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RESEARCH ARTICLE ARAŞTIRMA MAKALESİ

# Index-based evaluation of organic and heavy metal pollution in surface waters of Lake Mogan (Ankara, Türkiye)

## Mogan Gölü (Ankara, Türkiye) yüzey sularında organik ve ağır metal kirliliğinin indeks temelli değerlendirilmesi

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**Abstract:** This study aimed to estimate organic pollutants and heavy metals in the surface waters of three stations in Lake Mogan, during dry and rainy periods, using a set of indices. Lake surface waters; (a) Based on Organic Pollution Index (OPI) values (0.78–1.89), are classified as "Beginning to be polluted" and exhibit a eutrophic nutrient level (Eutrophication Index (EI): 1.09–14.55), (b) The average heavy metal concentrations across all stations during the dry period followed the order Fe > As > Ni > Pb > Cr > Cd > Cu, while during the rainy period they were Fe > As > Ni > Cr > Zn > Cu, (c) As (max.: 67 µg/L) and Fe (max.: 612.04 µg/L) concentrations exceeded the Environmental Quality Standard (EQS) values at all three stations in both periods, whereas Cd (> 0.72 µg/L) and Pb (> 2.5 µg/L) exceeded the limits recommended for aquatic life during the dry period, (d) Heavy Metal Pollution Index (HPI) indicated "Moderate – High pollution" at all stations during the dry period, while during the rainy period, HPI and Heavy Metal Evaluation Index (HEI) levels at all stations were classified as "Low pollution." According to the Potential Ecological Risk (PER) values, all stations were identified as "low risk" in terms of EQS during the rainy period, and also as "low risk" for aquatic life at all stations during dry and rainy periods, (e) While the potential source of organic pollution was determined to be residential areas, the sources of Fe, As, and Ni - identified as the primary metals threatening lake health - were found to be a combination of discharges originating from andesite stone processing facilities, residential areas, and agricultural activities. The results indicate the necessity of including eutrophication management in the basin's strategic plan and implementing long-term measures particularly targeting mining activities.

**Keywords:** Pollution, organic pollution indices, heavy metal indices, surface waters, Lake Mogan

**Öz:** Çalışmada, Mogan Gölü'nde üç istasyon yüzey sularında kuru - yaş dönemde olmak üzere, organik kirleticilerin ve ağır metallerin bir takım indeksler kullanarak tahmini amaçlanmıştır. Göl yüzey suları; (a) Organik Kirlenme İndeksi (OPI: Organic Pollution Index) değerlerine göre (0.78-1.89) "Kirlenmenin başladığı" ve ötrofik (Ötrofikasyon İndeksi (EI: Eutrophication Index) : 1.09 - 14.55) besin seviyesine sahiptir, (b) Tüm istasyonlara ilişkin ortalama ağır metal konsantrasyonları kuru periyot için Fe > As > Ni > Pb > Cr > Cd > Cu iken, yağışlı periyot için Fe > As > Ni > Cr > Zn > Cu şeklindedir, (c) As (maksimum: 67 µg/L) ve Fe konsantrasyonları (maksimum: 612.04 µg/L), her iki dönemde ve üç istasyonda Çevresel Kalite Standart (EQS: Environmental Quality Standards) değerlerini, Cd (> 0.72 µg/L) ve Pb (> 2.5 µg/L) ise kuru periyotta sucul yaşam için önerilen sınır değerleri aşmıştır, (d) Ağır Metal Kirlenme İndeksi (HPI: Heavy Metal Pollution Index) tüm istasyonlarda kuru periyot için "Orta – Yüksek kirlenme", yağışlı periyotta HPI ve Ağır Metal Değerlendirme İndeksi (HEI: Heavy Metal Evaluation Index) tüm istasyonlarda "düşük kirlenme" seviyesindedir. Potansiyel Ekolojik Risk (PER: Potential Ecological Risk) değerlerine göre ise EQS açısından yağışlı periyotta tüm istasyonlarda, - sucul yaşam - açısından da kuru ve yağışlı periyotta tüm istasyonlarda "düşük risk" düzeyindedir, e) Organik kirliliğin olası kaynağı yerleşim yerleri iken, göl sağlığını tehdit eden birincil metaller olarak belirlenen Fe, As ve Ni'in kaynakları andezit taşı işleme tesisleri, yerleşim yerleri ile tarımsal faaliyet kaynaklı deşarjların kombinasyonu olarak belirlenmiştir. Sonuçlar, havzanın stratejik planına ötrofikasyon yönetiminin dahil edilmesinin ve özellikle madencilik faaliyetlerini hedef alan uzun vadeli önlemlerin uygulanmasının gerekliliğini göstermektedir.

