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Spatial and Temporal Evaluation of Water Pollution Parameters in Seben Taşlıyayla (Bolu, Türkiye) Reservoir by Using the Water Quality Index and Multivariate Statistical Methods

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Abstract: This study aims to determine the spatial and temporal variations in the water quality of the Seben Taşlıyayla (Bolu) Reservoir and classify its water quality. For this purpose, water samples were taken monthly from three stations between March 2023 and February 2024, and then analyses were conducted; 21 physicochemical and 7 heavy metal parameters were examined, and the compliance of the obtained results with SWQR and WHO standards was tested. The parameters Pb^{+2} and TA were found to exceed standard limits, restricting water usage. Principal Component Analysis (PCA) was conducted to identify the main components of the water body. Through PCA, five principal factors were found to explain 92.824% of the total variance. It was determined that agricultural activities, heavy metals, and anthropogenic activities influenced the reservoir's water quality. Hierarchical Cluster Analysis (HCA) categorized the seasons into two clusters and the 28 parameters into three clusters. Regarding irrigation water quality parameters, the SAR value was classified as "Excellent," the % Na as "Good," the MH (>50) as "Unsuitable," the KR (<1) as "Suitable," and the RSC (<1.25) as "Safe/Good." Considering the Water Quality Index (WQI) calculated using annual mean values, the reservoir water was classified as "Excellent"; however, attention should be paid to spatial and temporal variations.

Keywords: Seben Taşlıyayla (Bolu) Dam, Water Quality Index, Irrigation Water Quality, Principal Component Analysis, Hierarchical Cluster Analysis

Seben Taşlıyayla (Bolu, Türkiye) Göleti Su Kirliliği Parametrelerinin Su Kalitesi İndeksi ve Çok Değişkenli İstatistiksel Yöntemler Kullanarak Mekansal ve Zamansal Olarak Değerlendirilmesi

Özet: Bu çalışma ile Seben Taşlıyayla (Bolu) Göleti su kalitesinin mekansal ve zamansal değişimlerini tespit etmek ve su kalitesi sınıflarını göstermek amaçlanmıştır. Bu kapsamda su örnekleri Mart 2023– Şubat 2024 tarihleri arasında üç istasyondan aylık olarak toplanmış ve analizler gerçekleştirilmiştir. 21 fizikokimyasal, 7 ağır metal parametresi incelenerek elde edilen sonuçların SWQR ve WHO standartlarına uygunluğunun tespiti yapılmıştır. Pb^{+2} ve TA parametreleri standartların üzerinde tespit edilmiş olup su kullanımını kısıtlamaktadır. Su kütlesinin ana bileşenlerini tespit edebilmek amacıyla temel bileşen analizi (PCA) uygulanmıştır. PCA analizi ile toplam varyansın %92,824'ünü açıklayan beş ana faktör belirlenmiştir. Göletin su kalitesine tarımsal faaliyetlerin, ağır metallerin ve antropojenik faaliyetlerin etki ettiği düşünülmektedir. Kümeleme analizi ile mevsimler iki, 28 parametre ise üç kümeye ayrılmıştır. Sulama suyu kalite parametreleri bakımından SAR "Mükemmel", % Na açısından "İyi", MH (>50) "Uygun Olmayan", KR (<1) "Uygun", RSC (<1,25) "Güvenli/İyi" olarak tespit edilmiştir. Verilerin yıllık ortalama değerlerine göre hesaplanan WQI değerine göre gölet suyu "mükemmel" olarak belirlenmiştir. Ancak mekânsal ve zamansal değişime dikkat edilmelidir.

Anahtar Kelimeler: Seben Taşlıyayla (Bolu) Göleti, Su Kalitesi İndeksi, Sulama Suyu Kalitesi, Temel Bileşenler Analizi, Hiyerarşik Kümeleme Analizi

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1. Introduction

Located in the Western Black Sea region, Bolu Province benefits from favorable transportation accessibility as it lies along the Istanbul-Ankara route. With its rich forest cover, it also holds significant potential for nature tourism. Additionally, its lakes are of great importance in terms of natural beauty (Bolu Province Report, 2002; Bolu Province Report, 2018; Kök & Akyurt- Kurnaz, 2020). The lakes, reservoirs, and other wetlands in the region provide venues for various events, festivals, and water sports, further enhancing the area's recognition and visibility (Bayhan, 2021). Among the reservoirs in the province, the Seben Taşlıyayla Reservoir covers an area of 8.333 km² with an elevation of 1,440 m in the forest-covered Aladağ Mountains, 38 km south of Bolu. Constructed for both irrigation and tourism purposes (Environmental Status Report, 2021), Taşlıyayla Reservoir, with its 833-hectare area, is approximately seven times larger than Lake Abant. Given its multifunctional use, monitoring the water quality of such water bodies is very important. Water quality monitoring plays an important role in matching water supply and demand. While analyzing water quality once a year or even less frequently may be sufficient for stable groundwater bodies, where chemical concentrations fluctuate very slowly over time, more frequent sampling is required for surface waters due to variations in pollutant concentrations (WHO, 2011). Water quality indices (WQIs) are essential for converting multiparametric water analysis data into a single numerical value, which simplifies the interpretation of large datasets. The acceptability of water quality criteria depends on prevailing conditions and may vary over time and across regions. Therefore, WQIs play a significant role in assessing the water quality of a source by considering time and factors. Sampling time significantly affects water quality parameters and the index value. Even though developing a universally accepted general WQI is highly challenging, researchers may develop indices specific to a region or water source. Most existing WQIs are tailored for surface water bodies (Poonam et al., 2013).

As stated before, water quality measurements provide important information for assessing the regional water quality status. As stated by Tunçkol and Akkemik (2013), there has been a rapid increase in unregulated tourism-related construction and secondary housing development around Taşlıyayla Reservoir. It was reported that this reservoir surrounded by urbanized zones may alter the region's climatic characteristics in the future. This study aims to present information on the reservoir's water quality status. The water quality was classified using multivariate statistical techniques. One of the reasons for choosing the study area is the limited number of studies on this particular area.

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2. Materials and Methods

2.1. Study area

Seben Taşlıyayla Reservoir is located at coordinates 41°31'56"N and 31°38'39"E and within the wildlife protection and improvement area. The three stations where water samples were collected are shown in Figure 1. Taşlıyayla Reservoir, with a water volume of 45 million m³ and an approximate depth of 12 m, is situated in a forested area with a lake surface area of 8.333 km². The water level of the reservoir reached its estimated level after 2009. The lake is fed by snowmelt, rainfall, Aladağ Stream, and several other sources (Kulkoyluoglu et al., 2017).

