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RESEARCH ARTICLE

# Hydrochemical characterization of the Ramsar-listed Koshi Tappu Wetland, Nepal

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## Abstract

Nepal abounds a vast array of freshwater bodies, from sub-tropical lowlands to glacier-fed highlands with varying water quality. This study evaluated the spatial variations in water quality at the Koshi Tappu Wetland, the first Ramsar site of Nepal, located in the eastern Tarai region within the Koshi Tappu Wildlife Reserve. Nineteen water quality parameters were chosen and analyzed from twenty-one different sampling points within the wetland. Parameters including pH, EC, TDS, turbidity, and DO were analyzed on-site, whereas $HCO_3^-$, $Cl^-$, $NH_4^+$, $NO_3^-$, $SO_4^{2-}$ $PO_4^{3-}$, $K^+$, TH, $Ca^{2+}$, $Mg^{2+}$, CaH, MgH, $Na^+$, and $Fe^{3+}$ were analyzed in the laboratory. Multivariate methods such as hierarchical agglomerative cluster analysis (CA) and principal component analysis (PCA), and geochemical indices such as piper and mixing diagrams were applied to assess the spatial variation in water quality. Findings indicated $Ca^{2+}$ as the principal cation and $HCO_3^-$ as the principal anion regulating the hydrochemistry of the wetland. Based on CA, three spatial clusters were observed, which depicted variations in chemical composition with the PCA results highlighting the primary contamination sources and controlling factors of the sampling locations with 84.13% of the total variance. Findings from the PCA and ionic relationship analyses elucidated that the hydrochemistry of the Koshi Tappu wetland is mainly controlled by carbonate weathering processes with minor contribution of silicate weathering and anthropogenic activities.

**Keywords:** *Wetland, spatial assessment, water quality, principal component analysis, cluster analysis*

## 1. Introduction

Wetlands support a variety of biological diversity owing to their productive, adaptive, complex, and dynamic nature. These also provide a living for millions of people by performing critical ecosystem functions, which provide both direct and indirect benefits including clean water, climatic regulation, food provision, and other spiritual values [1]. The wetland covers approximately 12.8 million km$^2$ (8.5 %) of the Earth's land surface on a global scale, with the inland wetland covering approximately 9.5 million km$^2$ (6.3%). Approximately, one-third of the world's drinking water demands come from surface sources such as rivers, canals, and lakes. The quality of water in these wetlands depends on weathering, soil erosion and precipitation processes; and also on industrialization, haphazard urbanization and agricultural activities [2, 3, 4, 5]. Hence, surface water quality of the wetlands is often subjected to widespread deterioration due to both natural processes and anthropogenic activities. Therefore, the protection of the integrity of world freshwater has been given topmost priority in the 21st century [6, 7].

Over the past few decades, many wetlands worldwide have been under pressure primarily due to drainage, industrial effluents, surface runoff, unsustainable resource harvesting, and other anthropogenic activities that affect water quality [8, 9]. Additionally, the construction of water infrastructures like river channels, dams, and hydropower, the introduction of non-native species, and nutrient enrichment affect water quality and nutrient availability [10]. The cumulative effects could increase the rate of conversion of wetlands to land in the long run.

In Nepal, about 5% of the total land area is covered by wetlands [11]. Low-laying Tarai consists of a majority of the wetlands (68.2%), followed by the high mountain (31.6%) and mid-hill (1%) [12]. These wetlands have several species of rare and endangered flora and fauna [13]. They provide a wide range of beneficial services and act as conservation and enhancement of water quality, recharging of drinking water supplies, agricultural development, prevention of erosion, maintenance of surface water flow, and prevention of floods. Wetlands preserve open spaces, landscapes, cultural values, provide recreation and tourism opportunities, and perform natural environmental monitoring [8, 9]. Among the wetlands in Nepal, ten have been designated as the Ramsar sites namely Koshi Tappu, Jagadishpur Reservoir, Ghodaghodi Lake Area, Beeshazari and Associated Lakes, Rara Lake, Phoksundo Lake, Gosaikunda and Associated Lakes, Gokyo and Associated Lakes, Mai Pokhari and Lake Cluster of the Pokhara Valley [14, 15].

Very few hydrochemical investigations have been carried out in Nepal as compared to the Ramsar-listed wetland across the world. The present paper focuses on the Ramsar-listed Koshi Tappu wetland to assess the spatial variation in surface water quality. The Koshi Tappu wetland is the first site from Nepal to be listed in Ramsar in 1987 [16]. It lies on the floodplain of Saptakoshi, a tributary of the Ganges and was established to protect the country's last wild water buffalo population. It is also one of the most important sites in the country for migratory and wintering water birds. There are, however, several threats to the wetland, including natural dynamics such as siltation and flash flooding, along with local activities such as overfishing, overgrazing, and agricultural run-off [17, 18]. Besides these, touristic activities also contribute to the addition of the pollutants in the wetlands [19]. Changing climatic conditions, rapid urbanization, unmanaged settlement and accelerating alien invasion species are also adversely affecting the site. Climate change may have contributed to the alteration of water quality and quantity in especially in the wetlands of fragile Himalayan regions [20, 21].

The combined effects of human activities and natural processes are responsible for surface water pollution, endangering the Koshi Tappu wetland's fragile ecology. Hence, in the Koshi Tappu wetland water pollution became a visible criterion. As a result, insights on water quality are very essential for effective water management. Therefore, the study has been performed to evaluate the spatial variation in the water quality of the Koshi Tappu wetland. In this study, the multivariate statistical approaches combined with geochemical indices were used to characterize the water quality of the Koshi Tappu wetland. The study could provide an important scientific foundation for water quality and environmental management of the Ramsar-listed wetlands, especially in the Himalayas. Furthermore, the findings will be highly relevant to the researchers and policymakers including other concerned stakeholders for assisting the conservation of aquatic biodiversity and supporting the people's livelihoods through improving the wetland services.

