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Research Article

Seasonal variations on physical features, water quality and vegetation in three key lakes of Far Western Nepal

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Abstract

Wetlands, especially lakes, are highly dynamic ecosystems with diverse ecological roles and significant economic benefits, including water purification, groundwater replenishment, nutrient retention and biodiversity conservation. This study assessed the hydrochemical characteristics, vegetation status and seasonal dynamics of three key wetlands: Ghodaghodi, Jokhar and Rani Lake, located in the lowland region of Sudurpashchim Province, Nepal. Hydrochemical analysis revealed that all measured parameters remained within WHO and National Drinking Water Quality Standards (NDWQS) guidelines; however, anthropogenic impacts, particularly in Jokhar Lake, led to elevated nitrate concentrations and reduced dissolved oxygen levels. Seasonal patterns showed increased temperature, electrical conductivity (EC), total dissolved solids (TDS), and nutrient concentrations during summer, likely due to runoff and increased human activities. The Water Quality Index (WQI) ranged from excellent in Rani Lake (WQI = 23.40-30.01) to moderately polluted in Jokhar Lake (WQI = 61.45-71.52), whereas Ghodaghodi showed excellent to moderately polluted status (WQI=41.01-51.12). Vegetation assessments revealed the highest species richness and diversity indices in Ghodaghodi Lake, followed by Jokhar and Rani lakes, with higher diversity attributed to complex landscapes and botanical garden proximity. Rani Lake, despite lower species diversity, maintained better water quality due to strict protection measures and minimal human interference. The study revealed significant seasonal variations in the water quality of all the study lakes. Ghodaghodi showed a reduced open water area and increased pollution in summer, Jokhar had high shoreline loss with moderate pollution year-round, while Rani remained stable with good water quality. Thus, the results underscore the importance of effective targeted conservation strategies to manage and preserve these unique wetland ecosystems. Additionally, this research also highlights the critical role of understanding and conserving wetlands under different management regimes in biodiversity conservation, water quality regulation under the context of global climate change.

Keywords: Hydrochemical variables, management regimes, vegetation dynamics, water quality, wetland ecosystems

Introduction

Wetlands, including swamps and marshes, are among the most productive ecosystems, often referred to as the "kidneys" of nature due to their role in maintaining ecological balance (Mirmazloumi *et al*., 2021). They act as visual interfaces between land and water (Ramachandra, 2008) and provide crucial ecological services such as carbon sequestration, water purification, sediment filtration, soil conservation, and habitats for diverse flora and fauna (Dordio *et al*., 2008; Knox *et al*., 2008; Trepel, 2010; Grazie and Gill, 2022). Additionally, wetland ecosystems support various ecological, economic, recreational activities and livelihood services (Ming *et al*., 2007; Mirmazloumi *et al*., 2021)

Recognizing their global importance, conservation efforts like the Ramsar Convention highlight the significance of wetlands in biodiversity protection and sustainable development, fostering collaboration among governments, scientists and local communities (Timalsina *et al*., 2025). Global climate change is projected to significantly affect wetland ecosystems, resulting in their degradation and modification. This poses greater challenges for wetland conservation and protection. Rising temperatures and reduced rainfall threaten the sustainability of existing water resources (Timalsina et al., 2025). Furthermore, climate change and increasing human activities have altered biodiversity and led to a decline in water quality, biodiversity loss and habitat degradation (Haig *et al*., 2019). Human-induced water quality changes introduce nutrients and pollutants like nitrogen, phosphorus, chloride, sulfate and sodium, leading to eutrophication and algal blooms (Smith et al., 1999; Paudel *et al*., 2022). Pollutants like heavy metals and trace elements accumulate in wetland organisms (bioaccumulation), disrupting trophic structures and posing ecological risks. These environmental pollutants adversely affect wetland flora and fauna, disrupting ecological balance, reducing biodiversity, and altering trophic interactions. Thus, the decline in wetland water quality and characteristics is an emerging issue for the sustainability of wetland ecosystems (Pant *et al*., 2021; Paudel *et al*., 2022).

Wetland ecosystems are dynamic and continuously evolving, characterized by intricate physical features, hydrochemical properties and diverse vegetation (Jing *et al*., 2023; Li *et al*., 2018). Morphological features such as shape, size, land cover and shoreline complexity influence hydrochemical and biological features (Sheela

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et al., 2011). Vegetation not only reflects the health of wetland ecosystems but also plays a vital role in mediating nutrient cycles and providing essential habitat for bird species (Addisu *et al.*, 2016). Additionally, the relationship between habitat structure and wetland bird assemblages shows the impact of habitat changes on community structure. Habitat structure is closely linked to avian assemblages, as recent studies show declines in water quality, vegetation diversity and populations of avifauna (Adhurya *et al.*, 2019; Ghosh & Das, 2020; Singha and Pal, 2023). Bird species richness, abundance, and guild composition are closely correlated with wetland size and the extent of open water surface area (Babbitt, 2000).

In Nepal, where wetlands span varied altitudes and ecological zones, these systems are increasingly at risk due to both natural and anthropogenic pressures, endangering the communities that depend on them (Neupane *et al.*, 2023; Timalsina et al., *2025*; Dahal *et al.*, 2025a, b). The degradation and reduction of wetlands lead to the loss of indigenous plant species, the encroachment of non-native flora and a decline in their ecological and socioeconomic value. Despite their importance, there is a notable lack of comprehensive data on these wetlands' physical characteristics, hydrochemistry, water quality and biotic composition. Sudurpashchim Province of Nepal, known for its diverse topography, climate, rich biodiversity, and cultural heritage, plays a vital role in sustaining and supporting wetland ecosystems. The lowland areas of the province, especially the districts of Kailali and Kanchanpur, are abundant in valuable wetland resources (Khatiwada *et al.*, 2021). These wetlands play a crucial role in supporting avifauna and sustaining local livelihoods by contributing to biodiversity conservation, water purification, and flood regulation. However, they are increasingly threatened by habitat degradation, water pollution and unsustainable resource exploitation, including the impacts of global climate change. This study evaluates the physical characteristics, hydrochemical profiles, and surrounding vegetation of Ghodaghodi, Jokhar and Rani Lakes to assess seasonal ecological changes and inform targeted wetland conservation strategies in the lowlands of Far Western region (Sudurpashchim Province), Nepal.

Materials and Methods

Study Area

The study focuses on the wetlands in the lowland region of Sudurpashchim Province, Nepal, namely, Ghodaghodi (28°41'20.39"N, 80°56'54.66"E), Jokhar (28°42'23.90"N, 80°37'21.48"E), and Rani Taal (28°49'57.76"N, 80°13'10.76"E) encompassing a range of diverse stagnant water, swamps and marshy areas. The key wetlands studied are Ghodaghodi, Jokhar and Rani, each with unique characteristics (Figure 1). The Ghodaghodi Wetland, located in Kailali district at an elevation of 205 masl, is a Ramsar-listed lake complex covering 2563 hectares. It comprises 14 interconnected oxbow lakes, marshes, swamps, streams and springs (Figure 1a). This complex is a vital biological corridor between the lowlands and the Siwalik region. The Jokhar Wetland, situated near the rapidly urbanizing Dhangadhi Sub-Metropolitan City in Kailali district (Figure 1 b). It covers 149 hectares, which includes three segments: Jokhar (12.45 hectares), Murphatta (2.51 hectares) and Murphatti (1.32 hectares) (DNPWC, 2021). The third one, Rani Wetland, is located within Shuklaphanta National Park in Kanchanpur district, a small, charming lake nestled in the Singhpur region, 13 kilometers east of the park office (Figure 1c). All these wetlands have diversity in plant species and support various avifauna.

