

# Hydrochemical Assessment and Water Quality Evaluation of Syarpu Lake, Nepal: Implications for Sustainable Management

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**Abstract**—Wetlands are vital ecosystems that provide essential services, including water purification, biodiversity preservation, and climate regulation. However, these ecosystems are under increasing threats from pollution, climate change, and anthropogenic activities. Syarpu Lake, located in Rukum district, Karnali Province, Nepal is an important freshwater resource facing similar pressures, yet its hydrochemical properties and pollution dynamics remain insufficiently studied. This research aims to bridge the knowledge gaps by conducting a comprehensive assessment of the lake's water quality, hydrochemistry, and trophic patterns to inform sustainable management practices. Bathymetric mapping revealed a maximum depth of 6.5 m and an average depth of 3.59 m, indicating significant sediment accumulation and reduced catchment area due to human activities and natural processes. Hydrochemical analysis identified calcium (35.06 mg/L) and bicarbonate (87.15 mg/L) as the dominant ions, with rock weathering emerging as the primary source of ion contributions based on Piper and Gibbs plots. The Carlson Trophic State Index (CTSI) classified the lake as eutrophic, with a mean value of 69.86, highlighting a concerning trend toward anoxic conditions due to nutrient enrichment. Despite moderate pollution levels, the lake's water was deemed suitable for irrigation, supported by sodium adsorption ratio (SAR < 2.25) and permeability index (PI: 23.92–38.05). These findings align with Sustainable Development Goals (SDGs) 6 (clean water and sanitation) and 15 (life on land), emphasizing the need for targeted conservation measures, such as sedimentation control, eco-friendly tourism management, and sustainable land-use practices, to protect Syarpu Lake's ecological health and ensure its long-term viability as a vital freshwater resource in the Himalayas.

**Keywords**—Wetlands, Bathymetry, pollution, eutrophication, Syarpu Lake, sustainable development goals

## I. INTRODUCTION

Wetlands are ecologically critical systems that support a range of functions including water purification, groundwater recharge, sediment retention, and habitat provision for diverse biota [1]. However, wetland ecosystems worldwide, including many in South Asia, are increasingly impacted by anthropogenic pressures such as agricultural runoff, urban encroachment, and unregulated land-use practices, which drive sedimentation and nutrient enrichment including the

impacts of global climate change [2]. These stressors reduce water quality, trigger eutrophication, and impair the ecological integrity and utility of freshwater lakes [3]. International frameworks such as the Ramsar Convention and Sustainable Development Goals (SDGs) highlight the need for improved freshwater monitoring and adaptive management strategies [4]. Realizing these goals in practice depends on the availability of site-specific, scientifically validated assessments that can inform effective lake and watershed-level interventions [5]. In this context, integrated studies that combine hydrochemical analysis, bathymetric mapping, and water use assessment are essential tools for evaluating the ecological condition of vulnerable freshwater systems such as high-altitude lakes in Nepal [6].

Chemical assessments and water quality evaluations are essential for comprehending the health of freshwater ecosystems, particularly regarding nutrient loading, pollution levels, and overall ecosystem stability [7]. Hydrochemical evaluations and particular water quality metrics should be applied to analyze the status of any wetland, encompassing measurements of Total Dissolved Solids (TDS), Electrical Conductivity (EC), Potential of Hydrogen (pH), Water Temperature (Temp), Dissolved Oxygen (DO), and various ion concentrations [8]. Besides, water quality indicators, including the Piper plot, and the Trophic State Index (TSI), offer insights into a lake's biological productivity and pollution sources, which are crucial for sustainable lake management [9]. Previous hydrochemical research indicated the importance of these water quality evaluations to study the status of rock weathering, and anthropogenic nutrient influx [1]. These pollution patterns can affect the lake's chemistry and trophic state, causing potential risks to aquatic health [3].

Nepal encompasses a wide variety of freshwater ecosystems, including high-altitude lakes that are ecologically and socio-economically important for supporting agriculture, local drinking water supply, biodiversity, and overall ecosystem balance [10]. Prior hydrochemical studies on Nepalese lakes such as Rara, Beeshazari, and Taudaha have shown considerable variability in water quality, shaped by both natural processes like rock

weathering and evaporation, and anthropogenic drivers such as agricultural runoff, tourism, and rapid land-use change [11]. These lakes, situated within climatically sensitive and geologically diverse regions, are particularly vulnerable to environmental stressors, including sedimentation, nutrient accumulation, and eutrophication, which can lead to the degradation of aquatic habitats and loss of biodiversity [12].

In contrast to these better-studied lakes, Syarpu Lake, a mid-hill freshwater body located in the Rukum District of western Nepal, remains notably underrepresented in hydro-environmental research [2]. Although the lake is exposed to similar pressures, including increasing agricultural activity in the watershed, informal tourism development, and localized sediment influx from upstream construction, no published research has conducted a combined hydrochemical and bathymetric assessment to quantify its ecological condition [13]. Moreover, the absence of data regarding its physical depth profile, pollutant dispersion patterns, and irrigation suitability limits the capacity for informed management. This gap is particularly concerning given the lake's growing importance as a water source and the potential for escalating eutrophication [6]. Therefore, a comprehensive, site-specific investigation is required to establish baseline water quality, understand pollutant pathways, and inform conservation and land-use planning tailored to this unique lake system [14].

Hence, this study presents the first integrated hydrochemical and bathymetric assessment of Syarpu Lake, aimed at characterizing spatial variations in water quality, identifying potential pollutant sources, and generating baseline data to support lake-specific monitoring and resource management. To effectively address these challenges, the study applies a combination of hydrochemical profiling, spatially distributed bathymetric mapping using Kriging interpolation, and irrigation suitability evaluation. These methods were selected for their ability to capture depth-related sediment dynamics, chemical variability, and practical water use potential in small, sensitive lake systems in the ecologically sensitive Himalayas. By addressing significant spatial and temporal data gaps, this research creates a foundational database on Syarpu Lake to inform sustainable management practices. Through this integrated methodological framework, the study establishes a scientific baseline for understanding the environmental status of Syarpu Lake and informs site-specific management and monitoring strategies relevant to SDGs. The approach and methodology used in this study may also be adapted to assess other freshwater lake systems facing similar pollution pressures, particularly in data-scarce, climate-sensitive highland regions. By providing a replicate model for integrated hydrochemical and bathymetric assessment, this work supports improved environmental monitoring and resource management of comparable inland water bodies.

## II. MATERIALS AND METHODS

### A. Study Area

Rukum District, located in the hilly part of Karnali Province, Nepal, encompasses an area of 2,877 km<sup>2</sup> and features an elevation range from 754 m to 6,072 m (Fig. 1) [14]. The district's annual temperature is 24.14 °C, which is 2.14% over the average temperature of Nepal, and it receives

186.87 mm of precipitation each year. The region exhibits a humid subtropical climate, characterized by cold winters and comparatively warm summers, with potential snowfall in the elevated areas. Syarpu lake, one of Rukum's greatest lakes, is situated in Banfikot Rural Municipality, namely between wards 3 and 5, at an elevation of 1300 m, with latitude of 28°41'49"N and longitude of 82°28'33"E. The lake is located 35 km from Musikot Airport and encompasses an area of 0.67 km<sup>2</sup>. Besides, the Bheri River receives discharge from Syarpu Lake, reflecting the main role of the lake in recharging the catchment area. The seasonal rainfall, the rivulets that are located nearby, and groundwater are the principal sources of water for Syarpu Lake. There is a natural forest that covers the eastern side of the lake, and the substrate is mostly composed of bedrock, with just a small amount of soil present in the benthic zone. In contrast, the major inlet of the lake in the northern part consists of muddy soil, likely due to frequent sediment deposition from upstream erosion and land-use change [2]. Local reports and preliminary field observations suggest that this process may be contributing to the gradual shrinkage of the lake's surface area, although quantitative data on sedimentation rates are currently lacking [6]. The lake's surroundings consist of forests, agricultural fields, and settlements.