## 2. Materials and Methods

### 2.1 Study area

The Koshi Tappu wetland lies in eastern Tarai region of Nepal within the Koshi Tappu Wildlife Reserve (KTWR). The KTWR is the first wetland of Nepal to be declared a Ramsar site in 1987 [22]. It consists of extensive marshland, reed beds, as well as freshwater marshes in the Sapta Koshi River floodplain. The KTWR extends between 87°01'-40°64'E longitude and 26°37'- 12°78'N latitudes covering an area of 17,500 ha. This includes a buffer zone of 17,300 ha situated in the flood plains of Koshi River within parts of Sunsari, Saptari, and Udaypur districts in southeastern Nepal (Fig. 1). The climate in the Koshi Tappu region is sub-tropical, with annual rainfall ranging from 1,300 mm to 2,051 mm. The area is prone to excessive flooding during the annual rainy season from June to September. Mixed deciduous riverine forests, grasslands, and marshy vegetation dominate the reserve's vegetation. The plain grasses cover approximately 68% of the reserve, while the forest covers only 6%. There is sparse settlements (approximately 215 households) in the vicinity of the study area. The residents rely on the wetland for irrigation, livestock grazing, fisheries, and food production.

The Koshi Tappu wetland forms a complex mosaic of lotic (running water) and lentic (standing water) ecosystems. This study was carried out in a laminar flow environment of a lotic wetland where the study sites were covered by aggressive invasive species of water hyacinth. The invasive alien species have direct impacts on the quality of aquatic environment [23].

### 2.2 Data collection and analysis

Twenty-one water samples were collected from the wetland in January 2020. Sample collection and analytical procedure were carried out in accordance with the standard methods [24]. A HANNA multi-parameter probe (HI-98129, HANNA, Romania) was used to measure temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS) onsite whereas dissolved oxygen (DO) and turbidity were measured with DO meter and turbidity meter, respectively. Chemical parameters like ammonium ($NH_4^+$), nitrate ($NO_3^-$), iron ($Fe^{3+}$), phosphate ($PO_4^{3-}$), sulfate ($SO_4^{2-}$) were analyzed by using a UV-visible spectrophotometer. Potassium ($K^+$), sodium ($Na^+$), calcium ($Ca^{2+}$), and magnesium ($Mg^{2+}$), were analyzed using Flame Photometer. While other parameters including chloride, total hardness, calcium hardness, magnesium hardness, and alkalinity were analyzed using the titrimetric method in the laboratory of

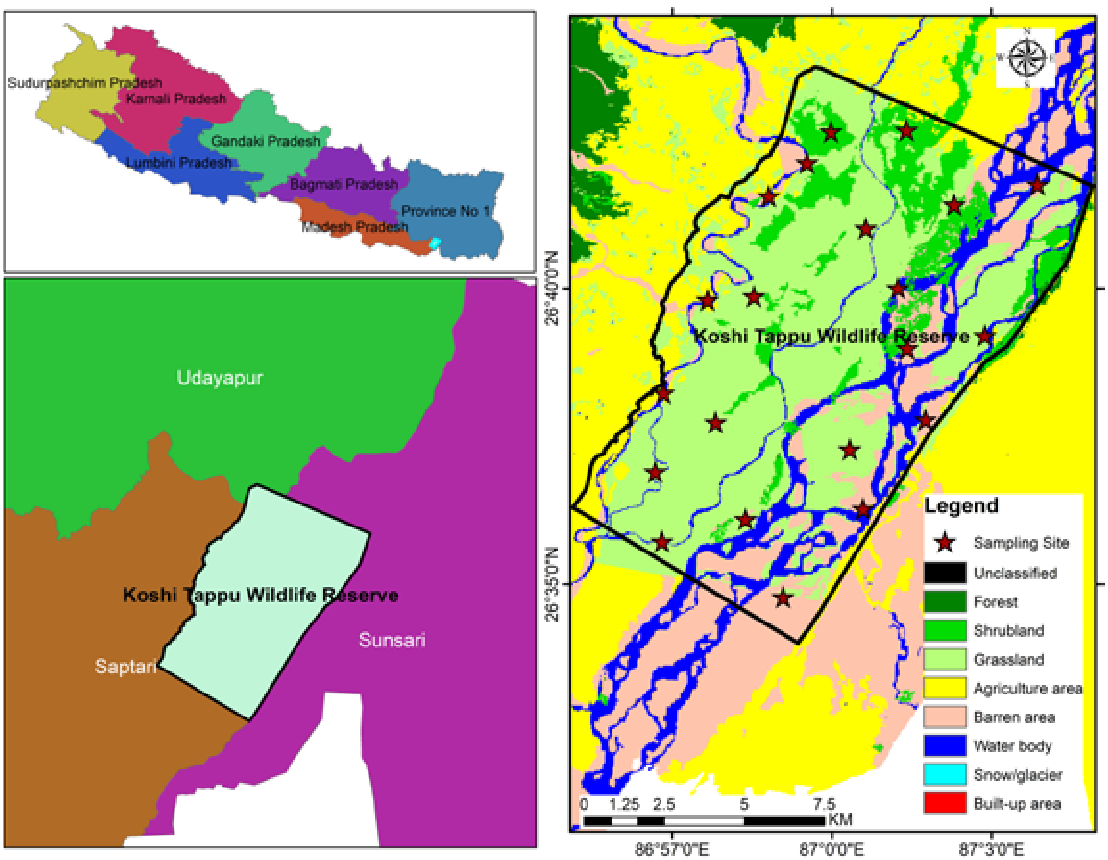


*Fig. 1.* *Location map of the study area with the sampling sites in the Koshi Tappu Area, Ramsar-listed wetlands from Nepal.*

the Central Department of Environmental Science, Institute of Science and Technology, Tribhuvan University (CDES-TU).