Physical Features

At each wetland, we recorded physical, vegetation and chemical features. The physical characteristics of wetlands during the winter and summer seasons of 2021 were systematically analyzed using satellite imagery in ArcGIS 10.8. High-resolution remote sensing data were processed to extract and quantify key spatial parameters of the wetlands, including total wetland area, shoreline length, open water surface extent, and vegetation cover. These parameters were delineated and measured using supervised classification and digitization techniques to assess seasonal variations. A handheld GPS device (Garmin eTrex 10) was used to record geo-referenced points for calculating the wetland area and shoreline length. Cloud-free LANDSAT satellite images were acquired for the study areas to ensure accurate remote sensing analysis. In addition, each wetland was surveyed once during both the winter and summer seasons of 2021 to capture seasonal variations. .

Water Quality

The water quality of the Ghodaghodi, Jokhar and Rani wetlands were analyzed by collecting water samples from different locations (Figure 1). Water samples were collected during the summer (March, April, and May) and winter (December, January, and February) seasons (2021) from the sampling sites of the wetlands. The parameters analyzed included temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}), major anions (Cl^{-}, NO_3^{-}, SO_4^{2-}, PO_4^{3-}), turbidity, alkalinity, total hardness (TH), dissolved oxygen (DO), biological oxygen demand (BOD) and chemical oxygen demand (COD). The standard methods outlined by the American Public Health Association (APHA, 2017) were followed for these assessments. Water samples were collected using acid-soaked (5% HNO_3) and rinsed polypropylene bottles and were stored at 4°C before laboratory analysis. In-situ parameters such as temperature, pH, EC, TDS, and DO were measured immediately in the field after sampling using Multiparameter probes, while the remaining parameters were assessed in the laboratory of the Central Department of Environmental Science and Central Department of Zoology, Institute of Science and Technology, Tribhuvan University, Nepal. Water sampling sites were strategically selected to represent the full extent of each wetland ecosystem, enabling a comprehensive assessment of physical features, vegetation, and water quality. A total of 12 sites in Ghodaghodi, 6 in Jokhar, and 5 in Rani wetlands were selected based on their relative size and ecohydrological features (Figure 1, Table 1). Three samples were taken on each site, resulting in 12, 6, and 5 sampling points, respectively, thereby ensuring proportional and representative coverage across the wetlands (Figure 1, Table 1).

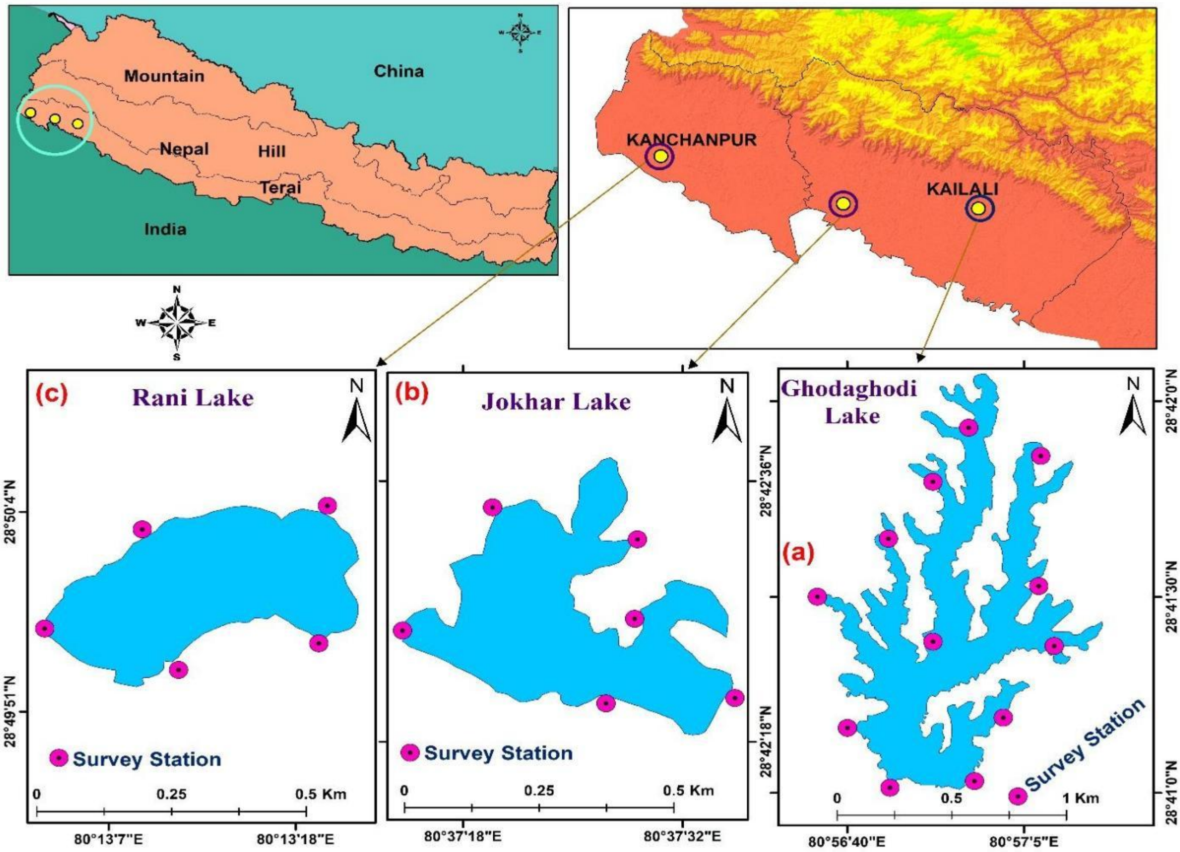

Figure 1. Study Wetlands: (a) Ghodaghodi; (b) Jokhar; and (c) Rani lakes of Sudurpashchim Province, Nepal