**Anahtar kelimeler:** Kirlenme, organik kirlenme indeksleri, ağır metal indeksleri, yüzey suları, Mogan Gölü

### INTRODUCTION

Eutrophication of lakes is a significant water quality issue that poses important environmental, economic, and social threats. The emergence of different dimensions of eutrophication in lakes is driven by increases in watershed-based nutrient inputs (Anny et al., 2017; Bahroun et al., 2022; Tokatlı et al., 2025; Özşeker et al., 2026), organic matter loads (Mishra et al., 2016; Al-Fanharawi and Al-Khafaji, 2023) and recreational activities. In this context, the use of specific indices serves as a tool not only for monitoring and assessing water quality status but also for preventing and mitigating the pollution process (Zeng et al., 2022).

The Organic Pollution Index (OPI) is a comprehensive index that includes a greater number of water quality components than standard values and integrates various pollutants with similar characteristics. The Eutrophication Index (EI), on the other hand, is used to facilitate and standardize the consistent comparison of water quality under different trophic conditions. In this context, both indices are employed as reference tools in monitoring programs, not only to assess the trophic status of surface water bodies but also to inform decision-makers about the condition of the water body.

Heavy metal contamination is known to be associated with anthropogenic sources such as mining, industrial and agricultural activities, as well as traffic emissions (Pulatsü and Topçu, 2015). Heavy metal pollution in surface waters can adversely affect not only drinking water and domestic–

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agricultural uses but also aquatic life and fisheries (Mollo et al., 2022; Varol and Tokatlı, 2023). The most commonly used indices for determining heavy metal contamination in aquatic ecosystems include the Heavy Metal Pollution Index (HPI; Rahman et al., 2014), which represents the overall effect of different metals, and the Heavy Metal Evaluation Index (HEI; Edet and Offiong, 2002), defined as a rating reflecting the combined impact of various heavy metals. The Potential Ecological Risk (PER) assessment has been proposed as a tool for identifying and managing water pollution problems associated with increasing heavy metal levels in surface waters (Rahman et al., 2014).

In surface waters, the Environmental Quality Standard (EQS) refers to the maximum concentration of pollutants that must not be exceeded in order for a water body (e.g., rivers, lakes, coastal waters) to remain healthy or to be suitable for its designated use (such as drinking water supply, recreation, or fisheries). In Türkiye, legal limits are evaluated within the framework of the 'Surface Water Quality Regulation' (TSWQR, 2023), which is aligned with the European Union Water Framework Directive. Lake Mogan, located within the boundaries of the 'Gölbaşı Special Environmental Protection Area' in Türkiye, is a wetland ecosystem of international importance (Anonymous, 2026). Although recent studies have addressed the role of point and non-point source pollutants in the basin (Pulatsü and Latifi, 2023; Pulatsü, 2024), the lake's water quality and eutrophication status (Özdemir et al., 2024; Coşkun and Demir, 2025), as well as its sediment quality (Binici and Pulatsü, 2022; Topçu and Atlığ, 2023), no study has been found regarding the use of indices for water quality assessment.

This study focuses on three stations selected based on potential pollution sources in the lake, during two periods dry and wet, with the following objectives: (a) to determine the organic pollution and eutrophication status of the lake through index calculations; (b) to identify spatial and temporal variations in heavy metals (Cr, Ni, Cu, Zn, As, Cd, Hg, Pb, Fe) across stations and periods; (c) to evaluate lake water quality in terms of heavy metal concentrations with respect to Environmental Quality Standards (EQS) and aquatic life within the framework of national and international regulations; (d) to estimate the level of heavy metal pollution in the lake using indices such as the Heavy Metal Pollution Index (HPI), Heavy Metal Evaluation Index (HEI), and Potential Ecological Risk (PER) assessment; and (e) to statistically assess the potential sources of organic pollutants and heavy metals in the lake water.