### 2.3 Statistical and geochemical analysis

All the mathematical and statistical computations were carried out using excel 2016 (Microsoft Office) and SPSS software (22.0). Multivariate statistical techniques including principal component analysis and cluster analysis were used to interpret the findings. PCA is one of the widely used data reduction techniques and is applied to normalized data to assess the correlation between variables [25]. It gives information about the most useful parameters, which define a complete dataset that allows data to be reduced without extreme loss of its original value [26]. The PCA demonstrates the participation of individual chemicals in several influence factors, which is common in hydrochemistry. PCA is used to extract significant principal components (PCs). The PCs are uncorrelated with each other, and each PC is significantly correlated to specific variables representing a different dimension of the water quality [27]. The characteristic roots (eigenvalues) of the PCs are a measure of the variances associated with them, and the sum of eigenvalues equals the total number of variables. Loadings represent the correlation of PCs and original variables, and scores represent individual transformed observations [25]. The loading values in this study are classified based on absolute loading values i.e., > 0.75; 0.75-0.50; and <0.50 as strong, moderate, and weak, respectively [28].

The multivariate cluster analysis includes a wide range of techniques for experimental data analysis. It was widely used to determine the similarity and dissimilarity of water quality and help to reveal the intrinsic characteristics between sampling sites based on the proximity or similarity [29]. The characteristics of classes are unknown in advance but can be determined through data analysis [30]. Based on similarities or differences between water quality variables all sampling sites were grouped in statistically significant clusters. In this study, hierarchical agglomerative CA was performed on the normalized data set with the help of Ward's method. It is an extremely powerful method to group the cases for hierarchical agglomerative clustering by using squared Euclidean as a measure of similarity (Willet 1987). The results are represented by a dendrogram that provides a visual summary of the clustering processes, exhibiting high internal (within a cluster) homogeneity and high external (between clusters) heterogeneity [31].

The geochemical characterization of hydrochemical variables was performed using the Piper diagram [32] and mixing plots.

## 3. Results and discussion

### 3.1 General Hydrochemistry

Table 1 and Fig. 2 showed the descriptive statistical summary of major hydrochemical compositions of the wetland. pH is the most important water quality parameter and indicates the acidic or alkaline nature of water. The pH of the wetland ranged from 7.54 to 7.28, with an average pH of 7.37 (Table 1), indicating slightly alkaline water. Dissolved oxygen was found to be a maximum of 5.60 mg/L and a minimum of 4.60 mg/L with an average of 5.00 mg/L. Electrical conductivity (EC) measures the ionic condition of water, which is greatly affected by temperature, the concentration of impurities, and the mobility of ions [34]. Minimum EC was recorded to be 220 µS/cm and the maximum was 240 µS/cm with a mean of 228 µS/cm (Table 1). In the present study, the EC shows low conductivity possibly due to low temperature, and fewer salt contents are present in the water.

The minimum total dissolved solid was recorded to be 110 mg/L and the maximum was 130 mg/L with a mean of 120 mg/L (Table 1). Turbidity is the amount of cloudiness, due to which visibility through water decreases and is caused by suspended particles or colloidal matter and chemical precipitations. Average turbidity was found to be 1.05 NTU. Total hardness ranged from 119.38 to 6.28 mg/L, with an average value of 49.04 mg/L with S.D. 19.33 (Table 1). Calcium hardness ranged from 108.22 to 29.66mg/L, with an average value of 41.03 mg/L (Table 1). In addition, maximum magnesium hardness recorded

17.99 mg/l and a minimum of 1.24 mg/L, with an average of 9.82 mg/L.

***Table 1*** *Descriptive statistics of physico-chemical variables of the Koshi Tappu Wetland, Nepal*

| Parameters | Min | Max | Mean | S D |
|---|---|---|---|---|
| **pH** | 7.28 | 7.54 | 7.37 | 0.07 |
| **EC** | 220.00 | 240.00 | 228.10 | 6.80 |
| **TDS** | 110.00 | 130.00 | 120.48 | 3.84 |
| **TH** | 6.28 | 119.38 | 49.04 | 19.33 |
| **Turbidity** | 0.36 | 2.76 | 1.05 | 0.62 |
| **DO** | 4.60 | 5.60 | 5.00 | 0.33 |
| **CaH** | 29.66 | 108.22 | 41.03 | 16.19 |
| **MgH** | 1.24 | 17.99 | 9.82 | 4.19 |
| **$Ca^{2+}$** | 11.86 | 23.29 | 15.46 | 2.69 |
| **$Mg^{2+}$** | 4.69 | 8.67 | 5.95 | 0.92 |
| **$K^{+}$** | 2.94 | 3.30 | 3.15 | 0.08 |
| **$Na^{+}$** | 7.20 | 14.50 | 8.55 | 2.06 |
| **$NH_4^{+}$** | 0.24 | 0.39 | 0.33 | 0.05 |
| **$Cl^{-}$** | 2.84 | 18.48 | 9.33 | 4.20 |
| **$Fe^{3+}$** | 0.28 | 0.43 | 0.36 | 0.06 |
| **$NO_3^{-}$** | 0.26 | 0.39 | 0.33 | 0.04 |
| **$SO_4^{2-}$** | 8.20 | 14.80 | 9.79 | 1.28 |
| **$HCO_3^{-}$** | 38.93 | 82.46 | 49.98 | 9.10 |
| **$PO_4^{3-}$** | 0.01 | 0.51 | 0.11 | 0.10 |

