

Characterization of Drinking Groundwater Quality Using Multivariate Statistical Analysis and Water Quality Index in the Cuvelai-Etosha Basin, Namibia

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Abstract: The quality of groundwater in the Cuvelai-Etosha Basin, a critical water source in northern Namibia, is increasingly influenced by both natural processes and anthropogenic activities. This study characterized the groundwater quality in the basin using multivariate statistical analysis and the Water Quality Index (WQI). Groundwater samples were collected from five wells that support the community across the basin, and a range of physicochemical and bacteriological parameters, including pH, electrical conductivity, total dissolved solids, nitrate, nitrite, dissolved oxygen, chloride, fluoride, ammonia, turbidity, sodium, calcium, magnesium, and E. coli, were analyzed. Multivariate statistical techniques, such as Principal Component Analysis (PCA), Cluster Analysis (CA), and Factor Analysis, were employed to identify patterns, sources, and correlations among the various water quality parameters. The WQI was calculated to provide an integrated measure of water quality, categorizing groundwater according to its suitability for consumption. The wells' WQI results indicate the following: excellent for GW5 (24.41), good for GW3 (58.45) and GW1 (61.57), poor for GW2 (107.76) and GW4 (127.33) for drinking based on the study's parametric indicators weight. WQI varies spatially within the basin, with certain areas exhibiting higher contamination levels due to runoff and inadequate water management practices. About 60% of the groundwater sources fall into the "excellent" to "good" quality categories, indicating minimal health risks and the need for effective management strategies. The PCA and CA revealed that key anions and cations, such as Electrical Conductivity, Total Hardness, Ca, Mg, and Cl, are the major contributors to the water quality, including natural geochemical processes and human-induced activities. The piper plot diagram identifies three groundwater types namely: Na-Cl type, mixed type (Ca-Mg-Cl), and the Mg-HCO₃ type, with Ca-Mg-Cl dominating the other types. This study provides crucial insights into the drinking groundwater quality of the Cuvelai-Etosha Basin and offers a methodological framework for future water quality monitoring and sustainable resource management in semi-arid regions.

Keywords: Groundwater, Multivariate Statistical Analysis, Water Quality Index, Wells

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1. INTRODUCTION

The northern part of Namibia is one of the driest regions in Southern Africa with unpredictable low rainfall and a very high evaporation rate. All the rivers in the region are ephemeral, and the storage potential of the available retention pans is not understood. Hence, surface water storage is often lost to evaporation at an average of 2800 mm/annum (Eino et al., 2025). Therefore, available groundwater wells within the basin require some element of quality monitoring. This quality is a critical component of freshwater resources. Groundwater originates from precipitation that infiltrates the ground, gradually percolating downward until it reaches the water table, which is the upper surface of the groundwater reservoir (Igbal et al., 2024). Li et al., (2018) attribute groundwater quality to the chemical, physical, and biological characteristics of water stored underground, influenced by natural processes and human activities.

Understanding the quality of groundwater within the Cuvelai-Etosha Basin is essential for sustainable water management and environmental preservation (Soetaert et al., 2022). The Water Quality Index and Multivariate Statistical Analysis have been performed to explore relationships among multiple water quality parameters (Ram et al., 2021). Chakraborty et al., (2022) attest that Multivariate Statistical and Water quality analyses help in identifying dominant factors that influence groundwater quality, discerning patterns of contamination, and classifying sampling sites based on similarities in water chemistry (Chakraborty et al., 2022).

Groundwater in the Cuvelai-Etosha Basin, is crucial for daily use, but its quality is not well-known (Soetaert et al., 2022). This inadequate information risks public health and effective water management. This study aims to assess groundwater quality using Multivariate statistical analysis and Water Quality Index (WQI) to ensure safety, identify any parameters above the allowable limits by standards and establish relationships among parameters using correlation matrix, principal component and factor analysis.

This study is of ultimate significance as it could serve as a preliminary guide to sustainable groundwater use in the Cuvelai-Etosha Basin. In addition, it provides data for developing water quality protection strategies and helping in identifying and mitigating groundwater pollution sources.

The characterized physiochemical parameters of groundwater include: the pH, electrical conductivity, turbidity, dissolved oxygen, major ions (calcium, magnesium, sodium, chloride), nutrients (nitrate, nitrite), and trace elements. These parameters provide insights into the hydrogeochemical processes that influence groundwater quality and the potential sources of contamination. Bacteriological parameters, particularly the presence of indicator organisms like *Escherichia coli*, serve as indicators of fecal contamination and potential health risks associated with waterborne pathogens (Kgabi et al., 2018).

2. MATERIALS AND METHODS

2.1 Study Area

The Cuvelai-Etosha Basin is a transboundary wetland area shared by Angola and Namibia, as shown in Figure 1. The area covers about 160,000 km². The basin encompasses diverse rocks of different physical, chemical, and mineralogical characteristics. The formation varies from fine-grained, silt-to-clay-rich sands; fine-grained, well-sorted and unconsolidated aquifer sands; and sparse aquitard clays, calcrete, and carbonate deposits, which influence the chemical composition of

groundwater through processes such as weathering and dissolution (Kgabi et al., 2018).

2.1.1 Selected Wells for Water Sample Collection

Wells were selected based on their usage. The study shows that at least fifty people draw water from the selected wells daily. The site location is displayed in Table 1.

2.2 Methods

2.2.1 Groundwater Sampling and Analysis

A preliminary assessment was conducted on more than 12 wells within the Cuvelai-Etosa Basin. From this evaluation, five wells were selected for sampling based on consent and permission of owners. Figure 2 shows the geographical location of the sampled groundwater. Water bottles of 1litre size and sterilized bottles of 500ml size were used to collect the water samples from the five wells. Five samples were taken from each well. Samples were collected in duplicate and tested in two different laboratories: The Namibia Water Corporation (NAMWater) and the Water Quality Laboratory in the Department of Civil and Mining Engineering, University of Namibia. Onsite test was carried out to determine the pH, Electric conductivity and turbidity of the sampled water. Other parameters, such as dissolved oxygen, major ions (Calcium, Magnesium, Sodium, Chloride), nutrients (Nitrate, Nitrite, Ammonia), and trace elements, were tested in the laboratory.

Table 2 shows the ideal and the acceptable limits according to the Ministry of Agriculture, Water and Land Reforms, Namibia. This standard is used to assess the quality of the sampled water and is often compared with WHO standards (Oluyemi, 2012; Igbadun et al., 2025).

