameters, including electrical conductivity (EC), total dissolved solids (TDS), and major ions, were well within WHO guidelines, the pH (mean 8.88) exceeded the recommended range for potable water. Geochemical modeling using Gibbs and Piper plots confirmed that the lake's chemistry is overwhelmingly controlled by rock weathering, specifically the dissolution of carbonate minerals in the catchment, which explains its natural alkalinity. A weighted arithmetic water quality index (WQI) classified the water as "Excellent" for drinking, yet this was contradicted by the presence of E. coli in several samples, indicating localized anthropogenic contamination. Irrigation suitability indices (SAR, Na%) also rated the water as "Excellent," posing no risk to soil health. This study establishes a crucial hydrochemical baseline, concluding that while Phoksundo Lake remains a pristine, rock-dominated system, emerging microbial contamination necessitates targeted monitoring and management to preserve its ecological integrity. Further investigation across different seasons and depths is recommended for a holistic understanding of the lake's dynamics.

Keywords: Phoksundo Lake, hydrochemistry, carbonate weathering, water quality index (WQI), irrigation suitability, microbial contamination, Himalayas

INTRODUCTION

Globally freshwater, constituting only 2.5% of Earth's total water, is a limited and indispensable resource vital for sustaining life (Shiklomanov, 1993). Lakes, covering just 3.7% of the planet's non-glaciated land surface, play a disproportionately critical role in supporting biodiversity, regulating the global water cycle, and providing essential ecosystem services (Downing *et al.*, 2006; Williamson *et al.*, 2009). These freshwater ecosystems are not only ecological hotspots but also sensitive indicators of environmental change, with shifts in their hydrochemical properties having cascading effects on water quality, aquatic life, and human well-being (Adrian *et al.*, 2009).

Hydrochemistry is the study of water's chemical composition or properties and its interactions with environmental processes, is crucial for understanding lake ecosystems. Natural processes such as rock weathering, precipitation, and evapocrystallization govern hydrochemical dynamics. These process contribute ions like Ca^{2+}, Mg^{2+}, and HCO_3^- from mineral -CO_2 interactions and K^+, Na^+, Cl^-, and SO_4^{2-} from silicate weathering and evaporite dissolution (Gibbs, 1970; Yao *et al.*, 2015). Analyzing hydrochemistry provides insights of water quality, pollution sources, and the impacts of both natural and anthropogenic pressures, determining water's suitability for uses such as drinking, irrigation, and other applications (Gaury *et al.*, 2018).

Phoksundo Lake which is located in the Higher Himalaya of Dolpa district, Nepal, at an elevation of 3,611.5 m, which have rich ecological and cultural significance of high-altitude communities. Located within Shey-Phoksundo National Park, which spans 3,555 km² with an additional 1,349 km² buffer zone, Phoksundo is a pristine oligotrophic lake known for its unique characteristics and fragile alpine environment (DNPWC & WWF, 2005). Its formation is due to the landslide damming following a mountain collapse potentially triggered by an earthquake, underscores its geological significance (Weidinger & Ibetsberger, 2000). The lake, with a maximum depth of 136.20 m and a storage volume of 398.73 MCM, is primarily fed by Himalayan snow and rain, with low suspended sediment concentrations and outflows influenced by snowmelt and base flow (DHM, 2019). Kanjiroba Himal, standing at 6,883 meters, located in a remote region of the Himalayan range in Nepal, adjacent to the Tibetan border, serves as the primary water source for this lake. Despite its remoteness, Phoksundo Lake faces numerous challenges. High-altitude lakes like Phoksundo are particularly vulnerable to pollution, climate change, and anthropogenic pressures such as tourism and infrastructure development (Sharma *et al*., 2010; Chauhan *et al*., 2023; Khadka *et al*., 2023). The increasing pollution levels and contribute the concentrations of harmful substances in such fragile ecosystems have been recorded, emphasizing the need for urgent climate change action and conservation measures (Liu *et al*., 2015; Pastorino & Prearo, 2020; Machate *et al*., 2023). Moreover, Ramsar-listed lakes in Nepal and other freshwater systems across the region face risks of contamination from geogenic and anthropogenic sources (Pant *et al*., 2021).

The 21st century is characterized by intensified human impact, causing unprecedented impact on freshwater ecosystems like Phoksundo Lake which threaten their ecological balance and the well-being of millions who depend on them (Naderian *et al*., 2024; Wang *et al*., 2023). Recognizing the critical need for sustainable management, this study aims to characterize the hydrochemical parameters of Phoksundo Lake, evaluate its water quality suitability for drinking, domestic, and agricultural use, identify pollution sources, and propose strategies to preserve its ecological and cultural significance for future generations, addressing gaps in previous research.

We have chosen thirteen sampling point including one outlet and two inlets. The main goal of this present research is to study the chemical and physical characteristics of the High mountain Ramsar site Phoksundo Lake and evaluate the degradation of the water quality and assessment of lake water for drinking, domestic use and agricultural purposes. One of the main objectives of this study is to find the present status of the lake. The water chemistry of lakes is not fully studied in past research so to fulfill this gap the present study is done in this lake.

MATERIALS AND METHODS

Study Area

Phoksundo Lake, situated in the Higher Himalaya of (Figure 1), Dolpa District, Karnali Province of Nepal. It is alpine pristine fresh water oligotrophic lake located at (3,638 m asl) altitude (Photograph 1). Phoksundo lake has been listed as Ramsar site no. 1694 in 23rd September 2007 (Karki *et al*., 2007) within the Shey Phoksundo National Park, a UNESCO World Heritage Site (UNESCO, 2007). It is located at 29˚10'23.451" N, 82˚56'17.1276" E, has an alpine climate with harsh winters, with temperatures dropping to -10°C and the lake freezing for four months. Summers are mild, with temperatures rising to 20°C and annual precipitation around 600 mm (DHM, 2019). It is the Nepal's second largest and deepest lake (145 m) which have magnificent turquoise color, color changing lake, covering an area of approximately 4.5-5 km² (Bhuju *et al*., 2007; DHM, 2019). Phoksundo Lake spans 494 hectares with a water volume of 409 million m³ and a discharge rate of 3.715 m³/s (Bhuju *et al*., 2007).This lake formed due to the damming of the Suli Gad River over massive landslide approximately 30,000 to 40,000 years ago (Yagi, 1997; Weidinger & Ibetsberger, 2000). People of Rigmo village, which resides on massive landslide over the lake are practicing a transhumant pastoral lifestyle, which their local economy that has increasingly to rely on tourism alongside traditional agro-pastoralism and cattle husbandry for income, and transportation (Kayastha *et al*., 2023). The surrounding geology of Phoksundo region consists of un-metamorphosed sedimentary rocks and glacial deposits, forming a U-shaped valley with prominent moraine features. The northern part of Phoksundo Lake has low-productivity soil, consisting of sand and gravel mixed with sandstone, siltstone, shale, and conglomerate. Whereas, the central and southern areas feature softer, loamy soil brought by rivers, with sand-mixed soil along riverbanks and streams (Fort *et al*., 2013). The water quality and hydrochemistry of the lake are crucial for maintaining its ecological balance and supporting the surrounding biodiversity, which includes several endemic and endangered species (Bhuju *et al*., 2007).