(All the units are expressed in mg/L except Tem: °C, EC: µS/cm, Turbidity: NTU and pH)

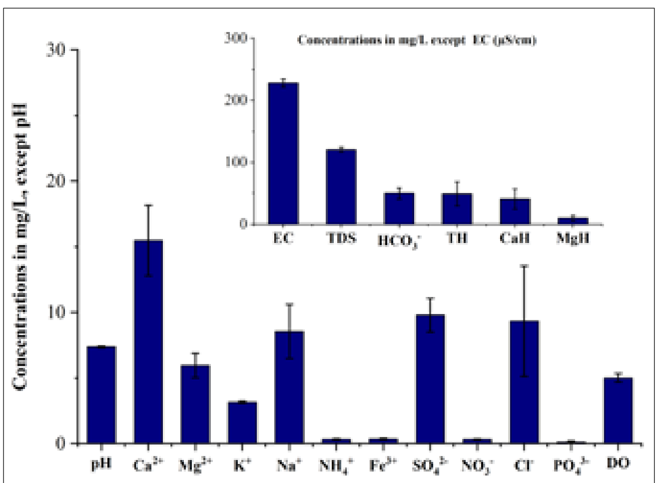


***Fig. 2:*** *Bar diagram with the ionic values represent the standard deviation of the Koshi Tappu wetland, Sunsari, Nepal*

The average calcium concentration was found to be 15.46 mg/L with S.D. 2.69 (Table 1) and the average magnesium concentration was found at 5.95 mg/L with S.D. 0.92 (Table 1). $Ca^{2+}$ and $Mg^{2+}$ are essential ions of surface waters mostly influenced by catchment geology. Results indicate that rock weathering is a dominant mechanism regulating the hydrochemistry of the Koshi Tappu wetland. Rock weathering generates elemental ions and work as a natural source of pollutants [34]. $Na^{+}$ was the second most abundant cation with an average concentration of 14.50 to 7.20 mg/L. The average concentration of $K^{+}$ ranged from 3.30 to 2.94 mg/l. $NH_4^{+}$ was the least abundant cation with an average concentration of 0.33 mg/l. The cationic dominance was found in the order of $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+} > NH_4^{+}$.

Alkalinity was recorded as the most dominant anion among the anionic group, which ranged from 82.46 to 38.93 mg/L, with an average value of 49.98 mg/L with S.D. 9.10 in the Koshi Tappu wetland (Table 1). The carbonate alkalinity occurs only in the absence of $CO_2$ and when pH is > 8.30 mg/L [35]. In addition, alkalinity is predominantly derived from the weathering of carbonate and silicates minerals. The second most abundant anion is $SO_4^{2-}$ ranging from 14.80 to 8.20 mg/l. The presence of chloride indicates the presence of animal-derived organic waste [36]. The average value for chloride of the Koshi Tappu wetland is 9.33 mg/L with S.D. 4.20 mg/L. In water, a higher concentration of chloride indicates organic pollution due to animal origin and agricultural discharge [37]. In this study, a lower concentration of chloride indicates less anthropogenic activities around sampling sites [38]. Nitrate is generally present in water by aerobic decay of organic nitrogenous compounds. In this study, maximum nitrate concentration was found to be 0.39 mg/L and a minimum of 0.26 mg/L, with an average of 0.33 mg/L. A very small amount of nitrate was observed in the Koshi Tappu wetlands. Atmospheric deposition, mineralization, nitrogen holding organic compounds, anthropogenic deposition, and precipitation are some sources of nitrate. [39] have obtained a higher concentration of nitrate in the Begnas Lake that could be due to high anthropogenic activities. Phosphate concentration in the water ranged from 0.01- 0.51 mg/L with an average of 0.11 mg/L (Table 1). In this study, concentration varies due to the fluctuation of surface water, weathering of rocks, soil decay plants, and animals remain [40]. The order of dominance of anions is $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^- > PO_4^{3-}$

Correlation analysis is usually used to characterize ion's source relationship. A Spearman correlation coefficient analysis was conducted to assess the correlation between various hydrochemical parameters. Table 2 shows the Spearman correlation coefficient of the Koshi Tappu wetland. The $Mg^{2+}$ exhibited a positive correlation coefficient with total hardness, $Ca^{2+}$ and calcium hardness, indicating that the major ions contribute to the water of the Koshi Tappu wetland. This significant positive correlation suggests that the leading cations such as $Mg^{2+}$, $Ca^{2+}$ were from different rocks. For example, silicates and carbonates supplied $Mg^{2+}$ and $Ca^{2+}$. $HCO_3^-$ had a significant correlation with $SO_4^{2-}$ and $Na^+$. The content of TH and $Mg^{2+}$ increases with the decrease of chloride at the same time increases the concentration of turbidity with the increase in chloride. The EC showed a positive and strong correlation with TDS (Table 2). The water of the Koshi Tappu wetland is affected by the interaction between rock and water, such as weathering of silicate minerals and calcium bicarbonate.

