Water quality and irrigation suitability of freshwater lakes in Sudurpaschim Province, Nepal: A case study of Alital and Bandatal

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Abstract: Water quality is an increasing concern globally due to climate change, rapid population growth, expanding industrial activities and intensive agricultural practices. This study evaluates the drinking water quality and irrigation suitability of Alital and Bandatal in the Sudurpaschim Province, Nepal, emphasizing their significance for local livelihoods and ecosystem sustainability. A comprehensive assessment was conducted using the Water Quality Index (WQI) and several irrigation-related parameters, including EC, SAR, PI, MAR, Na%, PS, CROSS, and RSBC. Results indicate that both the wetlands possess excellent irrigation potential, although moderate salinity was observed in some Bandatal samples. Based on EC and SAR correlations, Alital water was classified as C1S1, while Bandatal exhibited both C1S1 and C2S1 types. WQI values further confirmed excellent water quality, with scores of 8.61 ± 0.99 for Alital and 12.62 ± 3.62 for Bandatal, both within drinking water quality standards. These findings highlight the high water quality and irrigation suitability of the lakes, while also underscoring the need for ongoing monitoring in light of increasing urbanization and climate change pressures on these vital freshwater resources.

Keywords: Water quality index; Irrigation suitability; Sustainable water management; Sudurpaschim province.

Introduction

Freshwater lakes are vital ecological indicators, reflecting the health of aquatic ecosystems and significantly impacting the well-being of nearby communities[1]. The surface water quality plays an essential role in providing ecological services, as these lakes serve as interaction hubs between ecosystems and human activities[2,3]. Assessing physicochemical characteristics and calculating the Water Quality Index (WQI) are essential steps to determine the suitability of freshwater water for diverse uses, including drinking, domestic, irrigation, and industrial applications[4,5]. Water quality is influenced by natural processes, such as precipitation and weathering, and by human activities from industrial, agriculture runoff, and urban sources[6,7]. Lakes provide essential resources for drinking, irrigation, agriculture, and human consumption while playing crucial roles in groundwater recharge and the hydrological cycle through evaporation. Despite their importance, lakes are sensitive to environmental pollution and anthropogenic

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impacts, which threaten their ecological balance[8].

The industrial use, municipal water systems, and agriculture have significantly impacted water quality, particularly through chemical changes that affect both drinking and irrigation suitability[9,10]. Chemical characteristics of lake water bear direct implications on both ecological sustainability and economic activities[11]. Previous studies show that the environmental conditions around lakes depend on a complex interaction of natural processes, including precipitation, evaporation, and weathering, and anthropogenic factors, such as industrial and agricultural effluents[11,12]. Human-induced pressures, including population growth, agriculture, and urban sewage, have intensified nutrient inputs, accelerated eutrophication and led to environmental degradation that affects water quality, biodiversity, and water availability across the pristine freshwater bodies in Nepal[3,6,13].

Research on Nepal's primary water sources has highlighted the effects of natural and human-driven factors on water quality and chemical composition[3,6,7,14–16]. Focus has been placed on assessing the presence of ions such as potassium (K^+), sodium (Na^+), chloride (Cl^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}), as well as on understanding the influence of hydrogeochemical factors, including calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate ions (HCO_3^-)[20,26,35-39]. In developing nations, water contamination from pollutants like heavy metals, pathogens, pharmaceuticals, and industrial waste is a persistent issue, affecting both drinking and irrigation suitability[17]. The quality of irrigation water notably affects crop productivity, as shown by yield reductions in maize, rice, and wheat when water quality is low[6,7].

In Sudurpaschim Province, where lakes are widely used for irrigation and domestic purposes, studies on water quality remain scarce. Monitoring and evaluating these lakes through WQI assessments is essential for maintaining water quality and guiding management strategies amid urbanization and other anthropogenic pressures[18]. Additionally, climate change poses further risks, as rising temperatures and glacier melt in the Himalayas lead to fluctuating lake water levels and altered precipitation patterns, impacting water quality and aquatic ecosystems[19]. Effective mitigation and adaptation measures, including improved water resource management, are necessary to sustain these essential water sources, with international cooperation critical to addressing climate impacts on Himalayan lakes[19].

Globally, water resource challenges are emerging as pressing economic and social issues. In Nepal, lakes in the Central Himalayas-spanning the Terai to glacier-fed High Himalayas-hold immense ecological and cultural significance. These lakes provide drinking water and irrigation, support biodiversity, and contribute to local livelihoods, serving as ecological regulators that aid in flood control, stream flow maintenance, and recreation. Lakes in Sudurpaschim Province, with carbonate-dominant lithology, play crucial roles in supporting pisciculture, food security, and species habitats, and serve as rainwater harvesting sites and emergency water sources during crises. Despite their importance, the water quality of Alital and Bandatal has not yet been studied. In this context, this research aims to assess and compare the current water quality and potability of Alital and Bandatal, located in different ecological regions of Sudurpaschim Province. Evaluating their suitability for drinking and irrigation is critical in the context of local environmental variations and global climate change, given the region's evolving environmental challenges and the community's reliance on these vital resources.

Materials and Methods

Study area

This study focuses on two prominent freshwater lakes located in Sudurpaschim Province, Nepal: Alital Lake in Dadeldhura District and Bandatal Lake in Kanchanpur District (Figure 1). Covering an area of approximately 19,516 km² about 13.22% of Nepal's total landmass-Sudurpaschim Province features a diverse topography that spans from the lowland Terai plains to the highland regions. This geographical diversity encompasses both study sites, highlighting the ecological and environmental significance of Alital and Bandatal Lakes within the province.

