Journal of Environmental Protection, 2026, 17(8), 823-848
https://www.scirp.org/journal/jep
ISSN Online: 2152-2219
ISSN Print: 2152-2197

Biogeochemical Controls on C, N, and P Stoichiometry and Nutrient Cycling in Bedkot Lake, Chure Region of Far-Western Nepal

Maya P. Bhatt[1*], Ganesh B. Malla[2], Babi K. Kafle[3], Rebecca A. Coates[4], Seema Bhatt[1], Alfred Addo-Mensah[1], Jacob C. Yde[5]

[1]Department of Biology and Chemistry, Texas A&M International University, Laredo, TX, USA
[2]Department of Mathematics, Computer, Geology and Physics, University of Cincinnati-Clermont, Batavia, OH, USA
[3]Department of Chemistry and Engineering, Kathmandu University, Dhulikhel, Nepal
[4]Department of Chemistry, Carroll College, Helena, MT, USA
[5]Department of Civil Engineering and Environmental Sciences, Western Norway University of Applied Sciences, Sogndal, Norway
Email: *maya.bhatt@tamiu.edu

How to cite this paper: Bhatt, M.P., Malla, G.B., Kafle, B.K., Coates, R.A., Bhatt, S., Addo-Mensah, A. and Yde, J.C. (2026) Biogeochemical Controls on C, N, and P Stoichiometry and Nutrient Cycling in Bedkot Lake, Chure Region of Far-Western Nepal. *Journal of Environmental Protection*, **17**, 823-848.
https://doi.org/10.4236/jep.2026.178042

Received: June 30, 2026
Accepted: August 1, 2026
Published: August 4, 2026

Abstract

This study evaluates the controlling factors of carbon-nitrogen-phosphorus (C-N-P) and nutrient dynamics of a freshwater ecosystem, Bedkot Lake in far-western Nepal. Lake water samples were collected from eight different locations during two sampling events (dry summer period and wet monsoon season) for a total of sixteen samples, characterizing spatiotemporal variation of major chemical parameters and water quality. Key chemical parameters such as dissolved organic carbon (DOC), total dissolved nitrogen (TDN), dissolved inorganic nitrogen (DIN), and phosphorus were measured alongside other hydrochemical variables with the application of correlation analysis and advanced statistical approaches. The nutrient dynamics showed distinct spatial variations with chemical limitations within the lake. DOC and TDN showed very stable tight relationship with exceptionally low spatial variability. In contrast, the DIN concentrations were vastly different, indicating significant change between inorganic and organic nitrogen control across the lake ecosystem. Importantly, high nutrient ratio showed a high concentration of nitrogen over dissolved phosphorus. Such significant imbalance between nitrogen and phosphorus clearly indicates dissolved phosphorus appears as a limiting nutrient which controls overall productivity and the chemical equilibrium of the Bedkot Lake. Biogeochemical dynamics of Bedkot Lake are primarily controlled by internal nutrient cycling based on our analysis. Three most important envi-

ronmental gradients, such as reactive nutrient dynamics, hydrochemical/phosphorus regulation, and internal organic nutrient coupling, were observed based on correlation modeling. The highly synchronized relationship between dissolved organic carbon and nitrogen reflects the close linkage in organic matter processing within the lake. Dissolved inorganic nitrogen and ammonium show strong relationships, indicating internal microbial cycling and reflecting active internal transformation pathways of nitrogen dynamics. The lake functions as a stable ecosystem during the summer-monsoon season, although the lake is exposed to significant evaporation, and nutrient dynamics are controlled by complex interacting biogeochemical processes based on exploratory regression. Overall, water is safe for domestic and agricultural use with no clear evidence of widespread trace metal contamination.

Keywords

Bedkot Lake, Chure Region, Nutrient Stoichiometry, Biogeochemical Cycling, Dissolved Organic Carbon, Principal Component Analysis

1. Introduction

Nepal is a mountainous country situated in the central Himalaya region and the country is divided into five physiographic zones: Terai, Siwalik (Chure), Middle Mountain, High Mountain, and High Himalaya [1]-[6]. The Chure range extends from the Indus River in Pakistan in the west to the Brahmaputra River in India in the east [7] [8]. The Chure region consists of the youngest hills formed by river deposition during the formation of the Himalaya around 40 million years ago, and the region covers about 12.8% of the total land area of Nepal with elevations ranging from 200 m to 2000 m above sea level (asl) [8] [9]. The Chure region contains about 23.0% of the total forest area of Nepal [9] [10], and it has the most fragile and vulnerable ecosystem in Nepal due to climate change issues and human activities [8] [9]. Recent decades have witnessed increased landslides and soil erosion in the region, largely resulting from human-driven changes such as deforestation and the conversion of land for agriculture and human settlement. The Chure region is ecologically diverse and provides various ecosystem services to the downstream area, which influences the environmental quality [6].

The ecological functions of the Chure region environments have been altered due to changing natural biogeochemical cycles by human activities such as deforestation, land use change patterns, and construction activities [11] [12]. More severe ecological disruption has been identified particularly in wetland ecosystems. Wetlands are indispensable ecosystems that regulate Earth's natural purification systems, hence often described as the kidneys of the landscape, as they filter pollutants in water, decrease water velocity, absorb excess nutrients like nitrogen and phosphorus, support aquaculture, trap sediments, support biodiversity (habitat for numerous species) and maintain regional ecosystem health [11]-[16]. Various

stressors, including raising global temperatures, are responsible for water scarcity and accelerating water quality decline within the Himalayan landscape [17] [18]. Earlier, various investigations have evaluated the impacts of climate change and human activities on regional lake-pond water quality [11] [12] [19]-[21]; the underlying mechanisms driving these shifts in lakes across the Lesser Himalaya and lowland Terai-Chure regions remain undocumented.

Both natural and human activities interact in complex ways to shape the water quality of any river catchment [22]-[26]. Effects of anthropogenic activities in any aquatic ecosystem, including watersheds in the Chure region, affect regional water security issues, disrupt aquatic biodiversity, cause habitat loss, degrade water quality, and impact human health, ultimately affecting local economies by damaging sustainable tourism industries in the region. Consequently, this research focuses on quantifying the compounding impacts of climate change and human activities on biogeochemical pathways, with an explicit emphasis on carbon sequestration and nutrient dynamics at the foot of the Himalayas. To address this critical research gap, this study examines a low-elevation lake within the Chure landscape of Nepal. Evaluating this distinct, low-elevation stratified lake will provide a comprehensive understanding of how climate and anthropogenic pressure modulate lacustrine hydrochemistry, with a specific focus on carbon, major ions, dissolved organic matter (DOM), nutrient dynamics, trace elements, and water isotopes.

2. Study Area

Bedkot Lake (29.0238˚N; 80.3203˚E) is a natural wetland located in the Chure region of Kanchanpur district in far-western Nepal (**Figure 1**). Bedkot Lake area is about 5 hectares with a maximum depth of 11 m [27]. The lake is located at the foot of Mount Api (7132 m asl), which has natural beauty surrounded by hardwood tree species such as Sal (*Shorea robusta*), Saj (*Terminalia tormentosa*) and Rosewood (*Dalbergia sissoo*), and it is a religious tourist destination from the nearby towns, Mahendranagar and Dhanghadi.

Bedkot Lake is one of only 47 natural lakes in the Kanchanpur district [28]. The wetland ecosystem is located at 482 m above sea level (asl) and a habitat for numerous aquatic species, including crocodiles. Surface runoff with rich organic matter enters the lake from three sites in the east, north and west. The land surface is composed of soils and unconsolidated loose materials originating from soft rocks such as sandstone, mudstone, shale and conglomerate [7] [9] [29]. The climate in the region is subtropical to tropical with a mean annual air temperature (MAAT) of 30.5˚C, with a maximum of 44.5˚C during summer and a minimum of 2.5˚C during winter. The mean annual precipitation is about 1700 mm [30].

3. Materials and Methods

3.1. Sample Collection

Bedkot Lake sampling was conducted at eight different locations, with a total of

sixteen samples across two major seasons on 6 June 2025 and 1 July 2025 (Figure 1) to document spatiotemporal variation trends of chemical species. The two sampling seasons were selected to represent summer—early June (very hot)—and monsoon—July (very wet)—to investigate the distinct variation pattern in biogeochemical dynamics of the lake. Surface runoff from forested areas enters the lake through all sites except the small part in southern part. Physical parameters such as water temperature, pH, EC, and DO were measured from the lake during sampling using a handheld Hannah multimeter. Due to an unexpected field meter malfunction during the June 2025 sampling event, we were unable to collect EC, TDS, Salinity, and ORP data. Consequently, n = 8 for these parameters represents only the July 2025 sampling. For pH, nutrients and other parameters, data are available for both June and July 2025, yielding n = 16.