The methodology flow chart is shown in Figure 3. The flow chart explains the step-by-step procedure for the actualization of the study.

2.2.2 Groundwater Quality Index (GWQI)

Water Quality Index (WQI) is a single numerical value derived from multiple water quality parameters, summarizing the overall quality of water for a specific use, such as drinking (Gorai et al., 2016). It simplifies complex datasets, making it easier to assess and communicate water quality (Rajesh et al., 2019). The WQI grading categories typically range as shown in Table 3.

The groundwater quality was calculated as proposed in Soetaert et al., (2022) and described using equation (1)

$$GWQI = \sum(W_i \times q_i) = \sum \left[\left(\frac{wi}{\sum_{i=1}^n wi} \right) \times \left(\frac{Ci}{Si} \times 100 \right) \right] \quad (1)$$

where,

q_i is water quality rating,

W_i is the relative weight, and

S_i is the sub-index of i^{th} parameter

2.3 Multivariate Statistical Analysis

It is a statistical approach used to examine and interpret data involving multiple variables simultaneously (Aryafar et al., 2019). It strengthens the understanding of

relationships within the parameters used. The technique includes evaluating the correlation matrix, Principal Component Analysis (PCA), Cluster Analysis (CA), and Factor Analysis FA (Bodrud-Doza et al., 2016). The analyses were done using Minitab.

2.3.1 Correlation Matrix

Chakraborty et al., (2022) alluded that correlation coefficient matrix gives a measure of how well the variance of each parameter can be explained by relationships with the other. It displays correlation coefficients between sets of variables. It provides in tabular form the correlation coefficient between two variables, indicating the strength and direction of their linear relationship (Gorai et al., 2016 and Tratap et al., 2021). The values typically range from **-1** (perfect negative correlation) to **1** (perfect positive correlation), with **0** indicating no correlation.

2.3.2 Principal Component Analysis

PCA reduces data dimensionality by identifying principal components (linear combinations of variables) that explain the most variance (Chakraborty et al., 2022). It consists of eigenvalues, which indicate the amount of variance captured by each principal component. Higher eigenvalues mean the component explains more variability. *Loadings* referred to in Section 3 are the correlations between original variables and principal components, showing how strongly each variable contributes to a component (Okofe et al., 2022). Finally, the *Explained Variance* (%), shows the proportion of total variance attributed to each principal component.

2.3.3 Cluster Analysis

Parameters were grouped into clusters based on their similarities or distances. It comprises cluster centers, mean values of variables for observations within a cluster, representing the "center" of a group, and a dendrogram, where the heights represent distances at which clusters are merged (Rajesh et al., 2019).

In cluster analysis, the focus is to search for patterns in a data set by grouping the (multivariate) observations into clusters. The goal is to find an optimal grouping for which the observations or objects within each cluster are similar, but the clusters are dissimilar to each other. The similarity between observations were measured by squared Euclidean distances computed by equation (2) and Ward's method of divisive hierarchical clustering (Alvin, 2002).

$$\text{Euclidean distance } d_{ij} = \sqrt{\sum_{k=1}^p (x_{ik} - x_{jk})^2} \quad (2)$$

2.3.4 Factor Analysis

This identifies underlying factors that explain observed correlations between variables (Vitale, 2016). Factor loadings are correlations between variables and factors. Higher loadings mean a variable strongly relates to a specific factor. Eigenvalues help decide how many factors to retain (factors with eigenvalues > 1 are typically kept). *Communality* defines the proportion of a variable's variance explained by the extracted factors. Factor scores are numeric values representing each observation's placement on the derived factors (Chakraborty et al., 2022).

This study applied Factor analysis to interpret the hydrogeology and chemistry of wells in the Cuvelai-Etosh basin. Factor analysis leads to the determination of the basic independent dimensions of variables. Basically, weathering and anthropogenic activities are the two main processes responsible for altering the hydrogeochemical composition of groundwater (Ruiz-Pico et al., 2019; Christofi et al., 2020; Chen et al., 2022; Djafer et al., 2023). In general, the factors are connected to the largest eigenvalue and will be responsible for the greatest amount of variance in the dataset. The factor loadings are categorized as strong, moderate, and weak according to the total values of > 0.75 , $0.75 - 0.50$, and $0.50 - 0.30$, respectively (Ferhati et al., 2022 and Ferhati et al., 2023).

The variables for factor analysis are shown in Table 10. Parameters were captured across three factors (Factor 1, Factor 2, and Factor 3), and equation (3) estimated factor scores using the regression method.

$$f_{i,k} = \sum_{j=1}^p w_{j,k} Z_{i,j}, \quad w_{j,k} = \frac{\lambda_{j,k}}{\max(\psi_j, 0.01)} \quad (3)$$

$\lambda_{j,k}$ is the rotated loading of variable j on factor k , representing how strongly variable j loads onto factor k

ψ_j is the uniqueness, the portion of variable j variance not explained by any common factor. A small ψ_j means most of j variance is shared communality, so j should carry more weight.

2.3.5. Piper Diagrams

Piper diagrams are a specific type of ternary diagram use to plot the concentrations of the major cations and anions. It consists of two ternary diagrams: one for cations and one for anions; and a central diagram-shaped field into which the cation and anion values are projected. The relative percentage of three major cations (Ca, Mg and Na) are plotted on the ternary diagram to the left. The same is done with three major anions, (HCO_3 , Cl and SO_4). Then, the location of each point is projected up into the central area, and the intersection of the projections defines a point on the central field.

3. RESULTS AND DISCUSSIONS

3.1 Groundwater Quality Characterization

The physicochemical characterization of groundwater quality involved the examination of both physical and chemical properties of the groundwater (Priskila et al., 2023) as well as their interplay, to better understand the behavior and characteristics of groundwater (Okofu et al., 2022). The parameters tested were: EC, TDS, Na, NO_3 , NO_2 , F^- , Cl^- , TH, Ca, Mg, DO, NH_3 , pH, Turbidity and *E. coli*. Figure 4 shows the EC results from the UNAM and NAMWater laboratories. The line of agreement between the measured electrical conductivity at different laboratories validates the results.

Table 4 shows the results of the observed mean values and the acceptable limits of the parameters. EC, TDS, Na, NO_2 , F^- , Cl^- , DO and pH of all the wells were within the acceptable limit. However, parameters such as NO_3 , TH, Ca, Mg, NH_3 and Turbidity of some wells exceeded the acceptable limits.