Figure 1. Sampling Stations (adapted from Google Earth)

2.2. Water Analysis Measurements and Methodology

Water samples were taken monthly from three stations in the reservoir between March 2023 and February 2024, followed by analysis. Salinity, pH, temperature (WT), dissolved oxygen (DO), and electrical conductivity (EC) values were determined in situ using a YSI 556 MPS device. Water sample containers, which were properly cleaned a day before (Boyd & Tucker, 1992), were used for collecting water from the reservoir. Samples were taken from a depth of 10-15 cm below the surface. The collected materials were stored at +4°C until analysis in the laboratory (Demir et al., 2024). To assess water quality, the following parameters were measured using a WTW 7600 UV-VIS device: biological oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), phosphate, phosphorus (PO_4^{-3}-P), ammonium nitrogen (NH_4^+-N), nitrite (NO_2-N), nitrate (NO_3-N), total hardness (TH), total alkalinity (TA), sodium (Na^+), sulfite (SO_3^{-2}), sulfate (SO_4^{-2}), calcium (Ca^{+2}), magnesium (Mg^{+2}), chloride (Cl^-), and potassium (K^+). The analyses were conducted in accordance with the methods defined by APHA (2012). For heavy metal analysis, water samples were collected in polyethylene bottles pre-washed with 50% HNO_3 and deionized water, then acidified with 10 mL of HNO_3 per liter. Heavy metals, including zinc (Zn^{+2}), nickel (Ni^{+2}), cadmium (Cd^{+2}), mercury (Hg^{+2}), copper (Cu^{+2}), iron (Fe^{+2}), and lead (Pb^{+2}), were measured at the Central Research Laboratory of Kastamonu University using an Elmer Optima 2000 DV ICP-OES device (WHO, 2011; APHA, 2012).

2.3. Irrigation Water Quality Parameters

To determine the water quality of Seben Taşlıyayla Reservoir, the sodium adsorption ratio (SAR), Na^+ percentage (Na%), magnesium hazard (MH), Kelley's ratio (KR), and residual sodium carbonate (RSC) values were calculated using formulas (1) through (5). Measurement units were converted from mg L^{-1} to meq L^{-1} during the calculations (Eaton, 1950; Richards, 1954; Wilcox, 1955; Kelley, 1963; Paliwal, 1972; Ravikumar et al., 2013). Higher parameter values and continuous use as irrigation water can cause soil structure degradation, dispersion of soil clay, increased soil compaction when dry, and higher soil permeability when wet (Zaman et al., 2018).

$$SAR = \frac{Na^{+}_{meq}}{\sqrt{\frac{Ca^{+2}_{meq}+Mg^{+2}_{meq}}{2}}} \quad (1)$$

$$MH = \left(\frac{Mg^{+2}_{meq}}{Ca^{+2}_{meq}+Mg^{+2}_{meq}}\right) x\ 100 \quad (2)$$

$$KR = \left(\frac{Na^{+}_{meq}}{Ca^{+2}_{meq}+Mg^{+2}_{meq}}\right) \quad (3)$$

$$\%Na = \frac{(Na^{+}_{meq} + K^{+}_{meq}) x\ 100}{(Na^{+}_{meq} + Ca^{+2}_{meq} + Mg^{+2}_{meq} + K^{+}_{meq})} \quad (4)$$

$$RSC = (Alkanity\ x\ 0.0333) - (Ca^{+2}_{meq}+Mg^{+2}_{meq}) \quad (5)$$

2.4. Weighted Arithmetic Water Quality Index (WAWQI)

The WAWQI method classifies water quality based on purity levels using the analyzed parameters (Brown et al., 1972). The WAWQI was calculated using the following formulas:

$K = (1/(1/\sum_{i=1}^{n} S_n))$ formula was used to calculate "K" proportionality constant. "S_n" refers to the permissible standard value for the nth parameter

The quality rating scale (Q_n) for each parameter was calculated as follows:

$$Q_n = 100[(V_n - V_0)/(S_n - V_0)]$$

In this formula:

V_n is the measured concentration of the n-th parameter in the analyzed water,
V_0 is the ideal value of this parameter in pure water (V_0= 0; V_{pH}= 7; V_{DO}= 14,6),
S_n is the recommended standard value of the nth parameter.
The unit weight (W_n) for water quality parameters was calculated as:

$$W_n = K/S_n$$

The WAWQI value was determined using the following formula.

$$WAWQI = \Sigma Q_n W_n / \Sigma W_i$$

WQI values were categorized as follows:0-25: Excellent; 26-50: Good; 51-75: Poor; 76-100: Very Poor; >100: Not suitable for drinking (Brown et al., 1972; Tokatlı, 2020). Data obtained in this study were presented using radar diagrams in the Origin Pro 2024 software.

2.5. Statistical Analyses

Descriptive statistics, correlation analyses, and multiple comparison tests were conducted using IBM SPSS 23. Depending on dataset suitability, One-Way ANOVA and Kruskal-Wallis tests were conducted to reveal differences between means, with post-hoc analyses conducted using Tukey and Tamhane tests (Howladar et al., 2021). Spearman and Pearson correlation tests were performed based on the normality of the data distribution.

To group objects with similar surface water quality characteristics of the reservoir, HCA was performed using Ward's method, aiming to classify datasets based on similarities or differences (Barakat et al., 2016; Wang et al., 2017).

Factor Analysis - Principal Component Analysis (FA/PCA) was performed using varimax rotation. Factor analysis facilitates the interpretation of large datasets, reduces data dimensions, and summarizes the correlation between water components with minimal loss of original data (Helena et al., 2000; Alberto et al., 2001). The suitability of the PCA test was confirmed through the Kaiser-Meyer-Olkin (KMO) and Bartlett's tests, which yielded a KMO value of 0.886 and a significant Bartlett's test result (P=0).

3. Results and Discussion

In this study, surface water samples were analyzed in terms of physicochemical parameters and heavy metal levels. The analysis revealed that the spatial differences (stations) observed among these parameters were not significant (p>0.05), whereas the temporal differences (seasons, months) were significant (p<0.05). The differences between the mean values of $[SO_3^{-2}]$ and $[NO_2^-]$ could not be evaluated as these parameters were below measurable limits. Similarly, the temporal variations of $[Fe^{+2}]$ and $[Cu^{+2}]$ were not significant (p>0.05). The temporal (seasonal) variations of the parameters are indicated by different letters, with descriptive statistical results presented in Table 1.

DO is very important for aquatic life. While percent saturation is defined as the potential of water to dissolve oxygen at a given temperature and pressure, DO at 100% saturation is considered the optimal level for aquatic organisms (Thukral et al., 2005). The mean DO value was determined to be 14.13±1.07 mg/L, with the lowest value recorded in September (12.44 mg/L) and the highest in April (16.14 mg/L). When examining the annual mean values of the by season (Table 1), DO formed three main groups (fall, winter, and spring), whereas summer exhibited characteristics similar to both winter and spring. The oxygen content of water resources is primarily regulated by the decomposition of organic matter, oxidation of nitrogen compounds, photosynthetic aeration by aquatic plants, and oxygen demand from sediments. Reduced oxygen levels pose a threat to aquatic life, including river fish (Oketola et al., 2013). There was a very strong negative correlation between DO and EC, total suspended solids (TSS), COD, and BOD (r>0.80; p<0.01). The pond water was classified as first-class in terms of the DO parameter (SWQR, 2016). Sustainable agricultural development is constrained by the scarcity of freshwater resources and the deterioration of water quality in low-precipitation regions, which also negatively affects agricultural production quality (Malash et al., 2008; Jiang et al., 2012). In this study, the mean salinity value was measured to be 0.04‰±0.03, with the lowest value (0.01‰) recorded in January and February and the highest value (0.09‰±0.01) in September. Salinity was categorized into winter, spring, and summer groups, whereas fall exhibited similarities to both summer and spring. There was a very strong and positive correlation between salinity and pH, WT, SO_4^{-2}, Mg^{+2}, and Ca^{+2} (r>0.80; p<0.01).