### 3.2 Principal Component Analysis (PCA)

In this study, the PCA is applied to get information on hydrochemical parameters, which provides a meaningful reduction of dimensionality consisting of a large number of uncorrelated variables [26]. The results of PCs, variable loadings, and explained variance are presented in (Table 3). PCA is executed on 14 variables including TDS, major ions ($Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $NH_4^+$, $Cl^-$, $NO_3^-$, $SO_4^{2-}$ and $PO_4^{3-}$), alkalinity, total hardness, calcium hardness, and magnesium hardness of the 21 different sampling sites which shows the major variables governing water physicochemical properties of the Koshi Tappu wetland. PC1 accounts for 22.052% of total variance with strong positive loading values of $Ca^{2+}$, $Mg^{2+}$, and CaH. PC1 represents the similar origin of these ions and is driven from weathering of carbonate and silicate. PC2 accounts for 18.06% of total variance showing a strong correlation between $HCO_3^-$ and $SO_4^{2-}$, and moderate positive loading on $Na^+$, indicating the minerals compounds in the water. PC3 showed strong positive loading values of $PO_4^{3-}$, and moderate positive loading values of $Cl^-$ and TDS, with a total variance of 13.27%. These variables are highly correlated, indicating the presence of organic

***Table 2*** *Correlation coefficient of hydro-chemical variables of the Koshi Tappu Wetland, Nepal*

| | pH | EC | TH | Tur. | DO | CaH | MgH | TDS | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | $NH_4^+$ | $Cl^-$ | $Fe^{3+}$ | $NO_3^-$ | $SO_4^{2-}$ | $HCO_3^-$ | $PO_4^{3-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **pH** | 1 | | | | | | | | | | | | | | | | | | |
| **EC** | -0.06 | 1 | | | | | | | | | | | | | | | | | |
| **TH** | 0.16 | 0.03 | 1 | | | | | | | | | | | | | | | | |
| **Tur.** | **0.50$^{*}$** | -0.24 | -0.25 | 1 | | | | | | | | | | | | | | | |
| **DO** | 0.15 | 0.25 | 0.39 | -0.1 | 1 | | | | | | | | | | | | | | |
| **CaH** | 0.3 | -0.22 | **0.69$^{**}$** | -0.07 | -0.17 | 1 | | | | | | | | | | | | | |
| **MgH** | 0.18 | 0.02 | 0.35 | 0.04 | **0.68$^{**}$** | -0.25 | 1 | | | | | | | | | | | | |
| **TDS** | 0.08 | **0.58$^{**}$** | 0.16 | 0.3 | 0.09 | 0.06 | 0.06 | 1 | | | | | | | | | | | |
| **$Ca^{2+}$** | 0.3 | -0.21 | **0.69$^{**}$** | -0.07 | -0.16 | **1.00$^{**}$** | -0.25 | 0.06 | 1 | | | | | | | | | | |
| **$Mg^{2+}$** | 0.29 | -0.08 | **0.94$^{**}$** | -0.15 | 0.23 | **0.87$^{**}$** | 0.15 | 0.12 | **0.87$^{**}$** | 1 | | | | | | | | | |
| **$K^+$** | -0.2 | 0.32 | -0.08 | -0.03 | -0.2 | -0.03 | -0.09 | 0.41 | -0.04 | -0.1 | 1 | | | | | | | | |
| **$Na^+$** | -0.3 | 0.04 | -0.25 | -0.17 | -0.38 | -0.19 | -0.13 | -0.02 | -0.19 | -0.29 | 0.14 | 1 | | | | | | | |
| **$NH_4^+$** | -0.17 | 0.33 | -0.15 | 0.09 | 0.23 | -0.36 | 0.13 | 0.33 | -0.37 | -0.24 | 0.37 | 0.27 | 1 | | | | | | |
| **Cl-** | 0.22 | 0.1 | **-0.53$^{*}$** | **0.44$^{*}$** | -0.15 | -0.43 | 0.11 | 0.2 | -0.43 | **-0.50$^{*}$** | 0.36 | 0 | 0.11 | 1 | | | | | |
| **$Fe^{3+}$** | 0.4 | 0.26 | -0.03 | 0.11 | 0.19 | -0.3 | **0.52$^{*}$** | 0.06 | -0.3 | -0.11 | 0.35 | 0 | 0.14 | 0.4 | 1 | | | | |
| **$NO_3^-$** | 0.04 | 0.05 | 0.12 | -0.1 | 0.1 | 0.13 | -0.07 | 0.26 | 0.13 | 0.18 | -0.15 | -0.12 | -0.01 | 0.05 | -0.19 | 1 | | | |
| **$SO_4^{2-}$** | 0.01 | 0.32 | -0.22 | 0.05 | -0.14 | -0.13 | -0.16 | **0.43$^{*}$** | -0.12 | -0.21 | 0.18 | **0.53$^{*}$** | 0.1 | -0.06 | 0.05 | 0.04 | 1 | | |
| **$HCO_3^-$** | 0.04 | 0.22 | -0.24 | -0.06 | -0.1 | -0.17 | -0.13 | 0.24 | -0.16 | -0.23 | 0.07 | **0.53$^{*}$** | 0.04 | -0.12 | 0.07 | -0.04 | **0.95$^{**}$** | 1 | |
| **$PO_4^{3-}$** | -0.3 | -0.07 | -0.2 | -0.07 | -0.4 | -0.11 | -0.07 | -0.02 | -0.12 | -0.2 | 0.05 | 0.18 | 0.18 | 0.03 | -0.07 | -0.29 | 0 | 0.01 | 1 |

pollution. Similarly, PC4 has strong positive loading values of $NH_4^+$ and a moderate positive loading value of $K^+$ with a total variance of 11.4%. The source of these elements could be of anthropogenic origin because of the agricultural runoff. PC5 accounts for a total variance of 10.79% with positive and moderate loading values of MgH and moderate loading values of iron. PC6 shows strong values of $NO_3^-$ with a total variance of 8.56%. Nitrate is the final product of nitrogen oxidation, and it demonstrates the impact of anthropogenic pollution and agricultural fertilizers on water [30].