3.1.1 Electrical Conductivity (EC, $\mu\text{S}/\text{cm}$) of Sampled Wells

Table 4 (Column 2) shows the results of all parameters tested for the wells in the five locations during the period of the study. Electrical conductivity is a measure of the ability of water to conduct electricity. High conductivity is an indication of the presence of impurities or pollutants and dissolved salts, minerals or ions in water. In this study, the EC ranged between 38.7 to 183.5 $\mu\text{S}/\text{cm}$ within the basin, which are far below the allowable limit of 300 $\mu\text{S}/\text{m}$. The order of higher EC in the sampled wells is $\text{GW2} > \text{GW1} > \text{GW3} > \text{GW4} > \text{GW5}$.

3.1.2 Total Dissolved Solid (TDS, mg/l)

The TDS refers to the concentration of dissolved substances in water, which essentially makes the water not adequate for consumption at a certain threshold. High TDS can affect water taste and odour. This parameter was found adequate for the selected wells. The values range from 259 to 1229 mg/l , which are less than the acceptable value of 2000 mg/l in Namibia Table 4 (Column 3). The order of the wells' TDS value is $\text{GW5} < \text{GW4} < \text{GW3} < \text{GW1} < \text{GW2}$.

3.1.3 Sodium ion (Na^+ , mg/l)

The level of Sodium ion from the selected wells were tested. High Sodium ion in water can affect taste and odour, at the same time increase the blood pressure in individuals (especially those with sodium-restricted diets). Table 4 (Column 4) depicts the range of values for wells. The Na^+ were perfectly ideal for drinking. They range from 11 to 97 mg/l . For selected wells the maximum sodium levels are below 35% of the allowable limit (300 mg/l). The order of higher Na^+ value in the study wells is $\text{GW3} > \text{GW1} = \text{GW2} > \text{GW4} > \text{GW5}$.

3.1.4 Nitrate ion (NO_3^- , mg/l)

The monitoring of Nitrate level in water is essential for ensuring water quality and safety. According to Table 4 (Column 5), the nitrate levels range from 0.4 to 26.0 mg/l . High nitrate in water is an indication of contamination or agricultural runoff. It can lead to health related issues, especially for pregnant women and infants. For example, the blue baby syndrome. The NO_3^- levels were found to be excessive at sites GW1 and GW3. However, wells GW2, GW4 and GW5 had levels that were far below the threshold of the acceptable limit of 11 mg/l .

3.1.5 Nitrite ion (NO_2^- , mg/l)

In Table 4 (Column 6), the nitrite levels range from 0.08 to 0.80 mg/l . The nitrite level of the sampled water was significantly low compared to the acceptable limit. Hence, the water is adequate in terms of nitrite level. However, at the Okatoo site (GW2), nitrite concentration was found to be very high with a value of 0.8 mg/l as against the acceptable value of 0.15 mg/l .

3.1.6 Fluoride and Chloride ions (F^- and Cl^- , mg/l)

High concentration of Fluoride in water is often associated with discoloration of teeth, joint pain, and possibly thyroid problems. The F^- in the wells is sufficiently low and meets the required standard of Namibian portable water, which is in line with the World Health Organisation (WHO) Standard. The range of values yielded $0.2 \leq \text{F}^- \leq 0.5$ mg/l . None of the wells has Fluoride ion about 20% of the allowable limit (see Table 3, Column 7). Similarly, in Table 4 (Column 8), the Chloride ions of the selected wells conform to the standard limit of 300 mg/l , with GW1 and GW5 having the minimum

and maximum values of 0.9 and 132 mg/l, respectively. By and large, none of the wells had up to 50% value of the permissible limit. Therefore, the wells are adequate in the levels of F^- and Cl^- ions.

3.1.7 Total Hardness (TH, Ca^{2+} and Mg^{2+} , mg/l)

In Table 4 (Column 9), the mean observed values of the TH for each well are shown. Total Hardness is a measure of the concentration of dissolved minerals in water. These minerals are primarily Ca^{2+} and Mg^{2+} ions in water. They are highly correlated with TH. The TH values in the study area vary between 73 and 534 mg/l. It can be seen that higher values of TH correspond to higher concentrations of Calcium and Magnesium ions (see GW1 and GW2). The TH values in GW1 and GW2 are relatively high, while the TH value of GW2 is about 130% higher than the permissible value. However, GW3, GW4, and GW5 concentrations of TH met the adequacy of the permissible limit. In the same manner, the concentration of Calcium and Magnesium ions in GW1 and GW2 was high and far above their corresponding permissible limits (see Table 4, Columns: 10 and 11).

3.1.8 Dissolved Oxygen (DO, mg/l)

The level of the DO in the sampled wells is below the permissible limit (see Table 4: Column 12). This may signify the low influence of atmospheric diffusion on the groundwater due to its depth. The measured values range from 1.2 to 3.6 mg/L.

3.1.9 Ammonia (NH_3 , mg/l)

The ammonia concentration in the sampled wells is below the permissible value specified by the Namibian standards, except for the **GW2**, which exceeds the maximum value. However, the value is within the permissible value by the World Health Organization (WHO), which is ≤ 1.5 mg/l. The order of concentration of Ammonia value in the wells is $GW1 = GW3 < GW5 < GW4 < GW2$. This generally indicates that the water is safe for consumption and other uses, with minimal risk of ammonia-related health issues such as skin and eye irritation, specifically **with** GW1 and GW3. However, the NH_3 -N level in the **GW2** needs to be monitored and controlled.

3.1.10 pH (-) and Turbidity (NTU)

The Hydrogen ion concentration in water (usually referred to as pH value) is used to designate the acidity and alkalinity of water. The pH value of the wells ranges from 6.68 to 7.86, which is lower than the permissible value of 9. The turbidity is a measure of colloidal matters like silt and clay. The values from GW1, GW3 and GW5 are within the permissible value, whereas that of GW2 slightly exceeded the permissible value. However, that of GW4 is exceedingly greater than the threshold.

3.2 Water Quality Index (WQI)

The WQI has been used to assess the quality of the groundwater and the computation of the WQI are based on equation 1. The WQI was classified as previously discussed with reference to Table 3. Table 5 shows the computed WQI for the selected wells. The results highlight significant variability in water quality across the sites from poor to excellent water quality. The GW1, GW2 and GW3 are characterized as safe for consumption, but consistent monitoring is essential.