Table 1. Descriptive statistics of measured parameters

Parameters	Winter	Spring	Summer	Autumn	Annual
DO (mg L^{-1})	14.10±0.30^{b}	15.32±0.73^{c}	14.23±0.88^{bc}	12.85±0.45^{a}	14.13±1.07
Salinity (‰)	0.01±0.01^{c}	0.04±0.02^{b}	0.07±0.01^{a}	0.06±0.02^{ab}	0.04±0.03
pH	8.28±0.03^{c}	8.38±0.06^{b}	8.58±0.06^{a}	8.59±0.17^{a}	8.46±0.16
WT (°C)	7.35±1.23^{c}	10.64±1.98^{b}	15.94±1.37^{a}	15.19±3.53^{a}	12.28±4.13
EC (µS cm^{-1})	317.48±29.35^{b}	283.83±21.20^{c}	334.24±20.19^{b}	368.59±9.22^{a}	326.04±37.04
TSS (mg L^{-1})	0.02±0.00^{b}	0.02±0.00^{b}	0.56±0.45^{a}	1.09±0.51^{a}	0.42±0.55
COD (mg L^{-1})	0.26±0.28^{c}	0.07±0.10^{c}	0.85±0.32^{b}	1.26±0.21^{a}	0.61±0.53
BOD (mg L^{-1})	0.14±0.12^{bc}	0.00±0.00^{c}	0.19±0.16^{b}	0.67±0.19^{a}	0.25±0.29
PO_4^{-3} (mg L^{-1})	0.19±0.28	0.05±0.04	0.03±0.02	0.07±0.05	1.94±0.59
SO_4^{-2} (mg L^{-1})	8.29±9.72^{b}	5.60±5.69^{b}	30.47±7.22^{a}	33.06±7.96^{a}	0.08±0.15
SO_3^{-2} (mg L^{-1})	0.27±0.00	0.27±0.00	0.27±0.00	0.27±0.00	19.35±14.68
TH (mg L^{-1})	225.50±12.00^{c}	279.27±17.46^{a}	279.14±13.36^{a}	254.19±18.21^{b}	0.27±0.00
TA (mg L^{-1})	252.06±12.41^{c}	306.94±17.74^{a}	305.24±13.85^{a}	282.05±17.85^{b}	36.15±8.32
NO_2^{-} (mg L^{-1})	0.09x10^{-3}±0.00	0.09x10^{-3}±0.00	0.09x10^{-3}±0.00	0.09x10^{-3}±0.00	1.44±0.96
NO_3^{-} (mg L^{-1})	0.29±0.18	0.17±0.00	0.17±0.00	0.17±0.00	259.53±26.89
NH_4^{+} (mg L^{-1})	0.05x10^{-3}±0.00	0.05x10^{-3}±0.00	0.05x10^{-3}±0.00	0.07x10^{-3}±0.00	286.77±26.79
Cl^{-} (mg L^{-1})	2.50±0.78^{ab}	1.33±0.28^{c}	1.81±0.04^{b}	2.10±0.15^{a}	31.86±6.02
Na^{+} (mg L^{-1})	29.94±3.37^{b}	41.66±3.74^{a}	44.89±4.67^{a}	28.11±4.40^{b}	47.63±12.35
K^{+} (mg L^{-1})	1.10±0.27^{b}	1.01±1.00^{b}	2.68±0.48^{a}	0.95±0.64^{b}	0.09x10^{-3}±0.00
Ca^{+2} (mg L^{-1})	31.21±7.24^{c}	46.09±5.79^{b}	60.29±0.85^{a}	53.94±6.68^{ab}	0.20±0.10
Mg^{+2} (mg L^{-1})	23.84±1.52^{c}	31.00±0.65^{b}	37.69±1.76^{a}	34.90±5.56^{ab}	0.05x10^{-3}±0.00
Fe^{+2} (mg L^{-1})	2.00 x10^{-3}±0.00	2.00 x10^{-3}±0.00	2.00 x10^{-3}±0.00	3.51 x10^{-3}±0.00	2.38 x10^{-3}±0.00
Pb^{+2} (µg L^{-1})	0.17±0.05	0.54±0.38	0.46±0.32	0.13±0.05	0.32±0.30
Cu^{+2} (µg L^{-1})	3.00±0.00	3.33±0.71	4.56±2.46	3.00±0.00	3.47±1.38
Cd^{+2} (µg L^{-1})	0.05±0.00	0.09±0.07	0.05±0.00	0.13±0.08	0.08±0.06
Hg^{+2} (µg L^{-1})	0.01±0.00^{c}	0.01±0.00^{bc}	0.02±0.00^{a}	0.01±0.00^{ab}	0.01±0.00
Ni^{+2} (µg L^{-1})	2.00±0.00	1.33±1.00	2.00±0.00	2.00±0.00	1.83±0.56
Zn^{+2} (µg L^{-1})	3.00±0.00	2.56±0.73	5.89±3.72	3.56±0.88	3.75±2.27

Low pH values lead to the release of toxic metals that are harmful to aquatic life, while high pH values can negatively impact aquatic ecosystems by reducing the availability of DO, which is essential for organisms (Dewangan et al., 2023). In this study, pH values were measured to be 8.23 in January and 8.75 in October, with an annual average of 8.46±0.16. Post-hoc analysis indicated that the pH parameter formed similar groups for summer and autumn, whereas winter and spring formed two distinct groups. The pond water exhibited a slightly alkaline nature and varied within the range of 6-9 specified by SWQR (2016) throughout the year, classifying it as "very good" quality water. A highly significant positive correlation was observed between pH and salinity, temperature, TSS, COD, SO_4^{-2}, Mg^{+2}, and Ca^{+2} ($r>0.80$; $p<0.01$). Water temperature plays an important role in environmental dynamics and provides insights into the physical, chemical, and biochemical characteristics of the water source. Throughout the year, water temperature ranged between 5.97°C and 18.37±0.10°C (February-September), with an annual average of 12.28±4.13°C. Based on temperature measurements, three distinct groups were identified; while summer and autumn formed the first group, spring and winter constituted two separate groups. A very strong positive correlation was found between temperature and salinity, pH, SO_4^{-2}, Mg^{+2}, and Ca^{+2} ($r>0.80$; $p<0.01$). EC significantly influences agricultural productivity, as high EC levels can limit plant access to water by causing soil moisture retention (Bauder et al., 2011). In the present study, EC values were lowest in May (253.80 µS) and highest in October (379.80 µS), with an annual average of 326.04±37.04