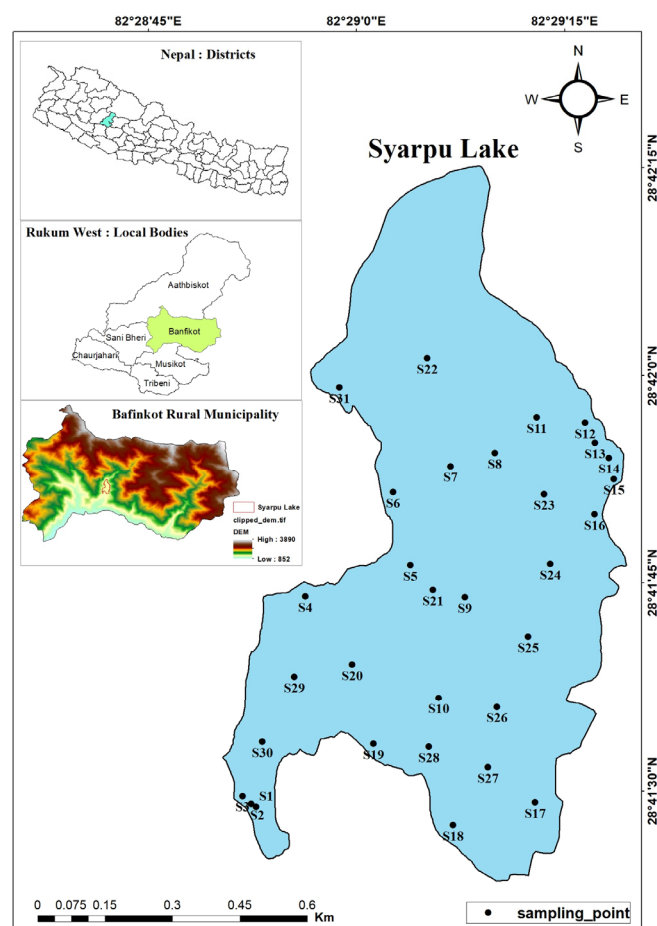


Fig. 1. Study area location in the Syarpu Lake, including the sampling points.

### B. Sampling Description

#### 1) Bathymetry

The sampling was conducted in April 2022 utilizing the line transect approach with an echosounder (depth

measurement instrument) and GPS coordinates (Garmin Venture SC) at each sampling location (S1-S31), as illustrated in Fig. 1. The scale was utilized to ascertain the lake's depth beneath 2 m, as the echosounder is incapable of measuring depths below this threshold. The lake's depth was assessed at 132 specific sites, resulting in the creation of a bathymetric map with ArcGIS 10.8 [1].

## 2) Hydrochemistry

Hydrochemical analysis samples were compiled representatively from the inlet, middle, outlet, nearby agricultural land, sediment deposition area, and fish trap area of the lake. Samples were obtained from 31 distinct locations using a 1-liter high-density polyethylene bottle (HDPE), which was thoroughly rinsed with the same water before collection. The gathered samples were appropriately labeled and stored at 4°C in insulated coolers immediately after collection to minimize biological activity and maintain chemical stability. Samples were kept at this temperature for no more than 48 hours before laboratory analysis. This protocol is suitable for preserving nutrients and major ions and follows established recommendations for short-term hydrochemical sample preservation [3].

Onsite measurements of TDS, EC, pH, Temp, and DO were conducted using a YSI Professional Plus multiparameter instrument (Pro Quatro, YSI, USA). Turbidity (TU) was measured in-situ with an Oakton TN-100 turbidity meter. Field analyses of Total Alkalinity (TA), Chloride (Cl<sup>-</sup>), free Carbon Dioxide (CO<sub>2</sub>), Magnesium Hardness (MgH), Calcium Hardness (CaH), and Total Hardness (TH) were carried out using standard procedures recommended by APHA [8]. In the laboratory at the Central Department of Environmental Science, additional hydrochemical parameters, including iron (Fe<sup>3+</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), sulphate (SO<sub>4</sub><sup>2-</sup>), phosphate (PO<sub>4</sub><sup>3-</sup>), bicarbonate (HCO<sub>3</sub><sup>-</sup>), calcium (Ca<sup>2+</sup>), potassium (K<sup>+</sup>), sodium (Na<sup>+</sup>), magnesium (Mg<sup>2+</sup>), and ammonium (NH<sub>4</sub><sup>+</sup>) were analyzed using a Hach DR 6000 UV-Vis spectrophotometer following standard methods [1].

All instruments were calibrated before use according to the manufacturers' guidelines to ensure measurement accuracy and match Quality Control/Quality Assurance (QA/QC) procedures. Certified standard solutions traceable to NIST (National Institute of Standards and Technology) were used for instrument calibration to ensure traceability and accuracy. Calibration curves with determination coefficients ( $R^2 > 0.99$ ) were established for laboratory analyses. Instruments were recalibrated routinely during sampling and analytical sessions. In addition to triplicate measurements, 10% of the total samples were reanalyzed to assess reproducibility. Reagent blanks and control samples were also included in every analytical batch to detect any contamination or instrument drift. These quality control measures ensured precision and consistency throughout the analysis [3]. To assess the analytical precision of key hydrochemical parameters, the Coefficient of Variation (CV) was computed. The CV values for selected parameters were as follows: NO<sub>3</sub><sup>-</sup> (9.09%) and PO<sub>4</sub><sup>3-</sup> (12.00%). All values fall within the commonly accepted threshold of < 20% for environmental water quality studies [15]. Accordingly, this trend can confirm the satisfactory precision and consistency of the measurements obtained in this study [16].

## 3) Assessment of the water quality for irrigation purposes

The irrigation water quality was assessed by analyzing particular physio-chemical parameters such as K<sup>+</sup>, Na<sup>+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, and HCO<sub>3</sub><sup>-</sup>. Besides, the irrigation appropriateness of water was assessed by determining the EC, sodium percentage (% Na), sodium adsorption ratio (SAR), cation ratio of soil structural stability (CROSS), magnesium adsorption ratio (MAR), Kelly's ratio (KR), and permeability index (PI), as illustrated in Table 1.

The EC value was categorized into three classes: EC < 700 µS/cm was deemed excellent, 700-3000 µS/cm was defined as good, and > 3000 µS/cm was considered fair quality for irrigation, as shown in other studies [17]. Water was categorized into five classes based on % Na: > 80% as inappropriate, 60-80% as dubious, 40-60% as allowed, 20-40% as good, and < 20% as excellent for irrigation. SAR and CROSS values categorized water quality into four distinct classes: > 26 as low, 18-26 as fair, 10-18 as good, and < 10 as excellent quality. The MAR categorized water into two classifications: MAR > 50 as unsuitable, and MAR < 50 as appropriate [17]. KR classified water as safe for values < 1 and unsafe for values > 1 [18]. The PI categorized water into three classes: class III for values < 25, class II for values between 25 and 75 and class I for values > 75 [19].