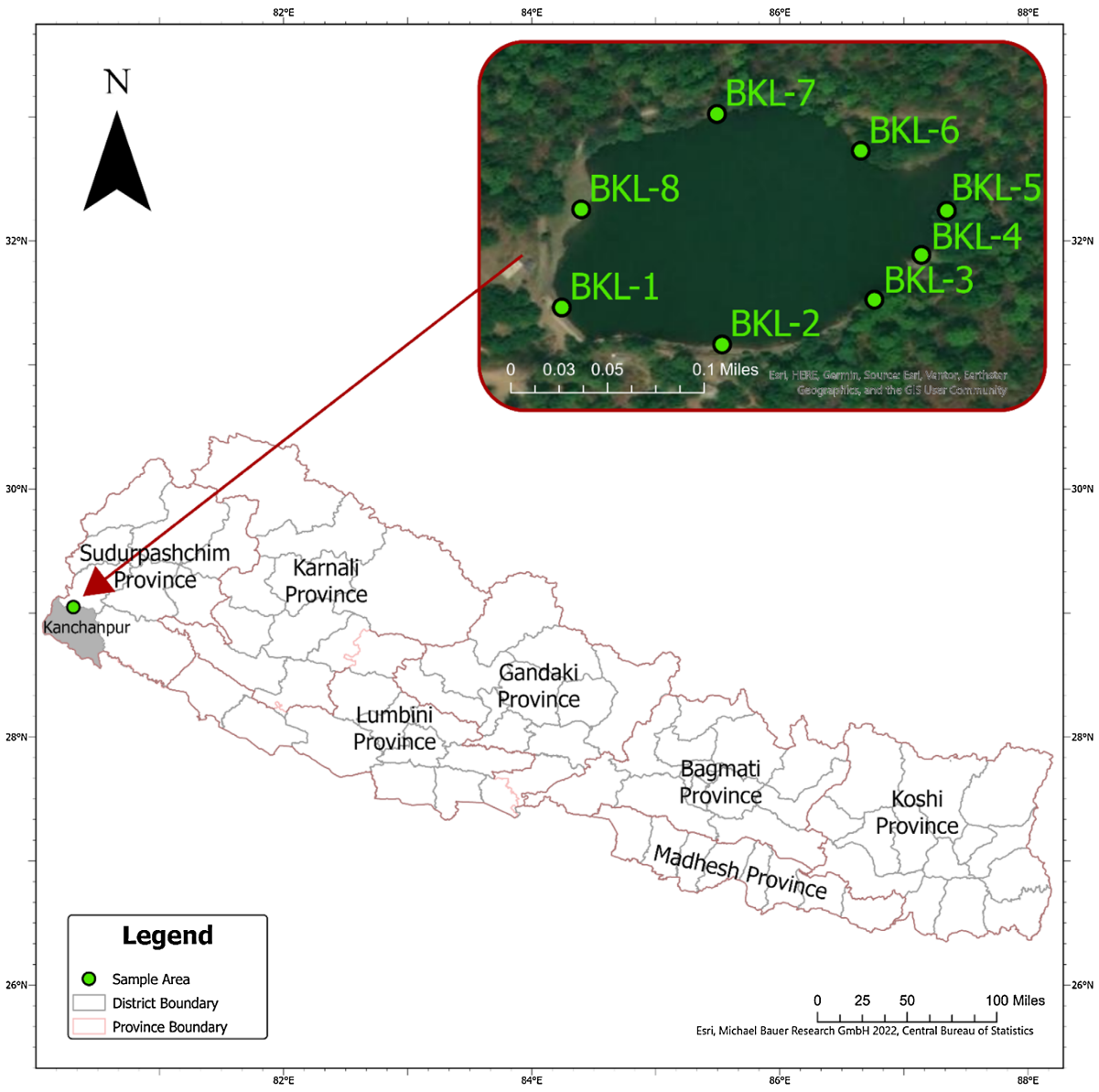

Figure 1. Sampling locations of Bedkot lake within Chure region of Kanchanpur district in far-western Nepal.

Samples were collected in 125 mL acid-washed polyethylene bottles, refrigerated in Nepal, and shipped on ice to the New Hampshire Water Resources Research Center of the University of New Hampshire, Durham, USA for the analysis of major base cations (Na^+, K^+, Mg^{2+}, Ca^{2+}), ammonium (NH_4^+), major anions (Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, PO_4^{3-}), dissolved organic carbon (DOC), total dissolved nitrogen (TDN), sodium adsorption ratio (SAR), and boron. Samples for anions, cations, DOC, dissolved nitrogen, and dissolved phosphorus were filtered through 0.7 μm precombusted (5+ hours at 450˚C) glass fiber filters (Whatman brand glass microfiber filters, Grade: GF/F). Water samples filtered through 0.45 μm polycarbonate membrane filter and acidified with nitric acid were sent to Carroll College in Helena, Montana, USA for analysis of trace elements (As, Cd, Co, Cr, Cu, Fe, Ni, Pb, Sb, Se, and Zn) and, unfiltered 20 mL water samples in PE bottles were sent to the University of Bergen, Norway, for analysis of water isotopes (δD and δ^{18}O).

3.2. Analytical Methods

Water samples were analyzed for major cations and anions, nutrients, dissolved organic carbon (DOC), total dissolved nitrogen (TDN) dissolved silica, and trace metals. Major cations (Na^+, K^+, Mg^{2+} and Ca^{2+}) were analyzed by ion chromatography with suppressed conductivity by Metrohm 940 Professional IC Vario with suppressed conductivity, with oxalic acid phase [31] and major anions (Cl^-, Br^-, NO_3^-, and SO_4^{2-}) were measured on an ion chromatography with suppressed conductivity by Metrohm 940 Professional IC Vario (US EPA 2007) method no. 300.1 [32]. Ammonium and orthophosphate (PO_4^{3-}) were analyzed by automated colorimetry using a SmartChem discrete analyzer using the automated phenate hypochlorite method with sodium nitroprusside enhancement (US EPA 2005) method no. 350.1 [33], and the automated ascorbic acid reduction method (US EPA 2005) method no. 365.1 [34], respectively. The DOC was analyzed as non-purgeable organic carbon with combustion and analysis of end products using a Shimadzu TOC-L following protocol of the United States Environmental Protection Agency (US EPA 2002) method no. 415.1 [35]. All the samples were injected into a 720˚C-furnace containing platinum catalyst (Pt on silica beads) where carbon compounds are converted to CO2 and measured with a Non-Dispersive Infrared Detector (NDIR). Total dissolved nitrogen (TDN) was measured in accordance with the method of Merriam *et al.* (1996) [36] using a Shimadzu TOCL in which nitrogen compounds are converted to NO and measured using a chemiluminescent N detector and the technique performs at 680˚C. Dissolved organic nitrogen (DON) was calculated by subtracting inorganic nitrogen (NO_3^--N + NH_4^+-N) from total dissolved nitrogen.

Water samples were analyzed at the New Hampshire Water Resources Research Center following strict quality assurance and quality control (QA/QC) protocols for major ions, nutrients, and dissolved carbon. Calibration models were constructed by using 4-to-7-point curves for instruments. Method Detection Limits (MDLs)

were defined at the 99% confidence threshold, yielding target analyte detection limits of 0.08 mg/L for Cl^-, 0.004 mg/L for NO_3^-, 0.06 mg/L for SO_4^{2-}, 3.4 µg/L for PO_4^{3-}, 5 µg/L for NH_4^+, 0.03 mg/L for Na^+, 0.003 mg/L for K^+, 0.05 mg/L for Mg^{2+}, 0.16 mg/L for Ca^{2+}, 0.05 mg/L for DOC, and 0.20 mg/L for TDN. Samples were analyzed periodically at an approximate frequency of every 10 to 15 samples within each analytical batch to monitor analytical accuracy via certified Quality Control Samples (QCS; Ultra Scientific or SPEX Certiprep). Laboratory executes a uniform acceptable precision limit of ±15% for laboratory duplicates for all measured parameters and an accuracy recovery limit of ±15% for quality control standard.

Samples were acidified with nitric acid after filtration through 0.45 µm polycarbonate membrane filter for trace element analysis. Trace elements such as arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), antimony (Sb), selenium (Se) and zinc (Zn) were analyzed by using inductively coupled plasma-optical emission spectroscopy (ICP-OES, PerkinElmer Avio 200) following the methods for the determination of metals in environmental samples [37]. Emission spectra were used to confirm the detection and elements without a resolved peak at the analyte wavelength were reported as not detected (ND). The emission wavelengths monitored were As, 193.696 nm; Cd, 228.802 nm; Co, 228.616 nm; Cr, 267.716 nm; Cu, 327.393 nm; Fe, 238.204 nm; Ni, 231.604 nm; Pb, 220.353 nm; Sb, 206.836 nm; Se, 196.026 nm; and Zn, 206.200 nm. Procedural blanks and calibration verification standards were analyzed periodically to ensure analytical accuracy and instrument stability. The detection limits of trace elements were 0.025 mg/L for As, 0.001 mg/L for Cd, 0.002 mg/L for Co, 0.001 mg/L for Cr, 0.009 mg/L for Cu, 0.001 mg/L for Fe, 0.002 mg/L for Ni, 0.002 mg/L for Pb, 0.015 mg/L for Sb, 0.030 mg/L for Se, and 0.002 mg/L for Zn.

The water isotope samples were analyzed using a Picarro (L2140-i) cavity-ring-down spectrometer with an autosampler and high-precision vaporizer and calibrated to the VSMOW-SLAP scale using the notation δ. The instrumental precision was 0.4‰ for δD and 0.05‰ for $\delta^{18}O$, while the derived precision for the second-order parameter d-excess (defined as d-excess = $\delta D - 8 \times \delta^{18}O$; [38]) was 0.6‰. For assessing the local meteoric water line and comparison with the isotopic composition in river water, data were compiled from the IAEA Global Network of Isotopes in Precipitation (GNIP) WISER database. For meteoric water, we use the available Nepalese station at Ghalegaun (28.2769˚N; 84.3098˚E) located *c.* 720 km to the north-east of Bedkot Lake at an altitude of 2103 m asl (n = 227; collected in 2016-2017). For river water, we compare it with data from Narayani River near the city of Bharatpur (27.7242˚N; 84.4289˚E), located *c.* 555 km east of Bedkot Lake at an altitude of 120 m asl (n = 358; collected in 2015-2017).

4. Results & Discussion

4.1. Summary of Measured Physicochemical Parameters in Bedkot Lake

The physicochemical properties, nutrient fractions, major ions, sodium adsorp-

tion ratio (SAR), trace elements, and stable water isotopes measured in Bedkot Lake are summarized in Table 1. The lake water was slightly alkaline, with pH ranging from 8.0 to 8.5 (mean = 8.23 ± 0.15), indicating a well-buffered freshwater system. Electrical conductivity (EC) and total dissolved solids (TDS) exhibited very little spatial variation (CV < 2%), suggesting that dissolved ionic conditions were relatively uniform across the lake.

Table 1. Descriptive statistics of physicochemical parameters, dissolved organic and inorganic nutrient fractions, major ions, agricultural suitability index (SAR), trace elements, and water isotopes in Bedkot Lake.