Table 1. Environmental characterization of study areas

S.N.	Name	Study site ID	Season	Latitude (N)	Longitude (E)	Location	Land use
1	Ghodaghodi	G1	Winter/Summer	28^0 41’ 020”	80^0 56’ 787”	South	Highway/Settlement
2	Ghodaghodi	G2	Winter/Summer	28^0 41’ 041”	80^0 56’	South	Highway/Settlement
3	Ghodaghodi	G3	Winter/Summer	28^0 41’ 139”	80^0 56’ 970”	East	Agriculture /Settlement
4	Ghodaghodi	G4	Winter/Summer	28^0 41’ 357”	80^0 57’ 133”	East	Forest
5	Ghodaghodi	G5	Winter/Summer	28^0 41’ 528”	80^0 57’ 118”	East	Forest
6	Ghodaghodi	G6	Winter/Summer	28^0 41’ 869”	80^0 57’123”	Northeast	Forest
7	Ghodaghodi	G7	Winter/Summer	28^0 41’ 838”	80^0 56’ 941”	North	Forest
8	Ghodaghodi	G8	Winter/Summer	28^0 41’ 655”	80^0 56’ 816”	North	Forest
9	Ghodaghodi	G9	Winter/Summer	28^0 41’ 529”	80^0 56’ 689”	Northwest	Forest
10	Ghodaghodi	G10	Winter/Summer	28^0 41’ 422”	80^0 56’ 651”	West	Forest
11	Ghodaghodi	G11	Winter/Summer	28^0 41’ 180”	80^0 56’ 689”	West	Forest
12	Ghodaghodi	G12	Winter/Summer	28^0 41’ 090	80^0 56’ 747”	Southwest	Forest/Temple
13	Jokhar Lake	J1	Winter/Summer	28^0 42’ 414”	80^0 37’ 236	South	Agriculture
14	Jokhar Lake	J2	Winter/Summer	28^0 42’ 355”	80^0 37’ 448”	South	Settlement
15	Jokhar Lake	J3	Winter/Summer	28^0 42’ 367”	80^0 37 590”	East	Forest
16	Jokhar Lake	J4	Winter/Summer	28^0 42’ 435”	80^0 37’ 494”	North	Forest
17	Jokhar Lake	J5	Winter/Summer	28^0 42’ 525”	80^0 37’ 481”	West	Botanical garden
18	Jokhar Lake	J6	Winter/Summer	28^0 42’ 562”	80^0 37’ 336”	West	Botanical garden
19	Rani Lake	R1	Winter/Summer	28^0 49’ 9433”	80^0 13’ 0419”	Southwest	Forest
20	Rani Lake	R2	Winter/Summer	28^0 49’ 877”	80^0 13’ 1005”	Southwest	Forest
21	Rani Lake	R3	Winter/Summer	28^0 49’ 8707”	80^0 13’ 1957	Southwest	Forest
22	Rani Lake	R4	Winter/Summer	28^0 50’ 0091”	80^0 13’ 1056”	West	Forest
23	Rani Lake	R5	Winter/Summer	28^0 50’ 0690”	80^0 13’ 1999”	North	Forest

Vegetation Survey
A vegetation survey was conducted to assess species composition, richness, and diversity around the selected wetlands, aiming to understand the ecological structure and compare vegetation characteristics across sites. A total of 36, 18, and 15 quadrats (three quadrats per sampling point) of size 10×10 m² for trees were sampled around Ghodaghodi, Jokhar, and Rani wetlands, respectively. The variation in the number of quadrats among wetlands was based on the size of each wetland, with larger wetlands receiving more sampling points to ensure representative coverage. Specifically, 12 points were selected in Ghodaghodi, 6 in Jokhar, and 5 in Rani. Point selection was based on wetland size and accessibility for uniform spatial distribution (Figure 1). At each point, three nested quadrats were laid: a 10×10 m² plot for trees, within which 5×5 m² quadrats for shrubs and 1×1 m² quadrats for herbs were sampled. Vegetation sampling was carried out within 50 meters of the wetland shoreline to capture the immediate riparian zone, which is ecologically significant due to its direct interaction with wetland hydrology and disturbance gradients. All plant species encountered were recorded and identified using standard floras (Shrestha et al., 2018; Rajbhandari et al., 2016). and voucher specimens were collected and submitted to the National Herbarium, Godavari, Lalitpur, Nepal.

Calculation of Wetland Physical and Ecological Parameters
Visual interpretation of the presence of water using a pan-sharpened image and reflectance at multiple bands was used to determine the threshold for the continuous water ratio index. The threshold was the same for all the study sites for a given season. Open water and vegetation cover areas were calculated after determining the threshold value for the index. The vegetation cover was taken as the differences between the open water area and the total area of the wetland were calculated (Margalef, 1983). The shoreline development was calculated as follows:

$$D = \frac{S}{2_{\sqrt{a \times x}}}$$

Where, D = Shoreline development, S = Shoreline length, a = Open water area

For the vegetation, Species richness and diversity were assessed using commonly applied ecological indices, including the Shannon-Wiener Diversity Index (Shannon & Weaver, 1949), Simpson's Diversity Index (Simpson, 1949), and Pielou's Evenness Index (Pielou, 1966). were calculated.

$$H = -\Sigma Pi \times LN(Pi)$$

where "Pi" is the proportion of each species in the sample and "LN (Pi)" is the natural logarithm of this proportion.

Simpson's Diversity Index (D) is calculated by,

$$D = 1 - \Sigma [(n/N)^2],$$

where 'n' is the number of individuals of a particular species and 'N' is the total number of individuals of all species.

The evenness was calculated as:

$$J = H/\ln(S)$$

where "H'" is Shannon–Wiener's diversity index and "S" is species richness.

Water Quality Index (WQI)
WQI is an important tool that assesses the suitability of water for drinking and domestic use by analyzing key physicochemical parameters. The water quality was classified based on its level of purity using the significant water quality variables through the application of the Weighted Arithmetic water quality index method (Brown *et al.*, 1970). The parameters considered for calculating the Water Quality Index (WQI) included pH, electrical conductivity (EC), total dissolved solids (TDS), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{+}), chloride (Cl^{-}), nitrate (NO_3^{-}), sulphate (SO_4^{2-}), and total hardness (TH). The WQI was calculated using standard equations.

$$WQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \ldots\ldots (1)$$

The quality rating Qi for each parameter is calculated by using the equation (2):

$$Q_i = \left[\left(\frac{V_0 - V_{id}}{S_n - V_{id}}\right)\right] \times 100 \ldots\ldots (2)$$

Similarly, the relative weight of each parameter is calculated by using equation (3):

$$W_i = \left[\frac{K}{S_n}\right], K = \left[\frac{1}{\Sigma \frac{1}{S_n}}\right] \ldots\ldots (3)$$

Where V_o is the actual value of the parameter obtained through analysis, Sn is the standard value proposed by WHO guidelines, and V_{id} is the ideal value in pure water, considered as 7 for pH and zero for other parameters (Brown *et al.*, 1970; Awasthi *et al.*, 2025).

Statistical Analysis
One-way analysis of variance (ANOVA) was used to compare the hydrochemical variables among the wetlands and an independent sample t-test was used to compare the variables between the summers and winter seasons.

Results and Discussion

Physical characteristics of the wetlands
The physical characteristics of the Ghodaghodi, Jokhar and Rani wetlands reveal unique ecological profiles. Table 2 presents a comparative analysis of these

characteristics during the winter and summer seasons of 2021, focusing on wetland areas, open water areas, vegetation cover, shore length, and shoreline development. In Ghodaghodi, the total wetland area remains constant at 906,300 m² throughout both seasons. However, there are notable seasonal changes in its other features. For instance, the open water area decreases significantly from 692,100 m² in winter to 531,900 m² in summer, indicating a reduction of about 23.2%. Conversely, vegetation cover increases from 214,200 m² in winter to 374,400 m² in summer, a rise of approximately 74.8%. The shore length remains the same at 18,420 meters. Shoreline development, which measures the complexity of the shoreline, increases from 6.25 in winter to 7.13 in summer, suggesting more intricate shoreline structures during the summer (Table 2).