Alital Lake is situated within the Churiya Range in Dadel dhura District, at coordinates 29°5′24″N and 80°29′24″E.

approximately 70 kilometers south of the district headquarters. Positioned at an elevation of 780 meters above sea level, the lake spans a core area of about 7 hectares. Located in the remote Alital Rural Municipality, this freshwater body plays a vital role in maintaining local ecological balance and supporting the community's water needs. Although Alital lacks a natural inlet, it is connected to nearby agricultural fields in Raksaun Dadelel Khet through an irrigation canal. The lake also sustains native fish species such as *Tautuga onitis* (Kalo Machha) and *Labeo rohita* (Rohu) and is surrounded by rich biodiversity, Bandatal Lake is located in the Terai region of Kanchanpur District, within Belauri Municipality, at coordinates 28°39′48.12″N and 80°24′55.23″E. It lies at an elevation of 154 meters above sea level and spans approximately 21 hectares, with a total basin area of 78.1 hectares. The surrounding landscape is predominantly forested (98.18%), interspersed with traditional farming areas. Bandatal experiences seasonal fluctuations in water depth, typically ranging between 2 to 3 meters. The region's climate is characterized by an average maximum temperature of 30.5°C during June and July, a minimum of 17.5°C in December, and an annual rainfall of approximately 1,422.7 mm. As a biodiversity hotspot, Bandatal supports a rich variety of flora and fauna, including notable species such as the swamp deer, leopard, rhesus monkey, and tiger, underscoring its ecological importance.

Lake basin ecology

Sudurpaschim Province exhibits contrasting climatic and ecological features across different regions. Kanchanpur located in the Terai, is characterized by a hot climate and dense settlements due to its fertile alluvial soil. Dadeldhura, on the other hand, lies in a mid-hill area with rugged terrain and sparser habitation. Both regions host a variety of flora, including *Shorea robusta* (Sal), *Terminalia tomentosa* (Saj), and *Syzygium cumini* (Jamun), which enhance the biodiversity of lakes. Alital's primary water source is rainfall, with additional inlets to the north and northeast, while Bandatal is largely dependent on monsoon rainfall. Geographic Information System (GIS) and Remote Sensing (RS) analyses indicate a minor area reduction in both lakes over time, pointing to sediment deposition and environment changes impacting the lake perimeters.

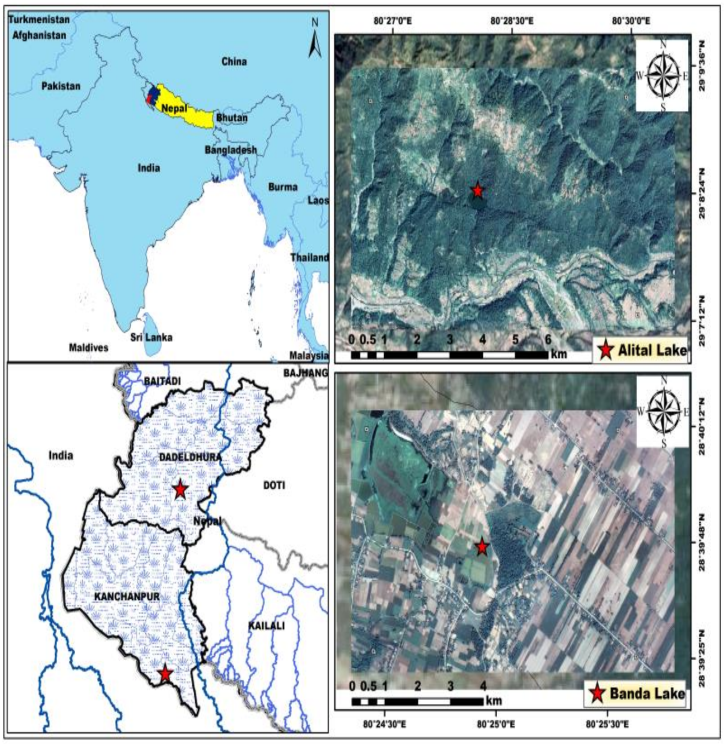

Figure 1: Map showing the study area of Alital and Bandatal, Sudurpaschim Province, Nepal.

This study aims to assess the water quality of Alital and Bandatal to analyze natural and anthropogenic influences on water quality in response to climate variability and human activities. Given the accelerated urbanization and climate change impacts on Himalayan freshwater ecosystems, conserving these lakes is critical. Through this comparative analysis, the study emphasizes the need for informed conservation strategies to protect these ecologically valuable freshwater resources for sustainable use and future generations.

Sampling and physicochemical analysis

Surface water samples were collected in May 2022 from multiple sites within the specified area, designated as Site A1 to A20 for Alital and that of B1 to B20 for Bandatal encompassing inlet, center, and outlet locations. The geographic coordinates of each sampling point were recorded using a hand-held global positioning system (GPS). Each polyethylene bottle was washed three times using sampling water, following the guidelines adapted from the American Public Health Association[20]. *In-situ* parameters such as temperature, pH, EC and TDS were measured immediately in the field after sampling.

The evaluation process involved the measurement of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), anions (HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{-}, PO_4^{3-}), and general parameters (pH, EC, TDS, alkalinity, total hardness, DO, BOD, COD, turbidity, and temperature) [33].However, this study includes only those parameters that are essential for assessing the Water Quality Index (WQI) and analyzing various irrigation water quality indices. Water samples were examined for physicochemical parameters as mentioned by an approved water and waste water assessment method[20] as shown in Table 1. Each water sample from the sampling stations was analyzed twice for each parameter to ensure accuracy.

Statistical analysis

Descriptive statistical analysis was conducted using Microsoft Excel and SPSS. Key parameters such as mean and standard deviation were calculated to evaluate the central tendency and variability of water quality indicators. These analyses provided insights into the suitability of water for drinking and irrigation purposes[23].