Parameter	n	Min	Max	Mean	SD	Median	Skewness	CV (%)
pH	16	8.0	8.5	8.2	0.15	8.3	0.210	1.8
EC	8	208	220	213.9	4.0	213.5	0.068	1.9
TDS	8	103	110	106.5	2.1	106.0	0.058	2.0
Salinity	8	0.01	0.01	0.01	0.000	0.010	na	na
OPR	8	3.04	28.70	12.39	12.75	3.27	0.654	102.8
DOC	16	1.75	3.18	2.36	0.38	2.35	0.757	16.2
TDN	16	0.35	0.63	0.46	0.09	0.45	0.440	18.5
DIN	16	0.003	0.249	0.11	0.09	0.096	0.171	83.7
DON	16	0.193	0.620	0.360	0.138	0.348	0.477	38.8
Cl	16	1.10	4.79	1.67	0.86	1.50	3.529	51.5
NO_3	16	0.000	0.208	0.019	0.052	0.002	3.702	276.0
PO_4	16	0.21	0.36	0.24	0.04	0.23	1.635	16.5
SO_4	16	0.01	0.04	0.015	0.010	0.014	1.877	66.1
Br	16	0.00	0.05	0.026	0.021	0.040	−0.517	80.6
Na	16	4.01	7.58	5.19	0.81	4.99	1.641	15.7
K	16	0.61	1.91	1.49	0.38	1.63	−1.033	25.1
Mg	16	5.81	9.52	7.53	0.94	7.52	0.203	12.5
Ca	16	4.84	12.55	8.30	1.92	8.01	0.326	23.1
NH_4	16	0.002	0.249	0.089	0.091	0.053	0.499	102.7
SAR	16	0.198	0.366	0.249	0.036	0.244	2.296	14.6
As†	0/16	ND	ND	NC	NC	NC	NC	NC
Cd†	2/16	0.006	0.006	0.006	0.000	0.006	NC	0.3
Co†	3/16	0.003	0.004	0.003	0.000	0.003	−1.182	15.5
Cr†	6/16	0.013	0.015	0.014	0.000	0.014	−0.488	2.5
Cu†	13/16	0.001	0.009	0.003	0.002	0.003	2.145	63.6
Fe†	16/16	0.009	0.027	0.019	0.006	0.018	−0.093	29.8
Ni†	0/16	ND	ND	NC	NC	NC	NC	NC

Continued

Pb†	0/16	ND	ND	NC	NC	NC	NC	NC
Sb†	4/16	0.017	0.025	0.020	0.003	0.020	0.212	17.0
Se†	0/16	ND	ND	NC	NC	NC	NC	NC
Zn†	16/16	0.007	0.010	0.008	0.001	0.008	0.784	12.1
$\delta^{18}O$	8	−4.05	−3.79	−3.96	0.10	−3.98	2.98	−2.53
δD	8	−34.0	−33.2	−33.7	0.3	−33.7	3.00	−0.89
d-excess	8	−2.9	−1.5	−1.8	0.5	−1.9	1.74	−27.78

NB: Units for all elements are reported in mg/L, except EC (μS/cm); pH and SAR are unitless; salinity (%), ORP (mv); and $\delta^{18}O$, δD, and d-excess are dimensionless ratios expressed in parts per thousand used as per mil (‰). †For ICP-OES analysis of trace elements, n is the number of samples with confirmed detections out of the 16 samples analyzed, where a confirmed detection is a resolved emission peak at the analyte wavelength. ND = not detected; NC = not calculated. ND values were not replaced with zero or unresolved numerical instrument outputs. Summary statistics were calculated from confirmed detections only. Skewness was calculated from detected values only and should be interpreted cautiously for elements detected in few samples; it is shown as NC where it could not be calculated. Due to an unexpected field meter malfunction in the field during the June 2025 sampling event, we were unable to collect EC, TDS, Salinity, and ORP data. Consequently, n = 8 for these parameters represents only the July 2025 sampling. For pH, nutrients and other parameters including major ions, data are available for both June and July 2025, yielding n = 16. Isotope samples were collected only during the rainy season (n = 8).

Among the dissolved nutrients, dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) averaged 2.36 ± 0.38 $mg \cdot L^{-1}$ and 0.46 ± 0.09 $mg \cdot L^{-1}$, respectively, with moderate spatial variability (CV = 16.2% - 18.5%). In contrast, dissolved inorganic nitrogen (DIN) and ammonium (NH_4^+) varied considerably among sampling sites (CV > 80%), indicating localized differences in nitrogen availability and biogeochemical activity. Dissolved organic nitrogen (DON) formed a relatively stable component of the dissolved nitrogen pool, although moderate spatial variation was also observed. Major ions occurred at generally low concentrations, consistent with the diluted nature of the lake water. Sodium, magnesium, and calcium showed low to moderate variability (CV = 12% - 23%), whereas chloride, sulfate, and bromide were more variable (CV > 50%). Nitrate displayed the greatest spatial heterogeneity (CV = 276%) and a strongly right-skewed distribution (skewness = 3.702), indicating that elevated concentrations were confined to only a few sampling locations. In contrast, orthophosphate concentrations remained relatively consistent across the lake (CV = 16.5%).

The mean SAR was low (0.249 ± 0.036), indicating excellent irrigation suitability with negligible sodicity risk. Oxidation-reduction potential (ORP) showed the greatest variability among the measured physicochemical variables (CV = 102.8%), reflecting differences in redox conditions among sampling sites. Trace element concentrations were generally low throughout the lake. Arsenic, nickel, lead, and selenium were not detected in any sample, whereas cadmium, cobalt, chromium, and

antimony were detected only occasionally (2 - 6 of the 16 samples). Iron, zinc, and copper were detected in most or all samples. Among these consistently detected elements, copper showed the greatest variability (CV = 63.6%) and a strongly right-skewed distribution (skewness = 2.145), indicating elevated concentrations at only a few sites. Iron exhibited moderate variability (CV = 29.8%) with an approximately symmetric distribution (skewness = −0.093), while zinc showed the least variation (CV = 12.1%) and only slightly positive skewness (0.784). For the less frequently detected elements, chromium, cobalt, and antimony displayed relatively low variability where detected (CV = 2.5% - 17.0%), and the two cadmium measurements were nearly identical (CV = 0.3%).

Trace element concentrations were evaluated against the World Health Organization (WHO) drinking-water guidelines (2026) [39] and the Food and Agriculture Organization (FAO) recommended limits for irrigation water [40]. Arsenic, nickel, lead, and selenium were excluded from the comparison because they were not detected. Iron, zinc, copper, chromium, and cobalt were all well below both WHO drinking-water guidelines and FAO irrigation limits. Cadmium was detected in two samples at approximately 0.006 mg/L, slightly exceeding the WHO guideline value of 0.003 mg/L, and antimony exceeded the WHO guideline of 0.020 mg/L in two samples (0.022 and 0.025 mg/L). Both cadmium concentrations remain below the FAO irrigation guideline of 0.01 mg/L, and no FAO irrigation guideline is available for antimony. Because the Cd and Sb concentrations were close to their analytical quantification limits, these results should be interpreted cautiously. Overall, the trace element data provides little evidence of widespread metal contamination, though future analyses using lower detection limits would help confirm the observed cadmium and antimony concentrations.

The composition of water isotopes, δD and δ^{18}O, in the surface waters of Bedkot Lake showed no significant spatial variations at the time of sampling. The mean values were relatively high (−33.7‰ ± 0.3‰ for δD and −3.96‰ ± 0.10‰ for δ^{18}O) compared to available regional meteoric water (−47.6‰ ± 48.0‰ for δD; −7.13‰ ± 5.75‰ for δ^{18}O) and river water (−71.4‰ ± 10.0‰ for δD and −10.60‰ ± 1.20‰ for δ^{18}O). The d-excess of −2.0‰ ± 0.5‰ was significantly lower than in local meteoric water (9.4‰ ± 5.8‰) and river water (13.4‰ ± 1.3‰). These isotopic features indicate that evaporation is a dominating control on the water balance of Bedkot, and they confirm observations from other endorheic lakes in Central Asia such as Qinghai Lake [41] and Ebinur Lake [42]. The Bedkot Lake evaporation line ($R^2 = 0.90$) is defined as:

$$\delta D = 2.58 \times \delta^{18}O - 23.45$$

The Bedkot Lake evaporation line intersects the local meteoric water line at δD = −39.2‰ and δ^{18}O = −6.12‰, which provides a first-order approximation of the mean meteoric water composition at Bedkot Lake (**Figure 2**). These values are slightly higher than the mean meteoric water composition of precipitation at Ghalegaun and consistent with the altitudinal difference between the sites and any differences in meteoric water provenance.

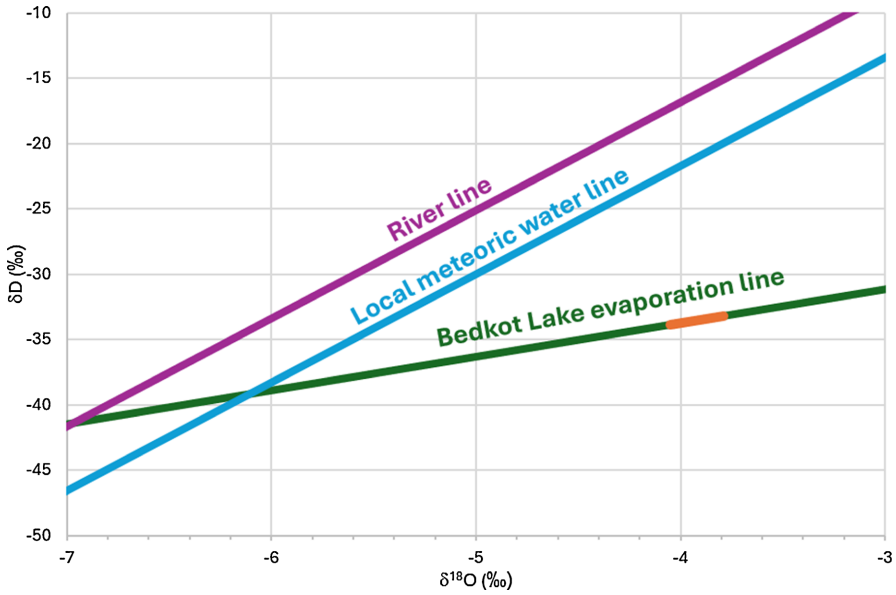

Figure 2. Co-isotope plot ($\delta^{18}O$, δD) showing the Bedkot Lake evaporation line (green) compared to the local meteoric water line ($\delta D = 8.29 \times \delta^{18}O + 11.47$) at Ghalegaun (blue), and the river line ($\delta D = 8.27 \times \delta^{18}O + 16.29$) of Narayani River (purple). The orange line marks the range of the samples collected at Bedkot Lake.