For Jokhar, the wetland area is constant at 156,600 m² in both seasons. The open water area shows a substantial increase from 2,700 m² in winter to 8,100 m² in summer, marking a 200% rise. Vegetation cover slightly decreases from 153,900 m² in winter to 148,500 m² in summer, a reduction of about 3.5%. The shore length remains constant at 3,002 meters. Shoreline development decreases significantly from 16.30 in winter to 9.41 in summer, indicating a simplification of the shoreline structure during the summer (Table 2).

In the case of Rani Wetland, it maintains a constant total area of 128,700 m² across both seasons. The open water area slightly decreases from 14,400 m² in winter to 12,728.43 m² square meters in summer, a decline of about 11.6%. Vegetation cover shows a minor increase from 114,300 m² in winter to 115,971.57 m² in summer, an increase of approximately 1.5%. The shore length remains unchanged at 1,860 meters. Shoreline development slightly increases from 4.37 in winter to 4.65 in summer, indicating a minor increase in shoreline complexity (Table 2).

Table 2. Physical features of the Ghodaghodi, Jokhar and Rani Wetlands, Sudurpashchim Province, Nepal

Physical features	Ghodaghodi		Jokhar		Rani	
	2021		2021		2021	
	Winter	Summer	Winter	Summer	Winter	Summer
Wetland Area (m²)	906300	906300	156600	156600	128700	128700
Open Water Area (m²)	692100	531900	2700	8100	14400	12728
Vegetation Cover (m²)	214200	374400	153900	148500	114300	115972
Shore Length (m)	18420	18420	3002	3002	1860	1860
Shoreline Development Index	6.25	7.13	16.3	9.41	4.37	4.65

Comparing the three wetlands, Ghodaghodi shows the largest decrease in open water area during summer seasons, which might be accompanied by an increase in vegetation cover. Due to the boating activities, Jokhar exhibits the highest shoreline development in winter but the most dramatic reduction in summer (Bilkovic *et al.*, 2019). Rani wetland showed the least seasonal variation in shoreline development than the Ghodaghodi and Jokhar Lakes. These results suggest that the wetlands under strict reserve areas face relatively lower anthropogenic interferences (Ostad-Ali-Askari, 2022).

Hydrochemical Characteristics

The hydrochemical assessment of Ghodaghodi, Jokhar, and Rani wetlands in 2021 revealed notable seasonal and spatial variations (Table 3). Among them, Ghodaghodi Lake showed relatively higher signs of water quality degradation, likely due to its larger size, high tourist influx, and dense surrounding vegetation, which promote more anthropogenic disturbances and organic litter input. In contrast, Rani and Jokhar wetlands are smaller and less affected by tourism, with Rani wetland in particular benefiting from stricter protection and lower human interference. Temperature across all wetlands showed a marked increase from winter to summer. Ghodaghodi rose from 20.93±0.47°C to 32.77±0.78°C, Jokhar from 20.63±0.48°C to 33.05±0.51°C, and Rani from 19.90±0.20°C to 31.14°C (Table 3), highlighting significant seasonal influence and possible thermal stress during summer.

pH values were within the WHO and NDWQS recommended range (6.5–8.5), with Ghodaghodi showing an increase from 7.98±0.45 to 8.18±0.56, Rani showing a slight decrease from 7.64±0.21 to 7.58, while Jokhar exhibited a more notable decline from 7.38±0.49 to 7.05±0.29 in summer. This drop in Jokhar could be indicative of localized acidification likely associated with urban effluents and agricultural runoff. EC increased significantly in Jokhar and Rani from winter to summer: from 151.60±39.36 μS/cm to 226.17±47.74 μS/cm and from 188.44±18.73 μS/cm to 275.8 μS/cm, respectively. Ghodaghodi's EC showed a marginal rise from 148.35±10.87 μS/cm to 154.75±45.38 μS/cm. All values were well below the WHO and NDWQS limits (1500 μS/cm), suggesting low mineralization. TDS followed a similar trend, increasing from 68.43±9.31 mg/L to 100.58±27.20 mg/L in Ghodaghodi, from 72.68±18.82 mg/L to 116.17±22.42 mg/L in Jokhar, and from 91.36±8.91 mg/L to 134.60±17.10 mg/L in Rani. All were within safe limits (≤1000 mg/L). DO, critical for aquatic life, showed slight increases across all lakes from winter to summer. Ghodaghodi ranged from 5.40±0.80 to 5.98±0.29 mg/L, Jokhar from 5.02±0.33 to 5.69±0.33 mg/L, and Rani from 6.06±0.34 to 6.17±6.17 mg/L, maintaining good ecological conditions, especially in Rani. Jokhar had the lowest DO levels, suggesting influence from urban runoff. Turbidity decreased significantly in Ghodaghodi (from 3.57±0.86 to 2.10±1.14 NTU) and in Rani (from 3.42±0.61 to 1.41±0.65 NTU), while Jokhar saw a minor increase (from 2.48±0.53 to 2.58±0.78 NTU). All values remained below the 5 NTU threshold (Table 3).

Na^+ and K^+ concentrations were low across all wetlands and within WHO limits. Na^+ ranged from 3.33±0.72 to 3.07±1.48 mg/L in Ghodaghodi, 4.77±1.67 to 4.25±1.49 mg/L in Jokhar, and 3.06±0.61 to 2.19±0.98 mg/L in Rani. K^+ increased slightly in all wetlands, highest in Jokhar during summer (1.82±0.80 mg/L), all far below the limit of 100 mg/L. PO_4^{3-} levels were within the WHO guideline of 1 mg/L, except for Rani wetland in summer (1.08±0.26 mg/L), indicating possible influence from surrounding agricultural runoff. Ghodaghodi dropped slightly from 0.68±0.24 to 0.60±0.16 mg/L, and Jokhar remained nearly stable. NH_4^+ increased notably in all wetlands during summer, especially in Ghodaghodi (0.67±0.51 mg/L), possibly due to increased decomposition of organic matter and anthropogenic input, but remained below the limit of 1.5 mg/L. Alkalinity decreased slightly in all wetlands during the summer: from 62.08±8.38 to 57.08±9.64 mg/L in Ghodaghodi, from 55.00±7.07 to 52.50±9.35 mg/L in Jokhar, and from 60.00±7.91 to 53.00±7.58 mg/L in Rani (Table 3). This may result from dilution by rainfall and spring-fed sources.