Water quality index (WQI)

The WQI functions as a comprehensive tool for assessing the suitability of surface water for various domestic purposes. It is a numerical rating that encompasses the overall impact of diverse water quality parameters. In this research, WQI was computed to ascertain the appropriateness of surface water for human consumption. Eleven parameters, namely pH, EC, TDS, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Cl^{-}, NO_3^{-}, SO_4^{2-} and HCO_3^{-} were considered. Finally, the WQI categorizes water into five classes based on its suitability for drinking. A WQI value below 50 indicates excellent water quality (Class A), while values above 200 (Class E) signify water that is unsuitable for drinking (Table 2).

Assigning a weight (w_i)

Assigning a weight to each chemical parameter based on its perceived impact on human health and its relative importance in determining overall water quality for the drinking purposes[21].The highest weight of 5 was assigned to the parameters with a significant impact on water quality (e.g., NO_3^{-}, EC, and TDS), while a minimum weight of 1 was assigned to parameters considered not harmful (e.g., Ca^{2+}, Mg^{2+}, K^{+}).

Table 1: Instruments used for onsite field measurement and laboratory analysis.

Parameter	Analytical method/Reagent	Unit
pH	Conductivity-TDS meter	-
Electrical Conductivity	Conductivity-TDS meter	μS/cm
Total Dissolved Solids	Conductivity-TDS meter	mg/L
Calcium (Ca^{++})	EDTA Titrimetric	mg/L
Magnesium Mg^{++})	EDTA Titrimetric	mg/L
Sodium (Na^{+})	Flame photometric	mg/L
Potassium (K^{+})	Flame photometric	mg/L
Bicarbonate (HCO_3^{-})	Titrimetric	mg/L
Carbonate (CO_3^{--})	Titrimetric	mg/L
Chloride (Cl^{-})	Argentometric Titration	mg/L
Nitrate (NO_3^{-})	Ion Selective Electrode	mg/L
Fluoride (F^{-})	Ion Selective Electrode	mg/L
Phosphate (PO_4^{3-})	Stannous Chloride	mg/L
Sulphate (SO_4^{--})	Barium Chloride	mg/L

Calculating the relative weight (Wi)

For each parameter the relative was calculated using Eq. 1.

Determining a quality rating scale (qi)

Determining a Quality Rating Scale (qi) for each parameter was done by dividing the concentration in each water sample by its respective standard, following the guideline values of world health organization[22] and multiplied by 100 as described in Eq. 2. Finally, to *WQI* was computed by calculating the Water Quality Sub-Index (SIi) for each chemical parameter. This sub-index is then used to determine the overall *WQI*, as described in Eqs.3 and 4.

$$\mathrm{Wi} = \frac{\mathrm{Wi}}{\sum_{i=1}^{n} \mathrm{W_i}} \qquad (1)$$

where W_i is the relative weight of each parameter, w_i is the weight of each parameter and n is the total number of parameters.

$$\mathrm{qi} = \left(\frac{\mathrm{Ci}}{\mathrm{Si}}\right) 100 \qquad (2)$$

Where qi= quality rating, C_i= concentration of each chemical parameter in each water sample in mg/L, S_i= WHO drinking water standard for each chemical parameter in mg/L except for conductivity (µS/cm) and pH.

$$SIi = Wi \times qi \qquad (3)$$

$$WQI = \sum_{i=1}^{n} SI \qquad (4)$$

Where SI_i is the sub-index of the i^{th} parameter, *qi* is the rating based on the concentration of i^{th} parameter and *n* is the number of parameters.

Table 2: Characterization of water quality based on water quality index (WQI) value[14].

Class	WQI Value	Water quality status
A	<50	Excellent
B	50-100	Good
C	100–150	Poor water
D	150–200	Very Poor water
E	>200	Water unsuitable for drinking

Irrigation water quality index (IWQI)

Various scholars have developed criteria and applied for assessing irrigation water quality[22, 23, 24, 25, 26]. In this study, the relevant criteria have been applied to analyze the irrigation suitability of water from Alital and Bandatal. The physicochemical analysis results were used to calculate key indicators of irrigation quality, including sodium adsorption ratio (SAR), sodium percentage (%Na), permeability index (PI), Kelly's ratio (KR), magnesium adsorption ratio (MAR), cation ratio of soil structural stability (CROSS), residual sodium bicarbonate (RSBC) and potential salinity (PS)[22]. These indicators were then compared with the standards set by the World Health Organization and the National Drinking Water Quality Standards[22] to evaluate the suitability of surface water from Alital and Bandatal for drinking, domestic and irrigation purposes..

Electrical conductivity (EC)

EC serves as a qualitative measure of inorganic pollution and provides insight into the presence of total dissolved solids and ionized substances within water[10,24]. It is instrumental in evaluating the risk of salinity, which is a crucial factor in determining water quality for crop cultivation. Elevated salinity levels can negatively impact plant health and lead to various salinity related issues[6,7]. An EC value exceeding 3000 µS/cm is categorized as 'Fair' and significantly affects crop productivity. A range of 700 to 3000 µS/cm is labelled as 'Good', while a measurement below 700 µS/cm indicates 'Excellent' water quality suitable for irrigation and crop cultivation[25,34].

Sodium percentage (Na%)

The sodium percentage is a crucial parameter in evaluating the suitability of irrigation water. When the sodium content in irrigation water exceeds 60%, it can adversely affect the physical properties of the soil. Additionally, the combination of sodium with carbonate can lead to the formation of alkaline soils[26,27]. The quality of irrigation water can be classified into five major categories based on sodium percentage (%Na) values; 'Excellent' (<20), 'Good' (20-40), 'Permissible' (40-60), 'Doubtful' (60-80), and 'Unsuitable' (>80)[28] (Table 3). The sodium percentage is calculated using the formula as[29]:

$$\mathrm{Na\%} = \frac{\mathrm{Na^+ + K^+}}{\mathrm{Na^+ + Ca^{2+} + Mg^{2+} + K^+}} \mathrm{X}\ 100$$

Sodium adsorption ratio (SAR)

SAR is a significant parameter used to evaluate cation exchange reactions in soil. It provides valuable insights into how soil interacts with cations, particularly sodium ions[29]

Table 3: Sodium percent water class[29].