Overall, the hydrochemical and isotopic results indicate that Bedkot Lake is a relatively stable freshwater system with limited spatial variation in most physico-chemical characteristics. Localized variability in nutrients, selected trace elements, and redox conditions points to site-specific biogeochemical processes, while the isotope data identify evaporation as a major control on the lake's water balance.

4.2. Carbon-Nitrogen-Phosphorus Stoichiometry and Dissolved Organic-Inorganic Nutrient Dynamics in Bedkot Lake

Table 2 summarizes three stoichiometric indicators, DOC:TDN, DIN:DON, and TDN:PO_4 (N:P), that characterize carbon-nitrogen coupling, nitrogen partitioning, and nutrient balance in Bedkot Lake. These ratios are widely used to evaluate nutrient availability, organic matter sources, nutrient limitation, and biogeochemical functioning in freshwater ecosystems. Together, they provide insight into the relative importance of organic and inorganic nutrient pools and the processes regulating nutrient cycling within the lake.

Table 2. Descriptive statistics of carbon-nitrogen-phosphorus stoichiometric ratios (DOC: TDN, DIN: DON, and TDN: PO_4) in Bedkot Lake.

Ratio	n	Min	Max	Mean	SD	Median	Skewness	CV (%)
DOC:TDN	16	4.312	6.069	5.146	0.526	5.229	0.171	10.23
DIN:DON	16	0.007	1.234	0.434	0.427	0.330	0.575	98.43
TDN:PO_4	16	11.986	83.010	39.642	19.417	35.285	0.752	48.982

1) DOC:TDN Ratio: The DOC:TDN ratio ranged from 4.31 to 6.07, with a

mean of 5.15 ± 0.53 and a median of 5.23. Spatial variation was low (CV = 10.23%), and the distribution was nearly symmetric (skewness = 0.171), indicating that the relationship between dissolved organic carbon and total dissolved nitrogen remained consistent throughout the lake.

The DOC:TDN ratio is commonly used to assess the composition and origin of dissolved organic matter. Higher values generally indicate greater inputs of carbon-rich terrestrial material, whereas lower values are more typical of organic matter produced within the lake through algal and microbial activity. The average ratio of approximately 5 suggests that dissolved organic matter in Bedkot Lake is derived from both watershed inputs and in-lake biological production. Given the largely forested and minimally disturbed catchment, terrestrial organic matter likely contributes substantially to the dissolved organic pool, while biological processing within the lake also appears to play an important role. The limited spatial variation in this ratio indicates relatively stable carbon-nitrogen stoichiometry across the lake despite localized differences in DOC and nitrogen concentrations. The stability is consistent with freshwater systems where nutrient recycling and microbial decomposition maintain a balanced organic nutrient pool.

2) DIN:DON Ratio: The DIN:DON ratio showed much greater spatial variation than the DOC:TDN ratio, ranging from 0.007 to 1.234 with a mean of 0.434 ± 0.427 (CV = 98.43%). The moderate positive skewness (0.575) indicates that elevated inorganic nitrogen occurred at only a few sampling locations.

Values below one indicate that dissolved organic nitrogen exceeds dissolved inorganic nitrogen. The observed mean ratio therefore shows that DON was the dominant dissolved nitrogen form throughout Bedkot Lake. This pattern is consistent with relatively low external nitrogen loading and suggests that nitrogen cycling is driven primarily by organic matter decomposition and microbial mineralization rather than by direct inputs of inorganic nitrogen. The large spatial variability further indicates that nitrogen transformation is not uniform across the lake. Areas with higher DIN:DON ratios may reflect localized mineralization, nitrification, sediment-water exchange, or watershed inputs, whereas lower ratios indicate stronger dominance of organic nitrogen.

3) TDN:PO_4 Ratio: The TDN: PO_4 ratio ranged from 11.99 to 83.01, with a mean of 39.64 ± 19.42 and a median of 35.29. The relatively large coefficient of variation (48.98%) demonstrates considerable spatial variability in the balance between dissolved nitrogen and phosphorus.

The TDN: PO_4 ratio is used to assess nutrient limitation in freshwater ecosystems. Although threshold values differ among systems and dissolved nutrient ratios should be interpreted cautiously, higher values generally indicate greater phosphorus limitation, whereas lower values suggest relatively greater nitrogen limitation. The mean ratio of approximately 40 therefore indicates that phosphorus was likely the more limiting nutrient across much of Bedkot Lake.

This interpretation is supported by the relatively low orthophosphate concentrations reported in Section 4.1. At the same time, the broad range of observed

values suggests that nutrient balance varies among sampling sites. Lower TDN: PO_4 ratios may reflect localized phosphorus release through sediment interactions, aquatic vegetation decomposition, or internal nutrient regeneration, whereas higher ratios indicate reduced phosphorus availability or greater nitrogen retention.

Overall Stoichiometric Interpretation: Taken together, the three stoichiometric indicators provide a consistent picture of nutrient dynamics in Bedkot Lake. The stable DOC:TDN ratio indicates strong coupling between dissolved organic carbon and nitrogen pools across the lake. The low average DIN:DON ratio shows that dissolved organic nitrogen is the dominant nitrogen form, highlighting the importance of internal nutrient recycling and organic matter decomposition. In contrast, the relatively high and spatially variable TDN: PO_4 ratio suggests that phosphorus availability may impose a stronger constraint on biological productivity than nitrogen under current conditions. Overall, the stoichiometric evidence indicates that Bedkot Lake remains a relatively stable freshwater ecosystem in which nutrient cycling is governed primarily by internal biogeochemical processes rather than by substantial external nutrient enrichment.

4.3. Correlation Matrix among Stoichiometric Ratios and Their Source Variables

Table 3 presents Pearson correlation coefficients among dissolved nutrient fractions (DOC, TDN, DIN, DON, and PO_4) and the derived stoichiometric indicators (DOC:TDN, DIN:DON, and TDN:PO_4). These relationships complement the descriptive results in Section 4.2 by identifying associations among nutrient pools and the processes regulating nutrient cycling in Bedkot Lake.

Table 3. Pearson correlation matrix of stoichiometric indicators and dissolved nutrient fractions in Bedkot Lake.

Variable	DOC	TDN	DIN	DON	PO_4	DOC:TDN	DIN:DON	TDN:PO_4
DOC	1							
TDN	0.840*	1						
DIN	−0.322	−0.231	1					
DON	0.737*	0.776*	−0.793*	1				
PO_4	−0.134	0.084	−0.263	0.221	1			
DOC:TDN	0.038	−0.505*	−0.112	−0.240	−0.300	1		
DIN:DON	−0.396	−0.353	0.957*	−0.841*	−0.239	−0.026	1	
TDN:PO_4	0.285	0.099	0.043	0.034	−0.523*	0.225	0.075	1

Note: * = Correlation is significant at <0.05 level (2-tailed).

DOC was strongly and positively correlated with both DON (r = 0.737, p = 0.001) and TDN (r = 0.840, $p < 0.001$), indicating close coupling between dissolved organic carbon and nitrogen pools (Figure 3 and Figure 4). The positive relationship between DOC and DON suggests that organic carbon production and de-

composition are closely linked to organic nitrogen dynamics, whereas the association with TDN reflects the important contribution of dissolved organic matter to the total nitrogen pool. The regression models further support these relationships, as DON increased by 0.27 mg/L for every 1 mg/L increase in DOC (R^2 = 0.543; Figure 3), while TDN increased by 0.19 mg/L per 1 mg/L increase in DOC (R^2 = 0.705; Figure 4).

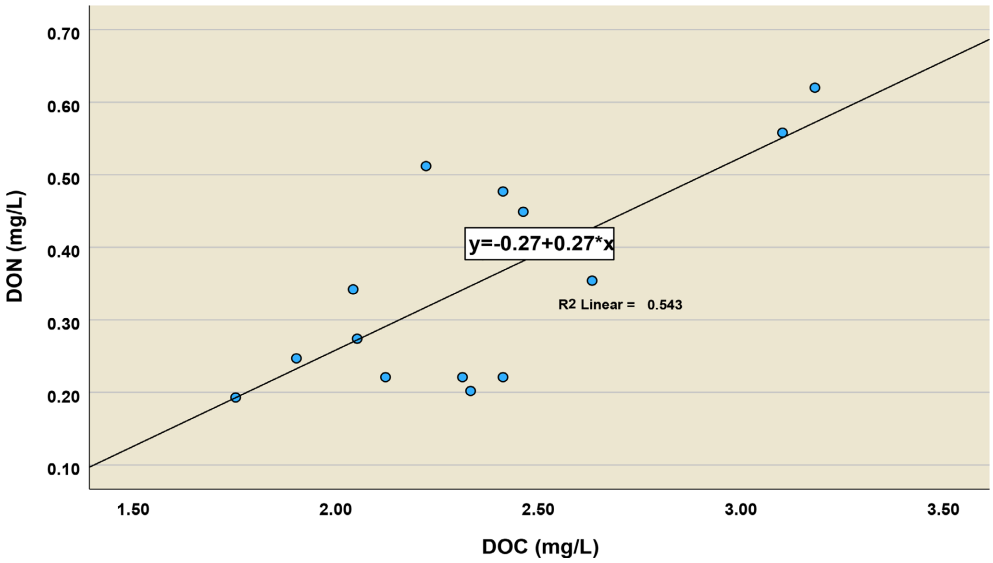

Figure 3. Relationship between DON and DOC in Bedkot Lake.