## MATERIALS AND METHODS

### Study area

Lake Mogan, the study site, is an alluvial dam lake located in the Lower Ankara River Basin, along the Ankara-Konya road, 20 km south of Ankara. The lake is primarily fed by precipitation and more than five small and medium-sized streams. Its surface area is approximately 5.6 km². Approximately 2 km from the southern end of the lake, Lake Mogan drains into Lake Eymir to the northeast through a transitional wetland–marsh zone, with an average elevation difference of 5 meters between the two lakes. Within the basin, there are two natural lakes, Mogan and Eymir, and two artificial lakes, İkizce (Topaklı) and Dikilitaş, constructed by the General Directorate of Rural Services for irrigation purposes. Lake Mogan is recognized as one of the 184 important bird areas in Türkiye (Anonymous, 2026).

### Selection of study stations

In this study, surface water samples were collected from stations selected to represent the pollution sources of Lake Mogan, based on previous studies. The characteristics of the selected stations are as follows:

**Station I:** A station receiving high inflow of wastewater from stone quarries.
**Station II:** The station closest to areas with dense residential settlements.
**Station III:** A station selected in a region with intensive agricultural activity.

The study area and the locations of the selected stations are shown in Figure 1.

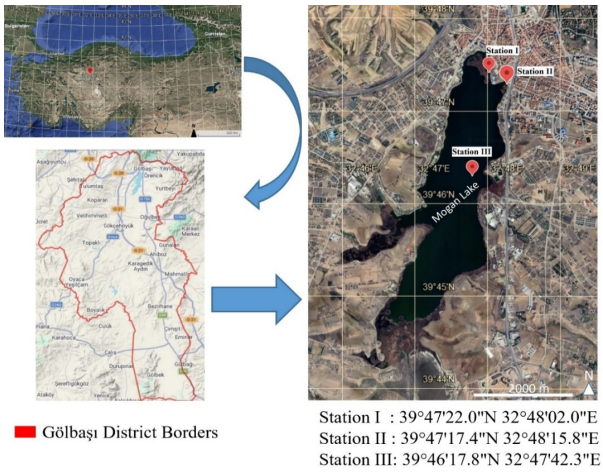



**Figure 1.** Map of the study area and selected stations

### Methods

Surface water samples from Lake Mogan were collected at a depth of 30 cm during the dry period (August 2025) and the rainy period (December 2025). The samples were transported to the laboratory under dark and cold conditions. Water temperature and dissolved oxygen were measured in situ using a YSI oxygen meter, while pH was measured on-site with a laboratory-type digital WTW pH meter, with a measurement range of 0–14 and a precision of 0.01.

### Laboratory analysis

The analyses of the water samples were conducted in an accredited laboratory, with four replicates for each measurement. In water samples filtered through 0.45 µm filter

paper, ammonia (SM 4500 $NH_3$ B, SM 4500 $NH_3$-F), nitrate, nitrite, and ortho-phosphate phosphorus (SM 4110 B) were analyzed. Phosphate and nitrate analyses were conducted according to SM 4110 B, while chemical oxygen demand (COD) was determined following SM 5220 B. Heavy metals (Hg, As, Cd, Cr, Pb, Ni, Cu, Zn, Fe) were analyzed based on TS EN ISO 17294-1.2 standards.

**Index calculations**

Descriptions of the indices used in this study are presented in Table 1.

The standard values used for calculating the Organic Pollution Index (OPI) for COD, DO, DIN, and DIP are 25mg/L; 8mg/L (TSWQR, 2023); 0.53mg/L (Willett et al., 2004); and 0.04mg/L (Maruo et al., 2016), respectively.

For calculating the Nutrient Pollution Index (NPI), the values used as the maximum allowable concentrations of $NO_3$-N (MACN) and $PO_4$-P (MACP) are 3mg/L and 0.05mg/L, respectively (TSWQR, 2023).

Within the scope of this study, two different categories were considered for the assessment of heavy metal pollution indices in the lake water:

In the first category, heavy metal levels in lake surface waters were evaluated within the framework of the 'Surface Water Quality Regulation' (TSWQR, 2023). For this purpose, in the estimation of HPI-1, HEI-1, and PER-1 (Table 1), the maximum allowable environmental quality standard values (Max. EQS) were used as the required Si and MACi values. According to TSWQR (2023), these values (µg/L) for Cr, Ni, Cu, Zn, As, Cd, Hg, Pb, and Fe are 142, 34, 3.1, 231, 53, 0.45, 0.07, 14, and 101, respectively.