3.3 Multivariate Statistical Analysis

3.3.1 Correlation Matrix

Table 6, shows the correlation between the physicochemical parameters of the groundwater. A high correlation coefficient (close to 1) implies a good positive relationship between two variables and a value of zero means no relationship at a significant level of $P < 0.05$. More specifically, the parameters $r > 0.7$ are strongly correlated, while an r between 0.5 and 0.7 represents a moderate (Alvin, 2002; Rahal et al., 2017).

The correlation matrices were prepared using the following parameters: pH, TDS, EC, TH, turbidity and major ions (Table 6). EC indicated a very strong correlation with TDS, NO_2 , Cl, TH, Ca, and Mg and a moderate correlation with Na and NH_3 . TDS indicated a high positive correlation with Cl, TH, Ca, as well as Mg, and a moderate correlation with Na and Turbidity. The pH values indicated no correlation with all parameters, whereas they showed good correlation with DO. TH exhibited a strong correlation with Ca, Mg, and NH_3 . Some groups indicated a strong to moderate correlation, $r > 0.7$; therefore, Na-F- NO_3 , Ca-Mg- NH_3 and Cl-Ca-Mg. This indicates that the variations in ionic concentration are mainly the result of weathering of the soil formation and the dissolution of minerals in the Cuvelai basin. Similar observations were made in the literature (Azaza et al, 2011; Mehdi et al., 2023).

3.3.2 Principal Component Analysis

Principal Component Analysis (PCA) has the goal to exploit and describe the data; it is applied to identify the principal parameters of groundwater (Ruiz-Pico et al., 2019; Christofi et al., 2020; Chen et al., 2022; Djafer et al., 2022; Ferhati et al., 2022; Ferhati et al., 2023). This kind of analysis is considered very helpful and used largely in hydrogeochemical studies (Wu et al., 2018). This study discusses the strength of multivariate analysis used to determine the characteristics of water quality in the region.

In this study, PCA is performed on a data set of 5 wells, based on 14 parameters. Table 7 displays the loadings of each variable on the first three principal components (PC1, PC2, and PC3). Higher absolute values indicate stronger correlations between variables and the components. PC1 highlights that EC, Mg, Ca, and TH have strong positive loadings, suggesting PC1 is associated with water hardness and mineral content. PC2 indicates that Na and NO_3 have significant positive loadings and moderate F loading, indicating that PC2 is associated with partial salinity. This could be linked to possible agricultural runoff, as Na and NO_3 are often associated with these sources. PC3 has no strong loadings, but it might capture some minor variations not explained by the first two components.

Table 8 shows the eigenvalues and the proportion of variance explained by each principal component (PC). PC1 has an eigenvalue corresponding to 53.1% of the total parameter variance. The PC2 has an eigenvalue associated with about 24% of the total parameter variance, while PC3 has an eigenvalue explaining 16.7% of the variance. Together, PC1, PC2, and PC3 explain approximately 93.5% of the total variance, indicating these three components capture most of the variation in the dataset.

3.3.3 Cluster Analysis (CA)

Figure 5 characterizes a dendrogram based on cluster analysis for the groundwater samples. CA combined the groundwater samples of the Cuvelai basin into three types of cluster as summarized in Table 9. Cluster 1 (**Blue Group**) includes EC, TDS, NO_2 , Cl, TH, Ca, Mg, and NH_3 . These parameters are closely related, likely representing the influence of dissolved ions and water hardness. Their grouping suggests shared sources, such as mineral dissolution. Cluster 2 (**Red Group**) comprises Na, NO_3 , and F-. This cluster reflects potential contributions from agricultural runoff, as nitrate and fluoride are often associated with fertilizers. Cluster 3 (**Green Group**), contains DO, pH, and Turbidity. These parameters are more indicative of physical and biological conditions in water, such as organic matter presence, oxygen levels, and microbial activity.

3.3.4 Factor Analysis

Factor 1 factorial plane accounts for over 53% of the variance. It is categorized by strong loads such as EC, TDS, TH, NO_2 , Ca, and Mg. In other words, it captures a significant amount of variance for variables with loadings close to 1 or above 0.75 and moderate loads between Cl and NH_3 (Table 10). Factor 1 illustrates the natural hydro-geochemical characteristics of the groundwater by water-rock interaction, which is mainly derived from the weathering of rocks and dissolution of minerals. The strong loads of EC, TDS, and TH in the wells are due to the components of quartzite and shale associated with the study area. The high load of Ca and moderate loads of chlorine can be traced to Cl - containing fertilizers as in (Djafer et al., 2022 and Ferhati et al., 2022).

Factor 2 of the groundwater in the basin area is categorized by strong loads of Na, NO_3 and F (Table 10). Communalities indicate how well each variable's variance is explained by the factors. Higher communalities (closer to 1) mean the model explains almost all the variance in the variable. EC, TDS, TH, Ca, pH, and Turbidity have high communalities (close to or equal to 1), meaning the extracted factors explain nearly all the variance in these variables. NO_2 , NH_3 , and DO have lower communalities, indicating that the model explains less of the variance in these variables compared to others.

A piper plot diagram is a graphical representation of the chemistry of water whereby cations and anions are shown by separate ternary plots. In Figure 6, a Piper plot diagram was used to provide insights into the chemical composition of groundwater for the five wells by visualizing the relative concentrations of key ions. The plot gives the combinations between major cations and the major anions in a triangular diagram of the groundwater. Cation Triangle (Bottom Left), represents the proportions of major cations and anions Triangle (Bottom Right), represents the proportions of major anions. Three groundwater types were identified from this diagram: Na-Cl type, mixed type (Ca-Mg-Cl), and the Mg- HCO_3 type, with Ca-Mg-Cl having dominance over the other types. The results show that 60% of the sampled water sources are the Ca-Mg-Cl mixed type, 30% in the Na-Cl mixed class, and 10% type in the Mg- HCO_3 type. For GW1, Cation Triangle shows that Ca (50%), Na (50%), Mg (30%), and the anion Triangle Cl (30%).