Table 1. Details of indices applied for assessing the irrigation water quality

| Water quality index                       | Abbreviation | Equation                                                                 | Reference |
|-------------------------------------------|--------------|--------------------------------------------------------------------------|-----------|
| Sodium percentage                         | %Na          | $\frac{(K^+ + Na^+) * 100}{K^+ + Na^+ + Mg^{2+} + Ca^{2+}}$              | [20]      |
| Sodium adsorption ratio                   | SAR          | $\frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$                              | [20]      |
| Cation Ratio of Soil Structural Stability | CROSS        | $\frac{(0.56K^+ + Na^+)}{\sqrt{(Ca^{2+} + 0.6 Mg^{2+})/2}}$              | [20]      |
| Magnesium adsorption ratio                | MAR          | $\frac{Mg^{2+} * 100}{Mg^{2+} + Ca^{2+}}$                                | [20]      |
| Kelly's ratio                             | KR           | $\frac{Na^+}{Mg^{2+} + Ca^{2+}}$                                         | [18]      |
| Permeability index                        | PI           | $\frac{(\sqrt{HCO_3^-} + Na^+) * 100}{(K^+ + Na^+ + Mg^{2+} + Ca^{2+})}$ | [19]      |

## 4) Trophic status

The Secchi depth was assessed using a 20 cm diameter Secchi disc prior to the collection of water samples. The disk was methodically immersed in the water until it became invisible, at which juncture the corresponding depth was recorded. The disk was descended by several centimeters and subsequently elevated until it resurfaced, at which juncture the second depth measurement was documented. The ultimate visible depth of the Secchi disc was established by averaging these two measurements. Besides, total phosphorus was quantified using the digestion method in accordance with APHA [8] recommendations. Additionally, Chlorophyll-a was quantified using the Trichromatic method.

## C. Analysis of Data

### 1) Bathymetry

ArcMap was utilized to process the field data, and the Kriging technique was employed to produce the bathymetry

map of the lake, as reported elsewhere [21]. Kriging interpolation was selected over other techniques such as inverse distance weighting (IDW) and spline interpolation because it accounts for spatial autocorrelation in the depth data, producing more accurate and statistically optimal estimates of lake bathymetry. This is particularly important for shallow lakes like Syarpu, where accurate depth variation modeling informs sedimentation and ecological analyses [3].

### 2) Hydrochemical analysis

Descriptive statistics were used for summarizing and explaining significant aspects of data on water quality, identifying patterns and trends in water quality data, and enhancing management strategies [22]. In addition, hierarchical agglomerative clustering was conducted to categorize normalized datasets utilizing Ward's approach and Squared Euclidean distance as a similarity metric [23].

### 3) Hydrochemical characterization

The Piper plot was used for analyzing the chemical composition and identifying patterns and processes of the lake water because it effectively classifies hydrochemical facies based on the relative abundance of major cations and anions [24]. This graphical method can offer clearer differentiation of water types than alternatives such as Stiff or Durov diagrams, making it particularly suitable for comparative environmental analysis. The Gibbs diagram was employed to identify the dominant geochemical processes controlling water chemistry, such as atmospheric precipitation, rock weathering, and/or evaporation–crystallization. Its strength lies in distinguishing source mechanisms based on TDS and ionic ratios, which can provide essential context for understanding solute origins in lake systems [25]. Additionally, a mixing diagram was developed to assess the contribution of silicate and carbonate weathering to the lake's ionic composition. This method is well-suited for distinguishing between geogenic inputs, particularly in lakes located within mixed geological formations, and it helps quantify the influence of rock–water interactions on major ion chemistry [1].

### 4) Assessment of the Carlson Trophic State Index (CTSI)

The Carlson TSI (CTSI) is the most popular method for calculating the trophic status of a lake [9]. The CTSI was chosen because it is a widely accepted and robust method for assessing the trophic status of freshwater lakes, integrating multiple parameters (Depth, phosphorus, and chlorophyll-a) to provide a comprehensive evaluation of productivity. However, it has limitations, particularly in shallow lakes like Syarpu Lake, where sediment resuspension can influence depth and phosphorus levels, potentially leading to overestimation of trophic status [26]. It can be estimated by applying Eqs. (1–4) as follows:

$$CTSI = \frac{TSI_{phc} + TSI_{sd} + TSI_{chl}}{3} \quad (1)$$

$$TSI_{phc} = 14.42 \times \ln(PH) + 4.15 \quad (2)$$

$$TSI_{sd} = -14.41 \times \ln(SD) + 60 \quad (3)$$

$$TSI_{chl} = 30.6 + 9.81 \times \ln(CHL) \quad (4)$$

where,  $TSI_{phc}$  = TSI of phosphorous,  $TSI_{sd}$  = TSI of Secchi depth,  $TSI_{chl}$  = TSI of Chlorophyll-a, SD = Secchi depth in m,

PHC = phosphorous concentration in  $\mu\text{g/L}$ , and CHL = Chlorophyll-a concentration in  $\mu\text{g/L}$ .

Any lake can be given a trophic state, e.g., eutrophic (highly productive), mesotrophic (moderately productive), and oligotrophic (low productive), according to the TSI values (Table 2), and the details provided by Sharma *et al.* [27].

Table 2. Carlson trophic state along with its characteristics associated with TSI values

| TSI value | Trophic Status  | Characteristics                                                                                        |
|-----------|-----------------|--------------------------------------------------------------------------------------------------------|
| > 80      | Hyper-eutrophic | Algal bloom, seasonal ichthyoid events, limited macrophyte presence.                                   |
| 70–80     | Hyper-eutrophic | Intense algal blooms are likely during the summer, frequently exhibiting hypereutrophic conditions.    |
| 60–70     | Eutrophic       | Prevalence of cyanobacteria, likely algal blooms, significant macrophyte issues.                       |
| 50–60     | Eutrophic       | Minimal threshold for classical eutrophy: Diminished transparency, unique to fisheries in warm waters. |
| 40–50     | Mesotrophic     | Water clarity is modest, although the likelihood of anoxia is rising over the summer months.           |
| 30–40     | Oligotrophic    | Ecosystem of a lake may stay oligotrophic, but some smaller lakes may lose oxygen in the summer.       |
| < 30      | Oligotrophic    | Water is clear, and oxygen is always in the hypolimnion                                                |

## III. RESULTS AND DISCUSSION

### A. Syarpu Lake's Bathymetry

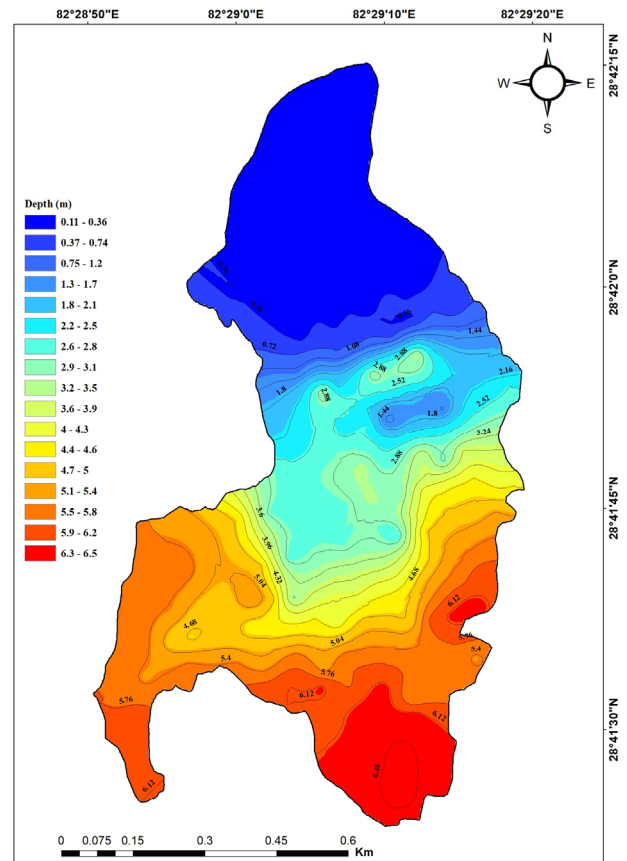


Fig. 2. Bathymetry map of Syarpu Lake.

The bathymetric map of Syarpu Lake displayed the arrangement and variety in water depth, varying from a

minimum of 0.2 m to a high of 6.5 m (Fig. 2). The total area of the lake's surface was estimated as 0.67 km<sup>2</sup> and the average depth was  $3.59 \pm 1.95$  m. The research investigation was done in the pre-monsoon period (April 2022), which might account for the reduced depth observed [28]. Another factor affecting the lake depth might be the annual sedimentation and the deposition of soil during the construction of rural roads. According to the locals, the lake depth attains up to 32 m during monsoon season, and sediments and stones are deposited which were carried out by the floods during the time. The lake began to dry over the winter and by the end of this season, more than half part of the lake entirely dried. To increase internal tourism, the local committee has constructed a ring road around the periphery of the lake [2]. However, the construction was carried out haphazardly without considering the environmental factors. The sand, stones, and mud fell into the lake contributing to the sedimentation of the lake [6].

