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ORIGINAL RESEARCH ARTICLE

Assessment of water quality parameters of Khageri Khola (river) in Chitwan, Nepal, from upstream to downstream using physicochemical, correlation, regression, principal component, and hierarchical clustering analyses

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Abstract

In Chitwan, Nepal, the Khageri Khola (river) is an essential water source for domestic use, irrigation, and ecosystem balance; however, comprehensive evaluations of its water quality remain limited. Twelve physicochemical surface water quality parameters were statistically assessed from six sampling sites. The findings were compared with the World Health Organization, Nepal Drinking Water Quality Standards, and Nepal Water Quality Guidelines for Agriculture and Conservation (NWQGAC). Most of the tested parameters were within the recommended limits of the World Health Organization, NWQGAC, and Nepal Drinking Water Quality Standards; however, ammonia (9.53 ± 1.21 mg/L), dissolved oxygen (7.08 ± 0.24 mg/L), and phosphate (7.31 ± 0.82 mg/L) exceeded NWQGAC irrigation limits by 6–7-fold, suggesting a potential risk of eutrophication. The coefficient of variation, mean, standard deviation, minimum, and maximum values were computed. Three potential pollution sources were identified using principal component analysis, including mineral weathering and ionic strength (PC1; 39.41%), agriculture and organic pollution (PC2; 28.49%), and ion-specific anthropogenic inputs (PC3; 17.44%). The dendrogram of hierarchical clustering analyses grouped the sites into Cluster A (Confluence with tributaries, Kalika River; Confluence with Rapti River; and Khageri Bridge, Ratnanagar), suggesting anthropogenic influences, and Cluster B (Confluence with Mani Khola; Confluence with tributaries, Chitrasari; and Khageri Bridge, Khageri River) with enhanced concentrations of nitrate, alkalinity, ammonia, and phosphate, indicating considerable agricultural and organic pollution. Strong linear relationships between various parameters, such as hardness and nitrate (r^2 = 0.999) and dissolved oxygen and phosphate (r^2 = 0.991), were identified through correlation and regression analyses, suggesting common sources of contamination.

Keywords: Khageri Khola; Water quality; Multivariate statistical analysis; Agricultural pollution; Principal component analysis; Hierarchical clustering analysis

1. Introduction

Water is one of the vital natural resources for sustaining life and ecosystems.[1] Groundwater is necessary for providing the water required for agricultural, industrial, and drinking purposes, especially in regions where surface water sources are limited due to seasonal variations.[2,3] Surface water quality is affected by multiple factors, including human activities, geological formations, and environmental factors. Assessment of surface water quality is therefore essential to ensuring its safe and sustainable use. Sufficient quantity and quality of safe water are needed for improving living standards, socioeconomic growth, and ecological balance.[4-6]

Approximately 5% of Nepal's total geographical area and 2.27% of the world's freshwater resources are found in this landlocked country.[7] Nepal contains several major watersheds comprising hundreds of sub-watersheds. The Chitwan district in Nepal is located on the border of the mountain and plain, and so it is mostly affected by temperature variations and precipitation patterns. Climate change poses additional challenges to water quality in the Chitwan region. Rainfall trends have changed over the past few years, with excessive monsoon rainfall causing flash floods and reduced rainfall leading to droughts during the monsoon. These climate-induced changes may further exacerbate water quality degradation in sensitive areas like the Khageri Khola sub-watershed, necessitating integrated water resource management approaches.[8-12] Furthermore, unsustainable infrastructure development, deforestation, and degradation have dried up and reduced the water sources in the Khageri Khola sub-watershed.[8] People in developing countries, including Nepal, are facing serious health risks due to sewage, agricultural, and industrial waste contamination in water supplies.

River water quality is influenced by geology, population density, geography, and land pollution.[13] Therefore, water quality assessment is an urgent need to provide an update on the conditions and suitability of water for various uses such as bathing, drinking, irrigation, and supporting ecosystems and aquatic life.[14] Various physicochemical parameters have been selected to assess surface water quality, evaluate the extent of contamination from external sources, and compare them with the World Health Organization (WHO)[15] and Nepal Drinking Water Quality Standards (NDWQS) recommended values.[16] Multivariate statistical analysis of these parameters further analyzes variation trends and identifies significant relationships, which are essential for identifying pollution sources and understanding the underlying factors influencing water quality.[17-19]

Shefat *et al.*[20] investigated the physicochemical water quality parameters of the Pasur River Estuary and reported that the surface water's pH ranged from 7.1 to 7.9, temperature from 20.7 °C to 33.7 °C, salinity from 8.5 to 16.2 practical salinity units, and dissolved oxygen (DO) from 5.9 to 8.4 mg/L. Mobin *et al.*[21] investigated the water quality of the Turag River, Bangladesh, and reported black-colored water with a bad odor. They suggested that the water quality of the Turag River was outside acceptable limits, and therefore, the water was polluted and hazardous to human health and aquatic ecosystems.

Water security encompasses sustainable availability of acceptable-quality water for human well-being, ecosystem protection, and socioeconomic development. Water security is a top priority in Nepal, with the government committing to improve water services through Climate-Resilient Water Safety Plans across 10 pilot water supply schemes.[22] The country's 16th five-year plan and national adaptation plan prioritize water security as a foundation for growth, food security, and resilient livelihoods. The International Water Management Institute's Nepal strategic roadmap (2024–2030) identifies six strategic priorities, including strengthening water systems resilience and advancing transformative water governance.[23] Elevated nutrient concentrations observed in Khageri Khola indicate an emerging risk to water security because continued nutrient enrichment may accelerate eutrophication, impair aquatic biodiversity, and increase treatment costs, thereby threatening sustainable water security in this region.[24,25]

The Khageri Khola (river) is the main source of water for local communities for domestic use, irrigation, and ecosystem balance. The river and its surface water systems have been increasingly under pressure due to improper and rapid urbanization, population growth, agricultural intensification, resource exploitation, and industrial development,[26,27] all of which have altered the physicochemical properties of surface water, thereby influencing its suitability for various uses. For the effective management of water resources and pollution control, it is necessary to comprehend the spatial and temporal fluctuations in surface water quality parameters.[28,29] As the local community is heavily dependent on surface water resources for drinking, irrigation, and agricultural productivity, there is a pressing need to assess the surface water quality of the Khageri Khola.

However, the quality of surface water has been seriously affected by the increasing inputs of pesticides, chemical fertilizers, heavy metals, untreated wastewater, and other pollutants released from industrial and municipal effluents, surface runoff, and other human activities.[17,30] Furthermore, natural processes such as soil erosion in nearby mountains and the weathering of rocks also affect

the dissolution of minerals and the overall chemistry of surface water.[16,31] Water originating from the upstream region of the Khageri Khola is essential for the livelihood of the people living downstream, as well as for agriculture, tourism, and wildlife in the Khageri Khola sub-watershed. Along with providing water for the Khageri Irrigation Project, this water sustains wildlife in the Barandabhar corridor, the Ramsar site, wetland birds at Bishazari Tal, and ecotourism.[16,32]

Despite the dependence of local people, animals, and the surrounding ecosystem on surface water in Khageri Khola in Chitwan, there is only limited information available about its physicochemical properties and quality. Existing literature on neighboring locations such as Kathmandu and Lalitpur[16,33] has focused on specific contaminants, leaving a research gap in understanding the overall quality of surface water and its spatial and temporal fluctuations.

The present study specifically focuses on the physicochemical quality of water in the Khageri Khola river system, which serves as both a surface water source and a contributor to groundwater recharge in the region.

This study aims to:

(i) Thoroughly assess 12 physicochemical parameters from six sampling sites along the river (from upstream to downstream).
(ii) Compare the obtained results with WHO,[15] Nepal Water Quality Guidelines for Agriculture and Conservation (NWQGAC),[5] and NDWQS[16] guidelines.
(iii) Identify the pollution sources using multivariate statistical analyses (principal component analysis [PCA], hierarchical clustering analysis [HCA], correlation analysis, and regression analysis).
(iv) Provide evidence-based recommendations for water quality management.

This approach provides a comprehensive assessment of the current state of surface water quality, identifies potential contamination sources, and recommends sustainable water management strategies. The results of this research will be beneficial for environmental planners, policymakers, and local governments and communities in their efforts to protect and manage this essential resource. Furthermore, assessing the surface water quality of the Khageri Khola region is not only an academic endeavor but also essential for maintaining the health and well-being of the local people and for ensuring ecosystem sustainability.

2. Materials and methods

2.1. Study area

Khageri Khola in the Chitwan district of Nepal was selected as the study site. It is located near the Barandabhar forest corridor on either side of the Mahendra Highway. The study area extends from 27° 27’ 11” to 27° 35’ 56” N and from 84° 18’ 38.6” to 84° 29’ 00.9” E. It has an altitude range of 196 m (upstream) to 167 m (downstream) above sea level. The sub-watershed covers portions of Ichhakamana Rural Municipality, Ratnanagar Municipality, Kalika Municipality, and Bharatpur Metropolitan City. The Khageri Khola sub-watershed experiences a subtropical monsoon climate with distinct wet seasons from June to September and dry seasons from October to May.[8,34] Average annual rainfall is approximately 1,800–2,200 mm, with over 80% occurring during the monsoon. The average annual temperature ranges from 22 °C to 28 °C. Land use includes agricultural land (50%; 251,000 ha), forest (30%), and urban/settlement areas (20%).[8,35] The water balance is mainly dominated by monsoon rainfall and groundwater recharge, with the rivers experiencing significant flow variation between seasons.[24] There are eight micro-watersheds within the sub-watershed.[8] The map of the research region is displayed in Figure 1.

2.2. Site selection

Six sampling locations were selected along the Khageri Khola from the Kalika Confluence (upstream) to the Rapti Confluence of the Khageri (downstream) along the river length. These locations were selected based on a gradient ranging from relatively less human-influenced areas to highly populated areas along the Kalika and Ratnanagar Municipalities. The description of sampling sites is presented in Table 1.

2.3. Parameter selection and data collection

Six sampling locations, from upstream Kalika Bridge to downstream Rapti Confluence, were selected, with five samples from each location. The water samples were collected in February 2025 during the pre-monsoon season. Some of the parameters, such as temperature, conductivity, DO, and pH, were assessed and measured in situ. For the assessment of other parameters, water samples were collected in pre-cleaned plastic bottles and were tightly sealed with inner and outer caps to prevent air exchange and labeled properly. The samples were then refrigerated at 4 °C–6 °C in the Saptagandaki Multiple Campus laboratory to prevent microbial degradation of analytes. Measurements of carbon dioxide (CO_2), total hardness, total alkalinity, and total dissolved solids (TDS), as well as nitrate (NO^{3-}), phosphate (PO_4^{3-}), chloride (Cl^-), and ammonia (NH_3) concentrations, were conducted. The methods and instruments used in this study are provided in Table 2. The American Public Health Association standard protocols[36,37] were followed for the collection, preservation,