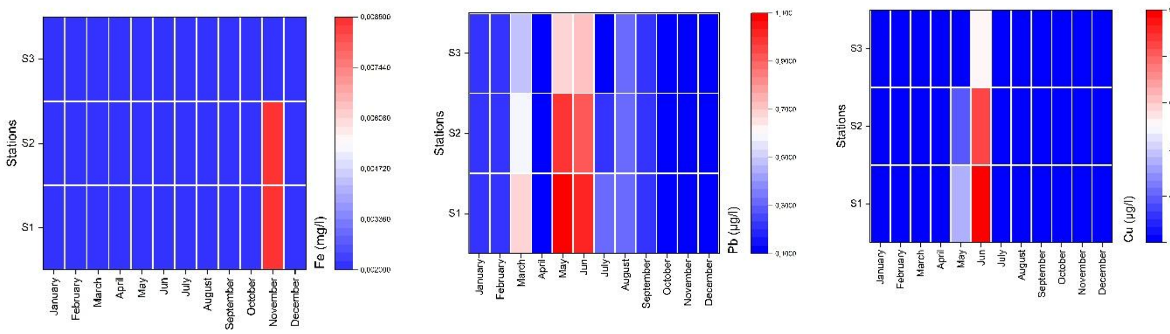
μS. Seasonal analysis showed that autumn formed the first group, winter and summer the second, and spring the third. Low EC levels may be attributed to periodic low precipitation in the region, the geological structure of the area, or surface water runoff that does not significantly affect stream salinity (Kalıpcı et al., 2017). As an indicator of salinity in water, EC can increase upon contact with pollutants (Şener et al., 2017). Moreover, as a result of increased salinity, evaporation leads to further increases in EC (Jiang et al., 2012; Zhang et al., 2016). The EC values measured in this study remained below the 400 μS threshold for Class I water quality as defined by SWQR (2016), classifying it as "very good" quality water. The EC parameter exhibited a very strong negative correlation with DO and a very strong positive correlation with COD and BOD ($r > 0.80$; $p < 0.01$). The concentration of TSS in water sources varies depending on precipitation, surface runoff, and flow velocity (Taşdemir & Göksu, 2001). The annual average SS value was measured to be 0.42±0.55 mg/L, with the highest value recorded in October (1.56 mg/L). Seasonal analysis indicated two distinct groups: winter and spring in one group, and summer and autumn in another. A strong positive correlation was identified between SS and pH, COD, BOD, and SO_4^{-2} ($r>0.80$; $p<0.01$).

COD and BOD are critical parameters used to assess the organic pollution load in water bodies (Galal-Gorchev et al., 1993). The average COD value was 0.61±0.53 mg/L, with the highest recorded value of 1.51 mg/L in October. The observed increase in COD during autumn is likely attributable to chemical pollutants from agricultural lands (Imneisi & Aydın, 2016; Kutlu & Mutlu, 2024). Seasonal variation analysis of COD revealed that summer formed the first group, autumn the second, and winter and spring together formed the third group. The pond water was classified as Class I "very good" quality water, as COD levels remained below the 25 mg/L threshold specified by SWQR (2016). COD exhibited a strong negative correlation with DO and a very strong positive correlation with pH, EC, SS, BOD, and SO_4^{-2} ($r > 0.80$; $p < 0.01$). The average BOD value was 0.25±0.29 mg/L, with the highest value recorded in October (0.88 mg/L). Seasonal variation analysis of BOD indicated that spring, summer, and autumn each formed separate groups, whereas winter was similar to spring and summer. Similar to COD, BOD values remained below the 4 mg/L threshold defined by SWQR (2016), classifying the water as "very good" quality. A strong negative correlation was found between BOD and DO, whereas a very strong positive correlation was observed between BOD and EC, SS, and COD ($r>0.80$; $p<0.01$).

There was a very strong relationship between TSS and COD ($r>0.80$; $p<0.01$). In the present study, the highest concentrations of TH and TA were recorded in June, with values of 297.30 mg/L and 324.42 mg/L, respectively. The annual average TH was measured at 259.53±26.89 mg/L, while the annual average TA was 286.77±26.79 mg/L. A highly significant positive correlation was observed between TH and TA ($r=0.99$; $p<0.01$). According to WHO (2011) standards, TH was below the upper limit, whereas TA exceeded the upper threshold of 200 mg/L. The buffering capacity of water, the presence of inorganic substances, and the availability of CO_2 utilized by aquatic plants for photosynthesis are directly related to the alkalinity level in water (Boyd et al., 2016). Additionally, alkalinity is a very important parameter for aquaculture, as well as for assessing the scaling potential of domestic and industrial water use facilities (Han et al., 2014). Continuous agricultural use of high-alkalinity water can negatively impact soil microbial activity and structure by increasing soil pH, EC, and total inorganic carbon content (Singh et al., 2022). Furthermore, elevated alkalinity can lead to the precipitation of Ca^{+2} and Mg^{+2} ions into insoluble minerals, causing Na^+ to become dominant, which may contribute to sodium hazard (Bauder et al., 2011). Therefore, continuous monitoring of high-alkalinity water is very important.

Although Cl^- is widely present in many water sources, plants require only minimal amounts, and excessive Cl^- concentrations can lead to toxicity (Bauder et al., 2011). The average Cl^- content of the reservoir was determined to be 1.94±0.59 mg/L, with the lowest value of 0.98 mg/L recorded in March and the highest value of 3.48 mg/L in December. Seasonal variation analysis of Cl^- levels indicated that spring, summer, and autumn formed distinct groups, whereas winter was found to be similar to summer and autumn. A strong negative correlation was observed between Cl^- and DO as well as sodium, whereas there was a strong positive correlation with EC and BOD ($r>0.60$; $p<0.01$). Excessive phosphate levels can lead to plankton blooms and excessive growth and proliferation of aquatic plants, thereby deteriorating water quality (Atay & Bulut, 2005). In the present study, the mean phosphate concentration was found to be 0.08±0.15 mg/L, with the highest value of 0.92 mg/L recorded in January. Fertilization of agricultural lands contributes to elevated phosphate levels around the lake, and excessive fertilization can lead to eutrophication. Agricultural practices, particularly in rural areas, are among the primary sources of phosphate in surface waters, and phosphate can also enter water bodies through wastewater treatment plants and sewage systems (Wetzel, 2001; Bulut et al., 2010; Manahan, 2010). According to SWQR (2016), the reservoir water was classified as "good" quality. A strong negative correlation was detected between phosphate and K^+ as well as Mg^{+2} ($r>0.60$; $p<0.01$). The SO_4^{-2} parameter exhibited an average concentration of 19.35±14.68 mg/L, with the highest value of 43.01 mg/L recorded in September. SO_4^{-2} levels remained within the standard limits specified by WHO (2011). Seasonal variation analysis indicated that summer and autumn formed one group, while winter and spring formed another. A very strong correlation was found between SO_4^{-2} and salinity, pH, temperature, TSS, COD, and Ca^{+2} ($r>0.80$; $p<0.01$). The sulfite parameter was determined to have an average concentration of 0.27±0.00 mg/L. Sodium concentrations ranged from a minimum of 23.23 mg/L in January to a maximum of 50.09 mg/L in December. The annual average sodium concentration was determined to be 36.15±8.32 mg/L, remaining below the WHO (2011) standard limits. Seasonal variation analysis of sodium indicated that spring and summer formed the first group, whereas autumn and winter formed the second. A very strong positive correlation was found between sodium and Ca^{+2} (r>0.80; p<0.01). When irrigation water contains higher levels of sodium compared to Ca^{+2} and Mg^{+2}, soil infiltration rates may decrease, leading to increased surface runoff (Bauder et al., 2011). The annual average K^{+} concentration was determined to be 1.44±0.96 mg/L, with the lowest values of 0.35 mg/L recorded in April, May, and November, and the highest value of 3.17 mg/L observed in June. Seasonal variation analysis indicated that summer formed a distinct group, while spring, autumn, and winter formed another. Ca^{+2} and Mg^{+2} cations in water contribute to increased soil permeability, making them crucial parameters in determining the suitability of water for irrigation (Mutlu & Uncumusaoğlu, 2024). The highest Ca^{+2} and Mg^{+2} concentrations were recorded in September, at 61.76 mg/L and 41.99 mg/L, respectively, while the lowest values were measured in January (21.85 mg/L) and February (26.16 mg/L). These values remained within the acceptable limit values (WHO, 2011). The average concentrations of Mg^{+2} and Ca^{+2} were determined to be 31.86±6.02 mg/L and 47.63±12.35 mg/L, respectively. Both Mg^{+2} and Ca^{+2} exhibited very strong positive correlations with salinity, pH, temperature, and each other (r>0.80; p<0.01). Nitrates represent the highest oxidation form of nitrogen compounds and are commonly found in surface water. Additionally, atmospheric nitrogen is transported into streams, lakes, rivers, and coastal waters through rainfall, contributing to increased nitrate levels (Schiffman, 1995; Oketola et al., 2013). Although nitrate concentrations in groundwater and surface water are generally low, excessive fertilization in agricultural areas can lead to nitrate contamination of groundwater, resulting in increased concentrations (WHO, 1985; Korkmaz et al., 2016). In the present study, nitrate and nitrite concentrations remained at low levels. The maximum nitrate concentration recorded was 0.53 mg/L, with an average value of 0.20±0.10 mg/L. Based on these findings, the reservoir water was classified as “very good” quality according to SWQR (2016).