Phoksundo Lake is famous for its striking turquoise color and breathtaking scenery, and is surrounded by majestic mountain peaks, glaciers, and rich flora and fauna (DNPWC, 2024). Located in Ward No. 8 of Shey Phoksundo Rural Municipality in Dolpa District, is home to a predominantly Bhote community of Lamas, Budhas, Baijis, and Gurungs, who practice agriculture and animal husbandry, with the ward's population comprising 193 males and 195 females out of the municipality's total of 3,635 residents across 861 households (Bhuju *et al*., 2007; NSO, 2021). The nearest village to the lake is Rigmo (Tsho), a typical Tibetan type of settlement. The region is culturally renowned for its Tibetan traditions, Bon-Po practices, Chorten, Gompas, vernacular architecture, and the transhumance lifestyle that reflects a unique way of life people are experiencing (Yonzon, 2001; Bhuju *et al*., 2007; DNPWC, 2024). Their beliefs, particularly those rooted in the Bon tradition and the Thashung Gompa, emphasize a profound respect for nature, viewing the lake and its landscapes as sacred (Gurung, 1980; Yagi, 1997). Locals believe that harming nature invites misfortune, reinforcing their commitment to preserving the lake pristine environment. Tourists primarily stay in Ringmo village, where local accommodation is available, with 65 houses and 11 hotels (DNPWC, 2024). In 2023, nearly 2,000 tourists visited between August and November (Devkota, 2023). In 2024, around 1,632 tourists visited within four months, generating approximately 1.05 million rupees in revenue. The park also reported a total of 6.5 million rupees in revenue from ecotourism, forest product sales, and fines in fiscal year 2023/024 (Neupane, 2024). Additionally, tourism has led to improved infrastructure, cultural preservation, and environmental conservation, enhancing the overall quality of life and promoting sustainable practices.

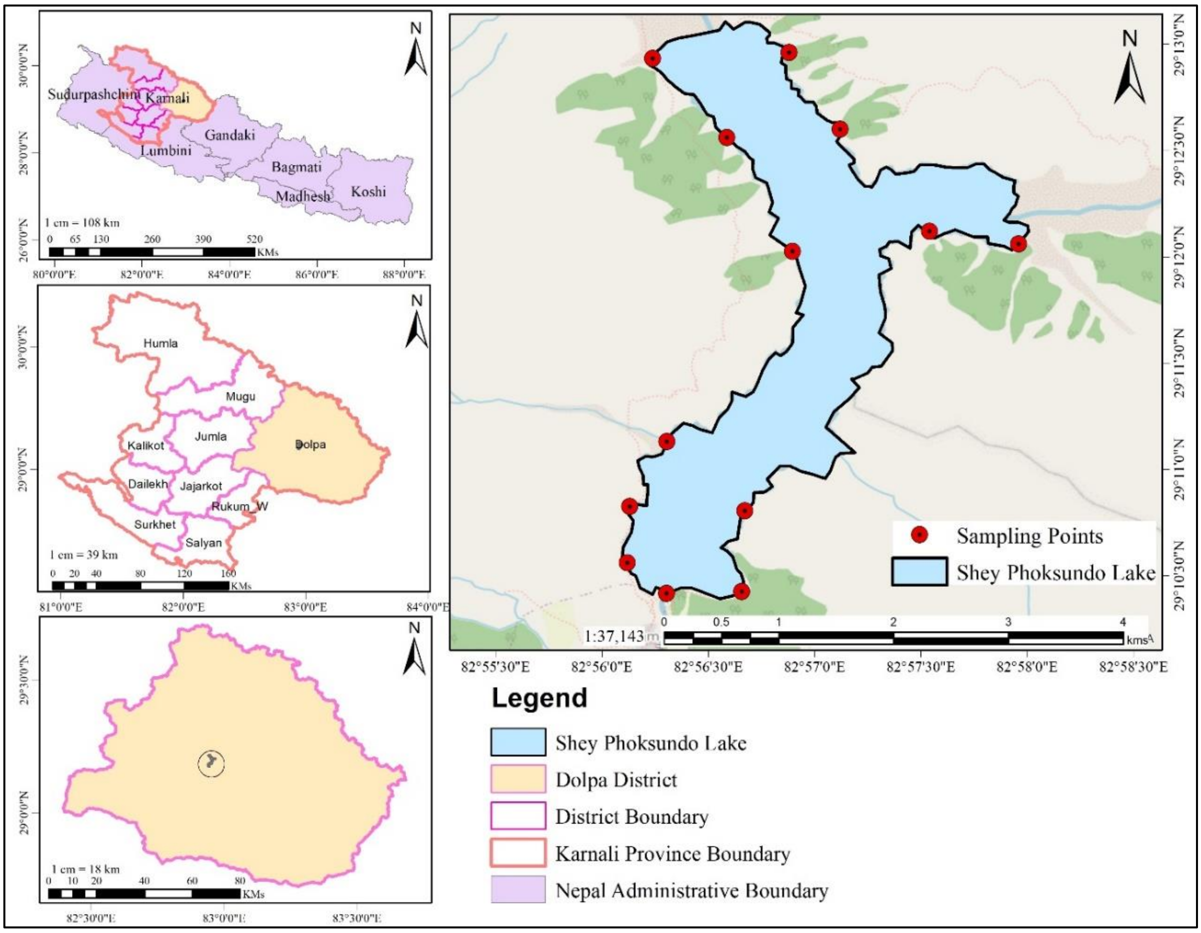

Figure 1. Outline map of Nepal with Phoksundo Lake, Dolpa

Photograph 1. Outline map of Nepal with Phoksundo Lake, Dolpa

Data Collection

The data were collected in June 2024 from 13 water samples sites at Phoksundo Lake. Sampling locations were strategically selected to represent different sections of the lakes, including the one outlet in southern side and two inlets on the northern side of lake, with considerations for geological, land use, and hydro-climatic factors. The middle section could not be accessed due to the unavailability of boats. Water was collected in pre-cleaned 1L HDPE bottles to maintain sample integrity, adhering to strict protocols to minimize contamination. On-site field measurements such as temperature and pH values were determined with a pH meter, calibrated using standard buffer solutions. Dissolved oxygen was measured in the field using a DO meter and total dissolved solids (TDS) and electrical conductivity (EC) were determined using a conductivity meter (HANNA), while turbidity was assessed with a Nephelometer (Turbidimeter).

The chemical parameters such as total hardness, calcium hardness, magnesium hardness, alkalinity, free carbon dioxide, and chloride content were measured using EDTA titration, the phenolphthalein indicator method, and argentometric titration, respectively. Iron, phosphate, sulfate, ammonia, and nitrate concentrations were quantified using the 1,10-phenanthroline spectrophotometric method, stannous chloride method, turbidimetric method, phenate method, and phenol disulfonic acid method, respectively. Major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) were analyzed using a flame photometer, while bicarbonate concentration was derived from the ion balance of total cations and anions (Tripathee *et al.*, 2014). After collection, samples were kept in an icebox and transported to the deleted for double-blind peer-review, where samples were refrigerated at 4°C until analysis. Gloves and masks were worn throughout sample collection and laboratory work to prevent contamination. Field blanks prepared with distilled water indicated no contamination occurred during sampling, storage, or transport. During laboratory analysis, distilled water was used, and freshly prepared standards with known concentrations were tested. Calibration curves were established to ensure accuracy, in line with the methods prescribed by (APHA, 2017) . All results were tabulated and compared to the World Health Organization (WHO, 2022) guidelines for drinking water quality.

Statistical Analysis

The statistical tests like maximum, minimum, average and standard deviation of physicochemical parameters of water were calculated in Excel workbook. Origin 2016 software and R software was used for analyzing hydro-chemical data, Gis ArcMap 10.8 was used to make the study area map. Heatmap was used to show the correlations between water quality parameters. Gibbs plot (Gibbs, 1970), Piper plot (Piper, 1944), Durov diagram, mixing diagram, and Wilcox diagram (Wilcox, 1948) were used to analyze the hydrochemical water quality status of Phoksundo Lake. Water Quality Index was calculated to reveal the suitability of water of Phoksundo Lake for drinking and irrigation which is introduced by Horton in 1965 (Horton, 1965), was later refined into the weighted arithmetic method by (Brown *et al.* 1970) and Na%, KR, SAR, MH, PI, and EC are utilized to evaluate the suitability of water for irrigation purposes.