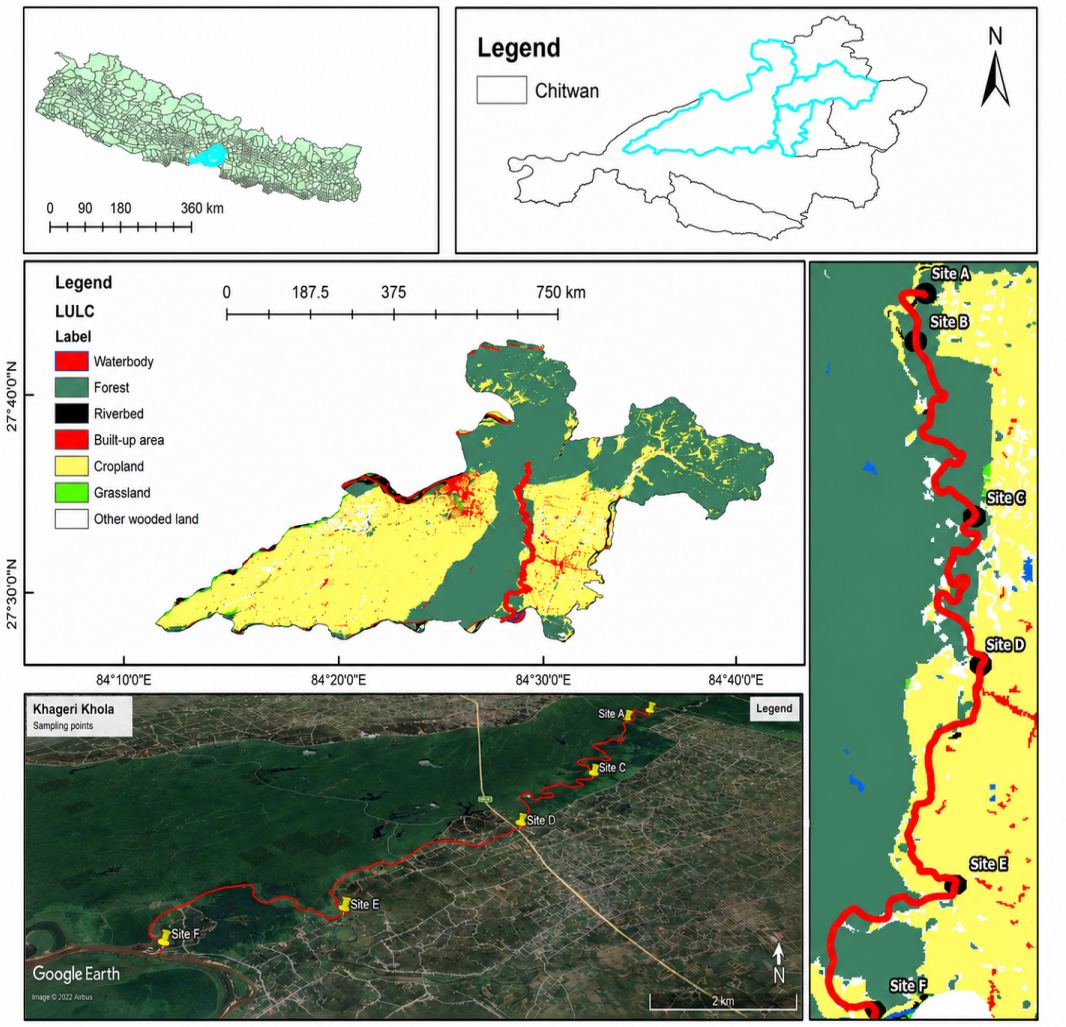

Figure 1. Study area of Khageri Khola (river) showing waterbody, forest, riverbed, built-up area, cropland, grassland, and other wooded land

Table 1. Description and geographical characteristics of sampling sites in Khageri Khola (river)

Sites	Location	Latitude	Longitude	Site description
A	Confluence with tributaries, Kalika	27.45331	84.31072	Located in a built-up area, with sand and gravel extraction activities observed
B	Khageri Bridge, Kalika River	27.68253	84.47758	Vehicle washing and cleaning activities were observed
C	Confluence with Mani Khola	27.65592	84.48772	Human activities, including fishing and clothes washing, were observed
D	Khager Bridge, Ratnanagar	27.55206	84.49103	Located near a market area, where sewage discharge into the river and river water diversion for agricultural activities were observed.
E	Confluence with tributaries, Chitrasari	27.61383	84.48167	Human activities, including fishing, clothes washing, and livestock rearing, were observed
F	Confluence with Rapti River	27.59892	84.48358	Located near a densely populated area, with recreational activities such as fishing observed

and analysis of surface water samples.

The parameters were selected based on their importance in terms of their potential for surface water contamination and their ability to capture the health and environmental issues related to the Khageri Khola watershed in Chitwan, Nepal. Although parameters such as pH and temperature are primarily influenced by natural processes, anthropogenic activities can alter them. Elevated temperature may result from thermal pollution (discharge of heated water from industrial processes, power plants, or urban runoff), while pH changes can occur due to acid rain or industrial effluent discharge. Therefore, monitoring these natural parameters is essential for detecting anthropogenic discharge.[5]

Based on the following criteria, the water quality parameters for this investigation were selected:

(i) Health relevance and WHO/NDWQS regulatory standards**:** Based on the direct or indirect influence of water quality parameters on human health, irrigation, and the ecosystem, as suggested by WHO[15] and NDWQS,[16] these parameters were selected for investigation.

(ii) Published literature**:** The selection of parameters in this investigation was based on numerous previous studies[16,31,33,38,39] conducted in neighboring regions of Nepal and the Indo-Gangetic Plains that found important factors influencing the quality of surface water at the selected sites.

(iii) Local context and prevalence**:** The parameters were selected based on the current anthropogenic and geological conditions in Bharatpur, Chitwan, and nearby areas, such as Kathmandu and the Terai regions of Nepal.[31,33,39-41] In this context, hardness is more common in the surface water of the Terai region of Nepal. Nitrates and phosphates were chosen due to the extensive use of fertilizers by local farmers. In Chitwan district, farmers heavily use urea, diammonium phosphate, and ammonium nitrate for agricultural production. These fertilizers contribute significantly to nitrate and phosphate levels in surface water through runoff and are recognized as important contributors to eutrophication even at relatively low concentrations in surface water ecosystems.

(iv) Feasibility of analysis**:** The parameters were selected based on the availability of reliable testing techniques and instruments in the laboratory to get accurate and reproducible results.

Table 2. Water quality parameters, analytical methods, and instruments used for water quality analysis

Parameter	Method	Instrument	References
Temperature	–	Mercury thermometer	42
pH	–	pH meter (model pH009)	43
DO	–	Digital dissolved oxygen meter	5
Free CO_2	Phenolphthalein titration method	–	44
Total hardness	Ethylenediaminetetraacetic acid titration method	–	44
Total alkalinity	Acid–base titration method	–	42,44
Total dissolved solids	Complete evaporation method	–	44
Conductivity	–	Conductivity meter (model 191)	45,46
Nitrate	Brucine colorimetric method	Spectrophotometer (Spectronic 21, Milton Roy Company, United States)	47
Phosphate	Ammonium molybdate method	Spectrophotometer (Spectronic 21, Milton Roy Company, United States)	42
Chloride	Argentometric titration method	–	44
Ammonia	Colorimetric method	Spectrophotometer (Spectronic 21, Milton Roy Company, United States)	5

Abbreviations: CO_2: Carbon dioxide; DO: Dissolved oxygen.

The flowchart shown in Figure 2 depicts the methodology adopted for water quality analysis.

2.4. Experimental measurement of physicochemical parameters

2.4.1. Temperature

Water temperature was measured using a mercury thermometer. The calibrated thermometer[42] was immersed in the beaker containing the sample, and the reading was recorded.

2.4.2. pH

The pH of the sample water was measured using a calibrated digital pH meter (HANNA, Italy). Before use, the meter was calibrated using buffer solutions with pH values of 4 and 7. Before and after each test, the glass electrode was properly cleaned with distilled water.[43]

2.4.3. Dissolved oxygen

The DO concentration of each sample was measured using a calibrated Eco Sense DO 200A Dissolved Oxygen meter (LABTRONICS, India). The electrode was washed, rinsed with distilled water, and placed into a beaker containing sample water.[5]

2.4.4. Electrical conductivity

The conductivity of the water was measured using a calibrated digital conductivity meter (HANNA, Italy). The electrode was cleaned and rinsed before and after each stable reading.[45,46]

2.4.5. Total alkalinity

Total alkalinity was measured by the titration technique. A 100 mL sample of water was transferred to a conical flask, and two drops of phenolphthalein indicator were added.

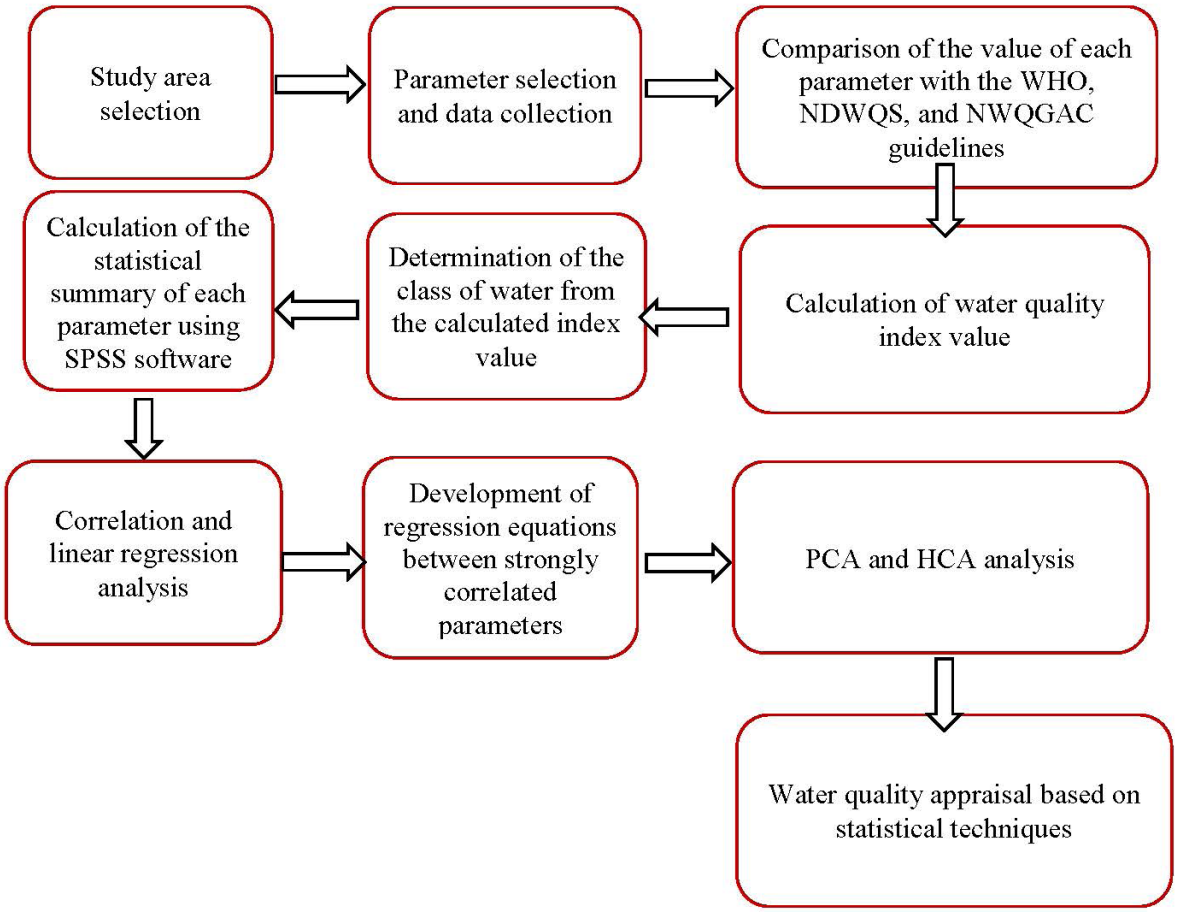

Figure 2. Flowchart of the methodology used for physicochemical water quality assessment
Abbreviations: HCA: Hierarchical cluster analysis; NDWQS: Nepal Drinking Water Quality Standards; NWQGAC: Nepal Water Quality Guidelines for Agriculture and Conservation; PCA: Principal component analysis; SPSS: Statistical Package for the Social Sciences; WHO: World Health Organization.

The appearance of a pink color indicated the presence of carbonate (CO_3^{2-}), which was then titrated with 0.02 N sulfuric acid (H_2SO_4) until colorless. Then, methyl orange was added and titrated until the color changed from yellow to red, showing bicarbonates (HCO_3^-). The alkalinity was then calculated using the formula provided by Trivedy and Goel.[46]

$$PA\ as\ CaCO_3\ (mg/L) = \frac{A \times normality\ of\ sulfuric\ acid \times 1{,}000 \times 50}{Volume\ of\ sample} \quad (1)$$

$$TA\ as\ CaCO_3\ (mg/L) = \frac{B \times normality\ of\ sulfuric\ acid \times 1{,}000 \times 50}{Volume\ of\ sample} \quad (2)$$

where:

(i) A is the volume of H_2SO_4 used with only phenolphthalein.
(ii) B is the volume of total H_2SO_4 used with phenolphthalein and methyl orange.
(iii) PA is phenolphthalein alkalinity.
(iv) TA is total alkalinity.