### B. Spatial Distribution of Hydrochemistry

Table 3 presents the statistical descriptions of the physicochemical characteristics of Syarpu Lake. The anions and cations in the lake exhibit a distinct hierarchy:  $\text{PO}_4^{3-} < \text{NO}_3^- < \text{SO}_4^{2-} < \text{Cl}^- < \text{HCO}_3^-$  for anions, and  $\text{NH}_4^+ < \text{Fe}^{3+} < \text{K}^+ < \text{Na}^+ < \text{Mg}^{2+} < \text{Ca}^{2+}$  for cations, respectively in the lake. The lake's Temp fluctuated from 17.2° C to 24.3° C, averaging  $22.15 \pm 1.44$  °C. The Temp change might be attributed to the increase in air temperature from morning to afternoon throughout the sample period [29]. The Temp aligned with that of Beeshazari and associated lakes, indicating that Syarpu Lake's water was conducive to the chemical and biological activity of organisms [30].

pH measures the concentration of hydrogen ions in water, indicating its level of acidity or alkalinity [31]. In both lentic and lotic aquatic systems, pH is crucial in influencing chemical speciation and biotic communities. Organic and inorganic compounds as well as the interaction with CO<sub>2</sub> influence the pH level of water. Elevated pH levels facilitate the precipitation of ions and can influence the equilibrium among CO<sub>2</sub>, and HCO<sub>3</sub><sup>-</sup> in aquatic environments. The average pH level of Syarpu Lake's water can be considered somewhat alkaline, suggesting a carbonate-dominated underlying lithology [32].

The obtained EC and TDS of water indicated inorganic contamination levels, and ionized species. Typically, elevated EC values are ascribed to intensified anthropogenic activities, reduced dilution, and substantial pollution loads [33]. The investigation revealed that the EC levels varied from 249 µS/cm to 320 µS/cm, averaging  $302.56 \pm 13.15$  µS/cm. The values were elevated compared to those recorded in Taudaha Lake, suggesting that the water in Syarpu Lake was moderately ionized with dissolved solids. One possible explanation for this phenomenon was that the lake area saw an increase in the number of man-made activities, such as aquaculture and fish traps. Additionally, the TDS ranged from 128.9 mg/L to 232.5 mg/L, potentially resulting from runoff from adjacent agricultural areas, including fertilizers and pesticides, as well as dissolved salts from local settlements and building sites surrounding the lake [10].

To evaluate the extent of organic pollution and DO in water, it is essential to quantify the concentration of DO, which inherently diminishes with a rise in organic pollution [31].

Multiple mechanisms, including air diffusion, aeration, and the rates of photosynthesis, respiration, and decomposition, all have an impact on the concentration of DO in water [34]. In the lake, the concentration of DO ranges from 5.38 to 8.50 mg/L, with a mean value of  $7.33 \pm 0.71$  mg/L. This indicated that the lake was experiencing moderate levels of organic pollution. A DO content of 6 mg/L is advised for the optimal growth and metabolic functions of aquatic creatures and fish. It was probable that the direct diffusion of oxygen from the atmosphere and the photosynthetic activity of autotrophs that maintain DO levels in the water were responsible for the lake's ability to support aquatic life and provide favorable conditions for fish farming [34]. The results of this research show that the lake is suitable for fish farming. Regarding turbidity, the maximum turbidity level in the lake was 12.51 NTU, perhaps due to the presence of plankton and non-native fish species that can disrupt bottom sediment while foraging for food. Turbidity is produced by suspended sediments, which include inorganic particles like clay or silt, as well as organic stuff such as algae, plankton, and material that is decaying [35].

In natural water sources, the presence of Ca<sup>2+</sup> and Mg<sup>2+</sup> ions, as well as HCO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and Cl<sup>-</sup> is the primary factor responsible for the TH composition [36]. The mean concentration of TH was  $87.15 \pm 7.27$  mg/L with CaH above MgH. The alkalinity of water is ascertained by the presence of OH<sup>-</sup>, HCO<sub>3</sub><sup>-</sup>, and CO<sub>3</sub><sup>2-</sup> [8]. In this investigation, it was noted that TH was only attributed to the presence of HCO<sub>3</sub><sup>-</sup>. The average concentration of HCO<sub>3</sub><sup>-</sup> was  $120.26 \pm 9.59$  mg/L. Weathering processes might have been responsible for the higher quantities of HCO<sub>3</sub><sup>-</sup> that were seen in lentic water bodies [37]. In addition, elevated Cl<sup>-</sup> levels in aquatic environments indicate pollution. The primary sources of Cl<sup>-</sup> include natural origins like mica rocks and human origins such as sewerage [38]. The average Cl<sup>-</sup> concentration was  $5.86 \pm 5.88$  mg/L, which was the lowest according to the guideline [8], indicating that the water was safe for Cl<sup>-</sup> levels.

The distinct arrangement of cations and anions revealed that the lake primarily consisted of carbonate and HCO<sub>3</sub><sup>-</sup> - lithology, resulting in mildly alkaline water (Table 3). Among the principal cations, Ca<sup>2+</sup> had the highest concentration at 35.06 mg/L, whilst NH<sub>4</sub><sup>+</sup> displayed the lowest concentration at 0.25 mg/L. Agricultural practices and the lake's closeness are the primary sources of K<sup>+</sup>, NH<sub>4</sub><sup>+</sup> and Na<sup>+</sup> ions, with residential waste from local livestock grazing and fertilizers [39]. The predominant anion in the lake was HCO<sub>3</sub><sup>-</sup>, averaging 87.15 mg/L, followed by Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup> at 5.86 mg/L and 3.12 mg/L, respectively. With a mean concentration of 0.25 mg/L, PO<sub>4</sub><sup>3-</sup> was the anion that came in the lowest concentrations. Geological weathering and human contributions in the lake were the primary factors that affected the variation of hydrochemical parameters, as reported elsewhere [40].

Overall, the parameters TDS, TA, Cl<sup>-</sup>, and NO<sub>3</sub><sup>-</sup> were within the aquatic requirements of Nepal water quality [41]. Nonetheless, the pH levels at several sampling locations, including S1–S6, S15, and S18–S20, were observed to be marginally elevated compared to the standard limits. Mg<sup>2+</sup> levels were observed to be somewhat elevated at sites S1, S23, and S24. The elevated pH and Mg<sup>2+</sup> levels were not observed with broader margins and might be managed by safeguarding the lake from agricultural runoff.