Iron (Fe), one of the heavy metals, is among the most abundant metals (Bernát, 1983). In this study, iron concentrations ranged between 0.0020 and 0.0088 mg/L, with an average of 0.0024±0.0016 mg/L. While iron concentrations above 0.3 mg/L can cause staining, concentrations below this threshold generally do not impart a distinct taste (Oketola et al., 2013). Since the values obtained in this study were below the limits specified for iron in SWQR (2016), the pond water quality was classified as “very good” in terms of iron. Lead (Pb) is a soft, malleable, and relatively inert metal known and used by humans since ancient times (Lovering, 1976). The annual average concentration of lead, a highly toxic metal, was found to be 0.32±0.30 µg/L, with the highest recorded value of 1.10 µg/L in May. According to SWQR (2016), the measured values were below the upper limit, and the pond water was deemed suitable, classifying it as “very good” in terms of lead quality. Copper (Cu) concentrations varied between 3.00 and 9.00 µg/L, with an average of 3.47±1.38 µg/L. These values exceeded the upper limit specified in SWQR (2016), rendering the pond water unsuitable in terms of copper contamination. The observed pollution is believed to be caused by surface runoff originating from wood production and agricultural lands due to heavy seasonal rainfall (Tokatlı et al., 2024). Cd^{+2} is released into the environment through wastewater discharge, contributing to air pollution and contamination from landfill leachate (WHO, 2003). Cd^{+2} concentrations ranged from 0.05 to 0.21 µg/L, with an average of 0.08±0.06 µg/L. Based on SWQR (2016), the pond water was classified as “very good” in terms of Cd^{+2} quality. Mercury (Hg) is another critical metal requiring close attention, as excessive accumulation in the body can cause neurological damage (Arshad & Shakoor, 2017). In this study, mercury concentrations varied between 0.008 and 0.020 µg/L, with an average concentration of 0.012±0.003 µg/L. The pond water complied with the standards specified in SWQR (2016). Nickel (Ni) is introduced into rivers and streams through the discharge of mining waste. Contaminated water, whether ingested or inhaled as airborne particles, is known to impact humans, animals, and birds. Reported health effects include respiratory disorders, birth defects, and vomiting. A study indicated that the scarcity of aquatic organisms in a river suggests long-term ecological impacts of zinc and nickel contamination. Additionally, elevated zinc and nickel levels in animals and birds that drink from streams were reported (Ntengwe & Maseka, 2006). The highest recorded values for nickel and zinc were 2.00 µg/L and 12.00 µg/L, respectively. The mean concentrations were determined to be 1.83±0.56 µg/L for nickel and 3.75±2.27 µg/L for zinc. These values were found to be within the standards set by SWQR (2016). Pilot diagrams illustrating the station-based and monthly variations in heavy metal concentrations are presented in Figure 2.