***Table 3. Varimax rotated component matrix of hydro-chemical variables of the Koshi Tappu Wetland, Nepal***

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **CaH** | **0.90** | -0.04 | -0.03 | -0.31 | -0.07 | -0.06 |
| **MgH** | 0.09 | -0.05 | -0.08 | 0.06 | **0.93** | 0.07 |
| **TDS** | 0.2 | 0.15 | **0.65** | 0.38 | 0.07 | 0.43 |
| **$Ca^{2+}$** | **0.95** | -0.09 | -0.06 | -0.08 | -0.16 | 0.02 |
| **$Mg^{2+}$** | **0.95** | -0.10 | -0.09 | -0.06 | 0.19 | 0.04 |
| **$K^+$** | -0.33 | 0.10 | 0.46 | **0.63** | -0.04 | -0.14 |
| **$Na^+$** | 0.01 | **0.71** | 0.03 | 0.26 | -0.31 | 0.00 |
| **$NH_4^+$** | -0.19 | 0.11 | 0.03 | **0.92** | 0.08 | 0.02 |
| **$Cl^-$** | -0.45 | -0.26 | **0.66** | -0.14 | 0.17 | 0.05 |
| **$Fe^{3+}$** | -0.24 | 0.12 | 0.34 | 0.03 | **0.65** | -0.27 |
| **$NO_3^-$** | -0.04 | -0.06 | -0.04 | -0.05 | -0.06 | **0.94** |
| **$SO_4^{2-}$** | -0.07 | **0.96** | 0.02 | 0.05 | 0.14 | -0.02 |
| **$HCO_3^-$** | -0.12 | **0.97** | 0.00 | -0.03 | 0.09 | -0.04 |
| **$PO_4^{3-}$** | -0.03 | 0.05 | **0.81** | 0.11 | -0.02 | -0.12 |
| **Eigenvalue** | 3.92 | 2.42 | 1.81 | 1.50 | 1.13 | 1.01 |
| **% of variance** | 22.052 | 18.06 | 13.27 | 11.4 | 10.79 | 8.56 |
| **Cumulative %** | 22.052 | 40.11 | 53.38 | 64.78 | 75.57 | 84.13 |

The factor loading of PC (Fig. 3) yield the similar results to the above-mentioned values. $SO_4^{2-}$, $HCO_3^-$ $Na^+$ has some positive correlation, whereas $Ca^{2+}$, $Mg^{2+}$, and CaH are closely associated with each other. Likewise, $PO_4^{3-}$ , TDS and $Cl^-$ on the other hand, have a positive relation. Similarly, $NH_4^+$ and $K^+$ are linked with each other, and MgH and $Fe^{3+}$ showed a good association. The result of PCA demonstrates that the majority of elements may be derived from the crustal origin; however, there have been shreds of evidences of some anthropogenic signature as well.

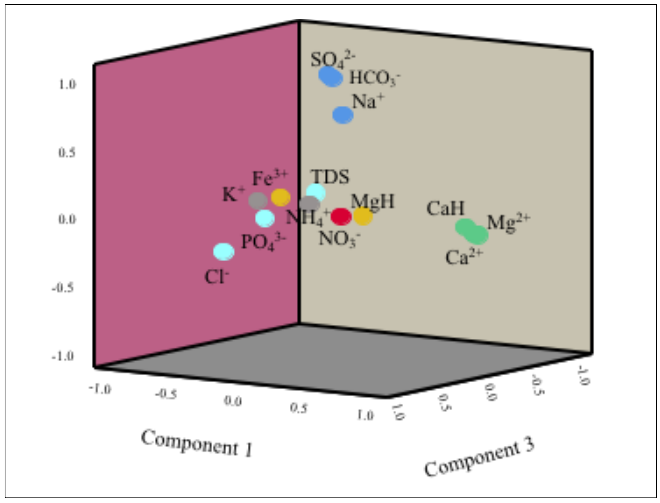


***Fig. 3.*** *Factor loading plot (the principal component analysis) of the Koshi Tappu Wetland, Nepal*

### 3.3 Cluster Analysis (CA)

In this study, the CA is used to detect the similarity classes of sampling sites. The number of the clusters was determined by analyzing 21 water samples information available in the study in terms of features and natural origin influenced by the similar sources of a type of strength. It provides a dendrogram grouping all 21 sampling sites into three clusters (Fig. 4). Each cluster provides similar water quality characteristics of surface water quality [41]. Each sampling site has been located in a certain cluster considering the whole 19 parameters and based on the Euclidian distance between each site. CA demonstrated the three clusters within distance 0-5. The water quality of the wetland degrades from top to bottom. Cluster I was formed with 12 sampling sites, which are (5, 9, 7, 11, 10, 6, 19, 12, 17, 16, 18 and 4). Cluster I indicates less polluted sampling sites. Eight sampling sites (15, 2, 1, 20, 14, 8, 2 and 13) were grouped in Cluster II. Cluster II indicates the moderately polluted areas, human disturbance, animal interference and agricultural discharges have some sort of signature in the sites. The remaining sampling site i.e., 3 were grouped in Cluster III, indicating the highly polluted sampling site. Less pollution in the sites is because the sampling area is surrounded by nonresidential areas; a naturally preserved area covered with forest and has very little human intervention. The settlements area with domestic waste, animal excreta, and agricultural runoff affected the moderately and highly polluted regions. Furthermore, human interference was high