2.4.6. Total hardness

The hardness of the water was measured using the ethylenediaminetetraacetic acid titration method with Eriochrome Black T as an indicator. The endpoint was identified by the color change of the indicator when all Mg^{2+} and Ca^{2+} ions were complexed by ethylenediaminetetraacetic acid.[44]

$$Total\ hardness\ as\ CaCO_2 \left(\frac{mg}{L}\right) = \frac{Volume\ of\ ethylenediaminetetraacetic\ acid\ used}{Volume\ of\ sample} \times 1{,}000 \quad (3)$$

2.4.7. Total dissolved solids

Total dissolved solids refer to the total quantity of organic and inorganic components (e.g., metals, minerals, salts, and ions) dissolved in a certain volume of water. A filtered sample of water was taken and transferred into a pre-weighed porcelain basin and then heated to complete evaporation. The dry porcelain basin containing the residue was then weighed, and the TDS concentration was calculated using the following formula:[44]

$$\text{Dissolved solids (ppm)} = \frac{(W2 - W1)}{100} \times 10^6 \quad (4)$$

where:

(i) W_2 is the weight of the dry porcelain basin containing the residue.
(ii) W_1 is the weight of an empty dry porcelain basin.

2.4.8. Free carbon dioxide

The amount of free CO_2 was calculated by titrating a 100 mL sample of water (containing 5–10 drops of phenolphthalein) with 0.05 N sodium hydroxide (NaOH) until a persistent pink color was obtained. The absence of pink color before titration indicated the existence of free CO_2. The free CO_2 concentration was determined using the following formula:[44]

$$Free\ CO_2\ (mg/L) = \frac{Volume\ of\ NaOH\ used \times normality\ of\ NaOH \times 44 \times 1{,}000}{Volume\ of\ sample} \quad (5)$$

2.4.9. Nitrate

Nitrate concentration was measured colorimetrically by treating 10 mL of water with 2 mL of NaOH, 10 mL of H_2SO_4, and 0.5 mL of brucine solution. The mixture was then heated in a water bath for 20 min, then cooled, and the absorbance was measured at 410 nm using a Spectronic 21 spectrophotometer (Milton Roy, USA). Nitrate concentration was determined using a standard calibration curve.[47] Nitrate concentration measured using the Brucine colorimetric method is specific for nitrate and does not require iron (Fe) correction for interference, as the reaction with brucine in acidic medium is selective for nitrate.

2.4.10. Chloride

The chloride concentration was measured using the argentometric technique. A 50 mL sample with a few drops of potassium chromate indicator was titrated with a standard silver nitrate solution until the yellow color changed to red, indicating the formation of silver chromate. A blank sample prepared using distilled water underwent the same procedure.[44]

2.4.11. Phosphate

Inorganic phosphorus concentration was determined by adding 2 mL of ammonium molybdate and five drops of stannous chloride to a 50 mL water sample. After 10–15 min, the resulting blue color was measured at 690 nm using a spectrophotometer. Distilled water with the same reagents was used as a blank.[42] The concentration of inorganic phosphorus was determined using a standard calibration curve.

2.4.12. Ammonia

Ammonia concentration was determined by a colorimetric approach. Phenol-nitroprusside solution (2 mL) and reagent B (2 mL) were added to a 20 mL sample, and the

mixture was diluted to 25 mL with distilled water. The mixture was kept for 1 h at 25 °C in the dark, and the absorbance was measured at 635 nm. The concentration of ammonia was calculated using a calibration curve.

2.4.13. Water Quality Index

The weighted arithmetic approach developed by Karuppannan *et al.*[2] and subsequently adopted by others[4,16,26,48-54] was used to determine the Water Quality Index (WQI) as follows:

$$\text{WQI} = \sum_{i=1}^{n} W_i Q_i / \sum_{i=1}^{n} W_i \quad (6)$$

where W_i represents the unit weight for the i-th parameter, n is the number of parameters or variables, and Q_i represents the quality rating of the i-th water quality parameter.

The unit weight (W_i) is inversely correlated to standards for the i-th parameter (S_n):

$$W_i = \frac{K}{S_n} \quad (7)$$

where K is the proportionality constant. The value of K was considered as 1 in this study and was determined using the equation below:[16,48]

$$K = \frac{1}{\Sigma \frac{1}{S_n}} \quad (8)$$

The quality rating (Q_i) is determined as:[16,47,48]

$$Q_i = 100\left(\frac{V_0 - V_i}{S_n - V_i}\right) \quad (9)$$

where V_i and V_o indicate the ideal and observed value of the i-th parameter at a given sampling site in safe water, respectively, and S_n signifies the standard permissible value of the i-th parameter.

Except for pH and DO, all ideal values (V_i) were considered to be zero.[4,27] For pure water, the ideal pH value is 7.0, whereas the permissible pH value for polluted water is 8.5. The standard permissible level for DO is 5 mg/L, whereas the ideal value is 14.6 mg/L. Thus, the following equation is used to determine the pH quality rating:[16,47,48,55]

$$Q_{pH} = 100\left(\frac{v_{pH} - 7.0}{8.5 - 7.0}\right) \quad (10)$$

where V_{pH} indicates the observed value of pH. If Q_i = 0, no contaminants are present, and if $0 < Q_i < 100$, the contaminant levels are within the recommended limits. If $Q_i > 100$, the contaminant levels exceed the permissible limits.[4,16,26,48-54]

3. Results

The detailed results of the variations in physicochemical parameters, including the maximum, minimum, mean, standard error, and range, are presented in Table 3. The standard error measures the uncertainty associated with the estimated mean value. Table 4 shows the comparison of the selected parameters with the recommended limits specified by the WHO, NWQGAC, NDWQS, and

Table 3. Summary statistics of the physicochemical water quality parameters

Parameter	Maximum	Minimum	Mean	Standard error	Range
Temperature (°C)	24.0	20.0	22.25	0.62	20–24
pH	8.5	7.9	8.2	0.1	7.9–8.5
Conductivity (µS/cm)	488	357	418	19.34	357–488
DO (mg/L)	7.7	6.2	7.08	0.24	6.2–7.7
TDS (mg/L)	700	200	467	80.28	200–700
Free CO_2 (mg/L)	58	45	51	1.95	45–58
Total hardness (mg/L)	293	227	250	10.01	227–293
Total alkalinity (mg/L)	131	99	115	5.68	99–131
Chloride (mg/L)	31	21	27	1.66	21–31
Phosphate (mg/L)	9.47	4.49	7.31	0.82	4.49–9.47
Nitrate (mg/L)	55.53	40.46	45.74	2.3	40.46–55.53
Ammonia (mg/L)	12.39	4.63	9.52	1.21	4.63–12.39

Abbreviations: CO_2: Carbon dioxide; DO: Dissolved oxygen; TDS: Total dissolved solids.

Table 4. Comparison of selected physicochemical parameters against WHO, NDWQS, NWQGAC, and irrigation water quality standards

Parameter	NWQGAC	NDWQS	Irrigation water quality	WHO	References
pH	6.4–9	6.5–8.5	6.5–8.5	6.5–8.5	18,56
Conductivity (µS/cm)	–	1,500	40,000	1,000	49,57
DO (mg/L)	5–8	5	–	>5	36,58
Chloride (mg/L)	–	250	100	250	5,59
Total hardness (mg/L)	300	500	–	500	5,18
Total alkalinity (mg/L)	250	–	20–100	500	43
Free CO_2 (mg/L)	<75	–	12	–	44
Phosphate (mg/L)	<1	–	–	0.1–1.0	43
Nitrate (mg/L)	300	50	300	50	49,59
TDS (mg/L)	–	1,000	-	1,000	36,58
Ammonia (mg/L)	–	1.5	30	1.5	16

Abbreviations: CO_2: Carbon dioxide; DO: Dissolved oxygen; NDWQS: Nepal Drinking Water Quality Standards; NWQGAC: Nepal Water Quality Guidelines for Agriculture and Conservation; TDS: Total dissolved solids; WHO: World Health Organization.

irrigation water quality guidelines.

3.1. Temperature

Although not specifically regulated by the WHO or NDWQS, temperature influences various water quality parameters, such as the solubility of gases and other biological activities. The average water temperature ranged from 20 °C–24 °C (Figure 3A). The highest temperature was recorded at Khageri Bridge, Ratnanagar (KBR; 24 °C) and Confluence with tributaries, Chitrasari (CCS; 23.5 °C), whereas the lowest temperature (20 °C) was observed at Confluence with tributaries, Kalika River (CK). The mean temperature was found to be 22.25 ± 0.62 °C.

Temperature impacts aquatic systems.[60] Warmer water decreases DO levels, increases nutrient breakdown, and causes algal blooms.[61,62] The optimal water temperature for irrigation is 15 °C–20 °C.[63] The recorded temperatures (20 °C–24 °C) exceeded this optimal range at some sampling sites, which may potentially influence irrigation efficiency and crop productivity.

For aquaculture, the optimal temperature is 18 °C–22 °C, suggesting that minor variations from this range may require management interventions to maintain suitable conditions. For drinking purposes, water temperature below 25 °C is acceptable.[15] indicating no immediate issues regarding drinking water quality. The observed variation in water temperature among sampling sites may be attributed to differences in local climatic conditions, solar radiation exposure, water flow characteristics, tributary inflows, and vegetation cover.

3.2. pH

pH measures the acidity or alkalinity of water (i.e., the concentration of free H^+ and OH^- ions), with pure water having a neutral pH of 7. The observed pH ranged from 7.9 to 8.5 (Figure 3B), indicating slightly alkaline conditions. The highest recorded pH value was 8.5 at CK and Confluence with Rapti River (CR), whereas the lowest pH value was 7.9 at KBR, with a mean of 8.2 ± 0.10. Higher pH values may be due to alkaline geology or vegetation, whereas lower pH values might be due to organic matter inputs. For irrigation, the recommended pH range is 6.5–8.5.[64,65] The observed pH values were within the recommended range but approached the upper limit, which may reduce nutrient availability and negatively impact crop productivity. The recommended pH range for aquaculture[64] and drinking water is 6.5–8.5,[15,66] which the observed values fell within, indicating suitability for aquatic life and human consumption.

3.3. Electrical conductivity

Electrical conductivity measures the tendency of water to conduct electricity, reflecting the concentration of dissolved ions. Generally, electrical conductivity increases with increasing temperature due to the enhanced mobility of ions.[45,46,67,68] The observed conductivity ranged 357–488 µS/cm (Figure 3C), with the highest value (488 µS/cm) at Confluence with Mani Khola (CMK), the lowest value (357 µS/cm) at CK, and a mean value of 418 ± 19.34 µS/cm. This