In the second category (HPI-2, HEI-2, and PER-2), the aim was to evaluate the heavy metal levels in lake water within the context of freshwater quality criteria for the protection of aquatic life. According to USEPA (2023), these values (µg/L) for Cr, Ni, Zn, As, Cd, Hg, Pb, and Fe are 11, 52, 120, 150, 0.72, 0.77, 2.5, and 1000, respectively.

**Statistical analyses**

In this study, the Kruskal-Wallis test was used to determine whether there were significant differences in measurement values between periods. Post hoc multiple comparison tests were applied to identify which periods differed: the LSD test was used when variances were homogeneous, and the Tamhane test was used when variances were not homogeneous. Comparisons of measurements between the dry and rainy periods were tested using the Mann-Whitney U test. For each station in the dry and rainy periods, the Wilcoxon test was used to determine whether there were significant differences between index values in the two different categories, while Spearman's correlation coefficient was applied to assess whether there were significant relationships among the measurement data. In this study, Principle component analysis/factor analysis (PCA/FA) with varimax rotation was performed to identify possible sources of heavy metals (Kolassa, 2020). All statistical analyses were performed by using SPSS 22.

**Table 1.** Explanations regarding the indices used in the study. (Organic Pollution Index-OPI, Eutrophication Index (EI), Nutrient Pollution Index (NPI), Heavy Metal Pollution Index (HPI), Heavy Metal Evaluation Index (HEI), Potential Ecological Risk (PER))

| Index | Calculation | Equation explanations | Value - pollution level | References |
|---|---|---|---|---|
| **OPI** | $OPI = (COD/COD_S) + (DIN/DIN_S) + (DIP/DIP_S) - (DO/DO_S)$ | COD: The chemical oxygen demand<br>DIN: Dissolved inorganic N<br>DIP: Dissolved inorganic P<br>DO: Dissolved oxygen<br>$COD\text{-}DIN\text{-}DIP\text{-}DO_S$: Standard levels | OPI<0 - Excellent water quality<br>0≤OPI<1 - Good water quality<br>1≤OPI<2 - Beginning to be polluted<br>2≤OPI<3 - Lightly polluted<br>3≤OPI<4 - Moderately polluted<br>OPI>4 - Heavily polluted | Chen et al. (2016) |
| **EI** | $EI = \frac{COD \times DIN \times DIP}{4500} \times 10$ | COD: The chemical oxygen demand<br>DIN: Dissolved inorganic N<br>DIP: Dissolved inorganic P | EI > 1 - Water quality is regarded as eutrophic | Liu et al. (2011) |
| **NPI** | $NPI = (C_N/MAC_N) + (C_P/MAC_P)$ | $C_N$: The levels of $NO_3$-N in water sample<br>$C_P$: The levels of $PO_4$-P in water sample<br>$MAC_N$: The maximum limit of $NO_3$-N<br>$MAC_P$: The maximum limit of $PO_4$-P | NPI<1- Insignificant pollution<br>1≤NPI≤2.5 - Slight pollution<br>2.5≤NPI<7 - Moderate pollution<br>NPI≥7 – Heavy pollution | Isiuku and Enyoh (2020) |
| **HPI** | $HPI = \sum (Q_i \times W_i) / \sum W_i$ | $Q_i = C_i / S_i \times 100$<br>Qi: The sub-index of the ith parameter<br>Wi is the unit weightage of the ith parameter (=k/ $S_i$)<br>k: Proportionality constant for metal (=1)<br>$C_i$: is the monitored value of heavy metal of ith parameter<br>$S_i$ : The standard permissible value of the ith parameter (µg/L) | HPI< 15- Low pollution<br>15≤HPI≤30 – Moderate pollution<br>30≤HPI≤100 – Moderate to heavy pollution<br>HPI>100 - High pollution | Zakir et al. (2020) |
| **HEI** | $HEI = \sum_{i=1}^{n} M_i / MAC_i$ | $M_i$: The monitored value of the ith metal (µg/L)<br>$MAC_i$: Maximum admissible concentration of the ith metal (µg/L)<br>(The standard permissible value of the ith metal (µg/L) | HEI<10 – Low pollution<br>10<HEI<20 - Moderate pollution<br>HEI>20 - High pollution | Kumar et al. (2019) |
| **PER** | $PER = \sum_{i=1}^{n} T_i \times C_i/S_i$ | $C_i$: The monitored value of the ith metal (µg/L)<br>$S_i$: The standard permissible value of the ith metal (µg/L)<br>$T_i$ =The individual metal's biological toxicity factor<br>The toxicity factor values are: 5 for Ni, Cu, Pb; 2 for Cr; 1 for Zn; 10 for As; 30 for Cd; 40 for Hg | PER<110 - Low risk<br>110<PER<200 - Moderate risk<br>200<PER<400 - Considerable risk<br>PER>400 -Very high risk | Sharifi et al. (2016) |