RESULTS AND DISCUSSION

Chemical Characteristics of Water

The results obtained from water sample analysis of Phoksundo are given in (Table 1), which shows a fresh aquatic environment. The water of lake is characterized by low temperatures (avg. 11.77°C, range: 11.00°C - 13.00°C), alkaline pH levels (avg. 8.88), which doesn't comply with (WHO, 2022) drinking water standard and National drinking water quality standard (NDWQS, 2022) (Table 1) because of the high bicarbonate concentration in water (Al-Khashman *et al.*, 2017) and moderate electrical conductivity (avg. 249.77 μS/cm), indicating a delicate balance and relative purity (Pal *et al.*, 2015). The total dissolved solids (avg. 123.46 mg/L) are relatively low, contributing to a favorable environment for aquatic life (Weber-Scan & Duffy, 2007). The cold temperature of Lake, plays a crucial role in preserving its water quality by maintaining high dissolved oxygen levels and minimizing nutrient release and heavy metal mobilization (Li *et al.*, 2013). The alkaline nature of the lake, driven by carbonate weathering (Thapa *et al.*, 2024), assist in understanding life evolution, environmental history, and resource exploration by preserving unique minerals, isotopic signatures (e.g., $\delta^{13}C$, $\delta^{18}O$), and supporting specialized microbial communities that may offer insights into ancient Earth systems (Xia *et al.*, 2024).

In course of nutrients levels, the lake have a healthy calcium presence (avg. 35.30 mg/L), balanced magnesium levels (avg. 9.75 mg/L), and minimal sodium influence (avg. 2.17 mg/L). Pollution indicators are largely within safe limits, including low ammonia (avg. 0.05 mg/L), chloride (avg. 4.20 mg/L), and iron levels (avg. 0.24 mg/L), as well as low nitrates (avg. 3.22 mg/L), which prevents excessive algal growth. These findings are similar to high altitude Rara lake (Bhatta *et al.*, 2022). Sulfate (avg. 16.94 mg/L) and phosphate levels (avg. 0.05 mg/L) are also favorably low. The lake bicarbonate (avg. 108.44 mg/L) and total alkalinity (avg. 88.62 mg/L) provide a good buffering capacity against pH fluctuations, while total hardness (avg. 124.31 mg/L) is moderate, supporting aquatic life. Calcium and magnesium hardness reflect a healthy balance of hardness ions. Additionally, the lake is well-oxygenated (avg. 8.68 mg/L of dissolved oxygen). These observations favour with those reported for the high-altitude lakes (Pant *et al.*, 2021, 2022). However, the presence of potential biological contamination (avg. 5.21 CFU/100 mL of fecal coliform) requires more monitoring. The presence of fecal coliform in the lake may be recorded from waste discharge from nearby villages, seasonal factors (Ksoll *et al.*, 2007), and contributions from waterfowl (Weiskel *et al.*, 1996), as intestinal bacteria, including E. coli, are known to persist longer in cold water and adapt better to freezing conditions (Hendricks, 1967).

The order of cations concentrations in Phoksundo lake is $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+} > NH_4^{+}$, consistent with previous studies of other high altitude lakes (Bhatta *et al.*, 2022; Thapa *et al.*, 2024). In terms of anions, the mean concentrations followed the order $HCO_3^{-} > SO_4^{2-} > Cl^{-} > PO_4^{3-}$, all within WHO guidelines, indicating water safety for use (Pant *et al.*, 2021).

Table 1. Chemical composition of Phoksundo Lake, Standard permissible limit of different parameters as prescribed by WHO (2022), NDWQS (2022) and besides this, the percentage compliance. All the units are in mg L⁻¹ except pH and EC are in µS/cm.

Para.	Minimum	Maximum	Mean	Std. Deviation	WHO Std.(2022)	NDWQS(2022)	Percentage compliance
Temp	11.00	13.00	11.77	0.73	-	-	-
pH	8.60	9.10	8.88	0.16	6.5-8.5	6.5-8.5	0%
EC	230.00	253.00	249.77	6.10	1500	1500	100%
TDS	113.00	129.00	123.46	3.57	1000	1000	100%
Ca^{2+}	31.20	43.20	35.30	3.86	75	200	100%
Mg^{2+}	3.90	14.64	9.75	2.67	50	-	100%
K^{+}	0.30	0.78	0.53	0.15	12	-	100%
Na^{+}	1.14	3.50	2.17	0.80	200	-	100%
NH_4^{+}	0.01	0.10	0.05	0.03	1.5	1.5	100%
Cl^{-}	1.42	7.10	4.20	1.48	250	250	100%
Fe	0.24	0.25	0.24	0.00	0.3	0.3	100%
NO_3^{-}	2.27	5.23	3.22	0.75	50	50	100%
SO_4^{2-}	14.60	18.29	16.94	1.17	250	250	100%
HCO_3^{-}	85.40	121.57	108.44	10.54	200	-	100%
PO_4^{3-}	0.03	0.09	0.05	0.02	5	-	100%
Alkalinity	70.00	98.00	88.62	8.26	-	-	-
TH	119.00	138.00	124.31	5.42	500	500	100%
CaH	78.00	108.00	85.38	9.92	-	-	-
MgH	16.00	60.00	39.00	10.27	-	-	-
DO	8.10	9.20	8.68	0.32	-	-	-
CO_2(aq)	2.20	6.60	5.21	1.21	-	-	-

The heatmap (Figure 2) shows some clear relationships among water quality parameters, showing significant positive and negative correlations. It emphasizes strong interrelations between calcium (Ca^{2+}) and total hardness (TH), while visually marginalizing the insignificant correlations. The strong dependencies can also be seen between ammonia and phosphate, which indicates a common source, such as organic matter decomposition or agricultural runoff (Syeed *et al.*, 2023). Comparable multivariate correlations in water quality have been observed in other studies, (Ghaemi & Noshadi, 2022; Wang *et al.*, 2023).

The table (Table 2) illustrates the linkages among water quality parameters. Temperature affects conductivity (EC), total dissolved solids (TDS), and decreases dissolved oxygen (DO). The mean pH shows weak correlations, with a slight association to bicarbonate. EC and TDS are strongly correlated, reflecting ionic concentration and closely linked to total hardness (TH), primarily assist by calcium (Ca^{2+}) and magnesium (Mg^{2+}). Nutrients such as ammonium (NH_4^{+}) and phosphate (PO_4^{3-}) are strongly associated, indicating shared pollution sources. Dissolved oxygen decreases with higher temperatures and magnesium (Mg^{2+}) levels, while turbidity shows a negative correlation with sodium and fecal coliform, suggesting clearer water contains fewer bacterial contaminants.

Hydrochemistry of the Phoksundo Lake.

The Piper diagram (Piper, 1944) for Phoksundo Lake (Figure 3) indicates that its water is consistently of the Ca^{2+}- HCO_3^{-} type throughout most samples, as indicated by their position in Zone A of the cation triangle, Zone E of the anion triangle, and Zone 1 of the central diamond. While calcium is always the dominant cation, several samples contain a certain percentage of magnesium. This suggests that the lake chemistry is not controlled by a single rock type but rather by the weathering of mixed carbonate rocks, including both limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), within its catchment area. Bicarbonates (HCO_3^{-}) dominate over sulfates (SO_4^{2-}) and chlorides (Cl^{-}), while calcium (Ca^{2+}) and magnesium (Mg^{2+}) surpass sodium (Na^{+}) and potassium (K^{+}). The results show that rock weathering plays a major and stable role in shaping the lake hydro chemical characteristics of the lake.

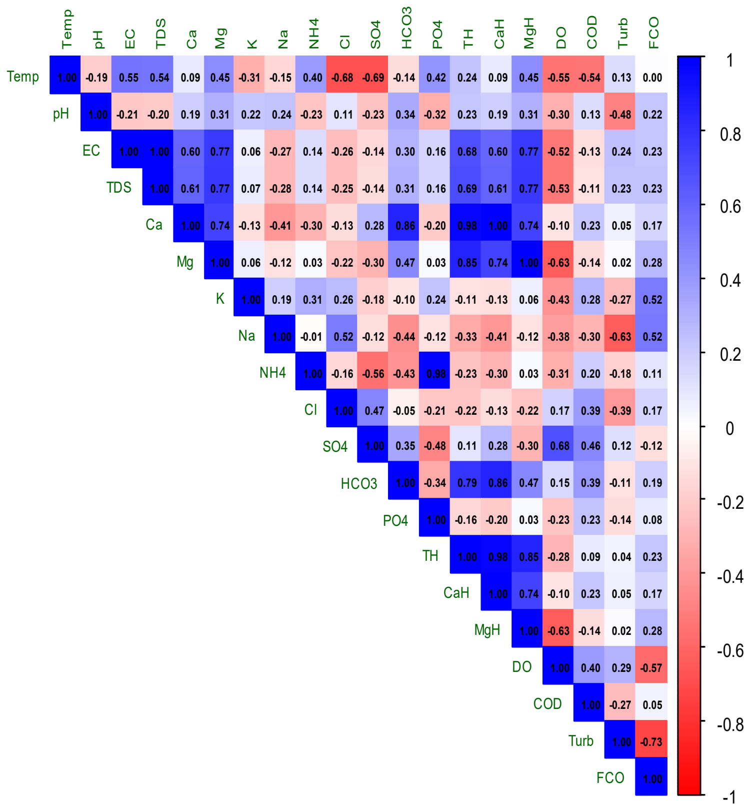

Figure 2. Heatmap showing the correlation matrix of water quality parameters of Phoksundo Lake. Blue indicates positive correlations, red indicates negative correlations, and the intensity reflects the strength of the relationship. Statistically insignificant correlations ($p > 0.05$) are excluded for clarity.