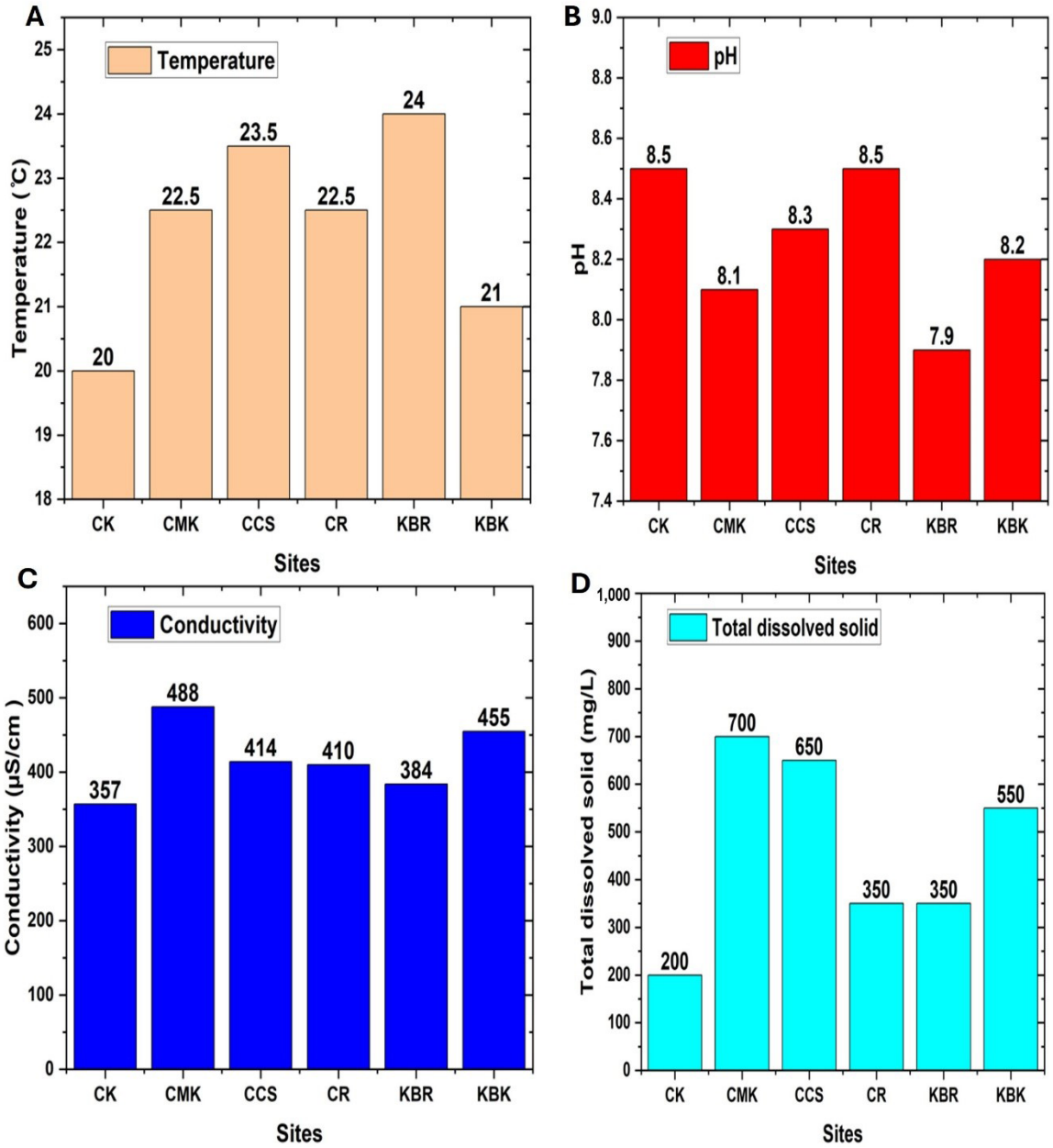

Figure 3. Variation of (A) temperature, (B) pH, (C) conductivity, and (D) total dissolved solids at different sampling sites
Abbreviations: CCS: Confluence with tributaries, Chitrasari; CK: Confluence with tributaries, Kalika River; CMK: Confluence with Mani Khola; CR: Confluence with Rapti River; KBK: Khageri Bridge, Khageri River; KBR: Khageri Bridge, Ratnanagar.

value was below the NWQGAC guideline limit (1,500 µS/cm) for irrigation water quality,[16,66] indicating suitability for irrigation.

Although the NDWQS and WHO15,16,66 do not provide specific conductivity thresholds for drinking water, the measured levels are appropriate for agricultural use. Thapa *et al.*[69] reported conductivity values of Jhimruk River water below 500 µS/cm, indicating high-quality freshwater systems in Nepal, which is consistent with the findings of this study. Higher conductivity at CMK (488 µS/cm) suggests higher concentrations of dissolved salts and minerals, possibly due to agricultural or industrial runoff, whereas lower conductivity at CK (357 µS/cm) indicates lower dissolved ion concentrations, possibly due to reduced inputs or greater dilution. Factors such as local geology, land use, and water flow patterns may also influence these variations.

3.4. Total dissolved solids

Total dissolved solids are the organic and inorganic substances (e.g., minerals and ions) dissolved in water. A high TDS value indicates a higher concentration of dissolved constituents in water. TDS ranged from 200 mg/L to 700 mg/L (Figure 3D). The highest TDS value (700 mg/L) was found at CMK, and the lowest value (200 mg/L) was observed at CK, with a mean value of 467 ± 80.28 mg/L.

According to the NWQGAC, the maximum allowable TDS limit is 1,000 mg/L for irrigation water;[16,66] thus, the observed TDS values were within this limit, indicating suitability for irrigation. The NDWQS and WHO[15,16,66] do not specify specific TDS limits; however, Acharya and Pant[70] demonstrated that TDS levels above 500 mg/L may affect taste. The observed TDS levels at some sampling sites exceeded 500 mg/L (maximum: 700 mg/L), which may slightly influence taste but remain within acceptable levels. Higher TDS at CMK (700 mg/L) and CCS (650 mg/L) suggest higher concentrations of dissolved solids, possibly due to agricultural or industrial runoff. Lower TDS values at CK (200 mg/L) and CR (350 mg/L) indicate lower concentrations of dissolved materials, possibly due to reduced runoff or increased dilution. Local geology and land use may also contribute to these variations.

3.5. Dissolved oxygen

Dissolved oxygen is essential for aquatic organisms and is influenced by water temperature and the presence of dissolved organic matter. DO ranged from 6.2 mg/L to 7.7 mg/L (Figure 4A). The maximum recorded DO value was 7.7 mg/L at CMK and Khageri Bridge, Khageri River (KBK); the lowest DO was observed at CK (6.2 mg/L), with the mean value of 7.08 ± 0.24 mg/L. Pantha *et al.*[71] highlighted that high DO levels are indicative of good water quality and low levels of organic contamination. The observed DO levels were within an acceptable range, suggesting the absence of significant organic pollution and microbial contamination. The NWQGAC, NDWQS, and WHO[15,16,66] do not set a specific DO limit but indicate that higher DO levels reflect lower organic contamination and better oxygen availability for aquatic ecosystems. Higher DO values (7.7 mg/L) at CMK and KBK may be attributed to increased water movement and enhanced oxygen mixing. Conversely, lower DO values at CK (6.2 mg/L) and CR (6.7 mg/L) may be associated with slower water flow and higher water temperatures. Additionally, organic matter decomposition can consume oxygen, potentially decreasing DO levels.

3.6. Free carbon dioxide

In the aquatic ecosystem, free CO_2 in water is generated by the respiration of aquatic organisms, with a portion dissolving in water as carbonic acid and the remainder diffusing into the atmosphere. The free CO_2 concentration in water (Figure 4B) ranged from 45 mg/L to 58 mg/L. The maximum free CO_2 concentration was 58 mg/L at KBR, whereas the minimum was 45 mg/L at CR, with a mean value of 51 ± 1.95 mg/L.

According to NWQGAC, CO_2 levels below 75 mg/L are acceptable for irrigation, indicating that all observed values were within this limit and suggesting minimal impact on irrigation water quality. NDWQS and WHO[15,66] guidelines do not specify CO_2 limits; however, Shahi *et al.*[72] reported that CO_2 concentrations above 50 mg/L can lower pH, affecting nutrient availability and potentially stressing aquatic organisms. The observed CO_2 levels in this study exceeded this reported threshold at some sampling sites, suggesting a potential influence on aquatic ecosystems and water quality. Higher free CO_2 levels at KBR (58 mg/L) and MK (54 mg/L) may be associated with organic matter decomposition or increased biological respiration, whereas lower levels at CR (45 mg/L) and CCS (48 mg/L) may be associated with lower organic matter decomposition or higher photosynthetic activity. Temperature also affects CO_2 solubility, with warmer waters potentially holding less CO_2.

3.7. Total hardness

The amount of calcium and magnesium present in the water determines total hardness, which is mainly obtained from sewage and the weathering of rocks and sediments.[73] The hardness of water (Figure 4C) ranged from 227 mg/L to 293 mg/L as $CaCO_3$. The maximum hardness value (293 mg/L) was observed at CMK, and the minimum hardness value (227 mg/L) was observed at KBK, with a mean value of 250 ± 10.01 mg/L. The NWQGAC and the WHO[15,16,66] recommend a maximum hardness of 300 mg/L for irrigation, and the measured values fall within this range, indicating suitability for agricultural use. The NDWQS sets a higher limit of 500 mg/L, indicating suitability for drinking water. However, Shrestha *et al.*[16] reported that hardness exceeding 200 mg/L indicates hard water, which can alter soil properties and thus decrease irrigation efficiency, cause scaling, and reduce detergent effectiveness. Similarly, Adhikari *et al.*[13] reported that high hardness levels could disrupt aquatic ecosystems. Higher hardness values at CMK (293 mg/L) and KBK (260 mg/L) are likely due to calcium-/magnesium-rich

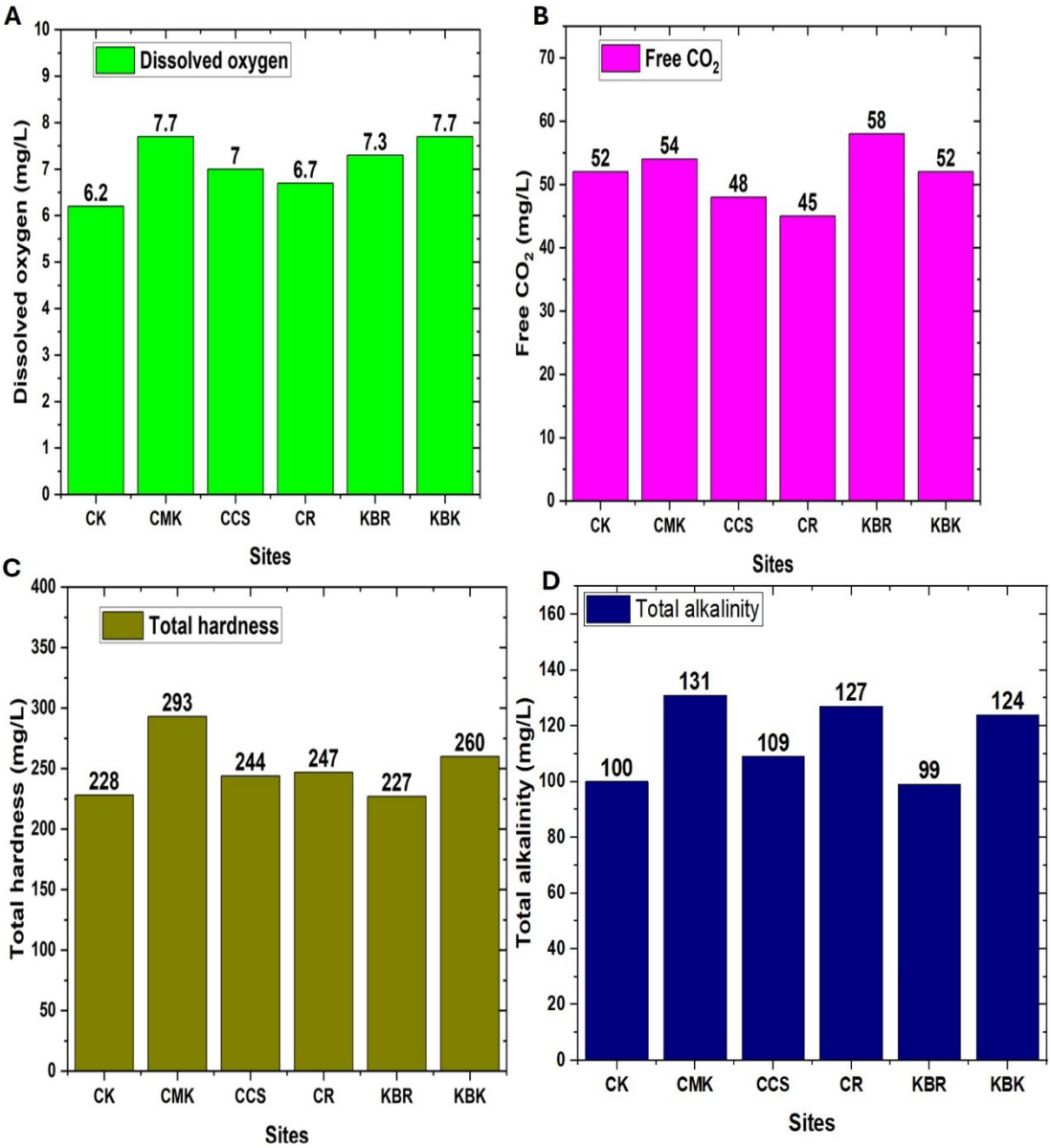

Figure 4. Variation of (A) dissolved oxygen, (B) free CO_2, (C) total hardness, and (D) total alkalinity at different sampling sites
Abbreviations: CCS: Confluence with tributaries, Chitrasari; CK: Confluence with tributaries, Kalika River; CMK: Confluence with Mani Khola; CO_2: Carbon dioxide; CR: Confluence with Rapti River; KBK: Khageri Bridge, Khageri River; KBR: Khageri Bridge, Ratnanagar.

geological formations, while the lower values at CK (228 mg/L) and KBK (227 mg/L) are likely due to different rock compositions or lower ion exchange or dilution and runoff from different types of land use.