Table 3. Descriptive statistics of hydrochemical parameters of Syarpu Lake

| Parameter               | Abbreviation                  | Statistical values* |         |        |                         | Allowable range [41]            |
|-------------------------|-------------------------------|---------------------|---------|--------|-------------------------|---------------------------------|
|                         |                               | Minimum             | Maximum | Mean   | Standard deviation (SD) |                                 |
| Water temperature       | Temp                          | 17.20               | 24.30   | 22.15  | 1.44                    | 4–30 °C                         |
| Potential of hydrogen   | pH                            | 8.01                | 9.30    | 8.88   | 0.36                    | 6.5–9                           |
| Electrical conductivity | EC                            | 249.00              | 320.00  | 302.56 | 13.15                   |                                 |
| Total dissolved solids  | TDS                           | 128.90              | 232.50  | 186.70 | 28.35                   | < 2000 mg/L                     |
| Dissolved oxygen        | DO                            | 5.38                | 8.50    | 7.33   | 0.71                    | 6–9 mg/L for cold water species |
| Turbidity               | TU                            | 4.05                | 12.51   | 7.17   | 0.98                    | < 25 NTU                        |
| Free carbon dioxide     | Free CO <sub>2</sub>          | 2.20                | 13.20   | 6.99   | 0.93                    |                                 |
| Chloride                | Cl <sup>-</sup>               | 2.84                | 36.92   | 5.86   | 0.88                    | < 600 mg/L                      |
| Bicarbonate             | HCO <sub>3</sub> <sup>-</sup> | 73.20               | 97.60   | 87.15  | 7.27                    |                                 |
| Total hardness          | TH                            | 104.00              | 142.00  | 120.26 | 9.59                    | 20–100 mg/L                     |
| Calcium hardness        | CaH                           | 68.00               | 106.00  | 87.64  | 9.08                    |                                 |
| Magnesium hardness      | MgH                           | 12.00               | 72.00   | 32.67  | 5.69                    | < 15 mg/L                       |
| Iron                    | Fe <sup>3+</sup>              | 0.40                | 1.34    | 0.77   | 0.07                    | 10 mg/L                         |
| Nitrate                 | NO <sub>3</sub> <sup>-</sup>  | 0.95                | 2.32    | 1.10   | 0.10                    | < 300 mg/L                      |
| Phosphate               | PO <sub>4</sub> <sup>3-</sup> | 0.05                | 0.88    | 0.25   | 0.03                    |                                 |
| Ammonium                | NH <sub>4</sub> <sup>+</sup>  | 0.15                | 0.49    | 0.25   | 0.05                    |                                 |
| Potassium               | K <sup>+</sup>                | 1.12                | 5.12    | 2.21   | 0.43                    |                                 |
| Sodium                  | Na <sup>+</sup>               | 2.24                | 10.29   | 4.58   | 0.88                    |                                 |
| Sulphate                | SO <sub>4</sub> <sup>2-</sup> | 0.85                | 22.50   | 3.12   | 0.54                    |                                 |
| Calcium                 | Ca <sup>2+</sup>              | 27.20               | 42.40   | 35.06  | 3.63                    |                                 |
| Magnesium               | Mg <sup>2+</sup>              | 2.95                | 17.54   | 7.96   | 1.33                    |                                 |

\*Note that: pH is dimensionless, TU is in NTU, T is in °C, EC is in  $\mu\text{S}/\text{cm}$ , and others are in mg/L.

### C. Cluster Analysis

Ward's linkage method was utilized, incorporating metrics including Temp, pH, EC, TDS, TH, CaH, MgH, free CO<sub>2</sub>, TU, PO<sub>4</sub><sup>3-</sup>, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup>, HCO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, Fe<sup>3+</sup>, K<sup>+</sup>, Na<sup>+</sup>, Mg<sup>2+</sup>, and Ca<sup>2+</sup> to cluster analogous sampling locations. As shown in Fig. 3, the dendrogram revealed that all 31 sample locations of the lake may be classified into four statistically significant clusters. These clusters were determined by a low distance threshold of < 5. The biggest amount of lake samples was found in Cluster 1, which accounts for 32.25 percent of the total samples. This cluster comprised 10 sampling sites (2, 3, 4, 5, 6, 7, 8, 11, 12, and 31), all situated in the lake's periphery, except for site 31. The sample sites were situated on the lake's eastern and western parts, and they showed very little change. This was because human involvement was not feasible in these areas owing to the steep slopes that were there [42]. Cluster 2 comprised merely 3.22% of the samples and was represented by a single sampling location, i.e., site 13. This site exhibited superior water quality compared to the other sites due to its receipt of water from adjacent little rivulets. Cluster 3 constituted the greatest proportion, encompassing 51.61% of the samples, and contained 16 sampling sites: 9, 10, 14, 15, 16, 17, 18, 19, 20, 21, 22, 26, 27, 28, 29, and 30 (Fig. 3). The locations of the sites included those that are located in the middle of the lake, close to human settlements, and around the perimeter of the lake. Site 28, situated inside this cluster, exhibited elevated concentrations of SO<sub>4</sub><sup>2-</sup> attributable to a combination of varied land use patterns in the adjacent regions comprising hotels, roadside areas, and agricultural lands. Cluster 4 comprised merely 12.90% of the samples and encompassed sites 1, 23, 24, and 25. The concentrations of Cl<sup>-</sup>, Mg<sup>2+</sup>, and SO<sub>4</sub><sup>2-</sup> at these sites were marginally elevated and might be attributable to runoff from adjacent agricultural land [43].

The analysis of the TDS dataset indicated that the mean TDS (mg/L) values of the lake water samples ranked as follows: cluster 3 > 4 > 1 > 2, as illustrated in Table 3. Cluster 3 exhibited the greatest TDS concentration, succeeded by

cluster 4, suggesting that these locations were relatively more contaminated, maybe due to anthropogenic influences such as agricultural runoff, urban developments, and hospitality establishments, in addition to geogenic variables [29]. Conversely, clusters 1 and 2 had comparatively reduced TDS relative to clusters 3 and 4, signifying a diminished degree of pollution. The results of cluster analysis may not correctly represent the quality of water and may not correlate perfectly with the allocation of various locations in Syarpu Lake. Similar findings were observed in the clustering that was carried out in Rajarani Lake and Taudaha Lake [44]. All these groups exhibited distinct patterns of hydro-chemical fluctuation in the lake water, affected by both human and geogenic causes [1].

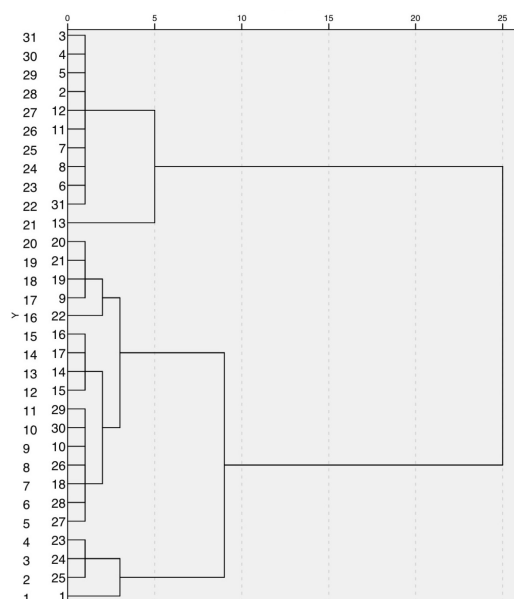


Fig. 3. The hierarchical clustering of sample sites provided the basis for the dendrogram that was generated.

### D. Hydrochemical Characterization

The categorization and naming of various kinds of water

are associated with the proportions of major geochemical ingredients that are present in both natural and artificial solutions [45]. The Piper Trilinear diagram was utilized to identify the type of water in Syarpu Lake (Fig. 4). The figure indicated that the predominant ions were strong acids ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ) in the presence of weak acids ( $\text{HCO}_3^-$ ) in most of the samples. Besides, the presence of alkali metals ( $\text{Na}^+$  and  $\text{K}^+$ ) was not significant in comparison with alkaline earth metals ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ). The prevailing hydrochemical facies in the lake were characterized by  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$  ions. Site 1 had a greater concentration of  $\text{Cl}^-$  due to significant anthropogenic influences such as bathing, laundering, and swimming. The distribution of principal anions and cations indicated that samples of the lake water were fresh, with carbonate weathering being the predominant process influencing the lake's hydrochemistry. It was discovered that the hydrochemical characterization of Syarpu Lake was comparable to those of other lakes in Nepal, such as Rupa, Begnas, and Ghodaghodi Lakes, with similar characteristics [11]. In the Himalayan region, the dominance of  $\text{HCO}_3^-$  and  $\text{Ca}^{2+}$  as the principal anion and cation, respectively was chiefly attributed to the extensive weathering of carbonate rocks [46].