Sodium (%)	Water class
<20	Excellent
20-40	Good
40-60	Permissible
60-80	Doubtful
>80	Unsuitable

Continuous use of water with a high SAR value can have detrimental effects on soil quality, leading to the breakdown of its physical structure. This breakdown can result in various soil issues, including reduced water infiltration, increased compaction, and decreased nutrient availability, ultimately impacting crop productivity and land usability. Richards (1954) classified irrigation water quality as 'Excellent' (<10), 'Good' (10-18), 'fair' (18-26), and 'Poor' (>26) presented in Table 4. Additionally, Richards (1954) provided the following relationship to calculate SAR[29].

$$SAR = \frac{Na^{+}}{\sqrt{\{(Ca^{2+} + Mg^{2+})/2\}}}$$

Magnesium adsorption ratio (MAR)

Higher concentrations of magnesium in water contribute to increased alkalinity, leading to reduced crop productivity. Elevated levels of Ca^{2+} and Mg^{2+} ions in irrigation water can elevate the pH of soil and restrict phosphorus availability. If the magnesium adsorption ratio (MAR)value is below 50, irrigation is considered 'Suitable'; however, if it exceeds 50, it is deemed 'Unsuitable. The following equation is suggested for computing MAR:

$$MAR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} X100$$

Kelly's ratio (KR)

The Kelly's ratio (KR) plays a crucial role in evaluating the suitability of irrigation water quality. This method's effectiveness depends on the concentrations of Na^{+}, Ca^{2+}, and Mg^{2+} present in the irrigation water. The KR value indicates whether irrigation is deemed safe when it is less than or equal to 1, or unsafe when it exceeds 1. The formula to calculate KR is as provided by Kelly:

$$KR = \left[\frac{Na^{+}}{Mg^{2+} + Ca^{2+}}\right]$$

Permeability index (PI)

The permeability index (PI) serves as a metric to evaluate the capacity of soil for water movement, which is determined by considering the concentrations of essential ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and HCO_3^{-}. In simpler terms, PI helps to assess the ability of soil to allow water passage based on the presence and levels of these specific ions. The PI values are classified into three main categories: (Class I for PI >75, Class II for 25-75, and Class III for PI <25). The calculation of PI values can be carried out using the formula:

Table 4: Classification of irrigation water based on SAR.

S.N.	Types of water and SAR value	Quality	Suitability for irrigation
1	Low sodium water (S1) SAR value: 0-10	Excellent	Suitability for all types of crops and all types of soils, except for those crops, which are sensitive to sodium
2	Medium sodium water (S2) SAR value: 10-18	Good	Suitable for coarse textured or organic soil with good permeability, Relatively unsuitable in fine textured soils.
3	High sodium water (S3) SAR value: 18-26	Fair	Harmful for almost all types of soil; Requires good drainage, high leaching gypsum addition
4	Very high sodium water (S4) SAR value: above 26	Poor	Unsuitable for irrigation

$$PI = \left[\frac{Na^{+} + K^{+} + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}}\right] \times 100$$

Cation ratio of soil structure suitability (CROSS)

CROSS is a water quality assessment index designed to comprehensively assess the influence of various cations, including Na^+, K^+, Ca^{2+}, and Mg^{2+}, on soil infiltration and structural stability. Unlike SAR, CROSS takes into account the intricate interactions among these cations to quantify their respective roles in either encouraging dispersion of soil or flocculation, thereby offering a more comprehensive measure of soil structure suitability. The irrigation water quality can be categorized as 'Excellent' (<10), 'Good' (10-18), 'Permissible' (18-26), and 'Unsuitable' (>26) based on the CROSS range. The formula to determine CROSS is as:

$$CROSS = \frac{Na^{+} + 0.56K^{+}}{\sqrt{(Ca^{2+} + 0.6Mg^{2+})/2}}$$

Potential salinity (PS)

Potential salinity (PS) acts as an indicator for categorizing the suitability of irrigation water for agricultural purposes, relying on concentrations of chloride (Cl^-) and sulfate (SO_4^{2-}). PS is determined by summing the concentration of chloride with half of the concentration of sulfate. A PS value less than 3 is classified as 'Suitable', while a value greater than 3 is classified as 'Unsuitable' for irrigation. PS is calculated using the equation provided below:

$$PS = (Cl^-) + \frac{1}{2}(SO_4^{2-})$$

Residual sodium bicarbonate (RSBC)

Residual sodium bicarbonate (RSBC) reflects the surplus of HCO_3^- over Ca^{2+} in water. Elevated RSBC levels indicate a high sodium hazard, and the high pH can render land infertile due to sodium carbonate deposition. RSBC is quantified as the difference between bicarbonate and calcium ions. The water with RSBC less than 1.25 is deemed 'Safe' for irrigation, while RSBC exceeding 1.25 is labelled 'Unsafe'. The formula for computing RSBC is as[27] (Table 5):

$$RSBC = (HCO_3^-) - (Ca^{2+})$$

Table 5: Water quality based on RSBC (after Richards 1954).

RSBC (epm)	Remark on quality
<1.25	Safe/good
1.25-2.50	Marginal/doubtful
>2.50	Unsuitable

Wilcox diagram

The Wilcox diagram, also known as the U.S. Salinity diagram, was initially introduced by Wilcox in 1948 and later refined by Torn in 1951. This graphical tool plays a vital role in assessing water suitability for irrigation. It divides irrigation water quality into four zones (C1, C2, C3 and C4) based on salinity hazard (EC) along the horizontal axis and four zones (S1, S2, S3, and S4) based on sodium hazard (SAR) along the vertical axis.