4. CONCLUSION

Groundwater quality and its suitability for drinking purposes were evaluated in the study area. The hydrogeochemical studies of the groundwater in the Cuvelai-Etosha Basin reveal the following closures:

- A total of 25 groundwater samples were collected and analysed for various physicochemical parameters. The pH of samples lies within the permissible limits set by the Department of Water Affairs and Forestry Water Quality Monitoring, Namibia, and the WHO Standards. Based on the EC and TDS, groundwater was 100% below the permissible limits. All the sites satisfied the Total Hardness requirement, except GW2, which exceeds the permissible limit by 30%.
- The analytical technique was used to represent the spatial variation of pH, EC, TH, and major ions such as Na, Ca, Mg, Cl, NH₃, NO₂, and NO₃. The higher concentrations Mg and Ca mostly appear in the GW1 and GW2 of the study area, which indicates that the intercalation of quartzite and shale formation increases concentrations.
- WQI was used to evaluate the groundwater quality and its suitability for drinking purposes. WQI classification varies from excellent quality in the GW5 area, representing 20% of the samples, good quality for the GW1 and GW3 areas, representing 40% of the samples, and poor quality for the GW2 and GW4 sites, representing 20% of the samples. However, no site was found unsuitable for drinking purposes. This shows that a small investment in the treatment of GW2 and GW4 will augment the existing water supply in the area.
- Multivariate statistical analyses were used for interpreting the characteristics of groundwater quality. A correlation matrix reveals the EC indicated a high positive correlation with TDS, TH, Ca, Mg, Cl, and NO₂, and a moderate correlation with Na and NH₃. TDS indicated a high positive correlation with TH, Ca, Cl, and Mg, and a moderate correlation with Na and turbidity. The pH values indicated no correlation with all parameters, whereas they showed a good correlation with DO. TH exhibited a strong positive correlation with Ca, Mg, and NH₃. Some groups indicated a strong-to-moderate correlation, $r > 0.7$, therefore Na-F-NO₃, Ca-Mg-Cl-NH₃, and Ca-Mg-Cl.
- Principal component analysis grouped the samples into three loadings. PC1 highlights that EC, Mg, Ca, and TH have strong positive loadings, suggesting PC1 is associated with water hardness and mineral content. PC2 indicates that Na and NO₃ have significant positive loadings and moderate F loading, indicating that PC2 is associated with partial salinity. PC3 has no strong loadings. The eigenvalues PC1, PC2, and PC3 corresponding to the total parameter variance are 53.1 %, 23.8 %, and 16.7 %, respectively. PCA revealed that key contributors to groundwater quality are TH, Calcium, and Magnesium under PC1, while PC2 is driven by Nitrate, and PC3 by Turbidity.
- Cluster analysis classified the groundwater samples into three types of cluster groups: Group I consists of EC, TDS, Cl, TH, Ca, Mg, NO₂, and NH₃. The

parameters are closely related, thus representing the influence of dissolved ions and water hardness; Group II contains Na, NO₃, and F, a cluster that reflects the potential contributions from agricultural runoff, as nitrate and Fluoride are often associated with fertilizers; and Group III includes DO, pH, and Turbidity.

- For the factor analysis, there are two factors related to the formation of groundwater quality in the study area. Factor 1 accounts for over 53% of the variance. It is categorized by strong loads such as EC, TDS, TH, NO₂, Ca, and Mg. The strong loads of EC, TDS, and TH in the wells are due to the intercalation of quartzite and shale associated with the study area. The moderate loads of chlorine can be traced to Cl-containing fertilizers. Factor 2 of the groundwater in the basin area is categorized by strong loads of Na, NO₃, and F.
- The piper plot diagram identifies three groundwater types, they are: Na-Cl type, mixed type (Ca-Mg-Cl), and the Mg-HCO₃ type, with Ca-Mg-Cl dominating the other types.

It is recommended that the selected groundwater should be treated by the relevant authority to support domestic usage.

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Figures:



Figure 1: Cuvelai-Etoshia Basin (Source: Google Earth)

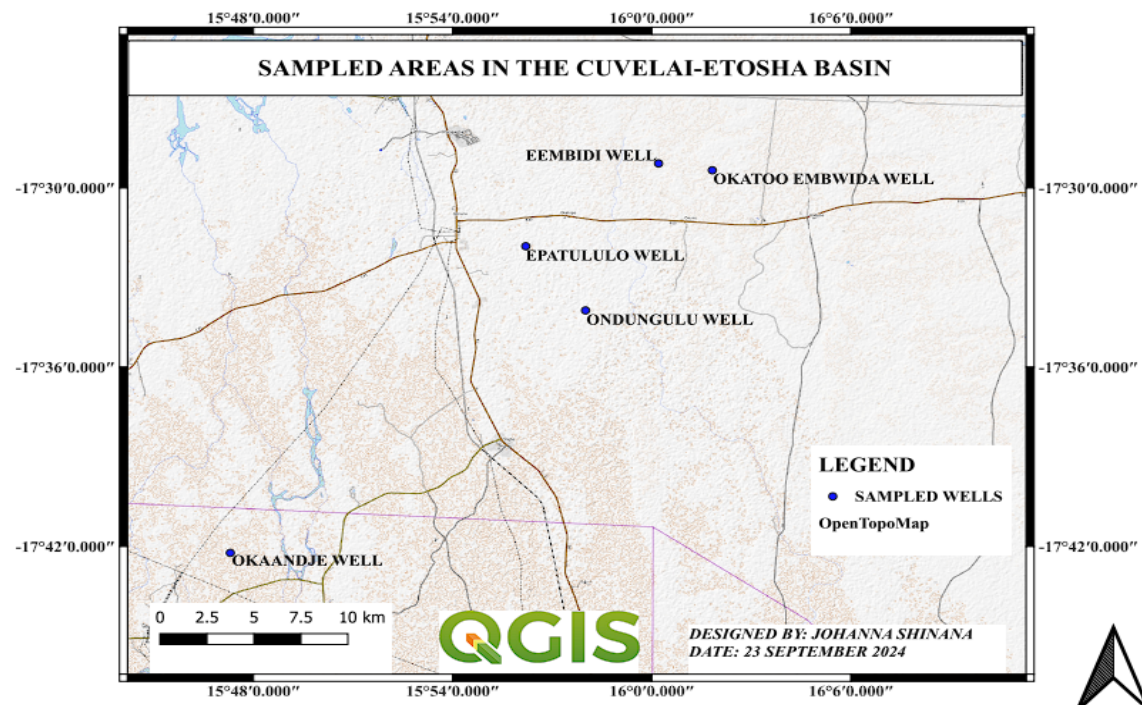


Figure 2: Location map of the study area showing the position of the selected wells.