BOD showed a seasonal drop in all wetlands, with Jokhar decreasing from 81.78±67.73 to 28.50±11.56 mg/L, Rani from 56.80±53.71 to 27.74±20.00 mg/L, and Ghodaghodi from 56.92±21.16 to 46.89±15.20 mg/L. The decline reflects dilution and lower organic pollution during monsoon-fed summer. COD followed a similar trend: Jokhar dropped from 111.80±92.22 to 49.83±20.05 mg/L, Rani from 79.36±70.75 to 47.04±37.23 mg/L, and Ghodaghodi from 81.28±26.29 to 77.09±23.55 mg/L. SO_4^{2-} concentrations were low and stable, increasing slightly in Ghodaghodi from 5.08±1.20 to 7.88±1.48 mg/L, remaining well below the 250 mg/L standard. Jokhar showed a minor decrease, while Rani remained nearly unchanged. Cl^- levels increased slightly in Ghodaghodi (7.87±2.80 to 13.18±5.44 mg/L), remained stable in Jokhar, and decreased slightly in Rani, all below the 250 mg/L limit. NO_3^- levels increased seasonally across all wetlands: Ghodaghodi (2.36±1.03 to 5.43±3.30 mg/L), Jokhar (5.01±3.42 to 6.74±1.00 mg/L), and Rani (3.53±2.89 to 4.78±1.49 mg/L), all below the WHO limit of 50 mg/L. Jokhar had the highest NO_3^- values, indicating strong influence from urban/agricultural runoff. Ca^{2+} concentrations remained within permissible limits (≤200 mg/L), showing a decrease in Ghodaghodi (from 20.00±3.36 to 17.33±6.07 mg/L) and a significant increase in Rani from 17.40±3.58 to 32.00±7.62 mg/L. Jokhar fluctuated slightly. Mg^{2+} ranged from 7.63±1.57 to 9.09±4.24 mg/L in Jokhar, 8.62±1.45 to 7.73±2.63 mg/L in Ghodaghodi, and increased markedly in Rani from 7.66±1.57 to 14.08±3.35 mg/L, remaining far below the WHO limit (50 mg/L). TH values were well below the threshold (500 mg/L), ranging from 34.67 mg/L to 64.80 mg/L, with Rani showing the greatest summer increase (Table 3). This increase reflects contributions from weathered minerals and surface runoff enriched with carbonates and silicates.

Table 3. General Hydrochemical Statistics of Ghodaghodi, Jokhar and Rani Wetlands (2021)

Parameters	Ghodaghodi (2021)		Jokhar (2021)		Rani Lake (2021)		WHO, 2011	NDWQS, 2022
	Winter	Summer	Winter	Summer	Winter	Summer		
Temp.	20.93±0.47	32.77±0.78	20.63±0.48	33.05±0.51	19.90±0.20	31.14	-	
pH	7.98±0.45	8.18±0.56	7.38±0.49	7.05±0.29	7.64±0.21	7.58	6.5-8.5	6.5-8.5
EC	148.35±10.87	154.75±45.38	151.60±39.36	226.17±47.74	188.44±18.73	275.8	1500	1500
TDS	68.43±9.31	100.58±27.20	72.68±18.82	116.17±22.42	91.36±8.91	134.60±17.10	1000	1000
DO	5.40±0.80	5.98±0.29	5.02±0.33	5.69±0.33	6.06±0.34	6.17±6.17	-	
Turb.	3.57±0.86	2.10±1.14	2.48±0.53	2.58±0.78	3.42±0.61	1.41±0.65	5	5
Na^+	3.33±0.72	3.07±1.48	4.77±1.67	4.25±1.49	3.06±0.61	2.19±0.98	200	
K^+	1.02±0.29	1.22±0.52	1.18±0.56	1.82±0.80	1.17±0.34	1.28±0.26	100	
PO_4^{3-}	0.68±0.24	0.60±0.16	0.61±0.24	0.57±0.14	0.92±0.12	1.08±0.26	1	
NH_4^+	0.30±0.22	0.67±0.51	0.16±0.14	0.51±0.16	0.38±0.19	0.58±0.42	1.5	
Alk.	62.08±8.38	57.08±9.64	55.00±7.07	52.50±9.35	60.00±7.91	53.00±7.58	-	
BOD	56.92±21.16	46.89±15.20	81.78±67.73	28.50±11.56	56.80±53.71	27.74±20.00	-	
COD	81.28±26.29	77.09±23.55	111.80±92.22	49.83±20.05	79.36±70.75	47.04±37.23	-	
SO_4^{2-}	5.08±1.20	7.88±1.48	7.93±1.68	7.33±0.79	5.84±2.51	5.36±2.19	250	250
Cl^-	7.87±2.80	13.18±5.44	5.87±1.75	5.83±1.72	7.23±1.89	6.78±1.47	250	250
NO_3^-	2.36±1.03	5.43±3.30	5.01±3.42	6.74±1.00	3.53±2.89	4.78±1.49	50	50
Ca^{2+}	20.00±3.36	17.33±6.07	17.33±3.56	20.67±9.63	17.40±3.58	32.00±7.62	200	

Mg^{2+}	8.62±1.45	7.73±2.63	7.63±1.57	9.09±4.24	7.66±1.57	14.08±3.35	50	
TH	42.00±6.71	34.67±12.13	34.67±7.12	43.33±22.11	34.80±7.16	64.80±14.39	150	500

One-way ANOVA of the hydrochemical parameters in the Ghodaghodi, Jokhar Lake and Rani Lake wetlands was conducted (Table 4, Figure 2). Temperature varies significantly in the wetlands with the season. pH showed variation with wetlands, but there was no appreciable variation with seasons in the wetlands. Similarly, TDS, EC, DO, SO_4^{2-}, and Cl^- vary significantly with wetlands and seasons. The turbidity, K^+, NH_4^+, NO_3^-, alkalinity, BOD, and COD were found to be in a similar range among the three wetlands, indicating no spatial variation; however, their values showed seasonal variation. Concentrations of K^+, NH_4^+, and NO_3^-, were observed to be high in the summer, whereas alkalinity, BOD, and COD were high in the winter. The parameters Na^+, PO_4^{3-}, Ca^{2+}, Mg^{2+} and total hardness do not show significant seasonal variation; however, they vary spatially among the wetlands (Table 4).

Na^+ is highest in Jokhar Lake (summer), PO_4^{3-} is highest in Rani Lake in summer, Ca^{2+}, Mg^{2+} and TH were observed highest in Rani Lake in summer, followed by Jokhar Lake, and Ghodaghodi wetlands. This pattern is consistent across various parameters, such as BOD, COD, and alkalinity, highlighting distinct water quality characteristics in each wetland. Rani Lake generally shows higher DO levels, which can be attributed to its strict reserve status and minimal anthropogenic interference. In contrast, Jokhar Lake, with lower DO levels, is influenced by urban runoff and agricultural activities, leading to higher BOD and COD levels. Ghodaghodi exhibits intermediate values, reflecting both the natural and anthropogenic influences. This seasonal variation is observed across multiple parameters, such as NO_3^-, Ca^{2+}, and Mg^{2+}.