According to this diagram, low salinity water (C1) is considered the most suitable for irrigation, medium salinity water (C2) is deemed permissible, high salinity water (C3) is classified as poor, and very high salinity water (C4) is considered extremely dangerous. The primary criterion for categorizing irrigation water based on sodium hazard is how exchangeable sodium impacts the physical state of the soil. Low sodium water (S1) suggests compatibility with most soil types, medium sodium water (S2) is significant, high sodium water (S3) may be detrimental, and extremely high sodium water (S4) is generally unsafe for irrigation purposes[31].

Results and discussion

Suitability for irrigation

The suitability of irrigation at 20 sampling points within each lake, Alital and Bandatal, has been evaluated using different methods, as illustrated in Fig. 2, Tables 6 and 7.

Sodium adsorption ratio (SAR)

If the SAR ratio of the water samples in the study area is <10, it is excellent for irrigation purposes. The SAR value for each water sample was calculated using the above equation (Richards, 1954). The mean SAR concentration in Alital water was 0.21± 0.01 while in Bandatal water, it was 0.46 ± 0.09. According to classification given in Table 3, both Alital and Bandatal water showed mean SAR value

<10, indicating that lake waters are excellent (Fig. 2) for irrigation.

Residual sodium bicarbonate (RSBC)

The sodium hazard also increases, if the water contains a high concentration of bicarbonate ion. As the soil solution becomes more concentrated, there is a tendency for calcium and magnesium to precipitate as carbonates thus, increasing the relative proportion of sodium as a consequence. RSBC can be calculated using the equation below employing data of alkalinity, calcium and magnesium. The mean RSBC concentration in Alital water was 0.70 ± 0.45 while in Bandatal water, it was 0.98 ± 0.91. Both Alital and Bandatal water showed mean RSBC value <2.50, illustrating that these waters are suitable for irrigation.

Sodium percentage (Na%)

It has been widely recommended that the percentage of sodium in irrigation water should not exceed 60, in order to avoid its deleterious effects on soil. Water quality classification is based on the percentage of sodium content, with Class I indicating quality when sodium is less than 20%, Class II when sodium falls within the range of 20 to 40%, Class III when it's between 40 to 60%, Class IV in the case of sodium ranging from 60 to 80%, and Class V when sodium content exceeds 80%. Soil permeability has been found to be affected by high sodium ratio. Water quality reflected by sodium percentage values can be categorized as shown in Table 9, Fig.3 The mean percent sodium concentration in Alital water was 13.85±0.65 while in Bandatal water, it was 20.38±4.92. In Alital, the water quality falls into the excellent category. On the other hand, water quality of Bandatal is classified as good (Table 9). This suggests that, in certain sampling points within Bandatal, the sodium percentage values were relatively high. Irrigation suitability of major 20 sampling points in Alital and Bandatal each has been evaluated using different methods and presented in Table 9. From the classification of EC suggested all the points are of "Excellent" category and concluded that the river water is acceptable for irrigation purposes. Similarly, the MAR value also shows that both the lakes were suitable for irrigation. MAR value <50 defines as suitable for irrigation purposes and >50 is unsuitable. Both the lakes, the mean MAR (<50) values belong to the safe category. However, two of the sampling points in Bandatal (i.e., B15 and B19) and one of the sampling points in Alital (i.e., A5) were not suitable for the irrigation purposes in terms of MH[35-39.]

Comparative water quality assessment of freshwater lakes

The water quality parameters of Alital and Bandatal lakes show both similarities and differences when compared to other lakes like Ramaroshan Lake Complex (RLC), Jagdishpur, Begnas, Phewa, and Ghodaghodi. Bandatal exhibits a wider range and higher variability in parameters such as EC (Electrical Conductivity), SAR (Sodium Adsorption Ratio), and WQI (Water Quality Index), indicating more fluctuating water conditions (Table 8). In contrast, Alital shows more stable and moderate values across most parameters, with lower standard deviations. Compared to RLC and Jagdishpur, both Alital and Bandatal have lower average EC and SAR values, suggesting less salinity and sodium hazard. However, RLC stands out with significantly higher Na% and SAR, indicating potential irrigation concerns. Lakes like Begnas and Phewa show lower values in most parameters, reflecting better water quality, while Ghodaghodi presents moderate values, aligning more closely with Alital. Overall, Bandatal appears more impacted or variable, whereas Alital and the other lakes generally reflect more stable and favorable water quality conditions.

Long term use of irrigation water influences the permeability and structural stability of soil. The Permeability Index (PI), which classifies irrigation water based on the concentrations of Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^-, serves as a key indicator of the long-term impact of water quality on soil properties. PI values are categorized into three classes: Class I (>75), Class II (25–75), and Class III (<25). In this study, the PI values for both lakes were found to be below 75, indicating suitability for irrigation.

In addition, the CROSS index was employed to evaluate the relationship between irrigation water quality and soil structural stability. This parameter, analogous to the Sodium Adsorption Ratio (SAR), classifies irrigation water

Table 6: Irrigation suitability assessment of Bandatal, Sudurpashchim Province, Nepal.