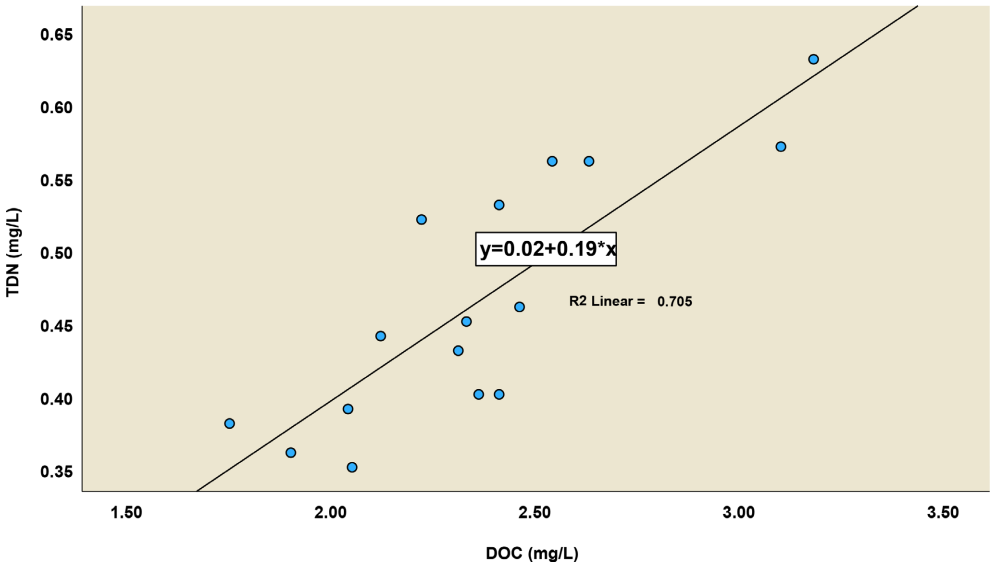

Figure 4. Relationship between TDN and DOC in Bedkot Lake.

The nitrogen fractions showed clear evidence of internal transformation. DIN was strongly and negatively correlated with DON (r = −0.793, $p < 0.001$), indicating that sites with higher inorganic nitrogen generally contained lower concentrations of dissolved organic nitrogen. This inverse relationship is consistent with active nitrogen cycling through mineralization, nitrification, assimilation, and mi-

crobial recycling.

As expected, the DIN: DON ratio was closely associated with its component variables. It was strongly and positively correlated with DIN (r = 0.957, $p < 0.001$) and negatively correlated with DON (r = −0.841, $p < 0.001$). Regression analysis showed that the DIN: DON ratio increased by 4.54 units for every 1 mg/L increase in DIN ($R^2 = 0.916$; Figure 5), whereas it decreased by approximately 2.6 units for every 1 mg/L increase in DON ($R^2 = 0.706$; Figure 6). These findings support the

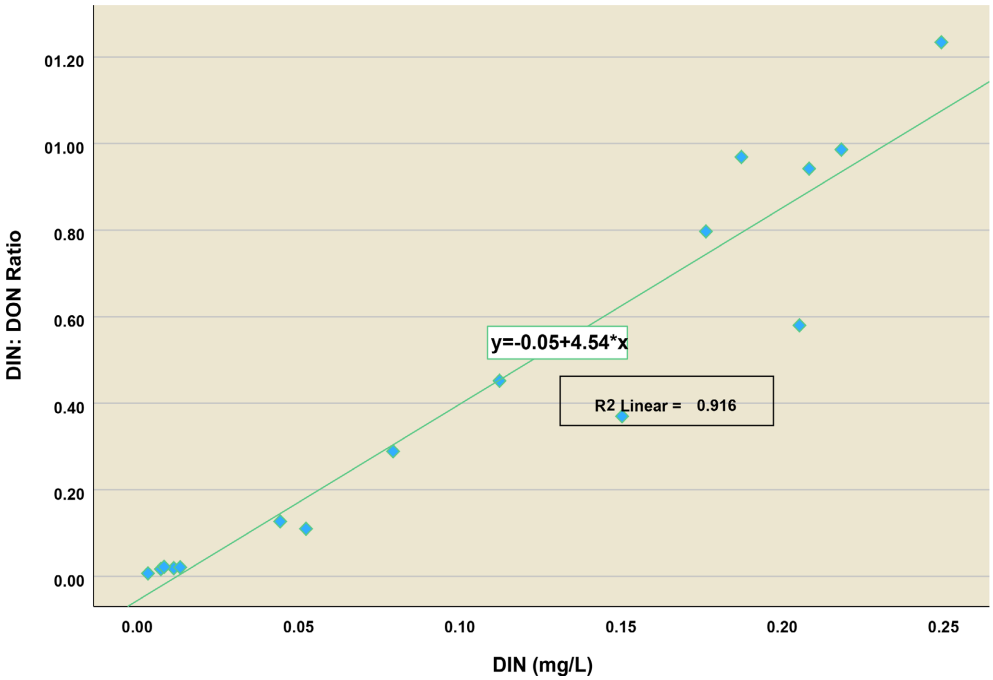

Figure 5. Relationship between DIN: DON Ratio and DIN in Bedkot Lake.

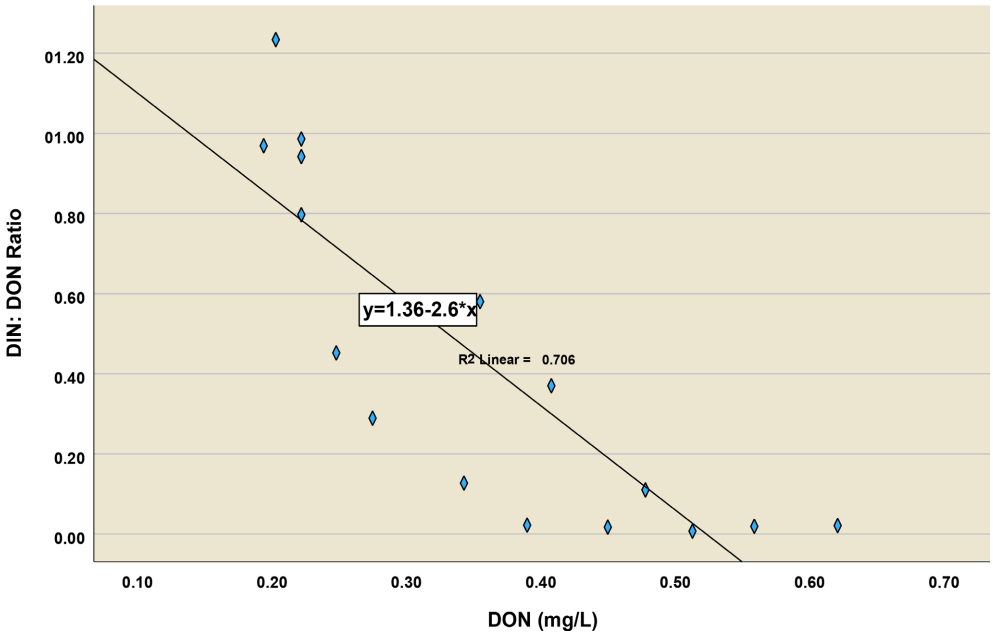

Figure 6. Relationship between DIN: DON Ratio and DON in Bedkot Lake.

conclusion that spatial variation in the DIN:DON ratio primarily reflects shifts between inorganic and organic nitrogen pools.

In contrast, the relationship between the DOC: TDN and DIN:DON ratios was weak and not statistically significant (r = −0.026). This suggests that variations in dissolved organic carbon relative to total dissolved nitrogen were largely independent of localized changes in inorganic nitrogen dominance. Carbon-nitrogen stoichiometry therefore remained comparatively stable despite spatial heterogeneity in nitrogen transformation. Phosphorus exhibited a different pattern. The TDN:PO_4 ratio was negatively correlated with phosphate concentration (r = −0.523, p = 0.038), indicating that increasing phosphate availability reduced the relative dominance of nitrogen. In contrast, the N:P ratio showed only weak associations with TDN (r = 0.099), DIN (r = 0.043), and DON (r = 0.034), suggesting that spatial variability in nutrient balance was influenced more by phosphorus availability than by changes in dissolved nitrogen.

The DOC:TDN ratio was moderately and negatively correlated with TDN (r = −0.505, p = 0.046) but showed practically no relationship with DOC concentration (r = 0.038). This indicates that variation in the ratio was driven primarily by differences in dissolved nitrogen rather than dissolved organic carbon. Overall, the correlation analysis supports the stoichiometric interpretation presented in Section 4.2. Dissolved organic carbon and nitrogen were tightly coupled, dissolved organic nitrogen represented the dominant nitrogen pool, and phosphorus availability appeared to increase influence on nutrient balance than nitrogen enrichment. This points to internal biogeochemical cycling, rather than external nutrient loading, as the principal mechanism regulating nutrient dynamics in Bedkot Lake.

4.4. Exploratory Multivariate Assessment of Controls on Stoichiometric Variability in Bedkot Lake

Because the dataset was limited (n = 16), bootstrap resampling (1000 iterations) was used to improve the stability of regression estimates and reduce sensitivity to sampling variability. Final models were developed using backward elimination to retain only ecologically meaningful predictors while minimizing overfitting. Owing to missing observations for several variables, SPSS applied listwise deletion, resulting in an effective sample size of eight complete cases for all regression analyses. The models are intended to identify potential ecological relationships rather than provide predictive equations, and their results should be interpreted with appropriate caution.