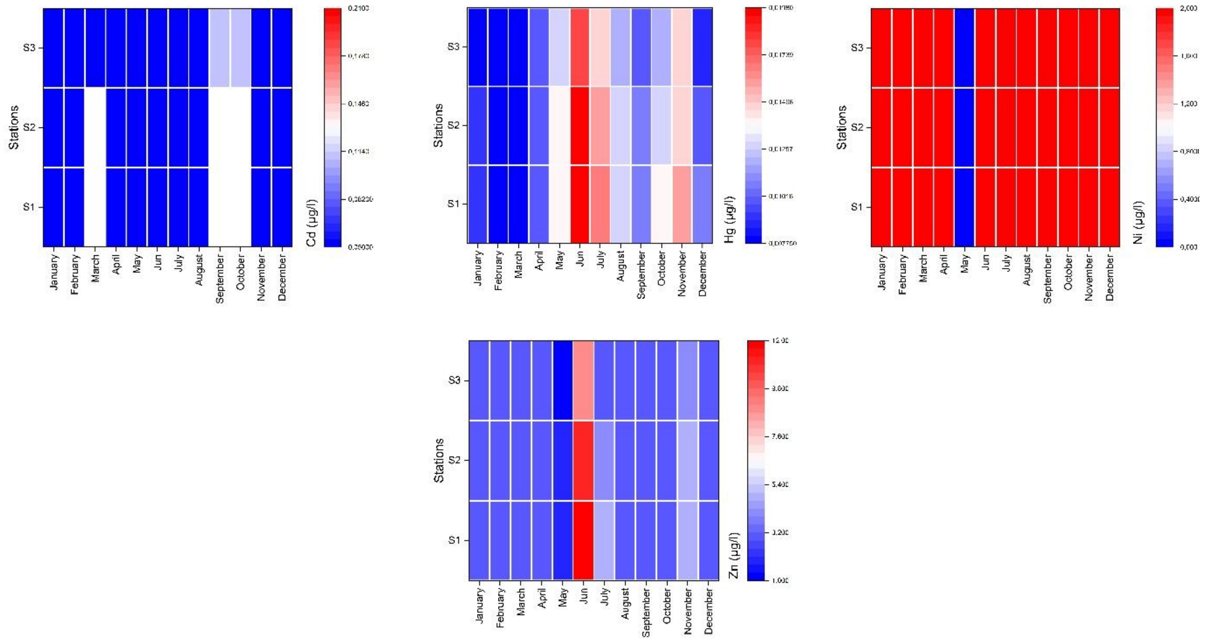


Figure 2. Diagrams of Heavy Metals in Seben Taşlıyayla (Bolu) Reservoir

3.1. Irrigation Water Quality

The SAR is used to explain infiltration rate issues under conditions where the sodium concentration exceeds the Ca^{+2} and Mg^{+2} concentrations (Anonymous, 2025). The SAR is based on the effect of sodium on the physical properties of soil (Korkmaz et al., 2016). The SAR values and diagrams for the reservoir are presented in Table 2 and Figure 3. Seasonally, the highest SAR value was recorded in spring at 1.17 meq L^{-1}, while the highest monthly measurement was in May at 1.26 meq L^{-1}. Station-wise, the highest SAR value was observed at Station 1 with 1.00 meq L^{-1}. In the present study, SAR values (<10) classified the water as first-class irrigation water, falling into the "Excellent" category. External factors, such as increased concentration due to plant water uptake, dilution through irrigation, or leaching with drainage water, resulted in minimal sodium solubility or precipitation (Korkmaz et al., 2016). In this study, the highest seasonal Sodium Percentage (Na%) was observed in spring (27.69%), while the highest monthly value was recorded in February (30.81%). Across stations, the measurement values were very close to each other, with the highest value recorded at Station 2 (24.36%). The Na% measurements ranged between 20 and 40%, categorizing the water quality as "Good." When the RSC value exceeds 2.5, irrigation water becomes unsuitable due to the adverse effects of permanent sodium carbonate accumulation in the soil (Eaton, 1950; Anonymous, 2025). High-RSC groundwater deteriorates soil structure, hindering crop growth (Korkmaz et al., 2016). Since RSC values were negative, no adverse effects were detected. The Magnesium Hazard (MH) parameter was highest in winter (55.74), with the highest monthly value recorded in February (31.38) and the highest station-wise value at Station 3 (52.75). The KR was highest in spring (0.38) seasonally and in February (0.44) monthly.

Table 2. Seasonal Irrigation Indices Values

Parameters	SAR	Na%	MH	KR	RSC
Winter	0.98	27.44	55.74	0.37	-3.38
Spring	1.17	27.69	53.13	0.38	-4.63
Summer	1.12	24.85	50.77	0.32	-5.94
Autumn	0.73	18.31	51.62	0.22	-5.41

Considering seasonal, monthly, and station-wise values, the reservoir was classified as "Excellent" in terms of SAR (0-10), "Good" in terms of Na% (20-40), "Unsuitable" in terms of MH (>50), "Suitable" in terms of KR (<1), and "Safe/Good" in terms of RSC (<1.25) Eaton, 1950; Richards, 1954; Wilcox, 1955; Kelley, 1963; Paliwal, 1972). The results were illustrated using radar diagrams (Figure 3).

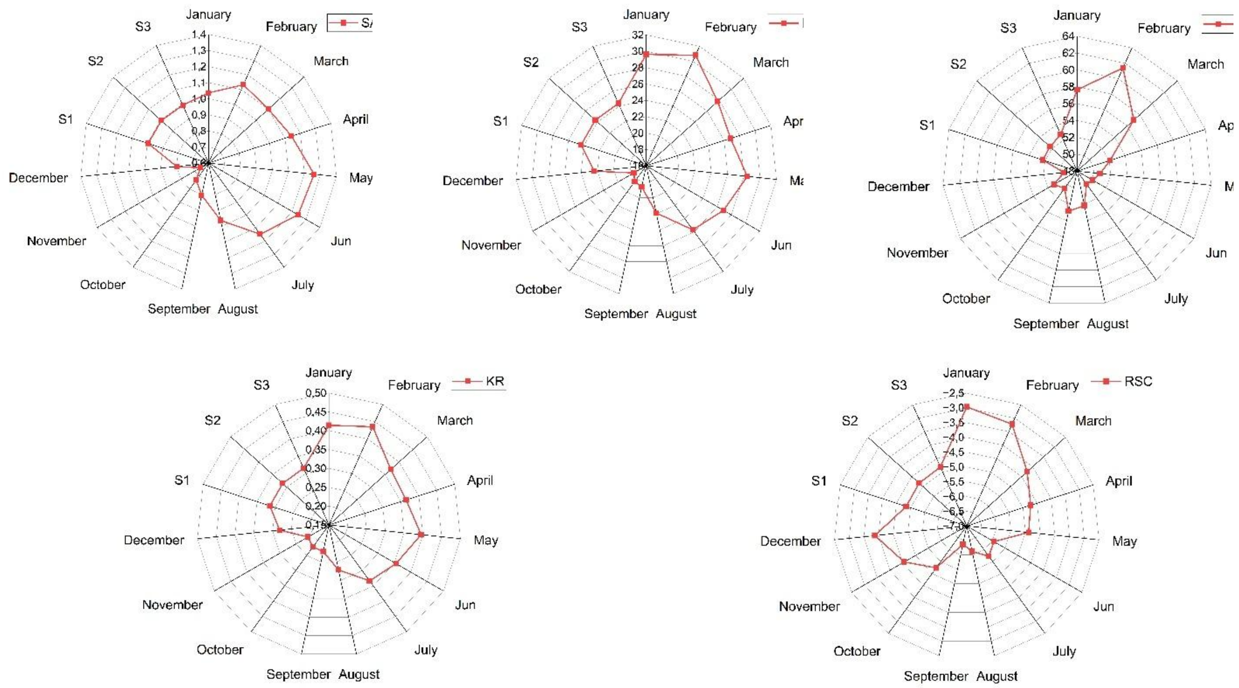


Figure 3. Radar diagrams for irrigation indices

A factor analysis was conducted for 28 parameters examined in this study assessing the water quality of the reservoir. As a result of the exploratory factor analysis (EFA), 21 parameters were grouped into five factors, explaining 92.824% of the total variance. The scree plot used to determine the appropriate number of factors identified five factors with eigenvalues higher than 1 (Figure 4). The factor values are provided in Table 3. The first factor accounted for 37.862% of the total variance, the second factor 21.804%, the third factor 14.624%, the fourth factor 10.565%, and the fifth factor 7.969%. The eigenvalues, scree plot of these factors are presented in Figure 4.

Table 3. Variance table for factor analysis

Components	Initial Eigenvalues			Total Explained Variance of Squa Loadings			Total Variance of Rotated Square Loadings		
	Total	% Varianc	% Cumulativ	Total	% Varianc	% Cumulativ	Total	% Varianc	% Cumulativ
1	8.896	42.362	42.362	8.896	42.362	42.362	7.951	37.862	37.862
2	5.582	26.581	68.943	5.582	26.581	68.943	4.579	21.804	59.665
3	2.385	11.358	80.301	2.385	11.358	80.301	3.071	14.624	74.290
4	1.460	6.952	87.253	1.460	6.952	87.253	2.219	10.565	84.855
5	1.170	5.571	92.824	1.170	5.571	92.824	1.674	7.969	92.824