Class	PS	Class	RSBC	Class	CROSS	Class	PI	Class	KR	Class	MH	Class	SAR	Class	Na%	Class	EC	ID
I	0.2	S	0.2	E	0.61	II	74.81	S	0.27	S	13.17	E	0.55	G	23.87	E	156	B1
I	0.19	S	0.25	E	0.62	I	80.98	S	0.29	S	3.75	E	0.56	G	25.02	E	164	B2
I	0.23	S	-0.4	E	0.61	II	68.55	S	0.27	S	9.41	E	0.54	G	23.9	E	178	B3
I	0.24	S	0.32	E	0.65	I	82.33	S	0.31	S	8.69	E	0.59	G	25.99	E	175	B4
I	0.28	S	0.57	E	0.58	II	70	S	0.22	S	22.59	E	0.49	G	21.14	E	190	B5
I	0.24	S	1.07	E	0.76	I	104.4	S	0.39	S	19	E	0.65	G	32.27	E	85	B6
I	0.44	S	0.69	E	0.54	II	72.49	S	0.21	S	11.15	E	0.48	G	20.03	E	241	B7
I	0.36	S	-1.1	E	0.6	II	49.7	S	0.22	S	19.23	E	0.51	G	21.56	E	243	B8
I	0.39	S	-1.1	E	0.57	II	47.6	S	0.22	S	23.79	E	0.49	G	20.62	E	240	B9
I	0.4	S	0.5	E	0.46	II	62.98	S	0.16	S	15.45	E	0.39	E	16.46	E	283	B10
I	0.33	S	0.63	E	0.51	II	65.64	S	0.18	S	16.28	E	0.43	E	18.11	E	263	B11
I	0.34	S	0.65	E	0.48	II	66.3	S	0.18	S	18.33	E	0.43	E	16.72	E	271	B12
I	0.33	S	0.69	E	0.42	II	67.83	S	0.16	S	16.3	E	0.37	E	15.78	E	258	B13
I	0.22	S	2.83	E	0.58	I	140.1	S	0.29	S	10.91	E	0.47	G	28.46	E	101	B14
I	0.3	S	1.33	E	0.46	II	52.66	S	0.13	U	59.17	E	0.35	E	14.02	E	347	B15
I	0.48	S	0.09	E	0.52	II	62.35	S	0.19	S	17.5	E	0.44	E	19.05	E	291	B16
I	0.37	S	1.48	E	0.36	II	73.79	S	0.13	S	11.26	E	0.3	E	14.4	E	253	B17
I	0.39	S	-0.1	E	0.46	II	57.59	S	0.17	S	26.5	E	0.39	E	16.39	E	292	B18
I	0.68	S	1.66	E	0.52	II	68.45	S	0.18	U	51.3	E	0.42	E	17.49	E	269	B19
I	0.29	S	1.13	E	0.46	II	64.85	S	0.16	S	45.96	E	0.37	E	16.28	E	312	B20

All values derived from (meq/L), except EC (µg/L), E: Excellent, G: Good, S: Suitable, U: Unsuitable

Table 7: Irrigation suitability assessment of Alital, Sudurpaschim Province, Nepal.

Class	PS	Class	RSBC	Class	CROSS	Class	PI	Class	KR	Clas	MH	Class	SAR	Class	Na%	Class	EC	ID
I	0.26	S	0.06	E	0.27	II	73.17	S	0.12	S	38.23	E	0.21	E	14.4	E	119	A1
I	0.31	S	-0.14	E	0.26	II	67.52	S	0.13	S	36.36	E	0.2	E	14.39	E	126	A2
I	0.27	S	0.04	E	0.27	II	69.54	S	0.12	S	44.41	E	0.2	E	14.16	E	124	A3
I	0.35	S	-0.3	E	0.27	II	57.37	S	0.12	S	41.32	E	0.21	E	14.12	E	127	A4
I	0.26	S	-0.41	E	0.27	II	44.75	S	0.12	U	50.42	E	0.21	E	13.67	E	129	A5
I	0.27	S	-0.34	E	0.27	II	57.45	S	0.13	S	38.23	E	0.21	E	14.21	E	125	A6
I	0.37	S	-0.44	E	0.26	II	50.01	S	0.12	S	41.67	E	0.21	E	13.53	E	127	A7
I	0.35	S	-0.44	E	0.26	II	48.84	S	0.12	S	43.24	E	0.2	E	13.22	E	128	A8
I	0.27	S	-0.26	E	0.27	II	57.56	S	0.13	S	44.41	E	0.21	E	14.22	E	127	A9
I	0.31	S	-0.14	E	0.27	II	66.03	S	0.13	S	38.23	E	0.22	E	14.22	E	129	A10
I	0.28	S	0.09	E	0.28	II	68.04	S	0.13	S	49	E	0.21	E	13.99	E	131	A11
I	0.3	S	0.08	E	0.27	I	76.7	S	0.13	S	32.06	E	0.22	E	14.22	E	132	A12
I	0.37	S	0.04	E	0.27	II	68.1	S	0.13	S	46	E	0.22	E	13.87	E	129	A13
I	0.26	S	0.45	E	0.28	I	82.93	S	0.13	S	44.41	E	0.22	E	14.23	E	128	A14
I	0.36	S	1.06	E	0.29	I	103.97	S	0.14	S	36.36	E	0.23	E	15.35	E	132	A15
I	0.27	S	0.76	E	0.26	I	83.15	S	0.12	S	46.15	E	0.21	E	12.69	E	129	A16
I	0.35	S	0.75	E	0.25	I	86.7	S	0.12	S	47.5	E	0.2	E	12.84	E	123	A17
I	0.36	S	0.7	E	0.25	I	91.18	S	0.12	S	41.32	E	0.19	E	13.28	E	132	A18
I	0.26	S	-0.2	E	0.26	II	54.76	S	0.11	S	48.85	E	0.2	E	12.89	E	131	A19
I	0.37	S	-0.06	E	0.27	II	59.84	S	0.12	U	50.26	E	0.21	E	13.55	E	138	A20

All values derived from (meq/l), except EC (µg/L), E: Excellent, G: Good, S: Suitable, U: Unsuitable