4.4.1. Regression Analysis of the DIN:DON Ratios

To examine factors associated with inorganic nitrogen dominance, the DIN:DON ratio was modeled as a function of DOC, TDN, oxidation-reduction potential (ORP), pH, and phosphate (PO_4):

$$\widehat{\text{DIN Ratio}} = -6.37 - 0.514\,(\text{DOC}) + 9.21(\text{TDN}) - 0.01(\text{OPR}) + 0.68\,(\text{pH}) - 4.396\,(PO_4)$$

Note: Regression analyses were based on eight complete cases after listwise exclusion of observations with missing values (*effective n* = 8).

The model accounted for 62.5% of the observed variation in the DIN:DON ratio ($R^2 = 0.625$). However, neither the overall regression ($p = 0.692$) nor any individual predictor reached statistical significance. Although these results do not support a reliable predictive model, the coefficient directions provide useful ecological context. Positive coefficients for TDN and pH suggest that higher dissolved nitrogen concentrations and slightly more alkaline conditions may favor greater inorganic nitrogen dominance. In contrast, negative coefficients for DOC and PO_4 indicate that increasing organic carbon or phosphate availability is associated with lower DIN: DON values and greater relative importance of dissolved organic nitrogen. ORP contributed little to the fitted model.

These findings are consistent with the correlation analysis (Section 4.3), indicating that nitrogen partitioning in Bedkot Lake reflects the combined influence of several interacting biogeochemical processes, including organic matter decomposition, microbial transformation, and nutrient recycling, rather than a single controlling factor.

4.4.2. Regression Analysis of the TDN:PO_4 (N:P) Ratio

A second regression model was developed to examine factors influencing the TDN:PO_4 (N:P) ratio using DOC, DIN, DON, and electrical conductivity (EC) as explanatory variables:

$$\widehat{\text{N : P Ratio}} = 666.06 + 27.79\,(\text{DOC}) - 130.28\,(\text{DIN}) - 321.90\,(\text{DON}) - 2.73\,(\text{EC})$$

Note: Regression analyses were based on eight complete cases after listwise exclusion of observations with missing values (effective n = 8).

This model explained 52.4% of the spatial variation in the N:P ratio ($R^2 = 0.524$), although the overall regression was not statistically significant ($p = 0.586$). Despite the lack of statistical significance, the regression coefficients provide insight into possible nutrient interactions. The positive DOC coefficient suggests that greater dissolved organic carbon may be associated with higher N:P values, whereas the negative coefficients for DIN, DON, and EC indicate an inverse relationship with the modeled ratio. DON exhibited the largest coefficient, implying that dissolved organic nitrogen may contribute more strongly to variation in nutrient balance than inorganic nitrogen within this dataset. Together with the correlation results presented in Sections 4.2 and 4.3, these findings suggest that nutrient balance in Bedkot Lake is influenced by interactions among dissolved organic matter, nitrogen transformation, and phosphorus availability rather than by a single environmental variable.

4.4.3. Regression Analysis of the DOC:TDN Ratio

The final regression model evaluated whether major ions associated with watershed inputs influenced the DOC:TDN ratio. Chloride, sulfate, sodium, magnesium, and calcium were included as predictor variables because they may reflect

weathering processes, hydrological transport, and catchment-derived inputs.

The fitted regression equation was:

$$\widehat{\text{DOC Ratio}} = 6.625 - 0.177\,(\text{Cl}) - 10.913\,(\text{SO}_4) - 0.036\,(\text{Na}) - 0.140\,(\text{Mg}) + 0.026\,(\text{Ca})$$

Note: Regression analyses were based on eight complete cases after listwise exclusion of observations with missing values (effective n = 8).

The model explained 33.2% of the observed variation ($R^2 = 0.332$) and was not statistically significant ($p = 0.467$). None of the individual predictors achieved statistical significance. Although exploratory, the coefficient estimates suggest that increasing concentrations of chloride, sulfate, sodium, and magnesium were associated with lower DOC: TDN values, whereas calcium showed a weak positive relationship. Sulfate had the largest negative coefficient, indicating a potentially stronger association with reduced carbon relative to nitrogen than the other major ions.

Overall, the results provide little evidence that spatial variation in dissolved organic matter composition is controlled primarily by watershed-derived ionic chemistry. Instead, they support the interpretation developed in the preceding sections that DOC: TDN remains comparatively stable across the lake and is regulated mainly by internal ecological processes such as organic matter production, decomposition, nutrient regeneration, and microbial cycling.

4.5. Principal Component Analysis of Nutrient Stoichiometry and Hydrochemical Controls in Bedkot Lake

Principal Component Analysis (PCA) was performed to identify the major environmental gradients underlying nutrient stoichiometry and hydrochemical variability in Bedkot Lake. The analysis included dissolved nutrient fractions (DOC, TDN, DIN, DON, PO_4, and NH_4) together with selected major ions (Cl, SO_4, Na, Mg, and Ca).

The suitability of the dataset for PCA was confirmed by a Kaiser-Meyer-Olkin (KMO) value of 0.529, indicating acceptable sampling adequacy for exploratory analysis, and a highly significant Bartlett's Test of Sphericity ($\chi^2 = 223.033$, df = 55, $p < 0.001$), demonstrating sufficient correlation among variables. Because hydrochemical and nutrient processes are expected to be interrelated, an oblique (Oblimin) rotation with Kaiser normalization was applied. The resulting component correlation matrix indicated only weak to moderate relationships among the extracted components, supporting the interpretation of distinct but related environmental gradients.

PC1: Organic Nutrient and Biogeochemical Processing Gradient: The first principal component was dominated by strong positive loadings for TDN (0.949), DOC (0.939), DON (0.798), and Mg (0.754), with a moderate contribution from Na (0.528). This component represents the primary organic nutrient gradient within the lake and reflects the close coupling between dissolved carbon and nitrogen pools.

The strong loadings of DOC, DON, and TDN are consistent with the correlation and stoichiometric analyses presented in Sections 4.2 and 4.3, indicating that internal organic matter production, microbial decomposition, and nutrient recycling are the dominant processes regulating nutrient availability. The contributions of magnesium and sodium suggest that mineral inputs accompany, but do not control, these biological processes.

PC2: Hydrochemical and Phosphorus Gradient: The second component was characterized by high positive loadings for chloride (0.955), sulfate (0.887), sodium (0.883), and phosphate (0.824), together with smaller contributions from TDN and DON.

This component reflects a hydrochemical gradient associated with watershed-derived dissolved ions and phosphorus availability. The grouping of phosphate with the major ions suggests that phosphorus distribution is linked to hydrochemical conditions rather than behaving independently. This interpretation agrees with earlier analyses showing that variation in the N:P ratio is influenced more strongly by phosphorus availability than by changes in dissolved nitrogen concentrations.

PC3: Relative Nitrogen Transformation Gradient: The third principal component showed strong positive loadings for NH_4 (0.942) and DIN (0.899), accompanied by negative loadings for DON (−0.756), Mg (−0.576), and Ca (−0.585).

This component distinguishes reactive inorganic nitrogen from the dominant organic nitrogen pool and likely represents localized nitrogen transformation processes such as mineralization, ammonification, and nitrification. The opposing loadings of DIN and DON further support the inverse relationship identified in the correlation analysis, indicating that inorganic nitrogen enrichment occurred only at selected locations rather than throughout the lake.

Overall, the PCA identified three complementary environmental gradients governing nutrient dynamics in Bedkot Lake: 1) internal organic matter cycling and carbon-nitrogen coupling (PC1), 2) hydrochemical variability associated with phosphorus availability (PC2), and 3) localized reactive nitrogen transformation (PC3). These components reinforce the conclusions drawn from the stoichiometric, correlation, and regression analyses, demonstrating that nutrient dynamics are controlled primarily by interacting internal biogeochemical processes together with secondary watershed influences. Table 4 presents the component correlation matrix obtained from the obliquely rotated PCA.

Table 4. Component correlation matrix from the obliquely rotated principal component analysis.

Component Correlation Matrix			
Component	1	2	3
1	1		
2	0.136	1	
3	−0.331	−0.248	1.000

The component correlations were generally weak, indicating that each principal component represents a distinct aspect of ecosystem functioning. PC1 and PC2 showed only a weak positive association ($r = 0.136$), suggesting limited overlap between internal nutrient cycling and hydrochemical controls. PC1 was moderately and negatively correlated with PC3 ($r = -0.331$), indicating that sites characterized by strong organic nutrient coupling tended to exhibit less pronounced reactive inorganic nitrogen dynamics. Similarly, the weak negative correlation between PC2 and PC3 ($r = -0.248$) suggests that hydrochemical variability and localized nitrogen transformation are only partially connected.

These modest component correlations indicate that the three principal components describe complementary, rather than redundant, ecological processes. Organic matter cycling, hydrochemical conditions, and reactive nitrogen transformation therefore represent separate but interacting controls on nutrient stoichiometry in Bedkot Lake.

The scree plot (Figure 7) showed a distinct decline in eigenvalues after the fourth component. According to the Kaiser criterion (eigenvalues > 1), four components could be retained because the fourth component had an eigenvalue of approximately 1.0. However, the first three components explained most of the total variance and were considered sufficient for ecological interpretation.

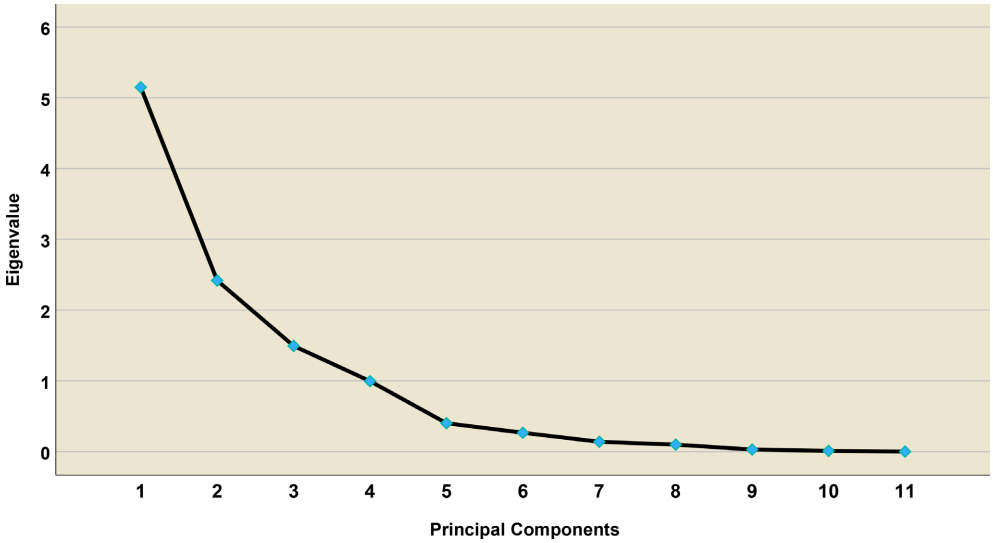

Figure 7. Scree plot of eigenvalues from the principal component analysis.