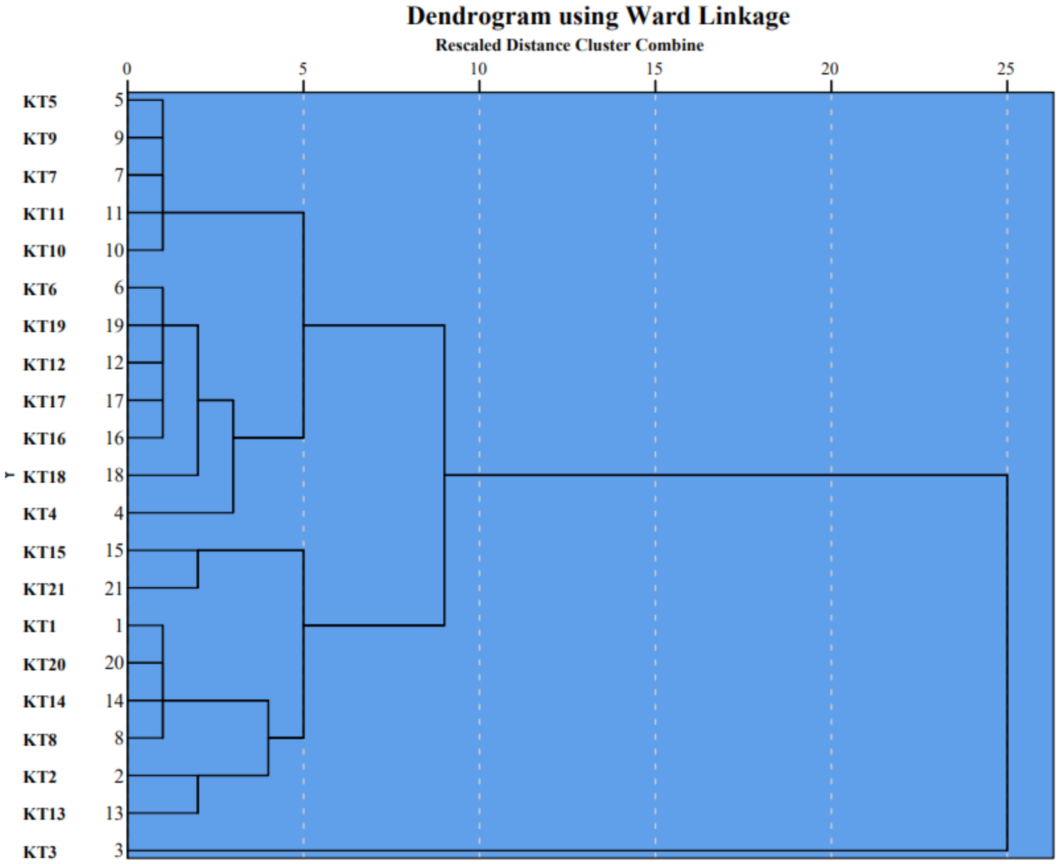


***Fig. 4.*** *Tree diagram of cluster analysis by using ward's method of the Koshi Tappu Wetland, Nepal*

in the polluted areas due to the road's connection and proximity to residential and agricultural areas.

### 3.4 Characterization of hydrochemical facies

Piper trilinear diagram was first proposed by Piper in 1944 and is one of the most effective graphical representations of water chemistry in the study. This diagram can indicate the surface water origins, types and hydrochemical processes of a study area. Piper diagrams are commonly used to show the corresponding concentrations of major ions such as cation and anion on two separate trilinear plots as well as a diamond plot, which projects the points from the two trilinear plots. As completely chemical characteristics of the water are illustrated in the central diamond-shaped field [32, 42].

The wetland's water type was identified through the Piper trilinear Diagram (Fig. 5). The piper diagram reveals the dominancy of a weak acid ($HCO_3^-$) over strong acid ($SO_4^{2-}$+ $Cl^-$) and alkaline earth metals ($Ca^{2+}$+$Mg^{2+}$) over alkaline metals ($Na^+$+$K^+$). It shows that $Ca^{2+}$ $HCO_3^-$ is the central dominant hydrochemical facies in the Koshi Tappu wetland. Major cation and anion arrangement suggested that the freshness of these water samples with carbonate weathering is a dominant mechanism regulating the wetland hydrochemistry. The hydrochemistry facies of the Koshi Tappu wetland is also comparable with the other wetlands of Nepal such as Ghodaghodi lake, Phewa Lake, Begnas Lake, Rupa Lake etc. [43]. The dominancy of $Ca^{2+}$ and $HCO_3^-$ in total cation and anion, respectively in the Nepal Himalayan region is due to the intense carbonate rock weathering [5].

### 3.5 Mixing diagram

Weathering of various rocks can result in various combinations of major ions. For example, carbonate weathering results in $Ca^{2+}$, $Mg^{2+}$ and $HCO_3^-$ silicate weathering results in $Na^+$, $K^+$, Si, $Ca^{2+}$, $Mg^{2+}$,and $HCO_3^-$ and evaporates dissolution or soil salts leaching mostly produces $SO_4^{2}$ [44]. $Na^+$- normalized molar ratios were presented in the mixing diagram to demonstrate the origin of the Koshi Tappu wetland