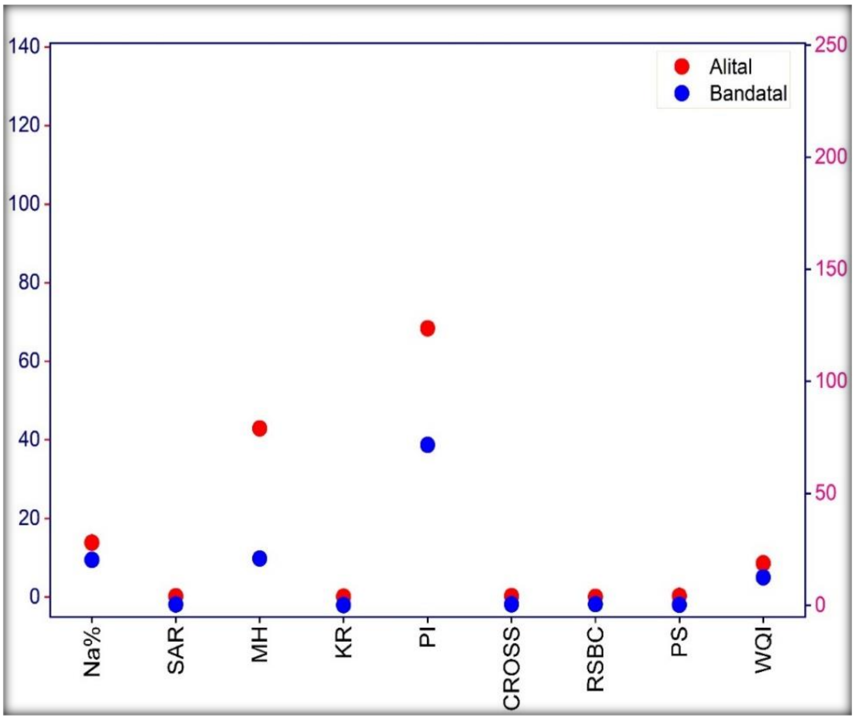

Figure 2: Average values of IWQI and WQI in Alital and Bandatal Lake, Sudurpaschim Province, Nepal.

Table 8: Irrigation water quality indices.

Lake		EC	Na%	SAR	MH	KR	PI	CROSS	RSBC	PS	WQI
Bandatal[a]	Min	84.90	14.02	0.30	3.75	0.13	47.60	0.36	-1.10	0.19	8.21
	Max	347.00	32.27	0.65	59.17	0.39	140.05	0.76	2.83	0.68	22.45
	Avg.	230.57	20.38	0.46	20.99	0.21	71.67	0.54	0.98	0.34	12.62
	SD	69.49	4.92	0.09	14.65	0.07	20.38	0.09	0.91	0.12	3.62
Alital[a]	Min	119.00	12.69	0.19	32.06	0.11	44.75	0.25	0.44	0.26	7.12
	Max	137.9	15.35	0.23	50.42	0.14	103.97	0.29	1.06	0.37	10.13
	Avg.	128.13	13.85	0.21	42.92	0.12	68.38	0.27	0.70	0.31	8.61
	SD	4.02	0.65	0.01	5.16	0.01	15.47	0.01	0.45	0.04	0.99
Ramaroshan Lake Complex (RLC)b	Avg.	95.49	34.25	2.22	22.99	0.41	66.01	2.72	-	-	
Jagdishpur Lake[c]		200.4	32.18	0.54	43.54						74.6
Begnas Lake[d]		69.41	16.51	0.18	39.07	0.17	91.81	0.22			4.33
Phewa Lake[e]		85.06	14.68	0.15	18.22	0.12	99.87	0.19			5.15
Ghodaghodi Lake		142	24.77	0.37	21.35	0.28	103.89	0.44			8.68

[a] = this study, [b] = [21], [c] = [18], [d] = [11], [e] =[4], and [f] =[12]

Water quality index (WQI)

Table 9: Water quality index.

ID	WQI	Class	ID	WQI	Class	ID	WQI	Class	ID	WQI	Class
B1	9.72	E	B11	13.92	E	A1	7.31	E	A11	8.78	E
B2	8.21	E	B12	13.93	E	A2	7.31	E	A12	7.12	E
B3	9.12	E	B13	12.96	E	A3	8.07	E	A13	9.49	E
B4	8.88	E	B14	8.52	E	A4	9.92	E	A14	7.42	E
B5	11.74	E	B15	22.45	E	A5	10.13	E	A15	8.17	E
B6	8.24	E	B16	13.01	E	A6	10.13	E	A16	8.81	E
B7	11.49	E	B17	12.80	E	A7	9.09	E	A17	8.51	E
B8	12.33	E	B18	13.27	E	A8	8.56	E	A18	8.19	E
B9	11.59	E	B19	18.35	E	A9	8.08	E	A19	8.92	E
B10	15.85	E	B20	16.03	E	A10	7.62	E	A20	10.00	E