3.8. Total alkalinity

Alkalinity is the capacity of water to neutralize a strong acid and the presence of OH^- ions, and is a good indicator of the presence of dissolved CO_3^{2-} and HCO_3^-.[74] Naturally, less polluted water is more alkaline than acidic. The alkalinity ranged from 99 mg/L to 131 mg/L (Figure 4D). The maximum value of alkalinity was 131 mg/L at CMK, and the minimum value was 99 mg/L at KBR, with a mean value of 115 ± 5.68 mg/L. The NWQGAC provides a maximum limit of 250 mg/L for irrigation, suggesting that the water is suitable for irrigation. The NDWQS and WHO[15,16,66] recommend 20–100 mg/L for general water quality; the observed values slightly exceed this range, and closer monitoring is recommended. Acharya *et al.*[66] reported the optimal alkalinity of water in three lakes in

the Barandabhar Forest Corridor, central Nepal, ranging from 106.10 mg/L to 135.13 mg/L (mean = 118.46 mg/L), which is comparable to the observed values in this study. Higher alkalinity at CMK (131 mg/L) and CR (127 mg/L) might have resulted from runoff from areas with carbonate-rich soils or geological formations. Lower alkalinity at CK (100 mg/L) and KBR (99 mg/L) suggests reduced buffering capacity, possibly due to different land use and lower concentrations of CO_3^{2-}.

3.9. Chloride

Chloride ion is a dominant anion in water and plays a crucial role in life; however, higher concentrations of Cl^- can cause health hazards. Cl– ranged from[21] mg/L to 31 mg/L (Figure 5A), with its maximum value (31 mg/L) observed at CR, its minimum value (21 mg/L) observed at CK, and a mean of 27 ± 1.66 mg/L. The NWQGAC guidelines recommend 100 mg/L of Cl^- for irrigation, and WHO recommends 250 mg/L for drinking water. Since the observed levels are markedly lower, the water is considered suitable for irrigation and drinking.[15,16,66] Bhatt *et al.*[75] reported that Cl^- levels below 30 mg/L are typically safe for freshwater ecosystems. Higher Cl^- levels at CCS (30 mg/L) and CR (31 mg/L) may be due to agricultural activities, runoff from roads, or industrial sources. The lower Cl^- levels at CK (21 mg/L) and KBK (23 mg/L) indicate less anthropogenic influence or greater natural dilution. Local geology and hydrological conditions also affect the natural Cl^- concentrations in the water.

3.10. Nitrate

Nitrate ions are generated by industrial wastes, sewage discharge, and agricultural runoff, and their concentration indicates the quality of water.[36,52,59,76-78] The concentration range of NO^{3-} in the current investigation ranged from 40.46 mg/L to 55.53 mg/L (Figure 5B), with the maximum value of 55.53 mg/L observed at CCS, the minimum value of 40.46 mg/L observed at KBK, and a mean of 45.74 ± 2.30 mg/L. The NWQGAC recommends 300 mg/L of NO_3^- for irrigation, suggesting that the observed levels are well within this range and suitable for agriculture. However, the NDWQS and WHO[15,16,66] recommend a lower limit of 50 mg/L for drinking water, suggesting that most sites are below this limit, except CCS (55.5 mg/L). Acharya *et al.*[79] reported that enhanced NO_3^- levels above 30 mg/L can cause eutrophication, influencing aquatic health. Adhikari *et al.*[13] reported that NO_3^- concentrations above 45 mg/L also impact aquatic ecosystems and agriculture. The higher NO_3^- concentration (55.5 mg/L) at CCS might be due to increased agricultural runoff (excessive use of fertilizer), while the lower NO_3^- concentration at KBK (40.46 mg/L) indicates higher dilution or less input.

3.11. Phosphate

Phosphate is a common fertilizer and a key ingredient in detergents. Thus, its major sources are sewage discharge, agricultural runoff,[78,80,81] animal excreta, and detergents.[82] In the present study, the PO_4^{3-} concentration ranged from 4.49 mg/L to 9.47 mg/L (Figure 5C), with the maximum value (9.47 mg/L) observed at KBR, the minimum (4.49 mg/L) observed at CK, and a mean of 7.31 ± 0.82 mg/L. The NWQGAC recommends a maximum PO_4^{3-} concentration of <1 mg/L for irrigation water, whereas the NDWQS and WHO15,16,66 recommend a low limit of 0.02 mg/L for drinking water. The observed PO_4^{3-} concentrations at all sites are substantially higher than these recommended limits, indicating severe nutrient pollution. Shrestha *et al.*[16] reported that elevated phosphate levels (>1 mg/L) in Nepalese water may cause eutrophication, algal growth, oxygen depletion, and deterioration of water quality and aquatic life. Higher phosphate concentrations at CCS (9.05 mg/L) and KBR (9.47 mg/L) might be due to agricultural runoff (fertilizers and animal waste) and sewage discharge (containing detergents), while the lower PO_4^{3-} concentrations at CK (4.49 mg/L) indicate greater dilution or less input. Therefore, immediate monitoring and intervention are needed to prevent ecological damage.

3.12. Ammonia

High levels of NH_3 are toxic to aquatic life ($NH_3 + H_2O \rightarrow NH_4OH$), impairing fish gill function and causing respiratory issues or ultimately death.[83,84] Elevated ammonia also causes eutrophication, algal growth, oxygen depletion, and water degradation.[13,16] The NH_3 concentration ranged from 4.63 mg/L to 12.39 mg/L (Figure 5D), with the maximum value of 12.39 mg/L observed at KBR, the minimum value of 4.63 mg/L observed at CR, and a mean of 9.53 ± 1.21 mg/L.

The NWQGAC guidelines allow a maximum NH_3 concentration of 1.5 mg/L for irrigation, which is substantially lower than the observed values, indicating the unsuitability of the water for irrigation. The NDWQS[15,16,66] limit is up to 30 mg/L of NH_3 for drinking water, indicating that the water is acceptable with respect to NH_3 concentration. The WHO generally aligns with the NDWQS limits. Higher concentrations of NH_3 at CCS and KBR (11.59 mg/L and 12.39 mg/L, respectively) might be due to agricultural runoff (fertilizers and manures) and sewage discharge. Lower concentrations of NH_3 observed at CMK and CR (8.15 mg/L and 4.63 mg/L, respectively) indicate less intensive agricultural activity or more effective waste management.

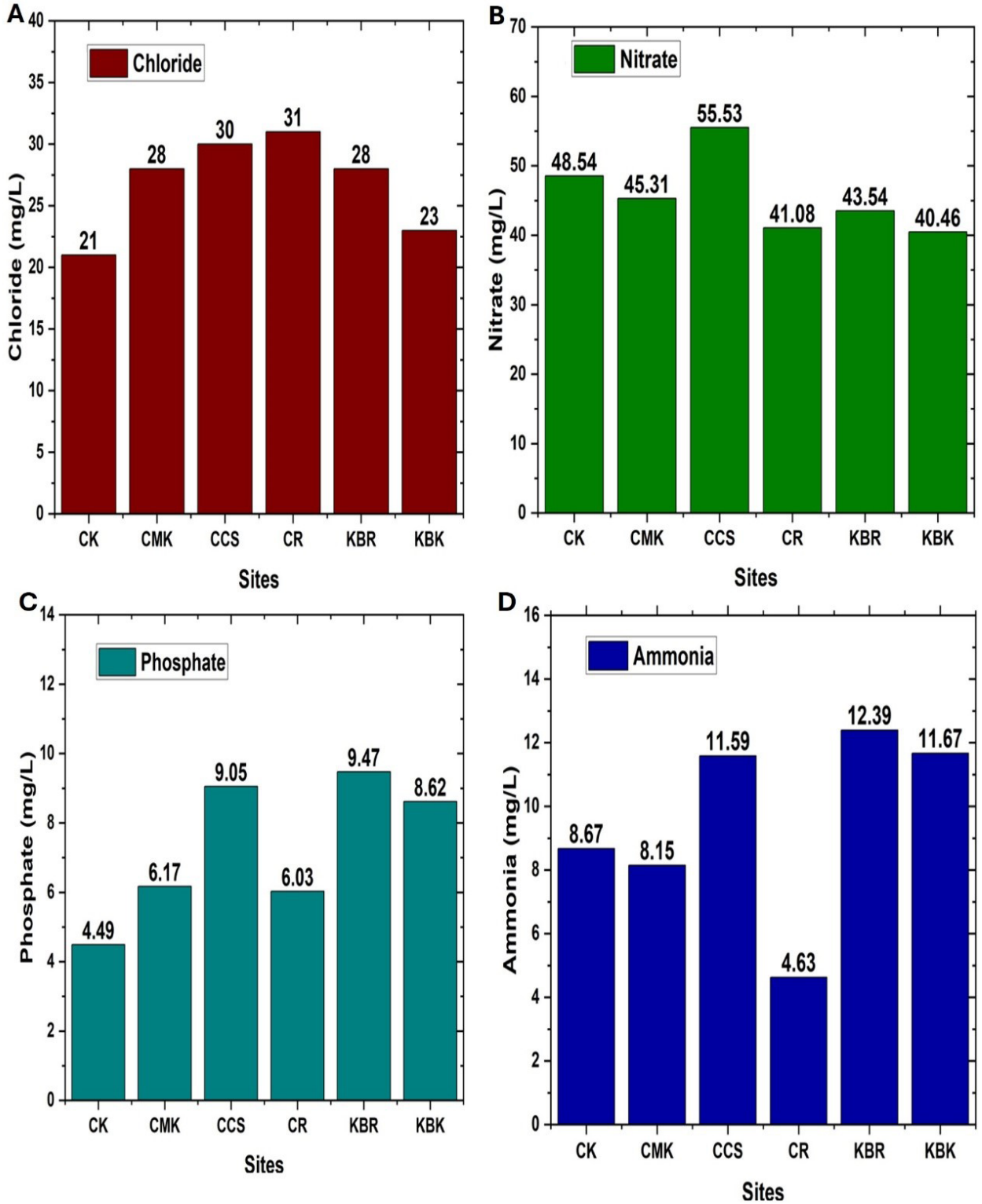

Figure 5. Variation of (A) chloride, (B) nitrate, (C) phosphate, and (D) ammonia at different sampling sites
Abbreviations: CCS: Confluence with tributaries, Chitrasari; CK: Confluence with tributaries, Kalika River; CMK: Confluence with Mani Khola; CR: Confluence with Rapti River; KBK: Khageri Bridge, Khageri River; KBR: Khageri Bridge, Ratnanagar.

4. Statistical analysis results

In this study, the Origin software package (OriginPro 2024, OriginLab Corporation, USA) was used to draw the graphs and perform the multivariate statistical techniques such as PCA, regression analysis, correlation analysis, and HCA for assessing the groundwater quality of Khageri Khola. For cluster analysis, minimum–maximum normalization was used, with Euclidean distance as a measure of similarity and Ward's technique for clustering.[3]

The traditional water quality data presentation techniques cannot adequately reveal the relationships among multiple water quality parameters because each parameter represents different physicochemical characteristics, making it difficult to determine the type and extent of water pollution.[26] Correlation analysis helps identify the relationships among variables and the factors controlling water chemistry. A positive correlation indicates that both variables increase together, whereas a negative correlation indicates that one increases while the other decreases. The correlation coefficient (r) ranges from −1 to +1.[3] According to Das *et al.*,[3,4] r values between 0.0 and ±0.5 indicate poor correlation, values from ±0.5 to ±0.8 indicate moderate correlation, and values from ±0.8 to ±1.0 indicate extremely high correlation. The magnitude of the correlation coefficient was calculated using **Equation 6**.[3,4,18] Regression analysis describes the mathematical relationship between parameters and determines the linear relationship between them.[3] Regression analysis was performed for highly correlated parameters, and the results are presented in Figure 6A–G.