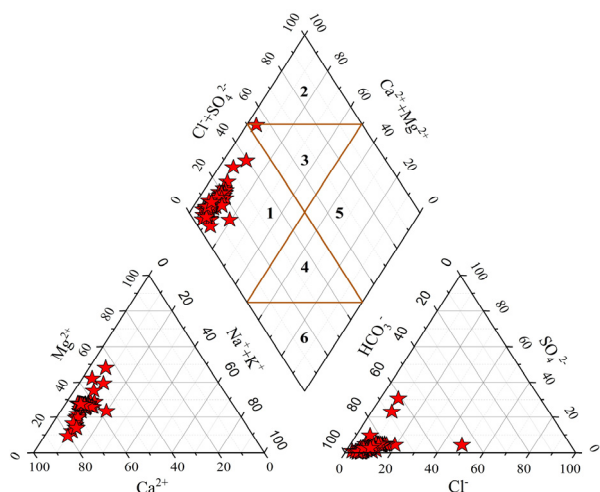


Fig. 4. Piper graphic illustrating the hydrochemical facies of Syarpu Lake.

### E. Controlling Mechanism of Hydrochemistry

#### 1) Gibbs diagram

The lake's chemical composition was affected by multiple sources, including silicate minerals, weathering of carbonate, and evaporites like halite formed during water evaporation,  $\text{Na}^+$  salts, and sulfide minerals. Human activities and cyclic salts also influenced the lake's chemical properties [47]. According to the Gibbs plot, the most important factor that determined the lake hydrochemistry was the process of rock weathering (Fig. 5). It was possible to get substantial insights into the processes of chemical weathering in the drainage zone next to the lake basin by observing the predominance of rock weathering in the lake basin. In the lake environment, the process of dissolving in various parent rocks, such as evaporites, silicates, and carbonates, resulted in the formation of varied conjunctions of dissolved anions and cations via the process of dissolution.  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions are released into the water as a consequence of the breakdown of carbonates, silicates, and evaporites. On the other hand,  $\text{Na}^+$  and  $\text{K}^+$  ions are obtained from evaporites and silicates. In contrast to  $\text{SO}_4^{2-}$

and  $\text{Cl}^-$ , which are derived from evaporites,  $\text{HCO}_3^-$  is primarily derived from carbonates and silicates. It is only via the weathering of silicates that silica may be obtained [48]. Human activities also influence the ion chemistry of the lake [46]. The escalation of human activity surrounding the lake, including tourism, agriculture, and residential usage, has resulted in anthropogenic effects on its water quality. The principal ion composition of the lake water aligns with natural water chemistry; nevertheless, heightened  $\text{Cl}^-$  concentrations in certain samples, such as site 1, suggest anthropogenic influences on the lake's water chemistry.

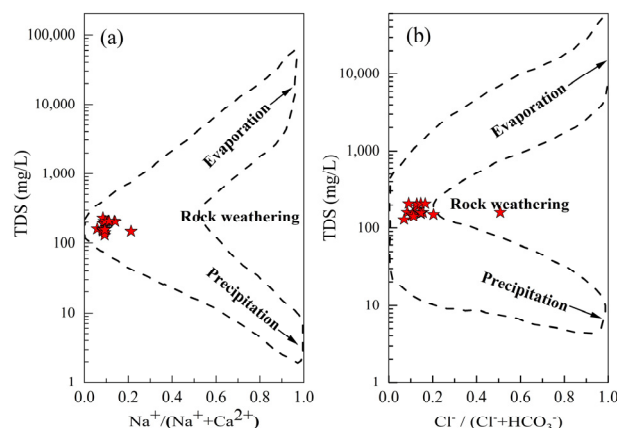


Fig. 5. Gibbs graph illustrating rock weathering as a fundamental natural regulatory mechanism for hydrochemistry in Syarpu Lake.

#### 2) Mixing diagram

The weathering and dissolution of evaporite, silicate, and carbonate were shown to be responsible for the surface water's hydrochemical composition. The  $\text{Na}^+$  normalized ratio was utilized to create an ions-mixing plot (Fig. 6) for a more precise comprehension of the origins of water ions. This figure facilitated a quantitative illustration of each source's effect on the overall composition of the water [49]. To evaluate the properties of rock weathering near Syarpu Lake, the ratios (in  $\mu\text{eq}$ ) of  $\text{Ca}^{2+}$  to  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$  to  $\text{HCO}_3^-$  were standardized using the  $\text{Na}^+$  concentration. The results indicated that most samples were situated nearer to the carbonate end member, implying that carbonate weathering is the predominant mechanism. Nevertheless, certain samples were positioned closer to the silicate end members, suggesting that these sampling locations may be in regions of significant silicate weathering (Fig. 6). It was probable that the hydrochemical characteristics of Syarpu Lake were the consequence of the dissolution and weathering of carbonate and silicate rocks, as shown by these ionic connections [3].

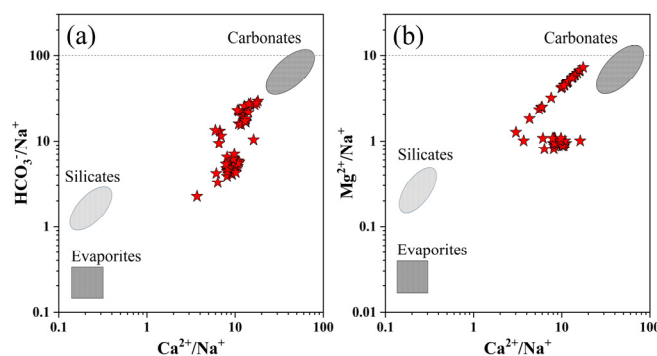


Fig. 6. Mixing diagram showing the molar ratios of (a)  $\text{Ca}^{2+}$  vs  $\text{HCO}_3^-$ , and (b)  $\text{Ca}^{2+}$  vs  $\text{Mg}^{2+}$ , normalized by  $\text{Na}^+$ .

### F. Evaluation of the Water Quality Used for Irrigation

Considering that the majority of Syarpu Lake's water was used for irrigation, it is essential to keep a close eye on its quality to ensure that the soil remains in good condition and achieves the highest possible agricultural production. Salinization poses a substantial issue in irrigated lands when inadequate water quality endures over time, especially in heavy and clay soils [50]. Elevated concentrations of dissolved ions in water could modify soil properties, with  $\text{Na}^+$  being a crucial factor in this phenomenon [4].

Table 4 displayed the findings of the assessment of irrigational suitability in Syarpu Lake, employing diverse methodologies. The  $\text{Na}^+$  danger was evaluated with the use of SAR, which indicated the degree to which cation-exchange interactions were occurring in the soil and irrigation water. Typically, elevated  $\text{Na}^+$  levels substituted  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  in soil, hence enhancing its impermeability [51]. Since the SAR values of this lake were found to be lower than 2.25, it was classified as excellent for irrigation (Table 4). The EC rating revealed that all sampling locations were within the "Excellent" category, concerning water suitability for irrigation. The % Na values, reflecting the  $\text{Na}^+$  danger level, varied from 6.66% to 26.89%, classified as "Good" to

"Excellent".

The KR reflects the high concentration of  $\text{Na}^+$  in water, making it unsuitable for irrigation purposes [52]. According to the findings of the present investigation, the water was appropriate for irrigation as the KR was lower than 0.25. On the other hand, the permeability of the soil is affected by the soil kind and irrigation water quality. Besides, the levels of  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{HCO}_3^-$  in water affect the soil profile [53]. The PI value ranged from 23.92 to 38.05 (Table 4), categorizing it between Categories II and III, which signified that the water possessed excellent to good permeability, rendering it ideal for irrigation.