Table 2. Correlation matrix summary showing the key relationships between water quality parameters

Parameter	Correlations	Description
Temperature (Temp.)	Positive with EC (r = 0.32), TDS (r = 0.31); Negative with SO_4^{2-} (r = -0.449*), DO (r = -0.36)	Higher temperatures increase conductivity but reduce dissolved oxygen.
pH	Positive with HCO_3^- (r = 0.25); Negative with SO_4^{2-} (r = -0.22)	Weak relationships overall, slightly influenced by bicarbonate and sulfate.
Electrical Conductivity (EC)	Strong with TDS (r = 0.999**), Mg^{2+} (r = 0.574**), TH (r = 0.533*)	Indicates ionic concentration in water. Strongly tied to dissolved solids and hardness.
Total Dissolved Solids (TDS)	Strong with EC (r = 0.999**), Mg^{2+} (r = 0.575**), TH (r = 0.543*)	Reflects dissolved ions, closely related to EC and hardness.
Calcium (Ca^{2+})	Strong with TH (r = 0.958**), Mg^{2+} (r = 0.598**), HCO_3^- (r = 0.664**)	Major contributor to hardness, often present with bicarbonate.
Magnesium (Mg^{2+})	Strong with TH (r = 0.764**), EC (r = 0.574**), TDS (r = 0.575**)	Another key hardness contributor, closely tied to EC and TDS.
Sodium (Na^+)	Negative with Turbidity (r = -0.456*)	Weak overall correlations, slight influence on water clarity.
Ammonium (NH_4^+)	Strong with PO_4^{3-} (r = 0.953**)	Suggests common pollution sources, such as agricultural runoff.
Chloride (Cl^-)	Minimal correlations with other parameters	Generally stable in water systems, no strong dependencies.
Sulfate (SO_4^{2-})	Positive with DO (r = 0.461*); Negative with Temp (r = -0.449*)	Associated with oxidative conditions, decreases at higher temperatures.

Bicarbonate (HCO_3^-)	Strong with TH (r = 0.616**), Ca^{2+} (r = 0.664**)	Major buffer in water, closely linked to hardness.
Phosphate (PO_4^{3-})	Strong with NH_4^+ (r = 0.953**)	Indicates nutrient pollution from similar sources.
Total Hardness (TH)	Strong with Ca^{2+} (r = 0.958**), Mg^{2+} (r = 0.764**), HCO_3^- (r = 0.616**)	Primarily influenced by calcium, magnesium, and bicarbonate.
Dissolved Oxygen (DO)	Positive with SO_4^{2-} (r = 0.461*); Negative with Temp (r = -0.36), Mg^{2+} (r = -0.40)	Higher oxygen levels linked to lower temperatures and sulfate presence.
Chemical Oxygen Demand (COD)	Positive with PO_4^{3-} (r = 0.33), NH_4^+ (r = 0.35)	Indicates organic pollution and nutrient presence.
Turbidity	Negative with Na^+ (r = -0.456*), FCO (r = -0.551**)	Clearer water has less sodium and bacterial contamination.
Fecal Coliform (FCO)	Negative with DO (r = -0.37), Turbidity (r = -0.551**)	Bacterial contamination inversely related to oxygen levels and water clarity.

Similar patterns of carbonate weathering dominance have been noted in other lakes across the Nepal Himalayas, including Rara (Bhatta *et al.*, 2022), Ramaroshan lake complex (Thapa *et al.*, 2024), Gokyo (Bhandari *et al.*, 2015), Phewa (Gautam & Shrestha, 2024), Begnas and Rupa (Pant *et al.*, 2019), as well as in the Gandaki (Pant *et al.*, 2018) and other river basins of Nepal (Bishwakarma *et al.*, 2024; Kandel *et al.*, 2024), attributing it to the carbonate-rich geology of its catchment.

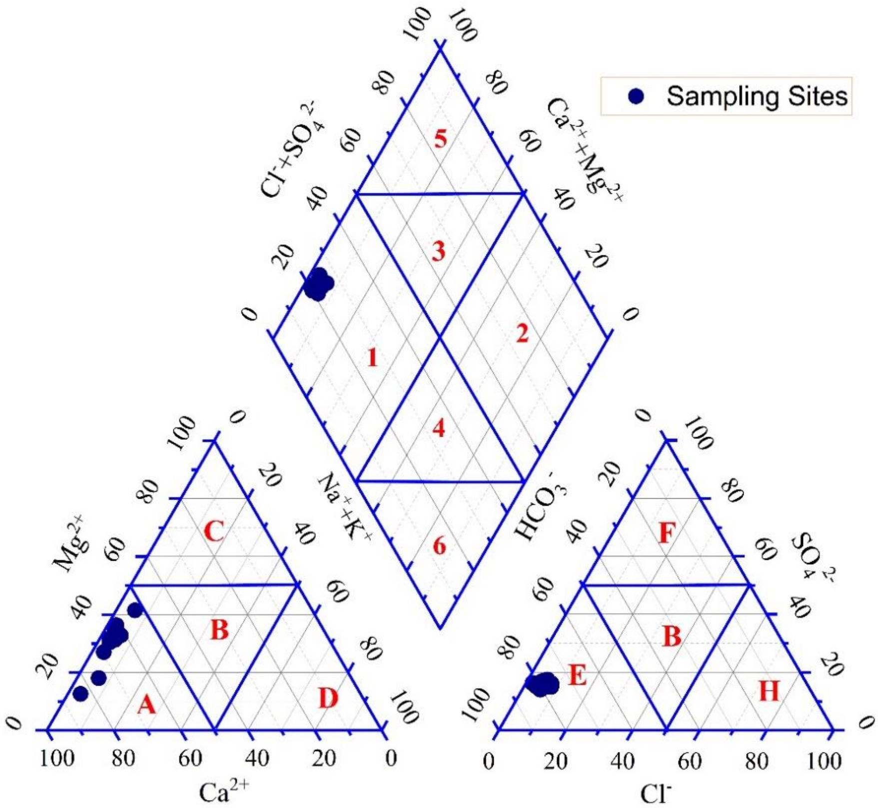

Figure 3. Piper diagram (Piper, 1944) showing types of water and concentration of different parameters in Phoksundo Lake

A Durov plot (Figure 4) is a graphical representation used to differentiate water quality based on major ions (cations and anions) and auxiliary parameters such as pH, TDS, and water type (Durov, 1948). Consistent with the Piper plot (Figure 3), the Durov diagram (Figure 5) illustrates that all water samples belong to the Ca-HCO_3 type. The below plot shows that water in Phoksundo Lake has a slightly alkaline pH ranging from 8.6 to 9.2, which sets it apart from other high-altitude Himalayan lakes like Ramaroshan (Thapa *et al*., 2024), Gokyo (Bhandari *et al*., 2015), Panchpokhari (Raut, 2015), Phewa (Gautam & Shrestha, 2024), and Begnas (Pant *et al*., 2019). This may be attributed to high carbonate dominated lithology, surrounded by carbonate-rich rocks, such as limestone, which release bicarbonates through weathering, naturally buffering the water and increasing alkalinity (Lehmann *et al*., 2023). The water also has low dissolved salts, indicating its clean and unpolluted nature. There is a little presence of chloride or sulfate, showing that the lake remains largely untouched by human activities (Novotny & Stefan, 2012).