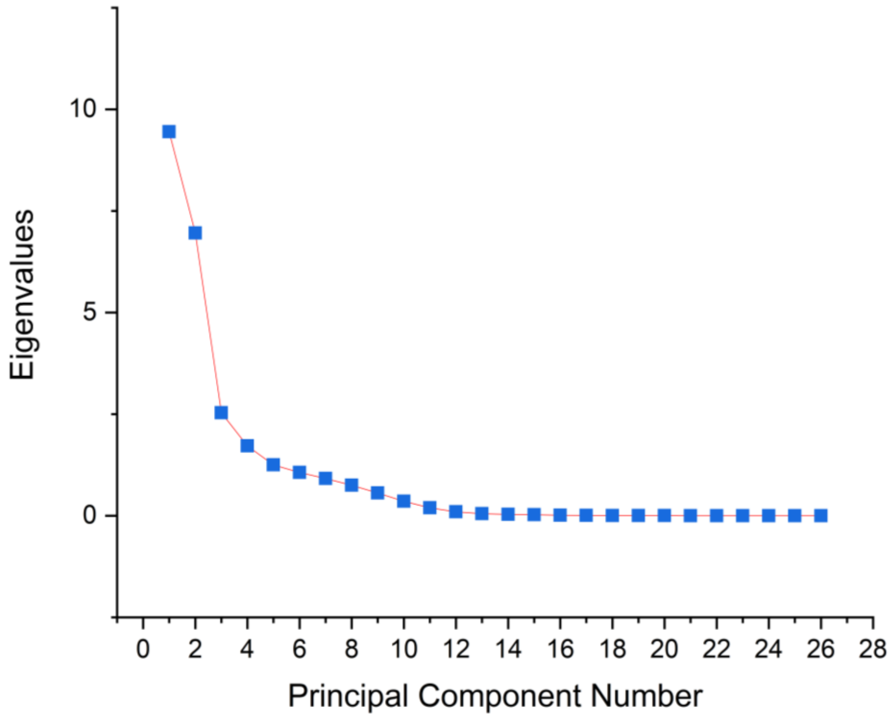


Figure 4. Scree plot of factor eigenvalues

Examining the identified factors, SO_4^{-2}, temperature, salinity, COD, pH, Ca^{+2}, TSS, and Mg^{+2} were found to have strong effects (>0.75) in the first factor, while BOD and EC had moderate positive effects (0.75-0.50) (Table 4) (Liu et al., 2003). The second factor was strongly negatively influenced by Cl^- (>0.75) and strongly influenced by total hardness, total alkalinity, and sodium. The third factor included zinc, copper, and mercury as strongly influential metals. The fourth factor comprised ammonium and Cd^{+2} with strong effects (>0.75). The fifth factor included nickel as strongly influential (>0.75) and K^+ as moderately positive (0.75-0.50) (Liu et al., 2003).

Table 4. Factor-Component values for reservoir

Parameters	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
SO_4^{-2}	0.98				
Temp.	0.93				
Salinity	0.90				
COD	0.90				
pH	0.89				
Ca^{+2}	0.85				
TSS	0.85				
Mg^{+2}	0.80				
BOD	0.73				
EC	0.70				
Cl^-		-0.87			
TH		0.87			
TA		0.87			
Na^+		0.84			
Zn^{+2}			0.92		
Cu^{+2}			0.91		
Hg^{+2}			0.79		
NH_4^+				0.87	
Cd^{+2}				0.76	

Ni^{+2}					0.85
K^{+}					0.70
Eigenvalue	7.951	4.579	3.071	2.219	1.674
Explained Variance	37.862	21.804	14.624	10.565	7.969
Explained Total Variance	92.824				

To determine seasonal similarities over a one-year sampling period, cluster analysis was performed using annual average values. The analysis identified two main clusters, with winter and autumn forming one cluster and spring and summer forming another (Figure 5).

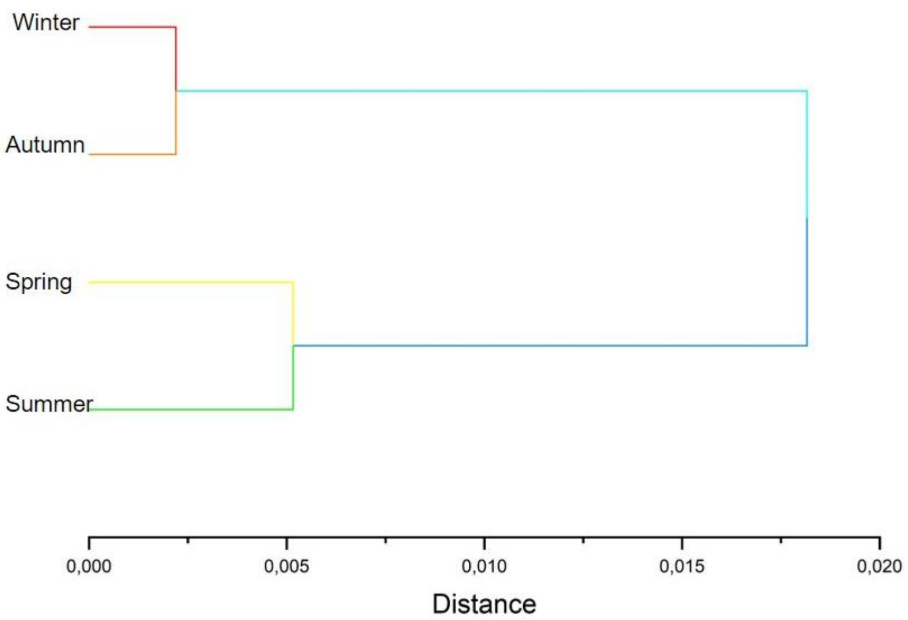


Figure 5. Dendrograms for seasonal clustering

Cluster analysis was also conducted to identify similarity groups among the measured parameters in the Seben Taşlıyayla Reservoir. Based on all examined variables, two main clusters were identified. The first cluster included all heavy metals except Cd^{+2}, along with DO, sodium, total hardness, alkalinity, phosphate, K^{+}, nickel, and nitrate. The second cluster comprised salinity, temperature, Ca^{+2}, Mg^{+2}, EC, TSS, BOD, COD, SO_4^{-2}, NH_4^{+}-N, and Cd^{+2}. These groups also contained further sub-clusters within them (Figure 6).