Table 4. Statistical variation of hydrochemical variables in the studied Lakes (One Way ANOVA)

Wetlands	Hydrochemical variables							
	DO		BOD		COD		Alk.	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Ghodaghodi	5.4 ± 0.23 aby	5.97 ± 7.85 abx	56.92 ± 6.1 ax	46.88 ± 2.78 ax	81.28 ± 7.58 ax	77.09 ± 4.38 ax	62.08 ± 2.41 ax	57.08 ± 0.14 ax
Jokhar	5.03 ± 0.13 by	5.69 ± 9.15 bx	81.78 ± 27.64 ax	28.5 ± 3.81 ax	111.8 ± 37.64 ax	49.83 ± 4.71 ax	55 ± 2.88 ax	52.5 ± 0.06 ax
Rani	6.06 ± 0.15 ax	6.17 ± 7.64 ax	56.8 ± 24.02 ax	27.74 ± 3.39 ax	79.36 ± 31.63 ax	47.04 ± 8.94 ax	60 ± 3.53 ax	53 ± 0.18 ax

Wetlands	Hydrochemical variables									
	Cl^-		NO_3^-		Ca^{2+}		Mg^{2+}		TH	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Ghodaghodi	7.87 ± 0.8 ay	13.17 ± 0.42 ax	2.36 ± 0.29 ay	5.42 ± 1.57 ax	20 ± 0.96 ax	17.33 ± 0.95 bx	8.62 ± 0.41 ax	7.73 ± 1.75 bx	42 ± 1.93 ax	34.66 ± 0.75 bx
Jokhar	5.87 ± 0.71 ax	5.83 ± 0.32 bx	5.01 ± 1.39 ax	6.73 ± 0.7 ax	17.33 ± 1.45 ax	20.66 ± 0.4 bx	7.63 ± 0.63 ax	9.09 ± 3.92 bx	34.67 ± 2.90 ax	43.33 ± 1.72 bx
Rani	7.24 ± 0.84 ax	6.78 ± 0.98 bx	3.54 ± 1.29 ax	4.78 ± 0.65 ax	17.4 ± 1.60 ay	32 ± 0.66 ax	7.66 ± 0.70 ay	14.08 ± 3.4 ax	34.8 ± 3.20 ay	64.8 ± 1.49 ax

Wetlands	Hydrochemical variables									
	Na^+		K^+		PO_4^{3-}		NH_4^+		SO_4	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Ghodaghodi	3.325 ± 0.2 bx	3.06 ± 0.32 abx	1.02 ± 0.08 ax	1.22 ± 0.42 ax	0.68 ± 0.06 abx	0.6 ± 0.15 bx	0.3 ± 0.06 ay	0.67 ± 0.04 ax	5.08 ± 0.34 by	7.87 ± 6.79 ax
Jokhar	4.77 ± 0.68 ax	4.25 ± 0.31 ax	1.18 ± 0.22 ax	1.82 ± 0.6 ax	0.61 ± 0.09 bx	0.57 ± 0.32 bx	0.16 ± 0.05 ay	0.51 ± 0.07 ax	7.93 ± 0.68 ax	7.33 ± 8.18 abx
Rani	3.06 ± 0.27 bx	2.18 ± 0.28 bx	1.17 ± 0.15 ax	1.27 ± 0.43 ax	0.93 ± 0.05 ax	1.08 ± 0.11 ax	0.38 ± 0.08 ax	0.58 ± 0.11 ax	5.84 ± 1.12 abx	5.36 ± 16.64 bx

Note: Different alphabets 'a-b' represent significant differences in the values among the lakes (One-way ANOVA) and 'x-y' represent significant differences in the values between summer and winter seasons ($p < 0.05$).

The increase in these parameters during summer can be linked to factors like increased runoff from surrounding areas. In Jokhar Lake, the NO_3^- levels rise significantly in summer influenced by carbonate weathering and runoff. Spatial and temporal analyses of hydrochemical variables provide a comprehensive understanding of the wetland dynamics. For instance, while Rani Lake maintains higher DO levels year-round due to its protected status, Jokhar Lake's water quality fluctuates more significantly due to external influences, particularly municipal effluents. Ghodaghodi intermediate values reflect its mixed influence from both natural processes and human activities. Monitoring these variations is crucial for effective water management and conservation strategies, ensuring the ecological health and sustainability of these wetlands (Table 4, Figure 2).

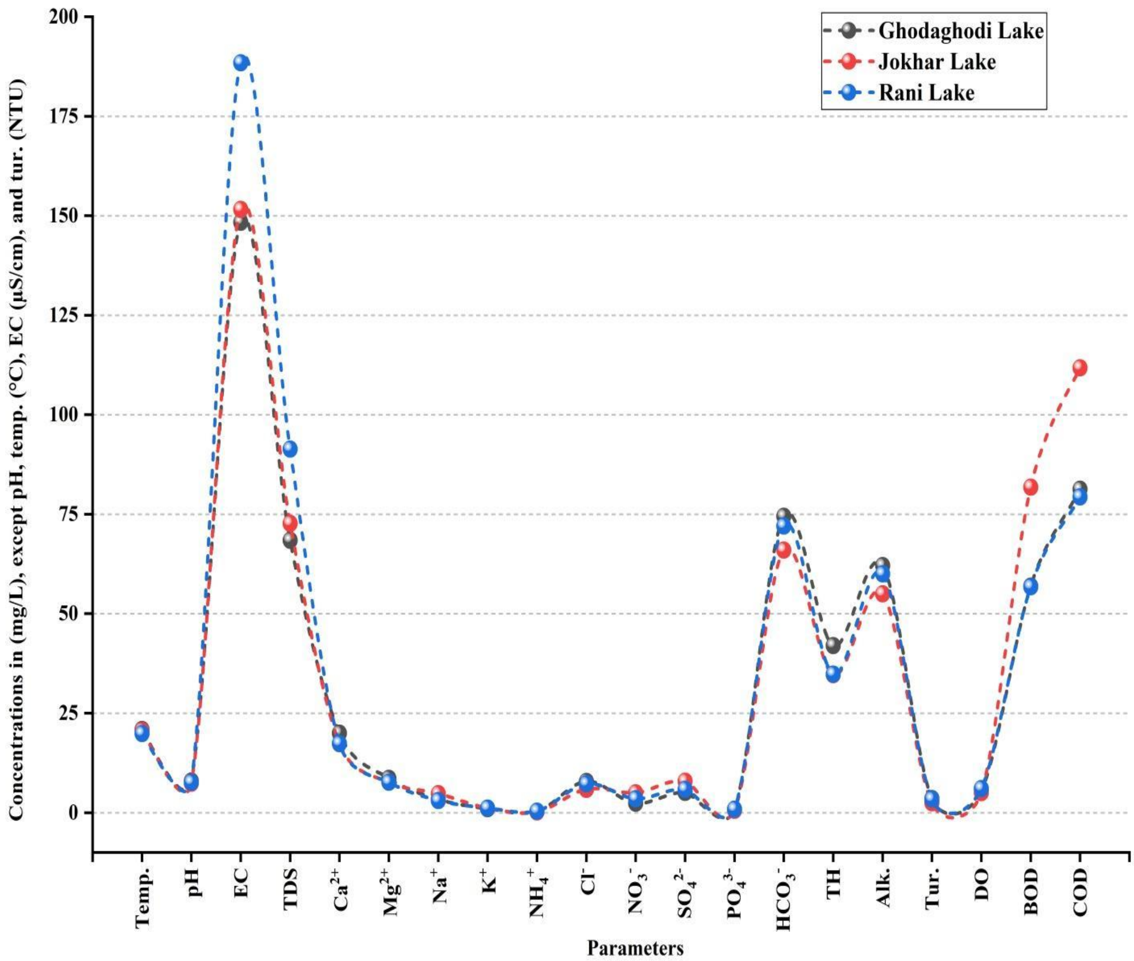

Figure 2. Overall Hydrochemical Variations in Ghodaghodi, Jokhar, and Rani Lake, Sudurpashchim Province, Nepal

Water Quality Index (WQI)

Evaluation of water quality involves aggregating various parameters into a single index (Awasthi et al., 2025; Dahal et al., 2025a, b). According to Sinha et al. (2004), the WQI is a crucial metric for assessing the suitability of water for human use. Water with a WQI < 25 is considered excellent and safe for consumption, indicating no pollution. As the WQI increases between 26 and 50, the water is deemed slightly polluted but still good. When the WQI ranges from 51 to 75, the water quality drops to a poor level, signifying moderate pollution.