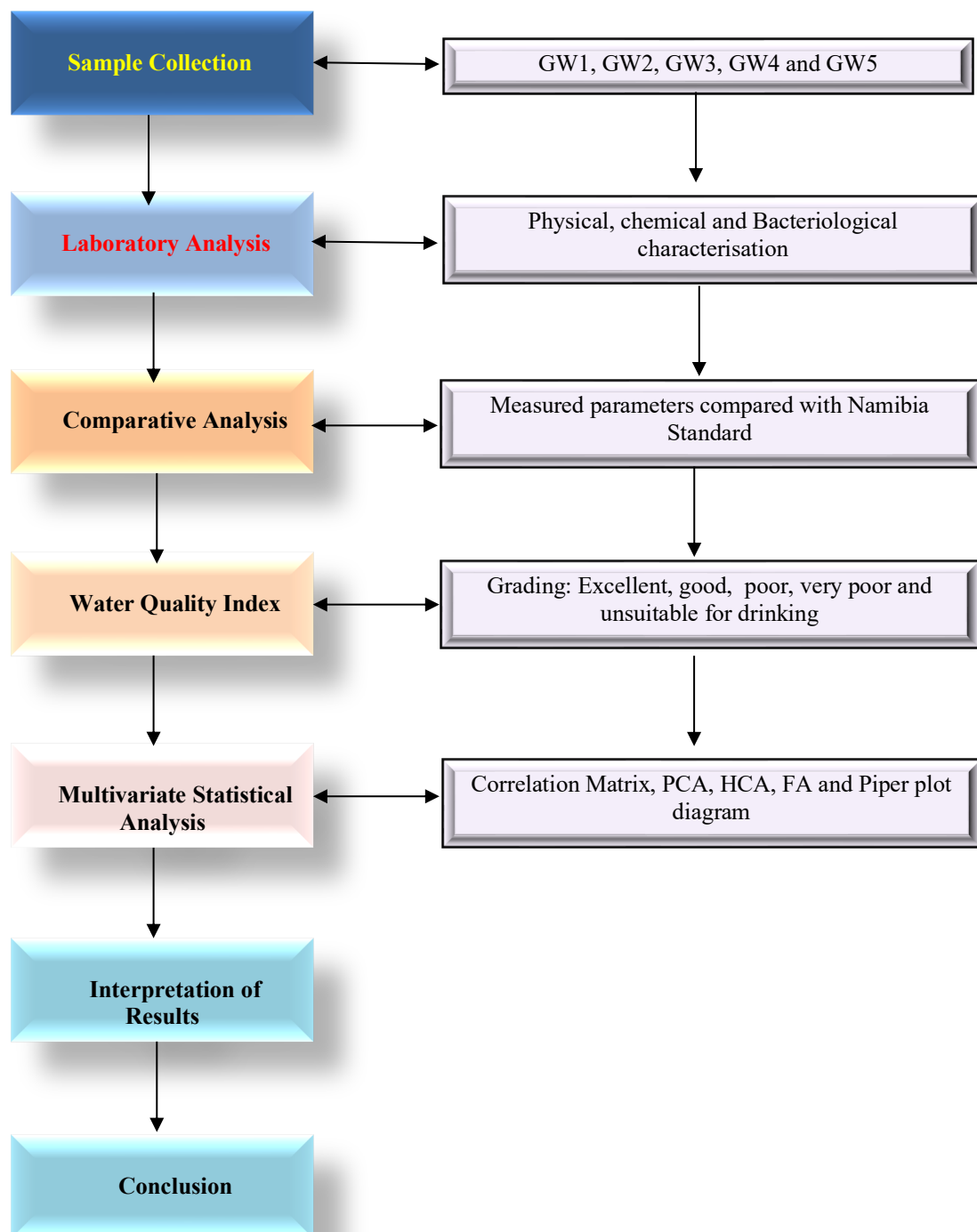


Figure 3: Methodology flow chart

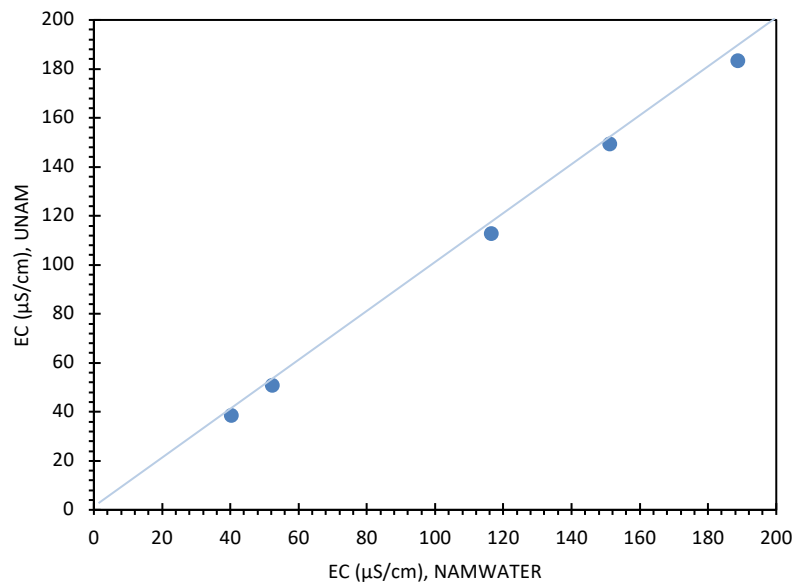


Figure 4: Comparison of measured EC from two different laboratories

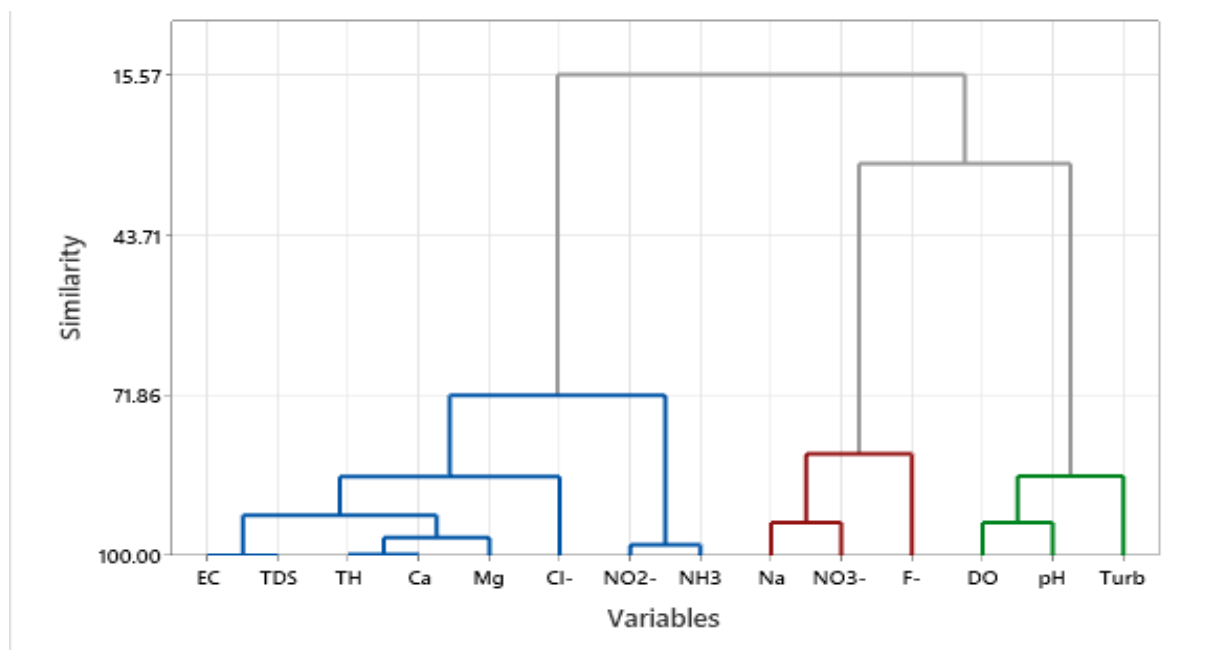


Figure 5: Dendrogram of hierarchical cluster analysis of samples

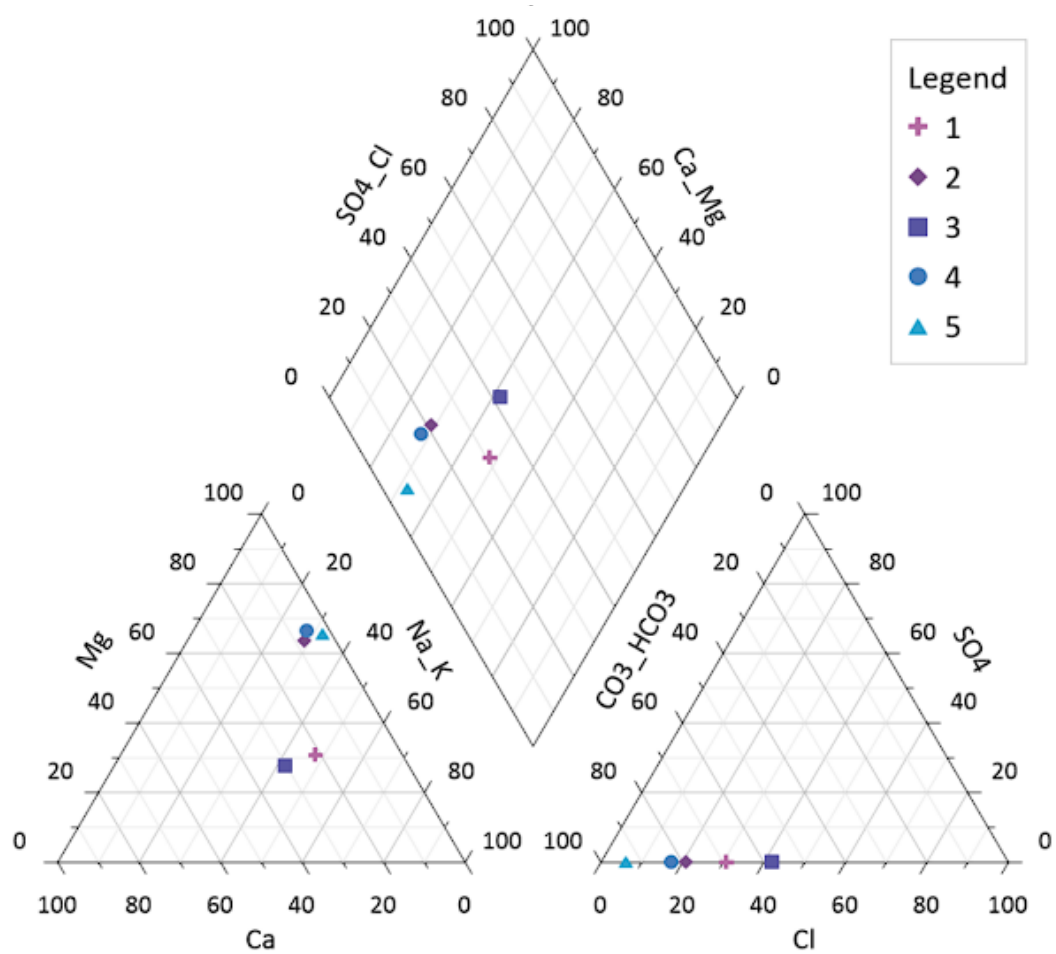


Figure 6: Piper Plot Diagram

Tables:

Table 1: Respective coordinates of the sampled wells.

Wells	Epatululo	Okatoo	Eembidi	Ondungulu	Okaandje
Coordinates	[15°56'12" E 17°31'57" S] GW1	[16°01'49" E 17°29'25" S] GW2	[16°00'12" E 17°29'11" S] GW3	[15°58'00" E 17°34'06" S] GW4	[15°47'20" E 17°42'12" S] GW5

Table 2: Water Quality Standard (Oluyemi, 2012; DWAF 2013)

Parameter	Abbreviations	Units	Ideal	Acceptable
Electrical Conductivity	EC	µs/cm	80	300
Turbidity	Turb	NTU	5	10
Ph	pH	-	6-8.5	6-9
Dissolved Oxygen	DO	mg/l	5	10
Hardness	TH	mg/l	200	400
Chloride	Cl ⁻	mg/l	100	300
Ammonium	NH ₄ ⁺	mg/l	0.2	0.5
Nitrate	NO ₃ ⁻	mg/l	6	11
Nitrite	NO ₂ ⁻	mg/l	0.1	0.15
Fluoride	F ⁻	mg/l	0.7	2
Calcium	Ca ²⁺	mg/l	80	150
Magnesium	Mg ²⁺	mg/l	30	70
Sodium	Na ⁺	mg/l	100	300
<i>E. coli</i>		Count/100 ml	0	1

Table 3: WQI Classification, (Ram et al., 2021)

WQI values	Grading
0-50	Excellent
51-100	Good
101-200	Poor
201-300	Very poor
>300	Unsuitable for drinking

Table 4: Results of the physicochemical and Bacteriological parameters of sampled wells