Controlling Mechanisms of Hydrochemistry

To analyze the factors influencing water quality, such as precipitation, rock weathering, and evaporation, Gibbs's diagram is commonly used (Gibbs, 1970). This diagram (Figure 5) represents the relationship between total dissolved solids (TDS) on the vertical axis and the ratios $Na^+ + K^+ / (Na^+ + K^+ + Ca^{2+})$ and $Cl^- / (Cl^- + HCO_3^-)$ on the horizontal axis. Based on observations from Fig. 5(a) and 5(b), found that the water quality of Phoksundo Lake is primarily governed by the weathering of surrounding rocks throughout all samples (Yagi, 1997: Weidinger & Ibetsberger, 2000). This pattern is common across all observed samples, suggesting that rock weathering plays a consistent role in determining the chemical composition of the water in the lake. Precipitation and evaporation appear to have a lesser impact on water quality in Phoksundo Lake. This trend remains relatively consistent across the upstream region of Nepal, where sedimentary geological settings are a key factor influencing hydrogeochemistry (Raut, 2015; Bhandari *et al*., 2015; Pant *et al*., 2018, 2019; Bhatta *et al*., 2022; Neupane *et al*., 2023; Thapa *et al*., 2024).

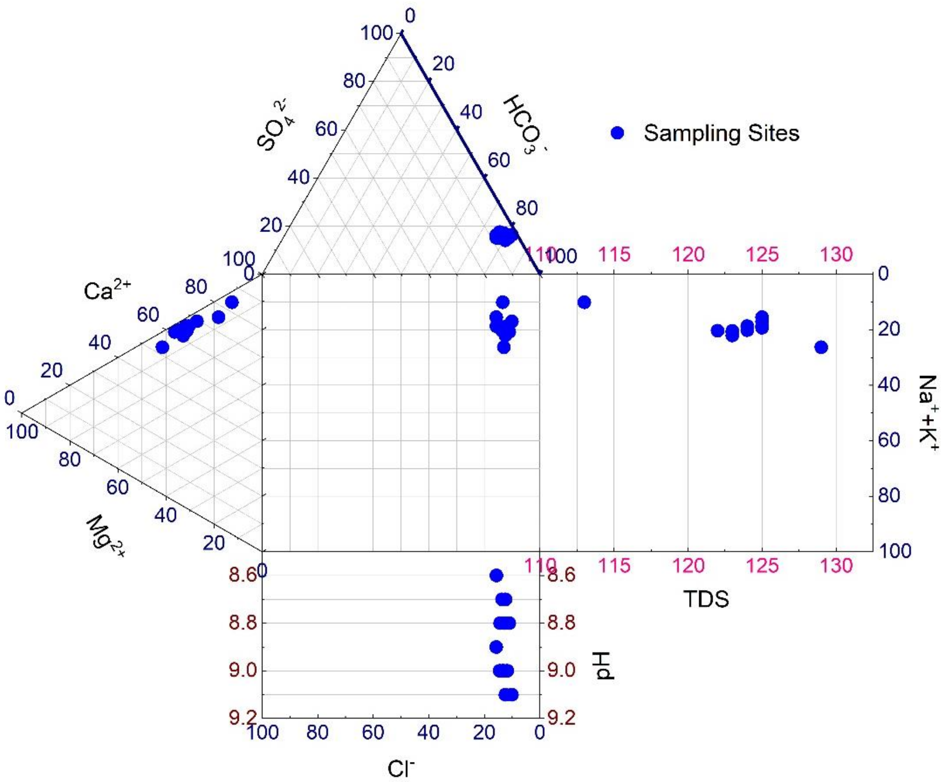

Figure 4. Durov diagram (Durov, 1948) showing hydrochemical facies of Phoksundo Lake

The mixing plot (Figure 6) indicates that most samples cluster near the carbonate end-member, suggesting that carbonate weathering is the dominant process in Phoksundo Lake. The Piper plot (Figure 3) shows a high concentration of calcium and magnesium, which likely indicates the prevalence of carbonate weathering in Phoksundo Lake.

The high presence of calcium and magnesium, as indicated in the Piper plot (Figure 3), may explain the carbonate weathering observed in Phoksundo Lake (Wu *et al*., 2024). The vibrant turquoise color of Phoksundo Lake may be attributed to its carbonate-dominant lithology, which enhances light scattering, along with suspended glacial flour produced by glacial weathering and erosion (Chutcharavan & Aciego, 2014). The presence of limestone, shale, and sandstone, which are the dominant rocks in Dolpa and Phoksundo Lake (Carosi *et al*., 2002), may contribute to the carbonate weathering observed in the lake. In Figure 6(a), the blue dots slightly exceed the carbonates region, indicating excess HCO_3^- likely from enhanced carbonate dissolution which may be due to elevated CO_2 level like biological activity and organic matter decomposition near the lake indicating the role of other geochemical processes beyond pure carbonate weathering.

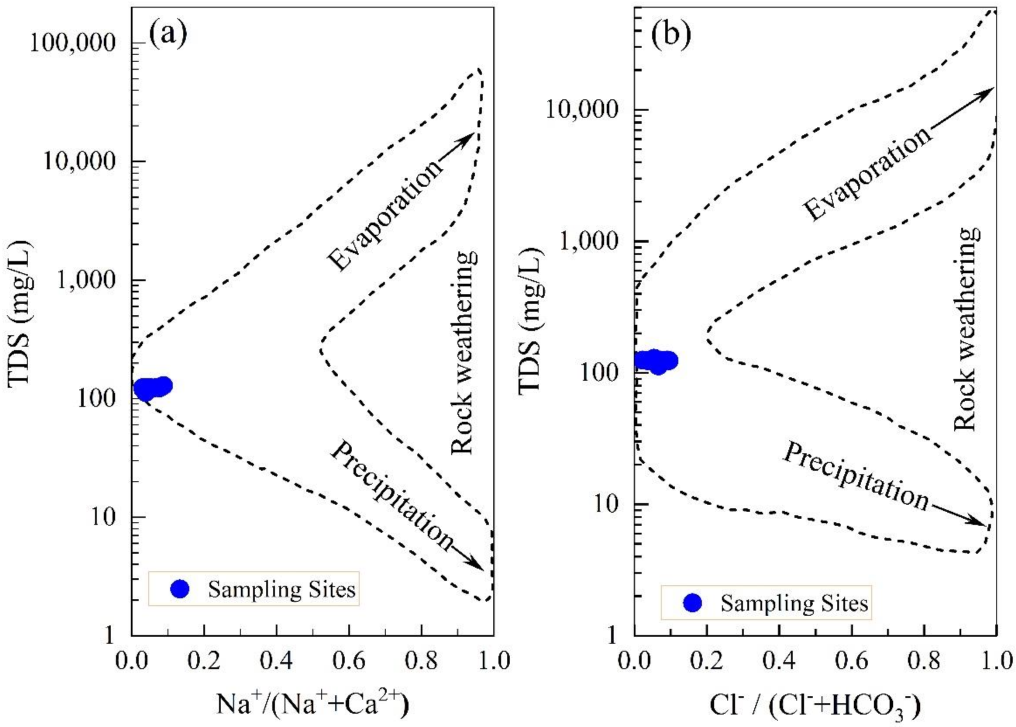

Figure 5. Gibbs's diagram showing ratio of (a) TDS versus $Na^+ + K^+$ / ($Na^+ + K^+ + Ca^{2+}$) and (b) TDS versus Cl^- / ($Cl^- + HCO_3^-$) (Gibbs, 1970)

Drinking and Irrigation Water Quality of Phoksundo Lake

The "weighted arithmetic water quality index" (WQI) has been applied to Phoksundo Lake to assess its suitability for drinking purposes (Table 3). The WQI is a method for assessing water quality that applied large datasets into a clear and concise format providing a clear and systematic representation of information (Banda & Kumarasamy, 2024). The WQI concept, introduced by Horton in 1965 (Horton, 1965), was later refined into the weighted arithmetic method by (Brown *et al.*, 1970) and has been widely studied to assess groundwater quality (Kachroud *et al.*, 2019).This index categorizes water quality into different ranges: 0-25 (excellent), 26–50 (good), 51-75 (poor), 76-100 (very poor), and greater than 100 (unsuitable for drinking). The standard permissible limits prescribed by (MPPW, 2005) are utilized to calculate the Water Quality Index (WQI) using the formula:

$$WQI = \sum (QnWn) / \sum Wn,$$

Where,

Qn = the water quality rating, calculated as $Qn = 100[(Vn - Vid) / (Sn - Vid)]$,

Vn = the observed concentration of each parameter,

Vid = the ideal value (assumed as zero, except for pH where it is 7), and

Sn = the standard permissible limit of each parameter.