Table 5. Water quality index of wetlands of lowlands, Sudurpashchim Province, Nepal

Wetlands	Ghodaghodi		Jokhar		Rani	
	Winter	Summer	Winter	Summer	Winter	Summer
WQI	43.01	51.12	61.45	71.52	23.40	30.01
Status	Slightly polluted	Moderately polluted	Moderately polluted	Moderately polluted	Excellent	Slightly polluted

Water with a WQI between 76 and 100 is classified as very poor, reflecting significant pollution. Finally, a WQI above 100 indicates that the water is excessively polluted and unsuitable for human use. This categorization helps in understanding the extent of water pollution and the necessary measures to ensure water safety (Table 5). Based on the WQI classification by Sinha *et al.* (2004), the water quality of wetlands in the lowlands of Sudurpashchim Province varies significantly across spatiotemporal levels. Ghodaghodi Lake transitions from slightly polluted (good) in winter (WQI = 43.01) to moderately polluted (poor) in summer (WQI = 51.12), indicating a seasonal decline in water quality. Jokhar remains moderately polluted (poor) throughout the year, with WQI values of 61.45 in winter and 71.52 in summer, showing a slight increase in pollution during warmer periods. Whereas Rani exhibits the better water quality among the three, with a WQI of 23.40 in winter, classifying it as excellent and fit for human consumption, and a slight increase to 30.01 in summer, still maintaining a good status (Table 5). The seasonal decline in water quality is mainly due to increased temperature, nutrient runoff, and human activities in summer, while better WQI in Rani Lake reflects strict protection and minimal disturbances inside the national park area (Sharma et al., 2021).

Hydrochemical Comparison of Wetlands

The hydrochemical composition of Ghodaghodi, Jokhar, and Rani Lake wetlands in Sudurpashchim Province reveals distinct differences and notable similarities when compared to other wetlands across Nepal. Ghodaghodi Wetland, with a pH of 8.08, indicates slightly alkaline water, while Jokhar Lake is neutral to slightly alkaline with a pH of 7.21, and Rani Lake is also slightly alkaline with a pH of 7.61. The TDS and EC values further differentiate these wetlands. Rani Lake exhibits the highest TDS (112.98 mg/L) and EC (232.12 µS/cm), indicating a higher concentration of dissolved ions, followed by Jokhar Lake with TDS of 94.42 mg/L and EC of 188.88 µS/cm, and Ghodaghodi with the lowest TDS (68.43 mg/L) and EC (151.55 µS/cm). These values suggest that Rani Lake has the highest mineral content, possibly due to natural mineral deposits and alluvial soil-water interactions (Table 6). The major ions present in these wetlands also show significant variation. Ghodaghodi has the highest HCO_3^- concentration at 72.68 mg/L, which is crucial for buffering capacity and maintaining pH stability. Jokhar Lake, on the other hand, has the highest Na^+ and SO_4^{2-} concentrations at 4.51 mg/L and 7.63 mg/L, respectively, likely due to municipal effluents, agricultural runoff and industrial discharge. Rani Lake shows the highest Ca^{2+} and Mg^{2+} levels at 24.7 mg/L and 10.87 mg/L, respectively, contributing to its higher TH of 49.8 mg/L (Sharma et al., 2021, Table 2).

Table 6. Summary statistics of the hydrochemical composition of the Sudurpashchim wetlands and their comparison with other Nepalese lakes.

Wetlands	pH	TDS	EC	Na^+	K^+	SO_4^{2-}	HCO_3^-	NH_4^+	PO_4^{3-}	Ca^{2+}	Mg^{2+}	NO_3^-	Cl^-	TH
Ghodaghodi[1]	8.08	68.43	151.55	3.2	1.12	6.48	72.68	0.48	0.64	18.66	8.17	3.89	10.52	38.33
Jokhar[1]	7.21	94.42	188.88	4.51	1.5	7.63	65.57	0.33	0.59	19	8.36	5.87	5.85	39
Rani[1]	7.61	112.98	232.12	2.62	1.22	5.6	68.93	5.6	1.0	24.7	10.87	4.15	7.005	49.8
Ghodaghodi[2]	7.97	85.42	160	3.00	3.35	16	219	1.73	0.9	26.6	2.3	1.45	5.65	-
Bedkot[3]	7.77	168	337	4.89	2.90	-	-	0.03	0.07	15.8	6.8	1.77	5.31	188
Jagadishpur[4]	7.58	156.4	288.1	-	-	-	147.6	-	-	-	-	0.23	-	-
Jhilmila[5]	7.35	56	102	5.8	2.5	0.46	26.46	0.28	0.19	7.6	2.8	0.31	9.7	82.5
Beeshazar[6]	7.55	50	84	-	-	-	-	0.07	0.34	-	-	1.75	9.02	47.2
Koshi Tappu[7]	7.30	120	228	8.55	3.15	9.79	49.98	0.33	0.11	15.46	5.95	0.33	9.33	49

[1] =This study; [2] = Bhatta et al., 2020; [3] = Pant et al., 2019; [4] = Bhatta et al., 2015; [5] = Pal et al., 2021; [6] = Pant et al., 2021; [7] = Neupane et al., 2023

These differences in ionic composition highlight the varying sources of pollution and natural mineral content in each wetland. For instance, the higher Na^+ and SO_4^{2-} levels in Jokhar Lake suggest significant anthropogenic activities, while the elevated Ca^{2+} and Mg^{2+} levels in Rani Lake indicate natural mineral deposits or agricultural inputs (Table 6). Nutrient levels further distinguish these wetlands. Rani Lake has significantly higher NH_4^+ and PO_4^{3-} concentrations at 5.6 mg/L and 1.0 mg/L, respectively, suggesting higher nutrient loading, possibly from mineralization and runoff. Jokhar Lake has the highest NO_3^- concentration at 5.87 mg/L, indicating potential nitrate pollution, which can lead to eutrophication and algal blooms (Smith, Tilman,& Nekola, 1999). Ghodaghodi, while having the lowest TDS and EC, still exhibits moderate nutrient levels, indicating some degree of pollution but relatively better water quality compared to the other two wetlands (Table 6).