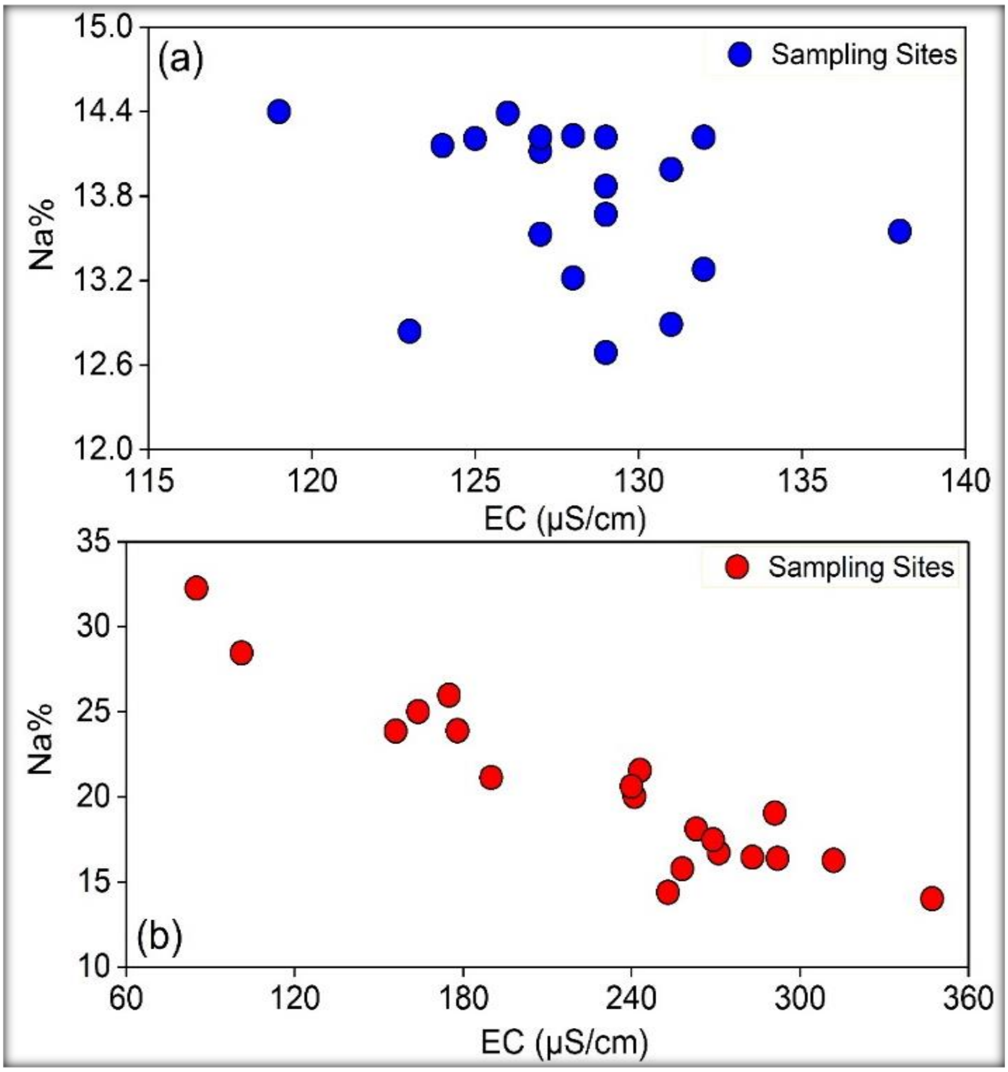

Figure 3: Classification of Lake water based on Na% versus EC values.

into four categories: excellent (<10), good (10–18), permissible (18–26), and unsuitable (>26). The CROSS values for both lakes fell within the excellent category. These findings are consistent with previous studies.

Interpretation of Wilcox diagram (Figure 4; Tables 7, 8) indicated major two classes: C1S1, C2S1. The results in C1S1 were found (low salinity and low sodium hazard) category indicating the best quality for irrigation purpose which completely effective for agriculture. Likewise, in C2S1 (medium salinity and low sodium hazard) category is suggesting nearly perfect for agriculture. All the samples of Alital were located in C1S1 zone whereas some of the samples from Bandatal were located in C2S1 zone.

The WQI of Alital and Bandatal was calculated based on the measured values of physicochemical parameters, following the standards set by the WHO (2011) and NDWQS (2005) for drinking water. The computed WQI values are classified into five types namely, excellent water (WQI <50), good water (50-100), poor water (100-200), very poor water (200-300) and water unsuitable for drinking (WQI >300)17, 18. Overall, the average WQI value for Alital and Bandatal water was 8.61±0.99 and 12.62±3.62 respectively. It is evident from the results that both Alital and Bandatal water fall under excellent category (Table 9) suggesting good status with possible use for drinking, irrigation, and industries based on the measured parameters.

Conclusion

This work examined the hydrochemical properties and irrigation suitability of Alital and Bandatal in Nepal's Sudurpaschim Province, revealing that both lakes exhibit slightly alkaline pH levels, with bicarbonate and calcium as dominant ions. Although both lakes are suitable for drinking, domestic, and irrigation uses, Bandatal shows relatively lower water quality, attributed to higher levels of TDS, EC, and other parameters due to lithological variations. While Alital's water is classified as soft, Bandatal falls under the medium-hard category, suggesting that irrigation in poorly drained areas may lead to salt accumulation on the soil surface. Both lakes are rated as excellent for irrigation based on SAR values, but the findings underscore the importance of regular water quality monitoring to address potential impacts of urbanization and climate change. Continued research, particularly on trace elements, microbial parameters, and long-term hydrochemical trends, will provide essential insights to support sustainable management of these lakes.

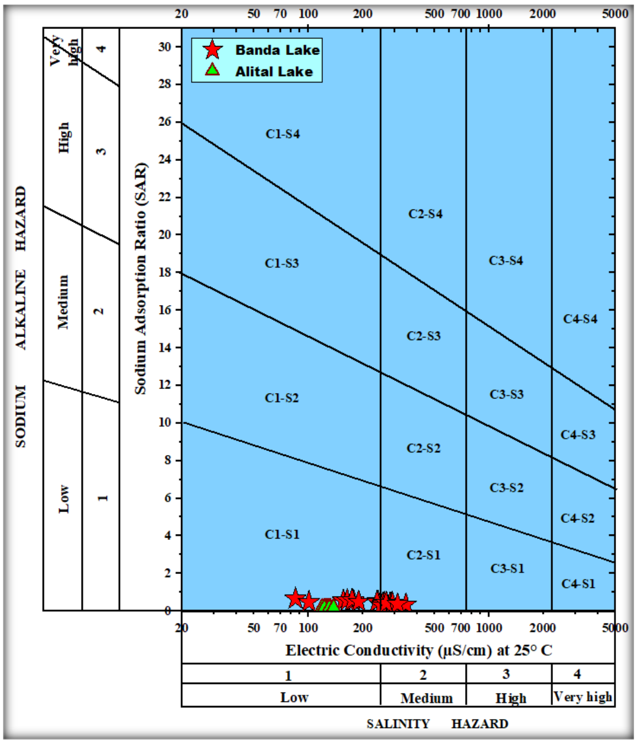

Figure 4: Wilcox diagram classifying irrigational suitability of Alital and Bandatal.

These findings are critical for regional water resource management and climate resilience planning in Sudurpaschim Province, helping ensure the health and utility of these water bodies for future generations.

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