Wells	EC (μ S/cm)	TDS (mg/l)	Na (mg/l)	NO ₃ (mg/l)	NO ₂ (mg/l)	F- (mg/l)	Cl- (mg/l)	TH (mg/l)	Ca (mg/l)	Mg (mg/l)	DO (mg/l)	NH ₃ (mg/l)	pH	Turb (NTU)	<i>E. coli</i> Count/100ml
Epatululo (GW1)	149.5	1002	97	12.3	0.1	0.20	132	365.8	265.4	100	1.70	0.01	6.87	2.05	Not detected
Okatoo (GW2)	183.5	1229	97	4.1	0.8	0.20	129	534.4	430.2	104	1.20	1.5	7.09	5.22	Not detected
Eembidi (GW3)	112.8	756	151	26.0	0.09	0.50	45	98.8	78.6	21	3.10	0.01	7.33	3.5	3
Ondungulu (GW4)	51.0	342	50	1.8	0.1	0.30	86	73.2	48.3	25	3.60	0.41	7.86	40	Not detected
Okaandje (GW5)	38.7	259	11	0.4	0.08	0.20	0.9	118.5	93.4	25	1.30	0.23	6.68	2.57	Not detected
NWQG¹	< 300	< 2000	< 300	11	0.15	2.0	300	400	150	70		0.5	9	5	1
WHO²	< 250	< 1000				1.5	200	500	100	50			< 9.2	5	

Table 5: Water Quality Index (WQI) for 5 wells

Site	WQI	Grading
GW1	61.57	Good
GW2	107.76	Poor
GW3	58.45	Good
GW4	127.33	Poor
GW5	24.41	Excellent

Table 6: Pearson's Correlation Matrix of Physicochemical Parameters

	EC	TDS	Na	NO ₃	NO ₂	F-	Cl-	TH	Ca	Mg	DO	NH ₃	pH	Turb
EC	✓ 1													
TDS	✓ 1	✓ 1												
Na	✓ 0.67	✓ 0.67	✓ 1											
NO ₃	⚠ 0.32	⚠ 0.32	✓ 0.88	✓ 1										
NO ₂	✓ 0.7	✓ 0.7	⚠ 0.18	✗ -0.25	✓ 1									
F-	⚠ -0.12	⚠ -0.12	✓ 0.64	✓ 0.79	✗ -0.34	✓ 1								
Cl-	✓ 0.77	✓ 0.77	⚠ 0.38	⚠ -0.01	✓ 0.52	✗ -0.32	✓ 1							
TH	✓ 0.88	✓ 0.88	⚠ 0.24	⚠ -0.13	✓ 0.82	✗ -0.55	✓ 0.76	✓ 1						
Ca	✓ 0.88	✓ 0.88	⚠ 0.25	✗ -0.14	✓ 0.85	✗ -0.53	✓ 0.72	✓ 0.99	✓ 1					
Mg	✓ 0.86	✓ 0.86	⚠ 0.24	⚠ -0.11	✓ 0.64	✗ -0.59	✓ 0.84	✓ 0.96	✓ 0.93	✓ 1				
DO	✗ -0.4	✗ -0.4	⚠ 0.25	⚠ 0.35	✗ -0.48	✓ 0.73	⚠ -0.11	✗ -0.68	✗ -0.69	✗ -0.62	✓ 1			
NH ₃	✓ 0.5	✓ 0.49	⚠ -0.03	✗ -0.45	✓ 0.96	✗ -0.39	⚠ 0.44	✓ 0.71	✓ 0.73	✓ 0.51	✗ -0.39	✓ 1		
pH	✗ -0.2	✗ -0.2	⚠ 0.19	⚠ 0.07	⚠ -0.08	✓ 0.5	⚠ 0.17	✗ -0.37	✗ -0.37	✗ -0.37	✓ 0.88	⚠ 0.05	✓ 1	
Turb	✗ -0.5	✗ -0.5	✗ -0.33	✗ -0.38	✗ -0.23	⚠ 0.09	⚠ 0.08	✗ -0.45	✗ -0.46	✗ -0.39	✓ 0.72	⚠ -0.01	✓ 0.85	✓ 1

The bold value indicates the correlation coefficient of > 0.60 at significant 0.05 levels

Table 7: Eigenvectors (Principal Component Loadings)

Variable	PC1	PC2	PC3
EC	0.33	0.239	0.002
TDS	0.33	0.239	0.002
Na	0.104	0.523	0.054
NO ₃	-0.032	0.504	0.252
NO ₂	0.303	-0.033	-0.207
F-	-0.187	0.441	0.026
Cl-	0.264	0.137	-0.307
TH	0.366	-0.018	-0.036
Ca	0.366	-0.02	-0.037
Mg	0.347	-0.006	-0.028
DO	-0.256	0.283	-0.321
NH ₃	0.251	-0.123	-0.312
pH	-0.149	0.211	-0.541
Turb	-0.187	-0.06	-0.547

Table 8: Eigenvalue analysis of the Correlation Matrix

Eigenvalue	7.430	3.330	2.336	0.905
Proportion	0.531	0.238	0.167	0.065
Cumulative	0.531	0.769	0.935	1

Table 9: Cluster Groups for Parameters

Cluster 1-a	EC, TDS, Cl, TH, Ca, Mg,
Cluster 1-b	NO ₂ , NH ₃
Cluster 2	Na, NO ₃ , F ⁻
Cluster 3	DO, pH, Turbidity

Table 10: Unrotated Factor Loadings and Communalities

Variable	Factor ¹	Factor ²	Factor ³	Communality
EC	0.899	0.436	0.003	0.998
TDS	0.899	0.437	0.003	0.998
Na	0.282	0.954	0.083	0.997
NO ₃	-0.087	0.919	0.384	1.000
NO ₂	0.826	-0.060	-0.316	0.785
F ⁻	-0.510	0.805	0.040	0.910
Cl ⁻	0.721	0.250	-0.470	0.803
TH	0.997	-0.033	-0.055	0.998
Ca	0.997	-0.036	-0.057	0.999
Mg	0.947	-0.01	-0.043	0.898
DO	-0.698	0.517	-0.490	0.994
NH ₃	0.685	-0.225	-0.477	0.747
pH	-0.407	0.384	-0.828	0.998
Turb	-0.509	-0.109	-0.835	0.969
Variance	7.4296	3.3295	2.336	13.0951
% Variance	0.531	0.238	0.167	0.935