Comparing Ghodaghodi, Jokhar, and Rani Lakes with other wetlands in Nepal reveals distinct hydrochemical differences. Ghodaghodi has a stable pH similar to Koshi Tappu Wetland but with lower TDS and EC (Neupane et al., 2023). Jokhar Lake shows elevated NO_3^- due to urban runoff, unlike Beeshazari Lake (Pant et al., 2021). Rani Lake has the highest TH in summer from carbonate weathering, unlike Jhilmila (Pal et al., 2021) and Bedkot (Pant et al., 2019). Koshi Tappu shows greater EC and TDS variability, while Beeshazari Lake has lower hydrochemical fluctuations (Pant et al., 2021). Ghodaghodi has the highest pH and moderate TDS and EC, reflecting balanced influences. Jokhar Lake has lower pH but higher TDS and EC, with low DO and high BOD/COD, indicating anthropogenic impacts. Rani Lake, with intermediate pH and the highest TDS, EC, and hardness, reflects significant ionic content from natural processes. Despite variations, all parameters meet WHO (2011) and NDWQS (2022) guidelines.

The hydrochemical composition of Ghodaghodi wetland indicates the highest HCO_3^- concentration, suggesting that it has the highest buffering capacity. Jokhar Lake, on the other hand, has the highest Na^+ and SO_4^{2-} concentrations, which show Jokhar has the highest mineral content due to agricultural runoff and industrial discharge. Whereas, Rani Lake has low TDS, showing that Rani Lake has better water quality among the three wetlands. Comparing these wetlands to others in Nepal, Bedkot Wetland shows significantly higher TDS (168 mg/L) and EC (337 µS/cm), indicating substantial ionic content and potential pollution sources (Pant et al., 2019). Jagadishpur wetland also has high TDS (156.4 mg/L) and EC (288.1 µS/cm), with a notable HCO_3^- concentration (147.6 mg/L), suggesting strong buffering capacity (Bhatta et al., 2015). In contrast, Jhilmila wetland has lower TDS (56 mg/L) and EC (102 µS/cm), indicating better water quality (Pal et al., 2021), while Beeshazari wetland exhibits very low TDS (50 mg/L) and EC (84 µS/cm), reflecting minimal pollution, which is comparable with the present study (Pant et al., 2021). Koshi Tappu wetland, with high TDS (120 mg/L) and EC (228 µS/cm), shows elevated Na^+ (8.55 mg/L) and moderate Ca^{2+} (15.46 mg/L), Mg^{2+} (5.95 mg/L), indicating significant mineral content, which showed distinct differences with the present study in terms of EC and TDS (Neupane et al., 2023).

Vegetation Analysis

The species richness of trees was high in Jokhar Lake (22 species), followed by Ghodaghodi Lake (21 species) and Rani Lake (16 species). There were 11 Shrub species in Ghodaghodi Lake, including 28 species of herbs. The number of species within shrubs was lesser in Rani Lake, while the herbs were 13 and 15 in the Jokhar and Rani lakes, respectively (Table 7).

Table 7. Species richness of trees, shrubs and herbs in the Study areas (Ghodaghodi, Jokhar and Rani Wetlands)

Vegetation	Ghodaghodi Lake		Jokhar Lake		Rani Lake	
	No. of species	Family	No. of species	Family	No. of species	Family
Trees	21	12	22	14	16	12
Shrubs	11	10	8	7	4	3
Herbs	28	12	13	10	15	8

Table 8. Diversity indices of trees, shrubs, and herbs in Study wetlands

Vegetation	Wetlands	Shannon Weiner's index (H')	Pielou's evenness index(J)	Simpson diversity index (D)
Trees	Ghodaghodi	2.24	0.30	0.82
	Jokhar	1.34	0.21	0.87
	Rani	0.70	0.13	0.69
Shrubs	Ghodaghodi	2.27	0.30	0.83
	Jokhar	1.54	0.17	0.76
	Rani	0.58	0.08	0.29
Herbs	Ghodaghodi	3.40	0.44	0.90
	Jokhar	1.94	0.27	0.83
	Rani	1.76	0.22	0.73

Shannon-Weiner's diversity index of the tree is highest in Ghodaghodi Lake with a value of 2.24, followed by Jokhar Lake and Rani Lake with a value of 1.34 and 0.70, respectively. Similarly, for shrubs and herbs, Ghodaghodi Lake has the highest Shannon-Weiner diversity index with values of 2.27 and 3.40, respectively. Similarly, Jokhar Lake has a diversity index of 1.07 and 1.94 for shrubs and herbs, respectively (Table 8). During winter, most herbs complete their life cycle and begin to dry up (Soni *et al.*, 2015). The higher species richness of trees in Jokhar Lake compared to the other lakes might be attributed to its vicinity (Upadhyay, 2022). Shrub and tree species were fewer in Rani Lake compared to the other two lakes, likely due to human activities such as grazing, selective logging, firing and land clearing. These disturbances typically create conditions that favor the regrowth or colonization of shrubs (Doherty, 1998). However, in Rani Lake, the lack of human disturbances may limit the natural regeneration and establishment of shrubs and trees (Ostad-Ali-Askari, 2022). Likewise, the Shannon-Wiener index is the highest in Ghodaghodi Lake compared to Jokhar and Rani Lake, indicating that Ghodaghodi Lake has a healthier ecosystem is characterized by efficient nutrient recycling, improved water quality, and the availability of shelter and breeding habitats for various species than the remaining wetlands in the lowlands of Sudurpashchim Province. This can be attributed to the high species diversity and specie s evenness in Ghodaghodi Lake, which is further enhanced by its complex landscape (Stein et al., 2014).Various studies have also demonstrated the influence of multiple environmental variables on bird diversity in the study regions. Birds use vegetation as habitat, so changes in vegetation cover might influence the number of birds in the wetlands. Similarly, vegetation type also determines the abundance of birds. The positive relation demonstrated by the abundance of birds with a density of trees might be attributed to the preference of birds for dense forests (González-Gajardo *et al*., 2009; Kačergytė *et al*., 2021; Malekian *et al*., 2022; Pant *et al*., 2024).

Thus, vegetation structure, influenced by human activities and landscape complexity, directly affects faunal diversity. These findings highlight the ecological significance of vegetation in supporting biodiversity and maintaining wetland ecosystem health in Sudurpashchim Province.

Conclusions

This study reveals the distinct ecological profiles and seasonal dynamics of Ghodaghodi, Jokhar, and Rani Wetlands in the lowlands of Sudurpashchim Province, Nepal. Ghodaghodi Lake, with the highest vegetation diversity, experiences notable seasonal changes, including a reduced open-water area and increased pollution during the summer. Jokhar Lake shows significant shoreline loss and remains moderately polluted year-round, while Rani Lake maintains relatively stable conditions with excellent water quality in winter and slight pollution in summer, likely due to effective protection measures. Hydrochemical parameters across all lakes remained within WHO and NDWQS guidelines, though anthropogenic pressures, especially in Jokhar, contributed to elevated nitrate levels and reduced dissolved oxygen. These findings underscore the importance of targeted, site-specific conservation strategies to address pollution sources, protect biodiversity and preserve the ecological integrity of each wetland. Thus, the study reveals the ecological dynamics and pollution challenges of Ghodaghodi, Jokhar, and Rani Wetlands, offering critical insights for sustainable wetland management in Sudurpashchim Province. By informing evidence-based, site-specific conservation strategies, it directly supports the advancement of sustainable development goals contributing to the protection of biodiversity, improvement of water quality and enhancement of climate resilience in the region.

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Conflicts of Interest: The author declares no conflicts of interest.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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