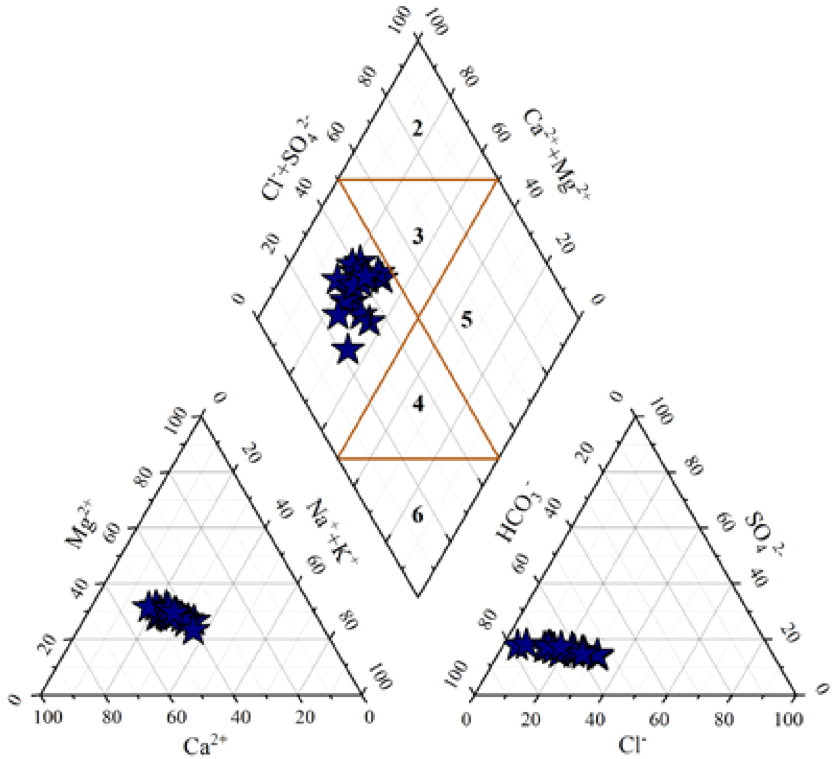

*Fig. 5. Piper diagram showing the $Ca^{2+}$-$HCO_3^-$ hydro-chemical facies of the Koshi Tappu Wetland, Nepal*

dissolved load produced by the chemical weathering in the wetland (Fig. 6a and b) with respect to three representative lithologies. The results clearly show that the majority of the wetlands waters were dominated by contribution of carbonate weathering followed by silicate weathering.

## 4. Conclusions

This study explores and examines the geochemical characteristics of surface water quality of the Koshi Tappu wetland, Nepal. With multivariate statistical methods and geochemical indices, the role of hydrochemical variables on the spatial distribution is analyzed. PCA identify the major controlling variables

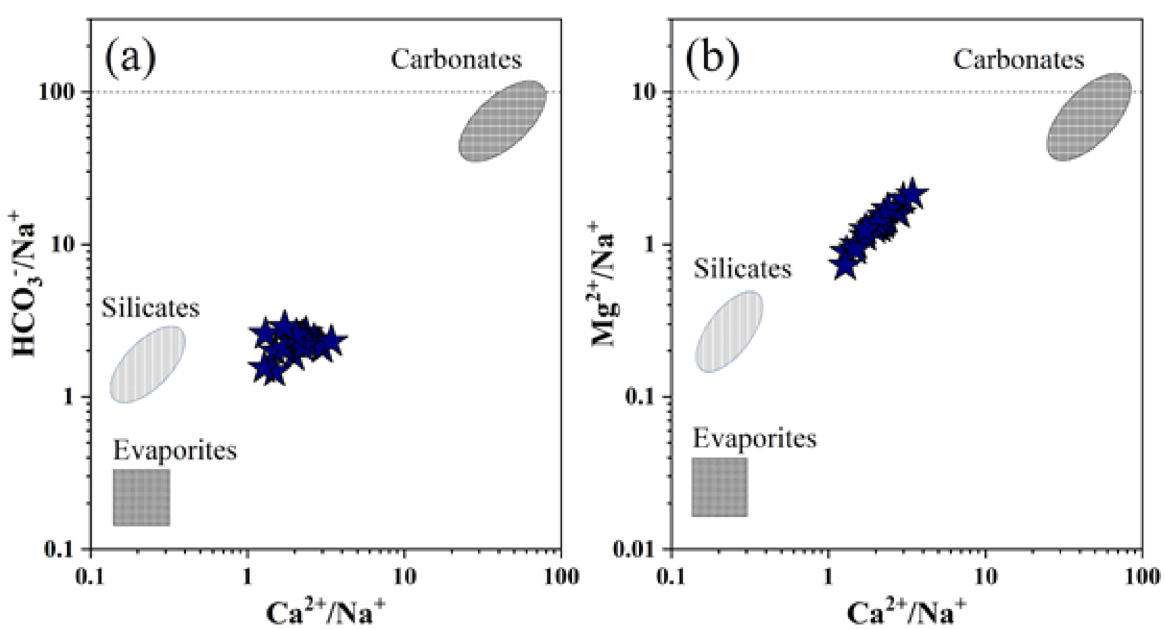


*Fig. 6. Mixing diagram of the Koshi Tappu Wetland, Nepal*

and their sources of water quality in the wetland. For spatial distribution, CA grouped twenty-one different sampling sites into three clusters, classifying relatively disturbed sites which help to categories the sampling sites into different categories. The major source of chemicals comes from weathering and anthropogenic activities. The major ions follow the pattern of $Ca^{2+}$> $Na^{+}$> $Mg^{2+}$ > $K^{+}$ for cations, and $HCO_3^-$>$SO_4^{2-}$>$Cl^-$ >$NO_3^-$>$PO_4^{3-}$ for anions. The characterization of hydrochemistry was carried out by plotting the piper diagram, and only $Ca^{2+}$-$HCO_3^-$ type of facies was observed, which exhibited the carbonate, dominated underlying lithology of the Koshi Tappu wetland. The mixing diagram showed that carbonate and silicate weathering are the major source of ions in the Koshi Tappu wetland. Thus, findings in this study may improve, understanding of the relationships between various hydro chemicals and provide some guidance on monitoring and assessment of surface water quality of wetlands. Thus, the water quality of the Koshi Tappu wetland needs to be further studied.

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