4.6. Partial Correlation Analysis of Nutrient Stoichiometry and Nutrient Controls in Bedkot Lake

Partial correlation analysis was conducted to determine whether the relationships among dissolved nutrient fractions and stoichiometric indicators remained after accounting for the influence of selected environmental variables (Table 5). Unlike Pearson correlation, partial correlation evaluates the direct association between two variables while controlling the effects of a third variable, providing additional insight into the mechanisms governing nutrient cycling in Bedkot Lake as shown

in Table 5.

Table 5. Partial correlation coefficients among stoichiometric indicators and dissolved nutrient fractions after controlling selected nutrient variables.

Partial correlation (a↔b)	Control variable (c)	Partial $r_{ab.c}$	*p*-value
DIN: DON ↔ N:P	PO_4	−0.060	0.831
DOC ↔ DON	TDN	0.250	0.368
DOC: TDN ↔ DIN: DON	DOC	−0.012	0.967
TDN ↔ PO_4	DOC	0.366	0.179
DIN ↔ NH_4	DON	0.685	0.005
DOC:TDN ↔ DIN:DON	PO_4	0.083	0.768

After controlling for phosphate concentration, the association between the DIN:DON ratio and the TDN:PO_4 (N:P) ratio was weak and not statistically significant (partial $r = -0.060$, $p = 0.831$). This result indicates that inorganic versus organic nitrogen partitioning contributed little to overall nutrient balance once the influence of phosphorus was removed, supporting earlier evidence that phosphorus availability plays a central role in regulating nutrient stoichiometry within the lake.

The positive correlation between DOC and DON persisted after controlling for TDN (partial $r = 0.250$, $p = 0.368$), although the relationship was not statistically significant. This finding suggests that coupling between dissolved organic carbon and organic nitrogen extends beyond their shared dependence on total dissolved nitrogen, consistent with the role of organic matter production and decomposition in sustaining nutrient cycling.

Controlling for DOC produced virtually no relationship between the DOC: TDN and DIN: DON ratios (partial $r = -0.012$, $p = 0.967$). This confirms that spatial variation in carbon-nitrogen stoichiometry was largely independent of localized shifts between inorganic and organic nitrogen forms. Similarly, the partial correlation between TDN and phosphate remained positive but non-significant after accounting for DOC (partial $r = 0.366$, $p = 0.179$), indicating only weak direct coupling between dissolved nitrogen and phosphorus once variation associated with organic carbon was removed.

Among all relationships examined, only the association between DIN and NH_4 remained statistically significant after controlling for DON (partial $r = 0.685$, $p = 0.005$). The persistence of this strong positive relationship indicates that inorganic nitrogen species are closely linked through internal nitrogen transformation processes, including mineralization, ammonification, and nutrient regeneration, rather than simply reflecting variation in dissolved organic nitrogen.

Likewise, controlling for phosphate produced only a weak and non-significant relationship between the DOC: TDN and DIN: DON ratios (partial $r = 0.083$, $p = 0.768$), indicating that phosphorus availability did not substantially alter the asso-

ciation between carbon-nitrogen stoichiometry and nitrogen partitioning. Overall, the partial correlation analysis showed that most pairwise relationships weakened after shared nutrient effects were removed, suggesting that nutrient dynamics in Bedkot Lake arise from multiple interacting biogeochemical processes rather than simple linear associations. The only robust independent relationship was observed between DIN and NH_4, emphasizing the importance of internal nitrogen transformation. Together with the stoichiometric, correlation, regression, and PCA results, these findings indicate that internal nutrient cycling and localized biogeochemical processes exert stronger control on ecosystem functioning than external nutrient enrichment.

4.7. Statistical Procedures and Diagnostic Assessment

All statistical analyses were performed using the latest version of IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). Statistical significance was evaluated at the 5% level ($p < 0.05$). Because several multivariate analyses were based on a limited number of complete observations (effective $n = 8$), bootstrap resampling with 1,000 replications and bias-corrected 95% confidence interval was employed to improve the stability and robustness of parameter estimates.

Pearson correlation, multiple linear regression, principal component analysis (PCA), and partial correlation analyses were subsequently conducted. Prior to PCA, all variables were standardized to Z-scores (mean = 0, standard deviation = 1) to remove the influence of differing measurement scales. The suitability of the dataset for PCA was assessed using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. Principal components with eigenvalues greater than 1.0 were retained and interpreted following *Oblimin rotation with Kaiser normalization,* allowing for potential correlations among the extracted components.

Diagnostic procedures were performed to evaluate the assumptions underlying the statistical analyses. For Pearson correlation and multiple regression, linearity, homoscedasticity, independence of observations, and the absence of influential outliers were assessed using scatterplots and standardized residual diagnostics. Multicollinearity among predictor variables was evaluated using tolerance values and variance inflation factors (VIF). For partial correlation analysis, linearity and the approximate normality of residual relationships were also examined before interpreting the results.

5. Conclusions

Biogeochemical controls on carbon-nitrogen-phosphorus (C-N-P) and nutrient dynamics were evaluated within Bedkot Lake in the Chure region of far-western Nepal. The observed pattern shows that the nutrient regulation is primarily driven by internal biogeochemical cycling rather than external watershed loading in a significantly evaporation-dominated Bedkot Lake during summer-monsoon, suggesting potential phosphorus limitation. The dissolved organic carbon and total

dissolved nitrogen (DOC:TDN) ratios remain highly consistent across the lake, indicating stable organic matter production and balance coupling with nitrogen processing. On the contrary, uneven distribution of dissolved inorganic nitrogen and dissolved organic nitrogen (DIN:DON) ratios highlights highly localized variations in nitrogen transformation. The dominance of organic pathways over direct inorganic enrichment suggests that dissolved organic nitrogen functions as a critical reservoir, which is mineralized into bioavailable form through microbial processes over time. The structural stability of carbon and nitrogen processing is limited by summer-monsoon conditions where dissolved nitrogen availability consistently overshadows dissolved phosphorus, identifying phosphorus as the primary limiting element restricting the ecosystem.

Statistical analysis confirmed that biogeochemical dynamics are governed by a complex network of tightly coupled nutrient cycles and independent environmental gradients within Bedkot lake.

The principal component and correlation analyses reveal a strong connection within organic nutrient contrasted by a distinct separation from reactive dissolved inorganic nitrogen and ammonium. Such separation emphasizes active internal nutrient transformation and redistribution. Hydrochemical regulations arise from interacting ecological processes like microbial turnover, decomposition, nutrient regeneration, and hydrological redistribution. This research confirms that the lake is freshwater ecosystem sustained by organic matter processing and phosphorus control based on summer-monsoon data. Environmental assessment confirms water quality with safety standards for domestic and agricultural applications, showing no systematic trace metal contamination.

6. Future Research Recommendations

The present research provides only a summer-monsoon season assessment of C-N-P control and nutrient dynamics within the Bedkot Lake, but several opportunities remain for advancing detailed understanding of ecosystem functioning. Complete seasonal monitoring representing pre-monsoon, monsoon, post-monsoon and winter periods is recommended to evaluate temporal variability of nutrient dynamics throughout the annual hydrological cycle as seasonal observations would provide clearer insight into nutrient regulation within aquatic ecosystems.

Future research should integrate biological indicators including chlorophyll-a, phytoplankton composition, dissolved oxygen profile, and microbial activity to strengthen interpretation of nutrient limitation and ecosystem productivity. Sediment-water interaction studies would also improve our understanding of internal nutrient loading and phosphorus regeneration. Stable isotope approaches, including nitrogen isotope and dissolved organic matter characterization, may further distinguish between autochthonous and allochthonous nutrient sources.

Finally, long-term integrated monitoring of complete hydrochemistry, including nutrients, biological indicators, and watershed processes, is essential for understanding clear ecological processes and supporting the sustainable manage-

ment of Bedkot Lake under changing land use and climate conditions. The conservation of the Chure region is absolutely necessary for protecting regional water quality and stabilization of the broader environmental condition stretching into the lowland Terai area in the region. Implementing these integrated watershed-level policies is necessary to mitigate the compounding impacts of changing climatic patterns and shifting land-use dynamics.

Acknowledgements

The authors would like to thank Aaron Perez and Adriana Perez at the Center for Earth and Environmental Studies of Texas A & M International University for their help in producing the sampling area map (**Figure 1**). The authors thank Jody Potter and other members at the center for the analysis of major ions, nutrients, DOC and TDN at the New Hampshire Water Resources Research Center of the University of New Hampshire, and Bassam Saif at the Chemistry Department of Carroll College in Helena, Montana, for his support in the analysis of trace elements. Thanks also to Pål Tore Mørkved at the Department of Earth Science, University of Bergen, for analyzing the water isotope samples. The authors thank Binod Bhatt for his support during the sampling in the field. The authors acknowledge Texas A&M International University's support for this research. The authors thank the Editor and the anonymous reviewers for their careful evaluation of the manuscript and for their constructive and insightful comments. Their thoughtful suggestions have significantly improved the clarity, scientific rigor, organization, and overall quality of the manuscript. We would like to express our sincere thanks to the editorial office for their diligent work and assistance with our submission.