The SPSS software (version 31, IBM Corporation, USA) was used to compute Pearson's r values for the 12 parameters (Table 5), using **Equation 6**.[3,4,18] While SPSS is a robust tool for correlation, regression, PCA, and HCA, the statistical methods employed are subject to certain limitations, including sensitivity to outliers and the assumption of linear relationships.[85] To minimize these limitations, the normality of the data distribution was verified, and appropriate data transformations were applied where necessary. Moreover, the interpretation of the statistical results considered the influence of geological structure on physicochemical parameters such as pH, temperature, and alkalinity.

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{n}}{\sqrt{\left[\sum X^2 - \frac{(\sum X)^2}{n}\right]\left[\sum Y^2 - \frac{(\sum Y)^2}{n}\right]}} \quad (11)$$

A large r between the two variables X and Y indicates a linear relationship of the type $Y = Ax + B$.

Surface water datasets are generally complex because they comprise numerous interrelated water quality parameters. Correlation and regression analyses simplify this complexity by identifying the most influential parameters, thereby facilitating data interpretation for scientists, decision-makers, and the public.[86] Correlation analysis measures the strength (degree) and direction of the linear relationship between two variables (e.g., hardness, pH, and NO_3^-), with r values ranging from +1 (perfect positive) to −1 (perfect negative), whereas 0 indicates no linear relationship.[4] Regression analysis provides a predictive equation, facilitating the modeling of the relationship between water quality variables (e.g., TDS and Cl^-).[3,19,28,36,60,87-89] The correlation matrix and significance levels (two-tailed) for the water quality parameters are presented in Table 5.

The Pearson correlation matrix presented in Table 5 shows Pearson's r values, p-values, and significance levels for various pairs of water quality parameters. The pH exhibited strong positive correlations ($r \geq 0.999$, $p < 0.05$) with total alkalinity ($r = 1.000$), free CO_2 ($r = 0.999$), TDS ($r = 0.999$), conductivity ($r = 0.999$), and PO_4^{3-} ($r = 0.997$, $p = 0.049$). These correlations suggest that these parameters tend to increase concurrently with pH, possibly because they are influenced by common geochemical processes, such as buffering capacity and dissolved ionic constituents.[3] The almost perfect correlation between total alkalinity ($r = 1.000$) and pH suggests that alkalinity plays a major role in regulating pH through the carbonate buffering system (e.g., CO_3^{2-}, HCO_3^-, and OH^- ions). Free CO_2 ($r = 1.000$, $p = 0.003$) was also strongly correlated with conductivity ($r = 1.000$), which may be attributed to the dissolution of CO_2 in water to form carbonic acid (H_2CO_3), followed by its dissociation into H^+ and HCO_3^- ions, thereby increasing conductivity.[5] TDS was strongly positively correlated with phosphate ($r = 0.999$, $p = 0.024$), suggesting that dissolved phosphate species contribute to the TDS concentration.

Additionally, NH_3 was strongly positively correlated with DO ($r = 0.999$, $p = 0.031$), Cl^- ($r = 0.999$, $p = 0.022$), and PO_4^{3-} ($r = 0.997$, $p = 0.046$). The positive correlation between NH_3 and DO is unexpected because nitrification generally consumes DO. However, this relationship may occur under specific environmental conditions, such as oxygen-rich waters experiencing active algal production or recent nutrient inputs. NH_3 and Cl^- may share common anthropogenic sources, including agricultural runoff and domestic sewage.[3,90] Similarly, the positive correlation between NH_3 and PO_4^{3-} may reflect their common origin from wastewater discharge and agricultural fertilizers.

Moreover, DO showed strong positive correlations with PO_4^{3-} (r = 1.000), Cl^- ($r = 1.000$), and NH_3 ($r =$

Table 5. Correlation analysis among physicochemical water quality parameters

Parameter		pH	Conductivity	DO	TDS	Free CO_2	Total hardness	Total alkalinity	Chloride	Phosphate	Nitrate	Ammonia
pH	*r*	1.0	–	–	–	–	–	–	–	–	–	–
	p (two-tailed)	–	–	–	–	–	–	–	–	–	–	–
Conductivity	*r*	0.999*	1.00	–	–	–	–	–	–	–	–	–
	p (two-tailed)	0.25	–	–	–	–	–	–	–	–	–	–
DO	*r*	0.995	0.990	1.00	–	–	–	–	–	–	–	–
	p (two-tailed)	0.063	0.089	–	–	–	–	–	–	–	–	–
TDS	*r*	0.999*	0.997	0.998*	1.00	–	–	–	–	–	–	
	p (two-tailed)	0.025	0.050	0.039	–	–	–	–	–	–	–	–
Free CO_2	r	0.999*	1.000**	0.990	0.997	1.00	–	–	–	–	–	–
	p (two-tailed)	0.028	0.003	0.092	0.053	–	–	–	–	–	–	–
Total hardness	*r*	0.985	0.991	0.963	0.978	0.992	1.00	–	–	–	–	–
	p (two-tailed)	0.110	0.085	0.174	0.135	0.082	–	–	–	–	–	–
Total alkalinity	*r*	1.000**	0.999*	0.995	0.999*	0.999*	0.985	1.00	–	–	–	–
	p (two-tailed)	0.000	0.025	0.063	0.025	0.028	0.110	–	–	–	–	–
Chloride	*r*	0.993	0.988	1.000**	0.997*	0.987	0.959	0.993	1.00	–	–	–
	p (two-tailed)	0.073	0.098	0.010	0.048	0.101	0.183	0.073	–	–	–	–
Phosphate	*r*	0.997*	0.993	1.000*	0.999*	0.993	0.969	0.997*	0.999*	1.00	–	–
	p (two-tailed)	0.049	0.074	0.015	0.024	0.077	0.159	0.049	0.025	–	–	–
Nitrate	*r*	0.985	0.991	0.964	0.978	0.992	1.000**	0.985	0.959	0.970	1.00	–
	p (two-tailed)	0.109	0.084	0.172	0.134	0.081	0.001	0.109	0.182	0.158	–	–
Ammonia	*r*	0.989	0.982	0.999*	0.994	0.981	0.948	0.989	0.999*	0.997*	0.949	1.00
	p (two-tailed)	0.095	0.120	0.031	0.070	0.123	0.205	0.095	0.022	0.046	0.204	–

Notes: Concentrations of chloride, phosphate, nitrate, TDS, total hardness, total alkalinity, DO, free CO_2, and ammonia are expressed in mg/L, whereas conductivity is expressed in µS/cm. *$p < 0.05$ and **$p < 0.01$ indicate statistical significance.
Abbreviations: CO_2: Carbon dioxide; DO: Dissolved oxygen.

0.999). The strong positive correlation between DO and Cl^- is atypical and may represent a spurious correlation resulting from site-specific conditions rather than a direct causal relationship.[3,4] Likewise, the positive correlation between DO and PO_4^{3-} is not commonly observed because phosphate enrichment is often associated with organic matter decomposition, which reduces DO concentrations. This unexpected relationship may instead reflect external phosphate inputs (e.g., fertilizers, detergents) into well-oxygenated waters. Similarly, total hardness was strongly correlated with NO_3^- (r = 1.000), suggesting that both parameters may originate from common sources, such as agricultural runoff and fertilizer application.[3,18]

4.1. Regression analysis

4.1.1. Conductivity vs. pH

The regression plot of conductivity versus pH shown in Figure 6A yielded the regression equation $y = 1.53x - 0.529$, with a maximum deviation of 0.00224 and an r^2 value of 0.976, indicating a very strong linear relationship. The high r^2 value (0.976) and low maximum deviation

(0.00224) indicate that the regression model provides a good fit for the relationship between conductivity and pH in the dataset. The above equation shows that for every unit increase in conductivity, pH increases by 1.53 units. This relationship may be attributed to chemical processes: as pH increases, H^+ decreases, allowing pH-active ions (e.g., HCO_3^-, CO_3^{2-}, OH^-) to dominate, which increases conductivity. The dissolution of limestone ($CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$) increases both pH and conductivity.[5] Here, the CO_2 equilibrium ($CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$) indicates that increasing pH shifts the equilibrium toward the formation of HCO_3^- and CO_3^{2-}, thereby increasing conductivity.[3,18,91]

4.1.2. pH vs. total dissolved solids

The plot of pH versus TDS shown in Figure 6B provides the regression line equation of $y = 1.46x - 0.455$, with a maximum deviation of 0.00331 and an r^2 of 0.859,

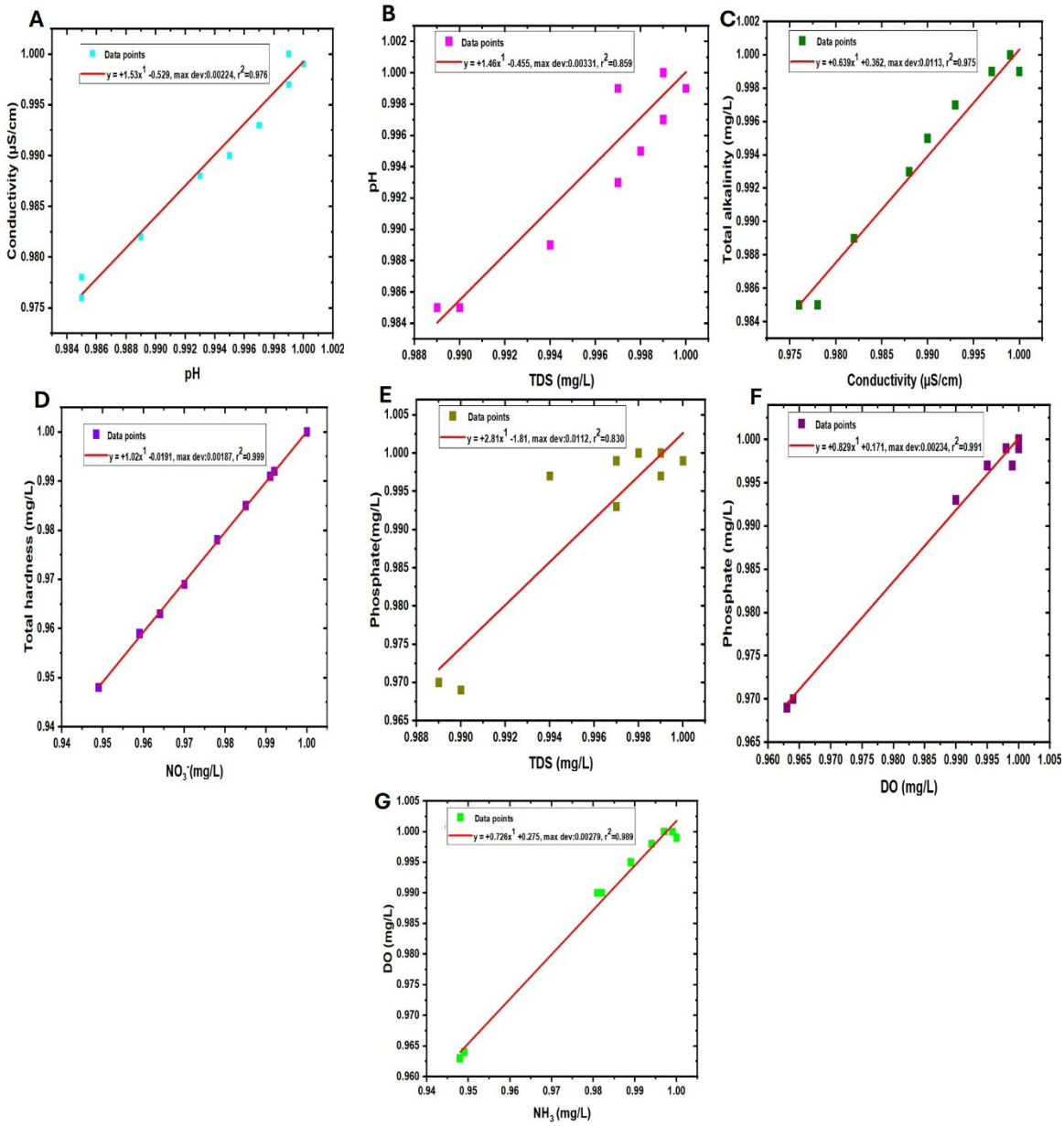

Figure 6. Regression plots showing the relationships between (A) conductivity and pH, (B) pH and TDS, (C) total alkalinity and conductivity, (D) total hardness and NO_3^-, (E) phosphate and TDS, (F) phosphate and DO, and (G) DO and NH_3
Abbreviations: DO: Dissolved oxygen; NH_3: Ammonia; NO_3^-: Nitrate; TDS: Total dissolved solids.

indicating a strong positive linear relationship between pH and TDS. The equation indicates that a one-unit increase in TDS corresponds to a 1.46-unit increase in pH. The higher TDS associated with higher pH values may be attributed to the presence of dissolved CO_3^{2-} and HCO_3^- ions,[3,16,92] which originate from mineral dissolution, industrial effluents, buffering processes, and agricultural runoff. The dissolution of carbonate minerals, such as calcite and dolomite, can increase both pH and TDS through the release of dissolved ions and HCO_3^- buffering.[5] Other factors, including industrial effluents and agricultural runoff, may also contribute to increases in both TDS and pH.