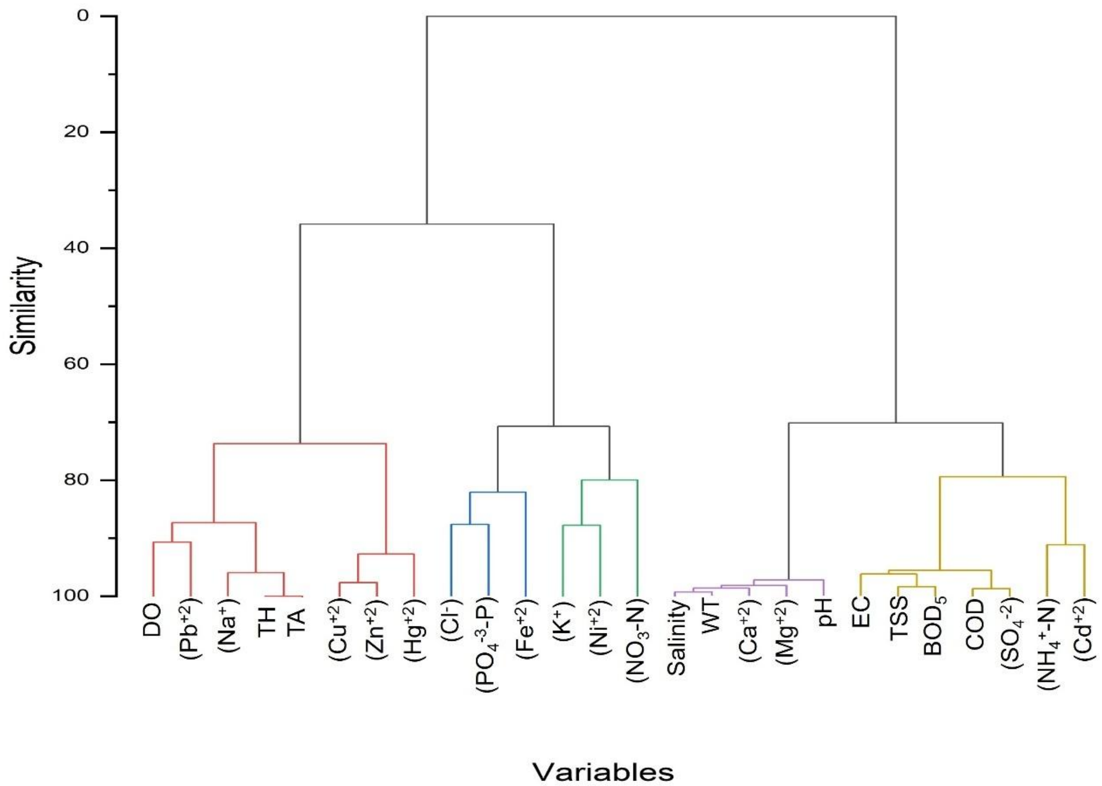


Figure 6. Cluster analysis of measured parameters

Based on the findings obtained in this study, the weighted arithmetic Water Quality Index (WQI) developed by Brown et al. (1972) was calculated. The annual mean WQI of the reservoir was determined to be 13.709. When analyzed according to seasonal variations, the lowest WQI value was observed in winter at 11.903, while the highest was recorded in summer at 19.995. When examined by station, the WQI values were found to be 16.173, 15.741, and 14.809 for the first, second, and third stations, respectively. Although the overall classification of the reservoir water fell within the “excellent” category, a monthly assessment revealed that in June, the WQI values for the first and second stations were 25.877 and 25.362, respectively. Since these values exceeded the upper limit of the first category, the water quality for this period was classified as “good.” An increase in mercury levels was observed during these months, which was reflected in the WQI. Activities that may contribute to elevated mercury concentrations in the reservoir should be closely monitored. The WQI values calculated for each month and station, along with the resulting heatmap, are presented in Figure 7.

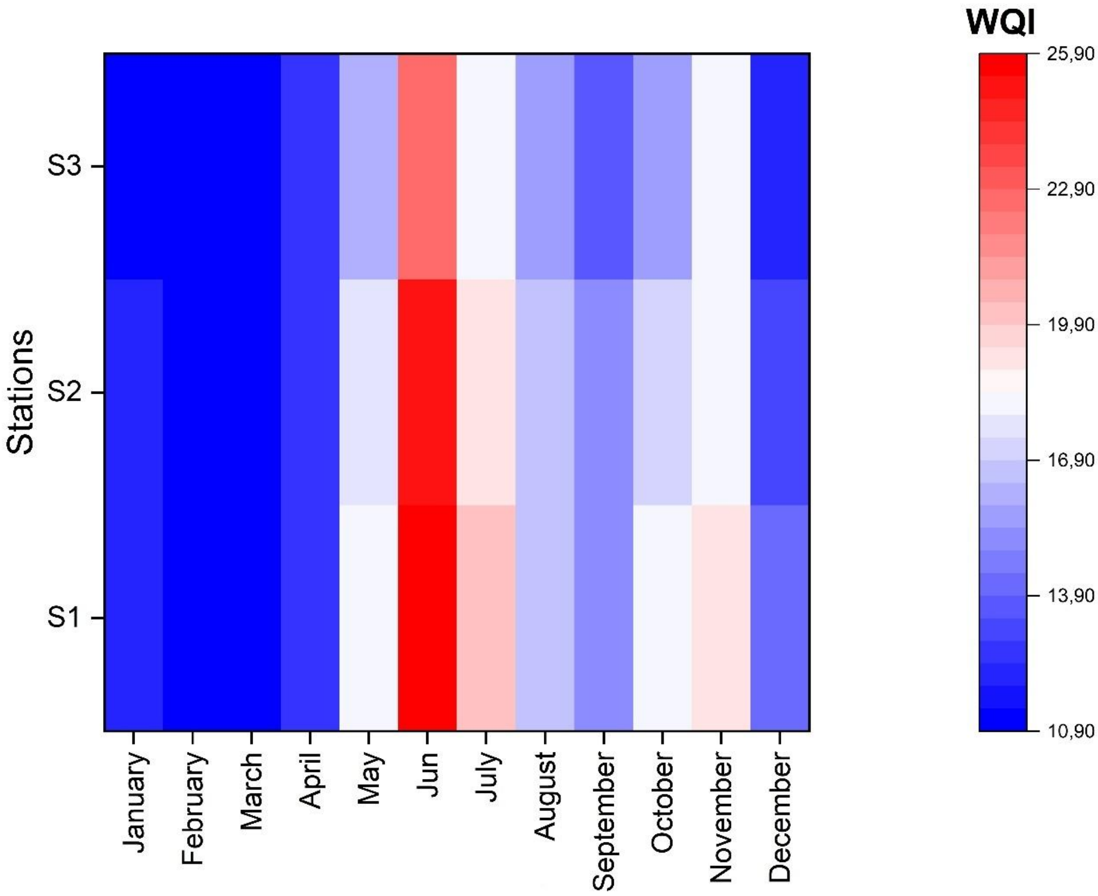


Figure 7. WQI values for reservoir

4. Conclusion

This study aims to investigate the concentrations of certain essential and toxic elements in the water of the Seben (Taşlıyayla) Reservoir in Bolu and to assess its suitability for drinking water and agricultural irrigation. HCA, FA/PCA, and the WAWQI were applied to the dataset. Additionally, to determine the suitability of the water for agricultural irrigation, the SAR, Na%, MH, KR, and RSC parameters were calculated.

Cluster analysis classified the seasonal variable into two clusters and grouped the 28 physicochemical and heavy metal variables into three main clusters: those with a very strong impact on water quality, those with a strong impact, and those with a moderate impact. Across all stations and months, copper concentrations and TA were found to exceed the limits specified by SWQR (2016) and WHO (2011).

Regarding the suitability of the reservoir water for agricultural irrigation, SAR (0-10) was classified as “Excellent,” Na% (20-40) as “Good,” MH (>50) as “Unsuitable,” KR (<1) as “Suitable,” and RSC (<1.25) as “Safe/Good.” If the reservoir water is used for agricultural irrigation, the potential adverse effects of Mg^{+2} should be closely monitored.

When considering the WQI results, the reservoir water was considered suitable for drinking, agricultural, and industrial use. However, attention should be paid to the increase in mercury levels in June at the first and second stations and to the consistently high copper concentrations, which exceeded the standards set by SWQR (2016) throughout the year.

The monitoring of the parameters included in the first and second factor components in the factor analysis is considered very important for ensuring the sustainability of the reservoir’s water quality.

5. Acknowledgement

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6. Compliance with Ethical Standard

a) Author Contributions

The published version of the manuscript has been read and approved by both authors.
1. E.M.: Study design, data collection, analysis and review, preparation of the original draft, and manuscript submission.
2. E.S.Ö.: Statistical analyses, data interpretation, preparation of the original draft, and manuscript submission.

b) Conflict of Interests

There is no conflict of interest, according to the authors.

c) Statement on the Welfare of Animals

Not relevant,

d) Statement of Human Rights

There are no human subjects in this study.

e) Declaration of Not Using AI

During the preparation of this manuscript, the authors used AI-based tools for grammar correction and to improve the fluency of the text. The study design, data interpretation, and critical analyses were developed and finalized solely by the authors, without the use of AI tools at this stage.

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