Wi = the unit weight of each parameter, derived using $Wn = k / Sn$,

Where, k is the proportionality constant, calculated as $k = 1 / \sum (1 / Sn)$.

The WQI of Phoksundo Lake (Table 3) was found to be excellent quality for drinking water among the samples collected. This aligns with the Water Quality Index (WQI) findings from other high-altitude lakes in Nepal, including Ramaroshan lake complex (Pant *et al.*, 2022), Begnas and Rupa lakes (Pant *et al.*, 2019) ,Tawang lake of eastern Himalaya of India (Sharma *et al.*, 2024) and that of Tibetan pleateau (Jin *et al.*, 2023; Qu *et al.*, 2019).

Irrigation Water quality

The analytical results have been observed for drinking water and irrigation purposes (Table 4). To preserve soil fertility and enhance crop yield, it is essential to monitor water quality. Low-quality water may be suitable for irrigating sandy, permeable soils where chemicals can seep deeply, but it can have detrimental effects on heavy clay soils. Parameters such as Na %, KR, SAR, MH, PI, and EC are utilized to evaluate the suitability of water for irrigation purposes.

Sodium percent

The Na % is used in classifying water for irrigation purposes. Na^+ binds with soil, reducing water movement (Ayers & Westcot, 1985), it reacts with CO_3^{2-} to create alkaline soils and with chloride to form saline soils, both of which hinder crop growth (Todd, 1980). According to Nepal Water Quality Guidelines for Irrigation Water (DoI, 2008) , the maximum permissible limit for Na % is 60 %, behind which it can negatively affect plant growth. An elevated concentration of Na^+ enhances soil hardness, leading to a reduction in soil permeability (Tavakkoli *et al.*, 2010).

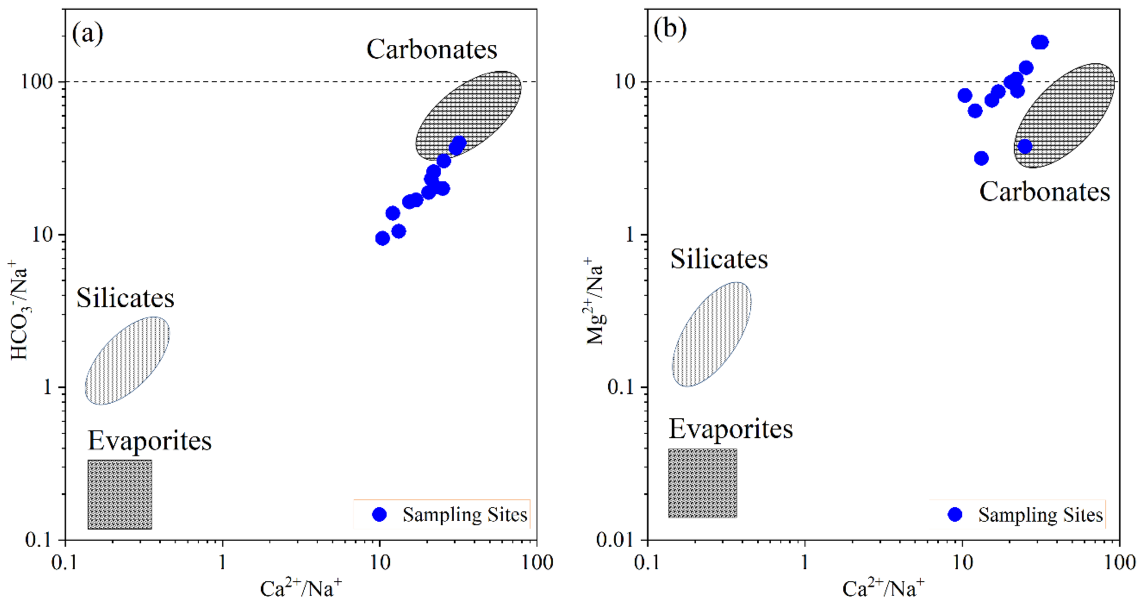

Figure 6. Mixing diagram of Na-normalized molar ratios of (a) Ca^{2+} vs HCO_3^- and (b) Ca^{2+} vs Mg^{2+} of Phoksundo Lake

Table 3. WQI calculation table of Phoksundo Lake, Dolpa

Para.	Sn	1/Sn	∑1/Sn	K= 1(∑1/Sn)	Wn = K/Sn	Vid	Vn	Qn	QnWn
pH	8.50	0.12	1.19	0.84	0.10	7.00	8.88	125.64	12.37
EC	1500.00	0.00	1.19	0.84	0.00	0.00	249.77	16.65	0.01
TDS	1000.00	0.00	1.19	0.84	0.00	0.00	123.46	12.35	0.01
Ca^{2+}	100.00	0.01	1.19	0.84	0.01	0.00	35.30	35.30	0.30
Mg^{2+}	50.00	0.02	1.19	0.84	0.02	0.00	9.75	19.50	0.33
K^+	100.00	0.01	1.19	0.84	0.01	0.00	0.53	0.53	0.00
Na^+	200.00	0.01	1.19	0.84	0.00	0.00	2.17	1.09	0.00
Cl^-	250.00	0.00	1.19	0.84	0.00	0.00	4.20	1.68	0.01
NO_3^-	50.00	0.02	1.19	0.84	0.02	0.00	3.22	6.45	0.11
SO_4^{2-}	200.00	0.01	1.19	0.84	0.00	0.00	16.94	8.47	0.04
HCO_3^-	600.00	0.00	1.19	0.84	0.00	0.00	108.44	18.07	0.03
PO_4^{2-}	1.00	1.00	1.19	0.84	0.84	0.00	0.05	4.62	3.87
					1.00	$WQI = \sum QnWn/Wn$			17.06

$$\textit{Sodium percentage (Na \%)} = \frac{(Na^+ + K^+)*100}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \text{ (Richards, 1954)}$$

The values of Na % in Phoksundo Lake (Table 4) are observed between 2.40 to 6.46 with an average value of 4.04. The Wilcox diagram (Figure 7), which plots Na % against EC, places the data in the "Excellent" category, indicating that Phoksundo Lake water is suitable for irrigation, consistent with the Sodium Adsorption Ratio evaluation.

Sodium Adsorption Ratio (SAR)

SAR indicates water salinity primarily increases due to alkali metals and sodium, which can be effectively assessed by analyzing the relative and absolute concentrations of various cations (Rengasamy *et al.*, 2022).

$$\textit{Sodium adsorption ratio (SAR)} = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \text{ (Richards, 1954)}$$

SAR values below 10 are classified as excellent, between 10 and 28 as moderate, and above 28 as harmful to crops.

At Phoksundo Lake, the SAR value is below 1 at all locations (Table 4), with an average of 0.084, which indicates excellent water quality for irrigation, as it suggests a minimal risk of sodium-related soil degradation or reduced permeability (Xie *et al.*, 2024)

Magnesium hazard

Magnesium hazard: Water with an MH value > 50 is found unsuitable for irrigation and detrimental to plant growth (Szabolcs & Darab, 1964).

$$\text{Magnesium hazard (MH)} = \frac{Mg^{2+} * 100}{(Ca^{2+} + Mg^{2+})} \text{ (Doneen, 1964)}$$

The water in Phoksundo Lake has indicated the value of MH (Table 4) in the range of 13.11-43.92 meq/l (avg. 31.41 meq/l) and considered as suitable for irrigation.