4.1.3. Total alkalinity vs. conductivity

The plot of total alkalinity versus conductivity shown in Figure 6C provides the regression equation of $y = 0.639x + 0.362$, with a maximum deviation of 0.0113 and an r^2 value of 0.975, indicating a strong positive linear relationship. Since conductivity (µS/cm) depends on the number and mobility[43,46,67,68] of the dissolved ions (e.g., K^+, Na^+, Mg^{2+}, Ca^{2+}, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-), while alkalinity represents the buffering capacity of water, primarily contributed by HCO_3^-, CO_3^{2-}, and OH^- ions,[3] a strong correlation between alkalinity and conductivity is expected due to the contribution of HCO_3^- and CO_3^{2-} ions to ionic concentration.[18,91]

4.1.4. Total hardness vs. nitrate

The plot of total hardness versus nitrate shown in Figure 6D provides the regression equation of $y = 1.02x - 0.0191$, with a maximum deviation of 0.0187 and an r^2 value of 0.999, indicating a strong positive linear relationship. Total hardness is mainly attributed to the presence of Ca^{2+} and Mg^{2+} ions, whereas NO_3^- is an anion in water that commonly originates from sewage discharge, agricultural runoff, and fertilizer application.[3,16,92] Although NO_3^- does not directly contribute to water hardness, the strong correlation ($r^2 = 0.999$) suggests that these parameters may originate from common sources or occur under similar environmental conditions. The dissolution of calcium- and magnesium-containing compounds associated with NO_3^- sources may contribute to the simultaneous presence of NO_3^- and hardness ions (Ca^{2+} and Mg^{2+}). Agricultural runoff, sewage, wastewater discharge, and manure runoff may introduce both Ca^{2+} and NO_3^- into aquatic systems, contributing to changes in water quality.[5,18,91]

4.1.5. Phosphate vs. total dissolved solids

The plot of PO_4^{3-} versus TDS shown in Figure 6E provides the regression equation of $y = 2.81x - 1.81$, with a maximum deviation of 0.0112 and an r^2 value of 0.830, indicating a moderately strong positive linear relationship. Since TDS measures the total concentration of dissolved ions (e.g., K^+, Na^+, Mg^{2+}, Ca^{2+}, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-), whereas PO_4^{3-} is generally present as orthophosphate species such as $H_2PO_4^-$ and HPO_4^{2-} in water,[3,18,91] the observed correlation may be associated with common sources contributing to both PO_4^{3-} and dissolved ions. These sources might include agricultural runoff (fertilizers containing PO_4^{3-} and dissolved salts), wastewater discharge (e.g., detergents and sewage containing PO_4^{3-} and dissolved salts), and industrial effluents (e.g., food processing and mining activities).[5] Moreover, the dissolution of fertilizers such as triple superphosphate can release PO_4^{3-} and Ca^{2+} ions, thereby contributing to increased TDS. Biological uptake (e.g., algal assimilation), adsorption, or precipitation may also reduce PO_4^{3-} concentrations independently of TDS.[3]

4.1.6. Phosphate vs. dissolved oxygen

The plot of PO_4^{3-} versus DO, as shown in Figure 6F, provides the regression equation of $y = 0.829x + 0.171$, with a maximum deviation of 0.00234 and an r^2 value of 0.991, indicating a very strong positive linear relationship. Normally, PO_4^{3-} and DO are expected to show an inverse relationship because high DO conditions (aerobic) may promote PO_4^{3-} retention through sediment interactions, whereas low DO conditions (anaerobic) may enhance PO_4^{3-} release during organic matter decomposition.[3,18,91] However, the dataset shows a strong positive correlation ($r^2 = 0.991$), which may be associated with external PO_4^{3-} inputs, such as fertilizers and sewage, that introduce PO_4^{3-} into oxygenated waters.[5] Under aerobic conditions, reduced phosphorus compounds may undergo oxidation processes, resulting in the formation of PO_4^{3-}, which could contribute to increases in both PO_4^{3-} and DO together.

4.1.7. Dissolved oxygen vs. ammonia

The plot of DO versus NH_3 shown in Figure 6G provides the regression equation of $y = 0.726x + 0.275$, with a maximum deviation of 0.00279 and an r^2 value of 0.989, suggesting an extremely strong positive linear relationship. Normally, DO and NH_3 are inversely correlated because nitrification consumes DO through the reaction: $NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$. High NH_3 concentrations generally indicate organic pollution (e.g., sewage), which can reduce DO through microbial degradation.[3,18,91] However, the dataset shows a strong positive correlation ($r^2 = 0.989$), which is an unexpected trend. Therefore, the positive correlation between NH_3 and DO may be attributed to factors such as algal activity (O_2 production with incomplete NH_4^+ uptake) or aerated water bodies

receiving continuous ammonia inputs.[5]

4.2. Principal component analysis

Principal component analysis is an important analytical tool for analyzing water quality data and helps to identify dominant pollution patterns, reduce data complexity, and support the interpretation of spatial variations in water quality.[26] It is a technique for data visualization and dimensionality reduction that converts high-dimensional data into a lower-dimensional form while preserving most of the original variability.[87] It works by identifying principal components (PCs) as linear combinations of the original variables that capture the maximum proportion of variance in the dataset.

Water quality data may contain multiple correlated parameters (e.g., pH, turbidity, DO, heavy metals, nutrients), and PCA helps to reduce dimensionality, identify relationships among variables, and reveal underlying patterns in the dataset.[6,88] Here, eigenvalues denote the variance explained by each PC, and PCs with eigenvalues >1 are commonly retained according to the Kaiser criterion. Generally, the first 2–3 PCs capture approximately 70%–90% of the total variance. Loadings, which represent the correlation between original variables and PCs, help interpret the contribution of each variable to the PCs (e.g., PC1 = overall pollution levels; PC2 = organic vs. inorganic pollution).[26]

Score plots identify grouping patterns among samples (e.g., clean vs. polluted sites), and biplots show sample–variable relationships.[87] Therefore, PCA aids in source identification (e.g., agricultural, industrial, or natural sources), parameter reduction, spatial/temporal trends, and anomaly detection.[26] Four procedures are involved in performing PCA: (i) data normalization, (ii) estimating factor loadings and factor scores, (iii) computing the correlation matrix, and (iv) extracting and interpreting the factors.[26,87] The Kaiser–Meyer–Olkin measure and Bartlett's test of sphericity assess the suitability of data for PCA.[6,26,87,88,92] Only eigenvalues greater than 1.0 were considered for PC retention.[93,94] PCA has helped in identifying the sources of variation between parameters, reducing data dimensionality, and evaluating the relationships and similarities among variables in the dataset.[26]

Factor analysis is related to PCA,[6,87,88] and the results of factor analysis (Table 6) include the factor-loading matrix, eigenvalues, cumulative variance (85.34% for three factors), and communalities.[95] The Kaiser–Meyer–Olkin value is 0.682 (adequate for PCA), and Bartlett's test was significant ($p < 0.05$).[6,87,88] The Origin software was used to perform PCA on the surface water quality dataset from six sampling sites and to compute the eigenvalues and variances for 12 parameters. Only the first three components have eigenvalues >1, as depicted in the Scree plot (Figure 7A).

The findings revealed that the eigenvalues for PC1, PC2, and PC3 are >1. The Scree plot (Figure 7A) depicts an inflection point at the third component. Thus, the first three components (PC1, PC2, and PC3) were selected as the PCs. Figure 7B and 7C depict the biplot and loading plot, respectively, illustrating the variation of water quality parameters at various locations.

Table 6. Eigenvalues, percentage of variance, and cumulative percentage of variance for the principal components

Principal component	Eigenvalue	Variance explained (%)	Cumulative variance (%)
PC1	4.72871	39.41%	39.41%
PC2	3.41866	28.49%	67.89%
PC3	2.09294	17.44%	85.34%
PC4	1.19112	9.93%	95.26%
PC5	0.56857	4.74%	100.00%
PC6	0	0.00%	100.00%

The first three PCs in this analysis explained 85.34% of the overall variance. Factor loadings indicate the correlation between PCs and the selected parameters. Strong, medium, and weak factor loadings are defined as absolute loading values greater than 0.75, between 0.5 and 0.75, and between 0.3 and 0.5, respectively. Factor loadings greater than 0.636[26] were selected for interpreting the results.

Using the PCA method, three major groundwater contamination sources were identified based on three varimax factors. These three varimax factors explained 85.34% of the variation—39.41% (PC1), 28.49% (PC2), and 17.44% (PC3). At each sampling location, the factor score coefficient was also calculated for all variables. A score near zero denotes that the location is moderately impacted by the chemical action of that particular factor, whereas scores >+1 or <−1 indicate that the location is fully or partially influenced by the parameters impacting the component.[96]

The eigenvalues indicate the variance captured by each PC. The findings revealed that PC1 and PC2 together

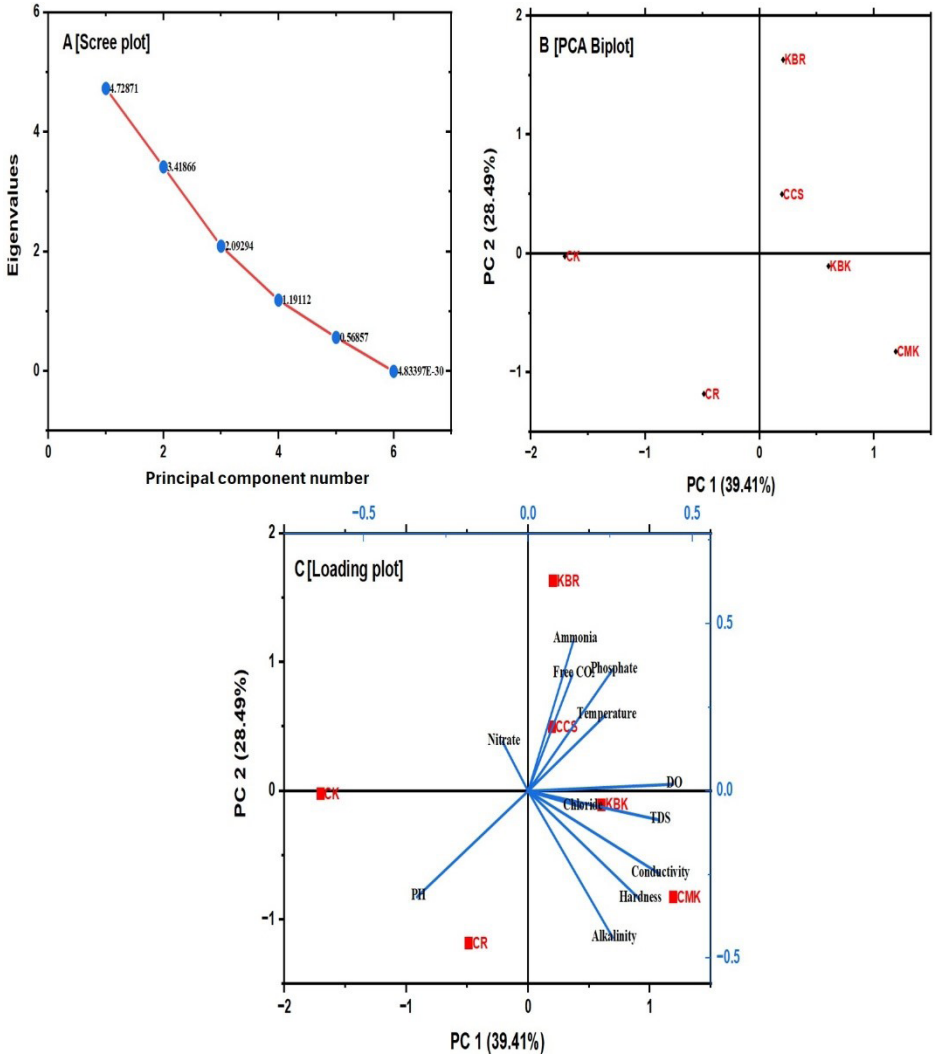

Figure 7. PCA plots of the water quality parameters. (A) Scree plot showing the variation of eigenvalues across principal components, (B) PCA biplot (PC1 vs. PC2) showing the distribution of variables and sampling sites, and (C) loading plot (PC1 vs. PC2) illustrating the contribution of variables to the selected principal components.
Abbreviations: CCS: Confluence with tributaries, Chitrasari; CK: Confluence with tributaries, Kalika River; CMK: Confluence with Mani Khola; CO_2: Carbon dioxide; CR: Confluence with Rapti River; DO: Dissolved oxygen; KBK: Khageri Bridge, Khageri River; KBR: Khageri Bridge, Ratnanagar; PC: Principal component; PCA: Principal component analysis; TDS: Total dissolved solids.