Alongside  $\text{Na}^+$ , it was essential to check the presence of  $\text{Mg}^{2+}$  in the water. Although  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  achieve equilibrium in water, elevated levels of  $\text{Mg}^{2+}$  in irrigation water can enhance alkalinity and negatively impact crop production [54]. Likewise, the lake's MAR rating indicates its suitability for irrigation purposes. The MAR values ( $< 39.2$ ) were within the acceptable range, signifying the availability of irrigation-grade lake water. Moreover, the CROSS values were classified in the "Excellent" group (Table 4). The obtained results, similar to other research on lakes in Nepal, indicate that the water from Syarpu Lake is appropriate for agricultural usage [32].

Table 4. Irrigation suitability assessment of Syarpu Lake

| Site | EC     | Class | %Na   | Class | SAR  | Class | CROSS | Class | MAR   | Class | KR   | Class | PI    | Class |
|------|--------|-------|-------|-------|------|-------|-------|-------|-------|-------|------|-------|-------|-------|
| S1   | 300.00 | Ex*   | 6.66  | Ex    | 0.46 | Ex*   | 0.63  | Ex*   | 32.07 | Ap*   | 0.05 | Sa*   | 23.92 | III   |
| S2   | 310.00 | Ex    | 11.26 | Ex    | 0.80 | Ex    | 1.05  | Ex    | 18.16 | Ap    | 0.09 | Sa    | 27.70 | II    |
| S3   | 310.00 | Ex    | 11.76 | Ex    | 0.79 | Ex    | 1.05  | Ex    | 17.25 | Ap    | 0.09 | Sa    | 28.79 | II    |
| S4   | 310.00 | Ex    | 12.27 | Ex    | 0.86 | Ex    | 1.12  | Ex    | 14.56 | Ap    | 0.10 | Sa    | 28.95 | II    |
| S5   | 320.00 | Ex    | 13.10 | Ex    | 0.90 | Ex    | 1.20  | Ex    | 19.62 | Ap    | 0.10 | Sa    | 30.22 | II    |
| S6   | 310.00 | Ex    | 14.03 | Ex    | 1.04 | Ex    | 1.36  | Ex    | 11.09 | Ap    | 0.11 | Sa    | 27.43 | II    |
| S7   | 294.50 | Ex    | 11.56 | Ex    | 0.81 | Ex    | 1.08  | Ex    | 15.69 | Ap    | 0.09 | Sa    | 27.08 | II    |
| S8   | 294.60 | Ex    | 12.69 | Ex    | 0.91 | Ex    | 1.18  | Ex    | 13.75 | Ap    | 0.10 | Sa    | 28.68 | II    |
| S9   | 308.00 | Ex    | 12.05 | Ex    | 0.87 | Ex    | 1.15  | Ex    | 13.95 | Ap    | 0.09 | Sa    | 26.73 | II    |
| S10  | 300.20 | Ex    | 12.73 | Ex    | 0.89 | Ex    | 1.19  | Ex    | 16.91 | Ap    | 0.10 | Sa    | 28.37 | II    |
| S11  | 302.20 | Ex    | 26.89 | Go    | 2.25 | Ex    | 3.00  | Ex    | 19.80 | Ap    | 0.25 | Sa    | 38.05 | II    |
| S12  | 304.50 | Ex    | 13.06 | Ex    | 0.95 | Ex    | 1.25  | Ex    | 14.20 | Ap    | 0.10 | Sa    | 27.87 | II    |
| S13  | 249.00 | Ex    | 12.98 | Ex    | 0.94 | Ex    | 1.24  | Ex    | 14.20 | Ap    | 0.10 | Sa    | 29.10 | II    |
| S14  | 319.70 | Ex    | 14.12 | Ex    | 1.00 | Ex    | 1.34  | Ex    | 22.46 | Ap    | 0.11 | Sa    | 30.09 | II    |
| S15  | 308.50 | Ex    | 13.47 | Ex    | 1.03 | Ex    | 1.32  | Ex    | 21.23 | Ap    | 0.11 | Sa    | 27.55 | II    |
| S16  | 317.80 | Ex    | 16.97 | Ex    | 1.26 | Ex    | 1.67  | Ex    | 22.46 | Ap    | 0.14 | Sa    | 30.37 | II    |
| S17  | 312.10 | Ex    | 13.91 | Ex    | 0.98 | Ex    | 1.31  | Ex    | 21.12 | Ap    | 0.11 | Sa    | 29.06 | II    |
| S18  | 308.70 | Ex    | 14.08 | Ex    | 1.00 | Ex    | 1.33  | Ex    | 18.86 | Ap    | 0.11 | Sa    | 31.39 | II    |
| S19  | 305.20 | Ex    | 14.87 | Ex    | 1.15 | Ex    | 1.45  | Ex    | 10.11 | Ap    | 0.12 | Sa    | 31.14 | II    |
| S20  | 306.90 | Ex    | 13.97 | Ex    | 1.08 | Ex    | 1.37  | Ex    | 8.62  | Ap    | 0.11 | Sa    | 28.40 | II    |
| S21  | 302.80 | Ex    | 13.28 | Ex    | 0.99 | Ex    | 1.27  | Ex    | 6.51  | Ap    | 0.10 | Sa    | 27.19 | II    |
| S22  | 318.20 | Ex    | 12.33 | Ex    | 0.89 | Ex    | 1.17  | Ex    | 11.65 | Ap    | 0.09 | Sa    | 27.40 | II    |
| S23  | 305.70 | Ex    | 15.86 | Ex    | 1.22 | Ex    | 1.67  | Ex    | 32.07 | Ap    | 0.13 | Sa    | 29.79 | II    |
| S24  | 305.10 | Ex    | 11.48 | Ex    | 0.80 | Ex    | 1.13  | Ex    | 39.20 | Ap    | 0.08 | Sa    | 28.18 | II    |
| S25  | 301.20 | Ex    | 12.33 | Ex    | 0.98 | Ex    | 1.28  | Ex    | 27.22 | Ap    | 0.10 | Sa    | 26.41 | II    |
| S26  | 292.80 | Ex    | 13.97 | Ex    | 1.00 | Ex    | 1.33  | Ex    | 18.50 | Ap    | 0.11 | Sa    | 29.59 | II    |
| S27  | 291.60 | Ex    | 15.49 | Ex    | 1.11 | Ex    | 1.43  | Ex    | 10.02 | Ap    | 0.13 | Sa    | 32.17 | II    |
| S28  | 292.50 | Ex    | 14.20 | Ex    | 0.99 | Ex    | 1.32  | Ex    | 19.23 | Ap    | 0.11 | Sa    | 30.43 | II    |
| S29  | 293.60 | Ex    | 12.58 | Ex    | 0.85 | Ex    | 1.14  | Ex    | 20.59 | Ap    | 0.09 | Sa    | 30.31 | II    |
| S30  | 295.00 | Ex    | 14.07 | Ex    | 1.02 | Ex    | 1.33  | Ex    | 20.59 | Ap    | 0.11 | Sa    | 32.25 | II    |
| S31  | 289.00 | Ex    | 12.14 | Ex    | 0.81 | Ex    | 1.08  | Ex    | 20.44 | Ap    | 0.09 | Sa    | 32.11 | II    |

\*Note that: Ex = Excellent, Go = Good, Ap = Appropriate, and Sa = Safe.

Table 5. Carlson Trophic State Index (CTSI) of Syarpu Lake

| Name of Lake |      | PHC (µg/L) | SD(m) | CHL (µg/L) | TSI <sub>phc</sub> | TSI <sub>sd</sub> | TSI <sub>chl</sub> | CTSI  | Trophic status |
|--------------|------|------------|-------|------------|--------------------|-------------------|--------------------|-------|----------------|
| Svarpu       | Mean | 97.6       | 0.12  | 6.21       | 70.14              | 90.96             | 48.5               | 69.86 | Eutrophic      |

### G. Trophic Status of the Lake

The CTSI value of Syarpu Lake, which had a mean CTSI value of 69.86, showed that the lake was eutrophic (Table 5). According to the CTSI score and the corresponding trophic state of the lake, the water was mostly characterized by blue-green algae, algal scum, and potentially major macrophyte

concerns (Tables 2 and 5). This was indicated by the fact that the lake had a trophic condition. The eutrophic state of the lake resulted from elevated concentrations of nutrients, causing anoxic conditions due to increased decomposition. The lake's elevated biological productivity, propelled by nutrient levels, stimulated the proliferation of microscopic

flora and sustains other components of the ecosystem. Excessive nutrient concentrations could result in severe algal blooms that are toxic to fish and potentially detrimental to humans, reduce DO levels, and disrupt the lake's ecological functionality. The outcomes of our research were supported by the findings of Tibebe *et al.* [55], along with Ozguven and Demir Yetis [56], who reported the eutrophic pattern of Big Soda Lake and Lake Tana.