Permeability Index

The Permeability Index (PI) evaluates irrigation water suitability based on its impact on soil permeability, influenced by ions such as Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^-

$$\text{Permeability index (PI)} = \frac{(Na^+ + \sqrt{HCO_3^-}) * 100}{Ca^{2+} + Mg^{2+} + Na^+} \text{ (Doneen, 1964)}$$

According to (Doneen, 1964), the Permeability Index (PI) is divided into three classes: Class I (>75%, suitable), Class II (25-75%, good), and Class III (<25%, unsuitable), with Classes I and II recommended for irrigation. The PI of Phoksundo Lake was found to be in class I category, suitable for irrigation purposes (Table 4).

Kelly Ratio

Kelly Ratio (Kelly,1940) and (Paliwal, 1967) proposed a method for evaluating and classifying irrigation water quality by analyzing the ratio of Na^+ to Ca^{2+} and Mg^{2+} concentrations.

$$\text{Kelly's ratio (KR)} = \frac{Na^+}{(Ca^{2+} + Mg^{2+})} \text{ (Kelley, 1940)}$$

A Kelly Ratio (KR) greater than 1 signifies excessive Na^+ levels in water. Consequently, water with a KR $\leq$ 1 is considered suitable for irrigation, while KR $\geq$ 1 is discouraged due to the risk of alkali hazards (Ramesh & Elango, 2012). The water in the Phoksundo Lake is found in the KR range of 0.02-0.06 meq/l and therefore declared suitable for irrigation (Table 4).

Electrical Conductivity

The electrical conductivity of irrigation water is a key indicator of its quality. Elevated conductivity in water indicates a high concentration of dissolved salts, which may disrupt the uptake of essential nutrients like nitrogen, phosphorus, and potassium (Alves *et al.*, 2018). The average electrical conductivity of Phoksundo Lake was measured to be 250 µS/cm, which indicates low ionic concentration and pristine water quality (Table 4).

Table 4. Irrigation Suitabilty evaluation of Phoksundo Lake

Parameters	Average Value	Category
Na %	4.04	Excellent
SAR (meq/L)	0.08358	Excellent
MH (meq/L)	31.4104	Suitable
PI (%)	399.836	Class I
KR (meq/L)	0.03698	Safe
EC (µS/cm)	250	Excellent

The parameters including EC, SAR, Na%, KR, PI, and MH indicate that the water in Phoksundo Lake is suitable for irrigation (Table 4). Studies on other highland lakes (Bhatta *et al.*, 2022; Jin *et al.*, 2023; Pant *et al.* 2022; Sharma *et al.*; 2024) possess similar carbonates weathering in Hindu Kush Himalayas and shows nearly similar suitability as that of Phoksundo Lake.

The below Wilcox diagram (Wilcox, 1948) shows the suitability for irrigational purpose of Phoksundo lake. The majority of samples fall under fresh classification (Table 5) while some are found to be slightly saline (Wilcox, 1948). This result indicates the increase in pH level (Figure 5) of some samples of lake, due to high carbonate weathering (Figure 6) of sedimentary rocks (Al-Khashman *et al.*, 2017).

Similar results obtained from the previous research studies of same altitude lakes such as Ramaroshan lake complex (Thapa *et al*., 2024), Rara and Ghodagohdi lakes (Bhatta *et al*., 2024), Begnas and Rupa lakes (Pant *et al*., 2019), and Phewa lake from Nepal (Gautam & Shrestha, 2024), whose water quality class falling in fresh classification (Wilcox, 1948).

Table 5. Wilcox Classification (Wilcox, 1948) of Water Quality for Irrigation in Phoksundo Lake

Group	Wilcox Classification	Water Quality for Agriculture
C1S1	Fresh	Completely safe for agricultural use
C1S2, C2S2, C2S1	Slightly saline	Generally suitable for agricultural use
C1S3, C2S3, C3S1, C3S2, C3S3	Moderately saline	Usable for agriculture with some caution
C4S4, C4S1, C1S4, C2S4, C3S4, C4S4, C4S3	Highly saline and harmful	Very detrimental to agricultural activities

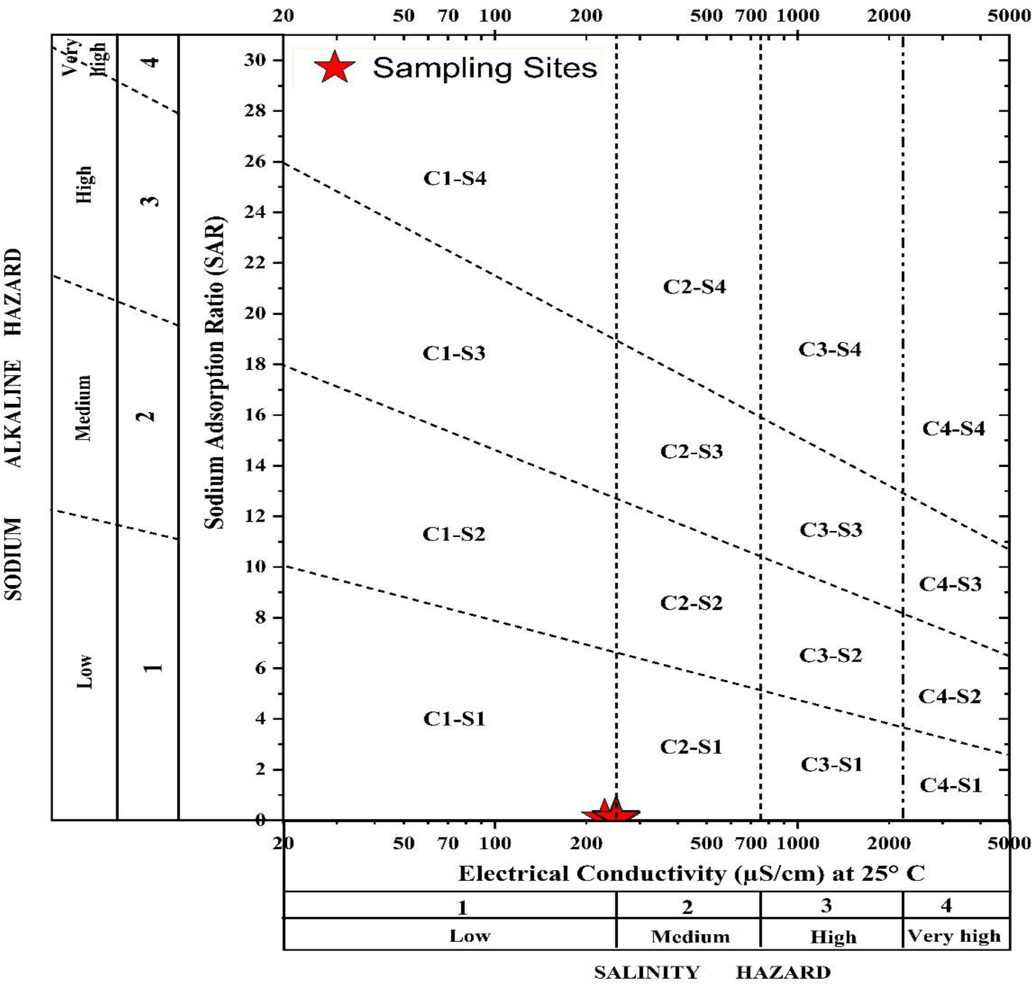

Figure 7. Wilcox diagram (Wilcox, 1948) showing the irrigation suitability of Phoksundo Lake