Author Contribution

MPB designed and implemented the project, conducted the chemistry data analysis, and led the manuscript writing, reviewing, and editing; GBM performed data analysis using multivariate modeling and contributed to writing, reviewing, and editing; BKK contributed to sample handling, reviewing, and editing; RAC analyzed trace element, participated in writing, reviewing and editing; SB assisted with chemistry data processing and participated in reviewing and editing; AAM contributed to methodology, writing, reviewing, and editing. JCY analyzed isotope data, participated in writing, reviewing, and editing.

Statement on AI-Assisted Language Editing

AI tools were used merely to polish the grammar of this manuscript. All research framework, data analysis and core conclusions are independently completed by the authors, and the text has been substantially revised to show the authors' original writing style.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] LRMP (1986) Land Resource Mapping Project. Summary Report 1986 Submitted to Then His Majesty's Government of Nepal by Kenting Earth Sciences Limited. Government of Canada.

[2] Hagen, T. (1998) Toni Hagen's Nepal: The Kingdom in the Himalaya. Himal Books, 251.

[3] Kansakar, S.R., Hannah, D.M., Gerrard, J. and Rees, G. (2004) Spatial Pattern in the Precipitation Regime of Nepal. *International Journal of Climatology*, **24**, 1645-1659. https://doi.org/10.1002/joc.1098

[4] WWF Nepal Program (2005) An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India, and China. Kathmandu, Nepal.

[5] Bhatt, M.P., Hartmann, J. and Acevedo, M.F. (2018) Seasonal Variations of Biogeochemical Matter Export along the Langtang-Narayani River System in Central Himalaya. *Geochimica et Cosmochimica Acta*, **238**, 208-234. https://doi.org/10.1016/j.gca.2018.06.033

[6] Jaishi, P.P., Budhathoki, S., Adhikari, L. and Neupane, A. (2024) Dynamics of Land Use Cover Change and Soil Erosion Rate in Chure Landscape of Sudurpaschim Province. *Journal of Ecology and Natural Resources*, **18**, Article 366.

[7] Upreti, B.N. (2001) The Physiography and Geology of Nepal and Landslide Hazards. Problem Mitigation to the Hindukush-Himalayas. ICIMOD.

[8] Ghimire, P. (2016) Chure Conservation Area: Lessons for the Management and Use of Natural and Biological Resources in Nepal. Case Study Report. South Asia Watch on Trade, Economics and Environment (SAWTEE).

[9] Uprety, Y., Tiwari, A., Karki, S., Chaudhary, A., Yadav, R.K.P., Giri, S., *et al.* (2023) Characterization of Forest Ecosystems in the Chure (Siwalik Hills) Landscape of Nepal Himalaya and Their Conservation Need. *Forests*, **14**, Article 100. https://doi.org/10.3390/f14010100

[10] DFRS (2015) District Forest Cover Maps of Nepal: Forest Resource Assessment (FRA). Department of Forest Research and Survey (DFRS), Ministry of Forest and Soil Conservation (MoFSC), Government of Nepal, Kathmandu, Nepal.

[11] Bhatt, M.P., Bhatt, S. and Gaye, B. (2013) Controls on Pond Water Chemistry within Kathmandu Valley, Nepal. *International Journal of Lakes and Rivers*, **6**, 153-172.

[12] Bhatt, M.P., Malla, G.B., Nuño, D.E., Bhatt, S. and Addo-Mensah, A. (2025) Spatio-Temporal Variations of Chemical Compositions through Empirical Modeling in Bartlett Pond, Laredo, Texas. *Journal of Water Resource and Protection*, **17**, 976-1003. https://doi.org/10.4236/jwarp.2025.1712051

[13] Mitsch, W.J. and Gosselink, J.G. (1993) Wetlands. 2nd Edition, Van Nostrand Reinhold.

[14] Osbourne, P.L. and Adcock, P.W. (1995) Creating Environmental Kidneys: Wetlands Ecosystems as Pollution Filters and Habitat Restoratives. *Wetlands Australia*, **14**, 37-43. https://doi.org/10.31646/wa.176

[15] Zedler, J.B. and Kercher, S. (2005) Wetland Resources: Status, Trends, Ecosystem Services, and Restorability. *Annual Review of Environment and Resources*, **30**, 39-74. https://doi.org/10.1146/annurev.energy.30.050504.144248

[16] Sharifi, A., Kalin, L., Hantush, H. and Isik, S. (2013) Wetlands: Earth's Kidneys. In: Lamar, J. and Lockaby, B.G., *Auburn Speaks*, Auburn University, 140-143.

[17] Xu, J., Grumbine, R.E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., *et al.* (2009)

The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods. *Conservation Biology*, **23**, 520-530. https://doi.org/10.1111/j.1523-1739.2009.01237.x

[18] Immerzeel, W.W., van Beek, L.P.H. and Bierkens, M.F.P. (2010) Climate Change Will Affect the Asian Water Towers. *Science*, **328**, 1382-1385. https://doi.org/10.1126/science.1183188

[19] Tartari, G., Tartari, G. and Mosello, R. (1998) Water Chemistry of High-Altitude Lakes in the Khumbhu and Imja Khola Valley, (Nepalese Himalaya). Limnology of High-Altitude Lakes in the Mt. Everest Region (Nepal). *Journal of Limnology*, **57**, 51-76.

[20] Bhatt, M.P., Bhatt, S. and Gaye, B. (2014) Controls on Gosaikunda Lake Chemistry within Langtang National Park in High Himalaya, Nepal. *International Journal of Geosciences*, **5**, 1100-1115. https://doi.org/10.4236/ijg.2014.510094

[21] Bhatt, M.P., Takeuchi, N. and Acevedo, M.F. (2016) Chemistry of Supraglacial Ponds in the Debris-Covered Area of Lirung Glacier in Central Nepal Himalayas. *Aquatic Geochemistry*, **22**, 35-64. https://doi.org/10.1007/s10498-015-9276-9

[22] Meybeck, M., Chapman, D.V. and Richard, H. (1990) Global Freshwater Quality: A First Assessment. Basil Blackwell, 306.

[23] Meybeck, M. (1998) Man and River Interface: Multiple Impacts on Water and Particulates Chemistry Illustrated in the Seine River Basin. In: *Oceans, Rivers and Lakes: Energy and Substance Transfers at Interfaces*, Springer, 1-20. https://doi.org/10.1007/978-94-011-5266-2_1

[24] Vörösmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B. (2000) Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science*, **289**, 284-288. https://doi.org/10.1126/science.289.5477.284

[25] Bhatt, M.P. and McDowell, W.H. (2007) Evolution of Chemistry along the Bagmati Drainage Network in Kathmandu Valley. *Water, Air, and Soil Pollution*, **185**, 165-176. https://doi.org/10.1007/s11270-007-9439-4

[26] Gavrilas, S., Burescu, F.L., Chereji, B.D. and Munteanu, F.D. (2025) The Impact of Anthropogenic Activities on the Catchment's Water Quality Parameters. *Water*, **17**, Article 1791. https://doi.org/10.3390/w17121791

[27] Neupane, P.K., Khadka, M., Adhikari, R. and Bhuju, D.R. (2010) Lake Water Quality and Surrounding Vegetation in Dry Churiya Hills, Far-Western Nepal. *Nepal Journal of Science and Technology*, **11**, 181-188. https://doi.org/10.3126/njst.v11i0.4142

[28] Samiti, R.S. (2017) 47 Natural Lakes in Kanchanpur of Far-West Nepal. International Collective in Support of Fishworkers.

[29] Singh, B.K. (2017) Land Tenure and Conservation in Chure. *Journal of Forest and Livelihood*, **15**, 87-102. https://doi.org/10.3126/jfl.v15i1.23092

[30] Department of Hydrology and Meteorology (2019) Hydro-Meteorological Data of Nepal, DHM, Government of Nepal, Kathmandu.

[31] American Society for Testing and Materials (2007) Analytical Methods for Cations, ASTM D 6919-03, West Conshohocken, PA.

[32] United States Environmental Protection Agency (2007) Method for the Determination of Anions, US EPA No. 300.1.

[33] United States Environmental Protection Agency (2005) Method for the Determination of Ammonium, US EPA No. 350.1.

[34] United States Environmental Protection Agency (2005) Method for the Determination of Phosphate, US EPA No. 365.1.

[35] United States Environmental Protection Agency (2002) Method for the Determination of Dissolved Organic Carbon, US EPA No. 415.1.

[36] Merriam, J., McDowell, W.H. and Currie, W.S. (1996) A High-Temperature Catalytic Oxidation Technique for Determining Total Dissolved Nitrogen. *Soil Science Society of America Journal*, **60**, 1050-1055. https://doi.org/10.2136/sssaj1996.03615995006000040013x

[37] United States Environmental Protection Agency (1991) Method for the Determination of Metals in Environmental Samples. EPA/600/4-91/010. Office of Research and Development, Washington, DC.

[38] Dansgaard, W. (1964) Stable Isotopes in Precipitation. *Tellus*, **16**, 436-468. https://doi.org/10.1111/j.2153-3490.1964.tb00181.x

[39] World Health Organization (2026) Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First, Second and Third Addenda. World Health Organization.

[40] Drechsel, P., Marjani Zadeh, S. and Pedrero, F. (2023) Water Quality in Agriculture: Risks and Risk Mitigation. FAO and IWMI.

[41] Liang, S., Guo, J., Wu, P., Feng, Y., Wang, X., Wang, G., *et al.* (2020) Hydrogeochemical and Isotopic Characteristics of Surface Water and Groundwater in the Qinghai Lake Catchment (China). *Arabian Journal of Geosciences*, **13**, Article No. 135. https://doi.org/10.1007/s12517-020-5103-8

[42] Zhu, S.D., Zhang, F., Zhang, Z.Y., *et al.* (2019) Hydrogen and Oxygen Isotope Composition and Water Quality Evaluation for Different Water Bodies in the Ebinur Lake Watershed, Northwestern China. *Water*, **11**, Article 2067. https://doi.org/10.3390/w11102067