## RESULTS

### Results on the spatial and temporal variations of certain water quality parameters and the organic pollution indices

In the study, water temperature and dissolved oxygen measurements varied significantly among stations in both the rainy and dry periods ($p<0.05$), whereas pH values showed a highly significant difference among stations only during the dry period ($p<0.001$) (Figure 2).

Based on the OPI values of lake surface waters, during the dry period, only Stations II and III had OPI values below 1 (Good water quality), whereas in the rainy period, all stations were at the "Beginning to be polluted" level ($1 \leq OPI < 2$). During the rainy period, the OPI value reached a maximum (1.89) at Station II, located closest to the area with dense residential settlements, followed by Station III (1.50) and Station I (1.11), respectively. While the Organic Pollution Index (OPI) and Nutrient Pollution Index (NPI) did not show differences among stations in the dry period ($p > 0.05$), significant differences were observed in the rainy period ($p<0.05$). Organic pollution indices (OPI, EI, NPI) showed temporal variations only at Stations II and III ($p<0.05$). The EI value was greater than 1 at all stations in both periods, indicating eutrophication. The highest EI value (14.55) was observed at Station I during the dry period, and during this period, EI values differed significantly between Stations I and III ($p<0.05$) (Figure 2).

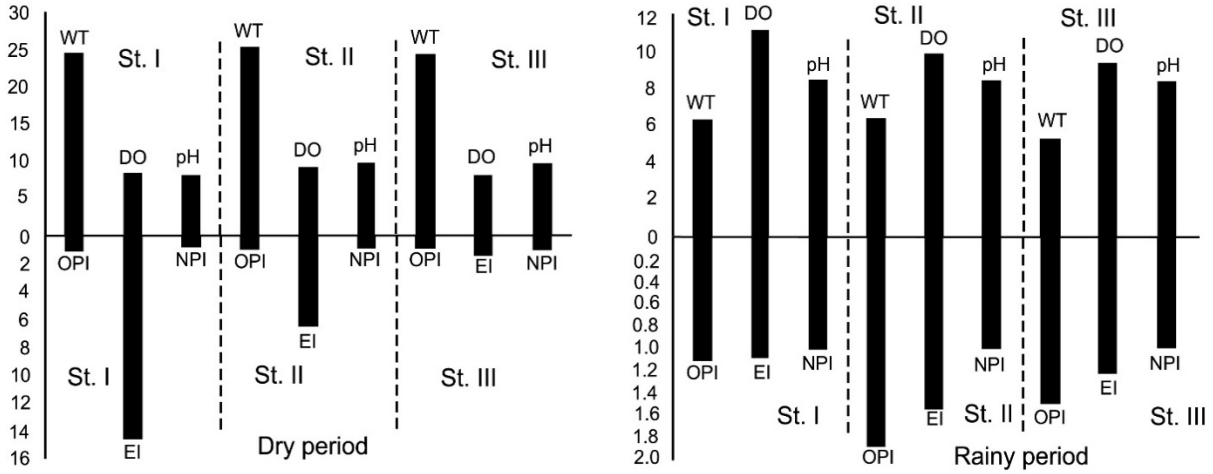



**Figure 2.** Variations of water temperature (WT-°C), Dissolved oxygen (DO-mg/L), pH, Organic Pollution Index (OPI), Eutrophication Index (EI), Nutrient Pollution Index (NPI) according to stations and periods

### Correlation analysis

Spearman's correlation coefficient was used to determine whether there were significant relationships among the measurement and concentration values of the six parameters considered in this study (Table 2). At all three stations, water temperature and DO showed a moderately significant negative (inverse) relationship. This result aligns with the notion that dissolved oxygen in surface waters is primarily controlled by water temperature (Pulatsü et al., 2014). At Stations I and III, very high positive correlations between OPI and EI were observed, with values of 0.729 and 0.994, respectively. This finding supports the role of organic pollution in the eutrophication levels of the stations. As shown in Table 2, the eutrophication levels at Stations I and II adversely affected dissolved oxygen, with a moderately significant negative relationship observed between EI and DO (−0.466 and −0.484, respectively; $p<0.05$). This is consistent with the fact that one of the characteristics of eutrophication in aquatic ecosystems is a decrease in dissolved oxygen levels (Pulatsü et al., 2014).