Although a natural occurrence, the change of a lake from oligotrophic to eutrophic might be accelerated in part by certain human activities [26]. Besides, human activities also altered the trophic status of a lake. Activities, such as washing, bathing, agricultural runoff, and sedimentation in the lake, might expedite algal bloom and lead to the eutrophication of the lake [57]. During the field visit, stressors such as land use change, encroachment, sedimentation from road building around the lake, and inadequate wetland governance were identified, indicating a pressing need for focused conservation efforts for the lake.

#### H. Study Outcomes vs. Sustainable Development Goals (SDGs)

The study outcomes aligned closely with the objectives of the SDGs, particularly SDG 6 (clean water and sanitation), and SDG 15 (life on land), as demonstrated in Fig. 7. For example, Target 6.3 of SDG 6 aims to enhance water quality by diminishing pollution and curtailing the discharge of harmful substances into aquatic environments. The analysis of Syarpu Lake's hydrochemical parameters, which identified major ions and the eutrophic state, provided critical data that supports this goal. These findings were consistent with research that emphasizes the role of continuous monitoring in mitigating pollution impacts on water resources and maintaining water quality for both human use and ecosystem health [58]. Furthermore, the research underlines the need for conservation measures to safeguard inland freshwater ecosystems, therefore supporting Target 15.1 of SDG 15, as observed in the larger background of sustainable natural resource management to retain biodiversity [59].

Conservation strategies must prioritize sustainable land use, comprehensive tourism management, and robust erosion control measures to mitigate further degradation of Syarpu Lake and ensure the lake's ecosystem remains viable for future generations [13]. Implementing sustainable land use practices involves establishing clear zoning regulations to minimize agricultural runoff and encouraging organic farming methods that reduce nutrient pollution. Tourism management should include the development of eco-friendly infrastructure, strict regulations on waste disposal, and education programs for visitors about the environmental significance of Syarpu Lake. Effective erosion control measures could involve constructing sediment traps, promoting reforestation, and stabilizing shorelines with native vegetation to prevent soil loss and sediment deposition. Similar strategies in regions affected by extensive agricultural development and expansion have demonstrated that reforestation and erosion mitigation measures, such as contour plowing and riparian buffers, can significantly reduce sedimentation rates and improve water quality [60]. Moreover, managing eutrophic conditions requires continuous, systematic water quality monitoring. Community engagement is crucial in these efforts, as local involvement in

conservation initiatives, such as citizen science projects and stewardship programs, has proven highly effective in maintaining long-term ecological balance. Achieving the SDGs and ensuring the sustainable management of freshwater ecosystems depend on such integrated and collaborative conservation approaches, which align environmental health with the well-being of local communities and biodiversity conservation [61].

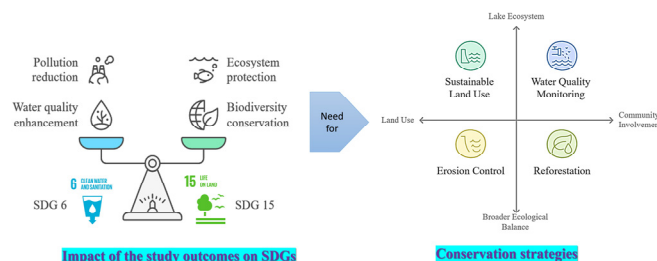


Fig. 7. Correlation of the study outcomes to sustainable development goals (SDGs) along with conservation strategies for sustainable management.

#### IV. LIMITATIONS AND FUTURE RESEARCH

This study offers a thorough evaluation of the hydrochemistry and water quality of Syarpu Lake; however, certain limitations must be recognized. The sampling was undertaken in a single season, limiting the capacity to consider temporal differences across other hydrological seasons. Moreover, the absence of long-term data hinders the comprehension of patterns and the effects of climate variability on the lake's ecosystem [7]. Although the study identified essential hydrochemical characteristics and pollution sources, it excluded biological assessments of aquatic biodiversity and sediment analysis, both of which could enhance the comprehension of ecological health and sediment movements. The restricted geographical scope of sample locations may result in an inadequate depiction of spatial differences in water quality [57].

Future research ought to concentrate on the long-term surveillance of Syarpu Lake to document seasonal and inter-annual fluctuations in water quality and hydrochemical attributes. This should be enhanced by integrating biological evaluations, including investigations of microorganisms, aquatic flora, and fauna, to gain a deeper understanding of the ecological consequences of eutrophication and pollution. Furthermore, sediment analysis must be performed to evaluate past contamination patterns and sedimentation rates. Extending the spatial coverage of sampling locations, encompassing upstream and downstream regions, will provide a more thorough understanding of hydrological and biological dynamics [62]. Additionally, although standard QA/QC procedures were followed, recovery testing using spiked samples was not performed during the laboratory analyses. Future studies should incorporate recovery efficiency testing to further validate accuracy, particularly for low-concentration parameters such as  $\text{PO}_4^{3-}$  and  $\text{NO}_3^-$ . Ultimately, investigations into the impacts of climate change on the lake's hydrological balance and nutrient dynamics could yield significant insights for adaptive management and conservation approaches [63].

#### V. CONCLUSION

This study provides the first comprehensive hydrochemical

and bathymetric evaluation of Syarpu Lake, offering critical insights into its water quality, hydrochemistry, and environmental challenges. Bathymetric mapping revealed a maximum depth of 6.5 m and an average depth of 3.59 m, indicating significant sediment accumulation and a shrinking catchment area caused by natural processes and anthropogenic activities. Hydrochemical analysis identified calcium (35.06 mg/L) and bicarbonate (87.15 mg/L) as the dominant ions, with rock weathering as the primary ion source, as confirmed by Piper and Gibbs plots. Despite these pressures, the lake's water quality was deemed suitable for irrigation, supported by a sodium adsorption ratio (SAR < 2.25) and a permeability index (PI: 23.92–38.05), demonstrating its potential to support local agriculture. The CTSI classified the lake as eutrophic, with a mean score of 69.86, reflecting elevated nutrient levels and the potential for anoxic conditions. While eutrophication is a natural process, the acceleration caused by human activities, such as unregulated construction, agricultural runoff, and land-use changes, has worsened the lake's ecological health. The presence of algal blooms and nutrient enrichment raises concerns about long-term water quality and ecosystem sustainability.

These findings emphasize the urgent need for integrated conservation strategies. Key measures include sedimentation control through erosion management, sustainable tourism practices, eco-friendly land-use planning, and community engagement in conservation initiatives. Implementing these strategies is crucial for preserving Syarpu Lake's ecological and economic value while contributing to SDGs 6 and 15. Future research should prioritize long-term, seasonal monitoring, microbiological assessments, and sediment analysis to address knowledge gaps and refine management approaches. Such efforts will help mitigate environmental pressures and ensure the sustainability of Himalayan freshwater resources.

#### CONFLICT OF INTEREST

The authors declare no conflict of interest.

#### AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: Kaphle, C. & Pant R.R.: Data collection, experiments, analysis and interpretation of results, draft manuscript preparation. Saqr A.M., Kafle, S., Sharma M.L., Varol, M., and Dhital, Y.P.: Writing-review, data analysis and co-wrote the paper. All authors reviewed the results and approved the final version of the manuscript.

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