explain approximately 67.89% of the total variance, making them the most significant components. PC3 provides an additional 17.44%, explaining a total of 85.34%, which is sufficient for dimensionality reduction. The eigenvectors (coefficients) indicate how each original variable contributes to the PCs. PC1 (39.41%) is dominated by conductivity (0.39948), DO (0.44118), hardness (0.33854), TDS (0.39799), and negatively influenced by pH (−0.338), indicating mineral content or ionic parameters (e.g., TDS, conductivity, hardness) and oxygen levels (DO), with an inverse relationship to pH (suggesting that increased mineral content may be associated with lower pH). PC2 (28.49%) is dominated by PO_4^{3-} (0.36347), free CO_2 (0.349), NH_3 (0.45447), and negatively influenced by pH (−0.316), hardness (−0.322), and alkalinity (−0.438), indicating a gradient between nutrient enrichment and buffering capacity. PC3 is affected by NO_3^- and Cl^-, which indicate ion-specific variations.

4.3. Hierarchical cluster analysis

Hierarchical cluster analysis is an unsupervised machine learning technique in which similar objects (e.g., water samples, monitoring stations) are grouped into clusters on the basis of their characteristics (water

quality parameters),[76] and the clusters are displayed as a tree diagram or a dendrogram.[87] Therefore, HCA is a powerful tool for grouping similar water samples (e.g., clean vs. polluted), classifying monitoring stations (spatial classification) such as upstream versus downstream pollution, identifying or tracking pollution sources (e.g., industrial, agricultural, domestic), identifying seasonal variations in water quality, reducing data complexity by clustering instead of analyzing each parameter separately, and facilitating anomaly detection [3,6,60,88,97].

In this study, Ward's approach (Figure 8A and 8B) and Euclidean distance[3,69,87,89] were applied to six sampling locations, grouping them into three main clusters.[3,26,95] This reduces monitoring sites from six to three, saving costs and time associated with testing and surveying.3 The dendrograms (Figure 8A and 8B) reveal several well-defined clusters. The cluster patterns indicated associations among conductivity, hardness, and alkalinity (mineral-related parameters);[98] DO and TDS (oxygen content in water vs. dissolved substances); temperature and Cl^- (thermal–salinity); free CO_2, PO_4^{3-}, and NH_3 (organic matter degradation or nutrient pollution);[99] and finally, pH and NO_3^- (acidity vs. fertilizer inputs or microbial activity). These clustering patterns helped in differentiating between groups of parameters driven by natural geochemistry from those impacted by anthropogenic pollution.[87]

The dendrogram (Figure 8B) groups the sampling sites into two main clusters based on similarity, in which cluster A (CK, CR, and KBR) shows moderate pH (8.45–8.5), moderate TDS (227–247 mg/L), and lower nutrient loads (moderate NO_3^-, PO_4^{3-}, $^{NH}_3$), indicating relatively lower pollution levels. Cluster B (CMK, CCS, and KBK) shows higher PO_4^{3-} (6.17–9.05 mg/L), higher alkalinity (550–700 mg/L), and higher NO_3^- and NH_3 levels, indicating the potential influence of agricultural runoff, industrial discharges, domestic effluents, elevated nutrient concentrations, and eutrophication risk. Thus, the HCA approach effectively differentiated sites with lower and higher pollution characteristics, aiding in identifying priority zones for remediation and developing efficient monitoring strategies.

5. Limitations

Sampling was restricted to the pre-monsoon season only, and stream discharge was not measured due to equipment constraints. Without flow data, pollutant loads (mass/time) could not be calculated. Therefore, future studies should include stream discharge measurements. Additionally, NO_3^- values may have slight positive interference from

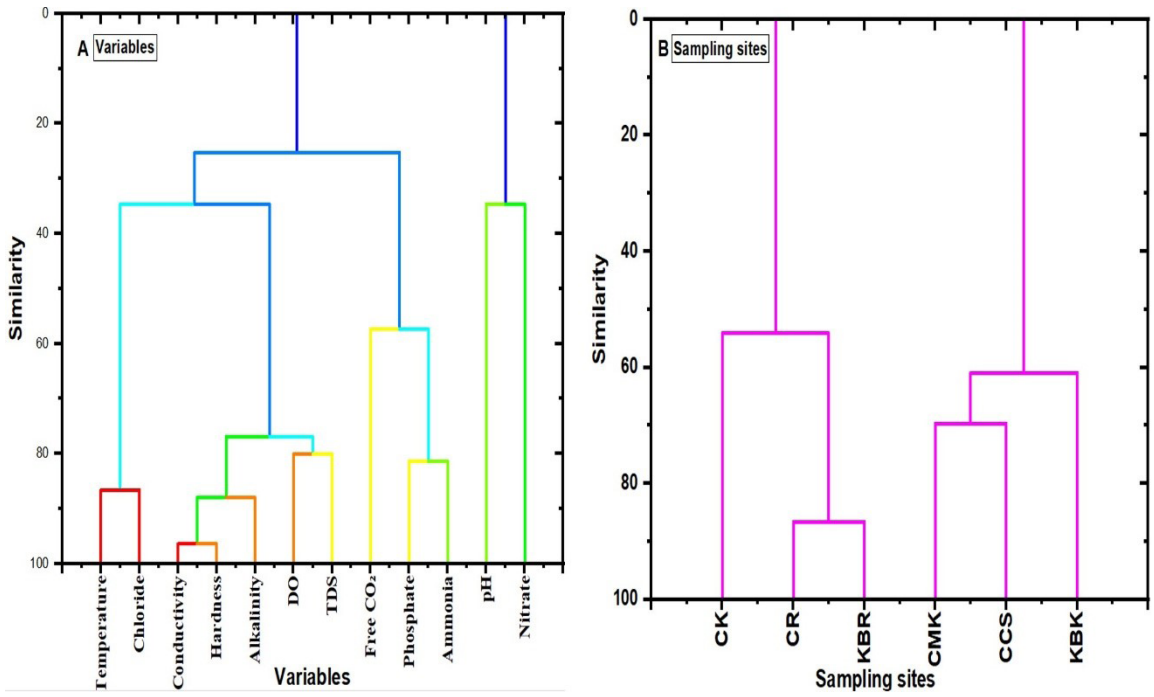

Figure 8. Hierarchical clustering analysis dendrogram showing clustering patterns of (A) variables and (B) sampling sites
Abbreviations: CCS: Confluence with tributaries, Chitrasari; CK: Confluence with tributaries, Kalika River; CMK: Confluence with Mani Khola; CO_2: Carbon dioxide; CR: Confluence with Rapti River; DO: Dissolved oxygen; KBK: Khageri Bridge, Khageri River; KBR: Khageri Bridge, Ratnanagar; PCA: Principal component analysis; TDS: Total dissolved solids.

iron as per the United States Environmental Protection Agency Method 352.1. Future studies should include the determination of dissolved iron to correct for the interference following the recommendations of United States Environmental Protection Agency Method 352.1. Natural parameters such as pH, TDS, and hardness are also influenced by local geology, which was not characterized. Despite these limitations, this study provides the first multivariate baseline assessment of the Khageri Khola, identifying clear pollution hotspots requiring management intervention.

6. Conclusion

The Khageri Khola (river) in Chitwan, Nepal, is a critical water source for irrigation, domestic use, and ecosystem support, yet a comprehensive water quality assessment remains limited. This study statistically evaluated 12 physicochemical water quality parameters from six sampling sites along the river during the pre-monsoon season. Univariate and multivariate statistical methods such as correlation, regression, PCA, and HCA were employed to evaluate the water quality status, identify potential pollution sources, and classify sampling locations based on their physicochemical characteristics.

Results were compared against WHO guidelines, NDWQS, and NWQGAC. It was found that most of the tested parameters were within WHO, NDWQS, and NWQGAC guidelines, with average temperature (22.25 °C ± 0.62 °C), pH (8.2 ± 0.10), conductivity (418 ± 19.34 µS/cm), TDS (467 ± 80.28 mg/L), alkalinity (115 ± 5.68 mg/L), free CO_2 (51 ± 1.95 mg/L), hardness (250 ± 10.01 mg/L), Cl^- (27 ± 1.66 mg/L), and NO_3^- (45.74 ± 2.30 mg/L). However, PO_4^{3-} (7.31 ± 0.82 mg/L), DO (7.08 ± 0.24 mg/L), and NH_3 (9.53 ± 1.21 mg/L) exceeded NWQGAC irrigation limits by 6–7-fold, indicating elevated nutrient enrichment and potential eutrophication risk, potentially leading to algal blooms, oxygen depletion, and degradation of the aquatic ecosystem.

The minimum and maximum values, standard deviation, mean, and coefficient of variance were calculated. PCA identified three potential contributing factors: (i) mineral weathering and ionic strength (PC1, 39.41%), (ii) agriculture and organic pollution (PC2, 28.49%), and (iii) ion-specific anthropogenic inputs (PC3, 17.44%). The resulting dendrogram from HCA grouped the sites into Cluster A (CK, CR, and KBR), with moderate parameters, indicating relatively lower anthropogenic influence, and Cluster B (CMK, CCS, and KBK), with elevated nutrients such as higher concentrations of alkalinity, PO_4^{3-}, NO_3^-, and NH_3, suggesting substantial organic and agricultural pollution.

Correlation and regression analyses confirmed a strong linear relationship between various parameters, such as hardness and NO_3^- (r^2 = 0.999) and DO and PO_4^{3-} (r^2 = 0.991), indicating potentially related controlling factors. This first multivariate assessment of Khageri Khola identified agricultural runoff as the likely major pollution threat, with PO_4^{3-} and NH_3 as critical parameters requiring targeted monitoring and management intervention. These findings underscore the need for ongoing monitoring and management to address nutrient pollution and ensure that water remains suitable for its intended uses. To protect Khageri Khola's water quality, policies should focus on reducing nutrient pollution, particularly from agricultural runoff.

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Conflict of interest

The authors declare that they have no competing interests.

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Availability of data

Data are available from the corresponding author upon reasonable request.

Further disclosure

The authors used the online version of Grammarly (https://www.grammarly.com/a/time-saving) for grammar and spelling checks and error correction, and QuillBot (https://quillbot.com/paraphrasing-tool) for rephrasing

a few complex sentences to improve readability during manuscript preparation. No generative artificial intelligence tools (e.g., ChatGPT and Gemini) were used for data generation, statistical analysis, figure preparation, result interpretation, or writing of the abstract or conclusion. All data, calculations, and scientific conclusions represent the original work of the authors. The authors take full responsibility for the accuracy, originality, and scientific integrity of the final manuscript.

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