**Table 2.** Correlation analysis of parameters by stations

| Stations | Parameters | DO | pH | OPI | EI | NPI |
|---|---|---|---|---|---|---|
| I | WT | -.828* | -.699* | -0.065 | 0.308 | 0.265 |
| | DO | 1 | .701* | -0.204 | -.466* | -0.079 |
| | pH | | 1 | 0.059 | -0.387 | -0.143 |
| | OPI | | | 1 | .729* | -0.382 |
| | EI | | | | 1 | -0.034 |
| | NPI | | | | | 1 |
| II | WT | -.634* | .667* | -.444* | .545* | 0.401 |
| | DO | 1 | -.802* | .444* | -.484* | -0.323 |
| | pH | | 1 | -.410* | .453* | 0.395 |
| | OPI | | | 1 | 0.3 | -0.298 |
| | EI | | | | 1 | 0.022 |
| | NPI | | | | | 1 |
| III | WT | -.921* | .786* | -0.329 | -0.342 | -.891* |
| | DO | 1 | -.738* | 0.3 | 0.32 | .844* |
| | pH | | 1 | -0.36 | -0.366 | -.792* |
| | OPI | | | 1 | .994* | .415* |
| | EI | | | | 1 | .416* |
| | NPI | | | | | 1 |

*p<0.05

**Results on the potential sources of organic pollution indices**

The factorial structure of certain physicochemical measurements and organic pollution indices by station is presented in Table 3. At Station I, water temperature (−0.984), dissolved oxygen (DO) (0.978), and pH (0.957) exhibit very high factor loadings on the first component. The second component includes OPI and NPI measurements, and this component explains 24.63% of the total variance. Pollutants specific to this station—where Sukesen Creek and the wastewater from andesite processing facilities are discharged—appear to be primarily responsible for changes in the physicochemical properties of surface waters, and secondarily for the increase in the organic pollution index (Table 3). At Station II, where residential areas are densely located, water temperature (0.931) and pH (0.929) in the first component show high positive factor loadings, while dissolved oxygen (DO) (−0.869) and OPI (−0.771) exhibit high negative loadings. In the second component, EI (0.975) shows a very high positive factor loading, whereas NPI (−0.967) shows a very high negative loading. This second component explains 35.65% of the total variance, suggesting that eutrophication and overall pollution pressure at this location are strongly influenced by external factors. At Station III, NPI (0.995) and dissolved oxygen (DO) (0.994) identified in the first component exhibit strong positive factor loadings. In the second component, EI (0.982) and OPI (0.849) also show high positive loadings, representing this group. This situation reflects the eutrophication status and exposure to organic pollution at Station III, which is located close to the discharge point of agriculturally derived wastewater (Table 3).

**Table 3.** Factorial structure of parameters by stations

| Parameters | Station I | | Station II | | Station III | |
|---|---|---|---|---|---|---|
| | PC1 | PC2 | PC1 | PC2 | PC1 | PC2 |
| WT | -0.984 | 0.043 | 0.931 | 0.272 | -0.995 | -0.092 |
| DO | 0.978 | -0.084 | -0.869 | -0.291 | 0.994 | 0.088 |
| pH | 0.957 | -0.008 | 0.929 | 0.263 | -0.994 | -0.094 |
| EI | -0.632 | 0.348 | 0.192 | 0.975 | -0.134 | 0.982 |
| OPI | 0.145 | 0.939 | -0.771 | 0.162 | 0.501 | 0.849 |
| NPI | 0.396 | -0.683 | -0.100 | -0.967 | 0.995 | 0.094 |
| Eigenvalues | 3.533 | 1.363 | 3.666 | 1.598 | 4.388 | 1.556 |
| Variance(%) | 56.97 | 24.627 | 52.091 | 35.65 | 70.421 | 28.649 |