Major ions Comparison to other lakes of Himalayan region

The major ions concentration of freshwater lakes in the Himalayan region are compared with different lakes (Table 4). Present study (pre-monsoon) has high concentrations of calcium (35.30 mg/L), magnesium (9.75 mg/L), bicarbonate (108.44 mg/L), and sulfate (16.94 mg/L). Rupa Lake has moderate nitrate concentration (2.46 mg/L) but has highest chloride (16.52 mg/L) ion (Pant *et al*., 2019). Begnas Lake has moderate calcium (17.5 mg/L), sulfate (9.77 mg/L), and bicarbonate (40.4 mg/L), nitrate (3.36 mg/L) and chloride (2.77 mg/L) levels are comparable to other lakes (Khadka & Ramanathan, 2013). Beeshazari Lake has nitrate (2.19 mg/L) and chloride (12.78 mg/L) concentrations recorded (Pant *et al*., 2021). Ghodaghodi

Lake shows a unique ionic composition with moderate bicarbonate (81.48 mg/L) and relatively low sulfate (0.045 mg/L) and chloride (0.38 mg/L) levels (Bhatta *et al*., 2022). Gokyo Lake stands its exceptionally high sulfate concentration (207.2 mg/L), while calcium (3.25 mg/L) and magnesium (0.64 mg/L) ions (Bhandari *et al*., 2015). Jagadishpur Lake features balanced concentrations of calcium (10.73 mg/L), magnesium (5.2 mg/L), and bicarbonate (100 mg/L), with a higher ammonium concentration (2.44 mg/L) (Sapkota *et al*., 2021). Koshi Tappu Wetland exhibits moderate levels of calcium (15.46 mg/L), magnesium (5.95 mg/L), and bicarbonate (49.98 mg/L) (Neupane *et al*., 2023). Mai Pokhari shows a significant phosphate level (1.88 mg/L) (Pradhan & Shah, 2021). Rajarani Lake presents low calcium (5.56 mg/L) and magnesium (1.96 mg/L) but a relatively high chloride concentration (11.64 mg/L) (Adhikari *et al*., 2020). Ramaroshan Lake shows modest calcium (12.02 mg/L) and bicarbonate (61.58 mg/L) levels, alongside low ammonium (0.13 mg/L) and phosphate (0.16 mg/L) concentrations (Thapa *et al*., 2024). Tilicho Lake features significant calcium (20.7 mg/L) and low sodium (0.86 mg/L) content (Aizaki *et al*., 1987), while Renuka Lake has the highest calcium (57.74 mg/L) and magnesium (38.3 mg/L) levels among the studied lakes, with high bicarbonate (146.42 mg/L) and phosphate (6.4 mg/L) (Das & Kaur, 2001), which gives the indication the weathering of carbonate dominance rocks (Bhatta *et al*., 2022; Das & Kaur, 2001; Tripathee *et al*., 2014; Tsering *et al*., 2019). Lastly, Pandoh lake have highest nitrate concentration (10.33 mg/L) (Anshumali & Ramanathan, 2007), due to sample which was taken in summer which is influenced by mineralization of N containing compounds (Håkanson, 1984; Anshumali & Ramanathan, 2007) among all other lakes and moderate levels of bicarbonate (49.17 mg/L), calcium (17.96 mg/L), and magnesium (3.31 mg/L). The average anionic concentration (mg/L) of the present study following the pattern of dominance is HCO_3^-> Ca^{2+}> Mg^{2+}, which is comparable to many other lakes of Himalayan freshwater ecosystem (Bhatta *et al*., 2022).

Table 6. Major ions concentration from some Himalayan freshwater lakes

Lakes	Ca^{2+}	Mg^{2+}	K^+	Na^+	NO_3^-	Cl^-	SO_4^{2-}	HCO_3^-	PO_4^{3-}	NH_4^+
Phoksundo[1]	35.30	9.75	0.53	2.17	3.22	4.20	16.94	108.44	0.05	0,05
Rupa[2]	-	-	-	-	2.46	16.52	-	-	0.15	0.17
Begnas[3]	17.5	2.17	1.2	3.08	3.36	2.77	9.77	40.4	0.16	-
Beeshazari[4]	-	-	-	-	2.19	12.78	-		0.42	0.07
Ghodaghodi[5]	21.48	2.78	2.76	3.52	0.15	0.38	0.045	81.48		0.255
Gokyo[6]	3.25	0.64	-	-	-	-	207.2	-	-	-
Jagadishpur[7]	10.73	5.2	2.92	8.53	0.99	10.89		100	0.2	2.44
Koshi Tappu[8]	15.46	5.95	3.15	8.55	0.33	9.33	9.79	49.98	0.11	0.33
Mai Pokhari[9]	-	-	-	-	1.39	-	-	-	1.88	0.99
Rajarani[10]	5.56	1.96	2.67	8.09	0.06	11.64	-	32.75	0.25	0.37
Ramaroshan[11]	12.02	3.51	1.67	5.89	0.44	4.41	0.48	61.58	0.16	0.13
Tilicho[12]	20.7	5.75	0.31	0.86	-	1.8	8.6	-	-	-
Renuka[13]	57.74	38.3	2.02	8.33	-	11.92	6.41	146.42	6.4	-
Pandoh[14]	17.96	3.31	2.06	3.82	10.33	2.37	2.74	49.17	1.28	-

Superscript: [1]:Present study (Pre-monsoon), [2*]: Pant *et al.* (2019), [3] : Khadka & Ramanathan (2013), [4] : Pant *et al.* (2021), [5] : Bhatta *et al.* (2022), [6] : Bhandari *et al.* (2015), [7] : Sapkota *et al.* (2021), [8] : Neupane *et al.* (2023), [9] : Pradhan & Shah (2021), [10] : Adhikari *et al.* (2020), [11] : Thapa *et al.* (2024), [12] : Aizaki *et al.* (1987), [13] : Das & Kaur (2001), [14] : Anshumali & Ramanathan (2007).

To preserve the ecological and cultural integrity of Phoksundo Lake in Dolpa, Nepal, a comprehensive and collaborative approach is essential. Rising tourism and water scarcity demand eco-friendly regulations, effective waste and sanitation systems, and erosion control. Community engagement, especially in Rigmo village, is key, with education and participatory monitoring fostering stewardship. Scientific efforts should include year-round water quality assessments, track microbial pathogens and studying climate impacts using low-cost sensors. Conservation plans must honor the region's rich heritage, including the thousand-year-old Tibetan traditions and the Pal Shenten Gonpa monastery. Sustainable tourism, environmental research, and coordinated action among local stakeholders, scientists, and authorities will ensure long-term protection of this ecologically, economically and aesthetically important Ramsar-listed Himalayan lake.

CONCLUSIONS

This study provides the first comprehensive hydro chemical assessment of Phoksundo Lake, a Ramsar site of critical importance in the Nepal Himalayas. The lake water of the lake is distinctly of the Ca-HCO_3 type, resulting directly from the predominant weathering of carbonate rocks in the watershed, which also makes the water inherently alkaline (mean pH 8.88), surpassing conventional drinking water regulations. This geological control is reflected in the ionic dominance order of $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$ and $HCO_3^{-} > SO_4^{2-} > Cl^{-} > PO_4^{3-}$. Based on its chemical composition, the water is excellent for irrigation and suitable for domestic use by the local Rigmo community. This work reveals a significant paradox: whereas the lake inorganic chemistry indicates a pristine, rock-dominated ecosystem with negligible contamination, the presence of fecal coliforms suggests increasing anthropogenic influences. These findings highlight how vulnerable this high-altitude habitat is. Even though the lake is still close to its natural state, immediate and proactive management measures are necessary to reduce the effects of its present state and avoid further deterioration.

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AUTHOR CONTRIBUTIONS

Manyal, D., and Pant R.P.: Study conception and design. Manyal, D., Gaire N.P., Dhakal, Y.B.: Data collection, Bhattarai, C., Manyal, D.: Analysis and interpretation of results, draft manuscript preparation. Manyal, D., Bhattarai, C., Paudel, B.K.: Laboratory analysis. Pant, R.P., Awasthi, M.P., Bohora, R., Paudel, B.K., Rawal, S.: Writing- review and co-wrote the paper; Pant, R.P., Awasthi, M.P., Bohora, R., Rawal, S.: Writing-review and co-wrote the paper. All authors reviewed the results and approved the final version of the manuscript.

CONFLICT OF INTERESTS

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the author, upon reasonable request.

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