**Results on the spatial and temporal variations of heavy metal concentrations**

The variation of heavy metals by stations and periods is presented in Table 4. In terms of average concentrations across all stations, the examined heavy metals followed the order Fe > As > Ni > Pb > Cr > Cd > Cu during the dry period, whereas in the rainy period they were ranked as Fe > As > Ni > Cr > Zn > Cu. At all three selected stations, Zn and Hg were not detected during the dry period, while Cd, Hg, and Pb were not detected during the rainy period (Table 4). Across both periods and all three stations, the concentrations of Cr, Ni, Cu, Zn, and Pb remained below the environmental quality standard limits reported for lakes. However, As concentrations exceeded the maximum environmental quality standard value of 53 µg/L in both periods and at all three stations, reaching a maximum of 67 µg/L at Station III during the rainy period. The Fe concentration exceeded the EQS value at Station III during the dry period and at all stations during the rainy period, with the maximum Fe concentration (612.04 µg/L) recorded at Station III in the rainy period (Table 4).

Among the heavy metals considered in the study, the concentration levels of Cr, Ni, Zn, As, and Fe do not pose a risk in terms of the - Freshwater Quality Criteria for the Protection of Aquatic Life - across both periods and all three stations. However, during the dry period, Cd concentrations ranged between 1.22 and 1.62 µg/L across all three stations, while Pb concentrations varied between 4.37 and 4.71 µg/L at Stations I and II, exceeding the values recommended by USEPA (2023) for the - Freshwater Quality Criteria for the Protection of Aquatic Life - for Cd (0.72 µg/L) and Pb (2.5 µg/L). The concentrations of Ni (6.31 ± 0.18 µg/L), As (67.51 ± 1.47 µg/L), and Fe (612.04 µg/L) detected at Station III were recorded as the highest values for these three metals in the study.

**Table 4.** Variation of heavy metal concentrations depending on stations and periods

| Heavy metals | Stations | Dry period | Rainy period |
|---|---|---|---|
| | | Mean ± SD (µg/L) | Mean ± SD (µg/L) |
| Cr | I | 2.61 ± 1.92$^{aA}$ | 0.98 ± 0.74$^{aB}$ |
| | II | 2.00 ± 3.00$^{aA}$ | 1.77 ± 0.15$^{bA}$ |
| | III | 1.53 ± 2.12$^{aA}$ | 2.41 ± 0.20$^{cB}$ |
| Ni | I | 3.35 ± 0.16$^{aA}$ | 5.13 ± 0.35$^{aB}$ |
| | II | 4.06 ± 0.25$^{bA}$ | 5.88 ± 0.19$^{bB}$ |
| | III | 4.65 ± 0.43$^{cA}$ | 6.31 ± 0.18$^{cB}$ |
| Cu | I | 1.65 ± 0.39$^{aA}$ | 0.52 ± 0.57$^{aB}$ |
| | II | 1.56 ± 0.18$^{aA}$ | 0.73 ± 0.67$^{aB}$ |
| | III | 0.36 ± 0.15$^{aA}$ | 0.00 ± 0.00$^{aB}$ |
| Zn | I | 0.00 ± 0.00$^{aA}$ | 1.61 ± 0.31$^{aB}$ |
| | II | 0.00 ± 0.00$^{aA}$ | 1.48 ± 0.21$^{aB}$ |
| | III | 0.00 ± 0.00$^{aA}$ | 0.00 ± 0.00$^{aA}$ |
| As | I | 53.15 ± 1.22$^{aA}$ | 58.22 ± 1.88$^{aB}$ |
| | II | 54.09 ± 1.94$^{aA}$ | 63.20 ± 1.15$^{bB}$ |
| | III | 53.71 ± 0.94$^{aA}$ | 67.51 ± 1.47$^{cB}$ |
| Cd | I | 1.62 ± 0.14$^{aA}$ | 0.00 ± 0.00$^{aB}$ |
| | II | 1.54 ± 0.09$^{aA}$ | 0.00 ± 0.00$^{aB}$ |
| | III | 1.22 ± 0.07$^{aA}$ | 0.00 ± 0.00$^{aB}$ |
| Hg | I | | |
| | II | - | - |
| | III | | |
| Pb | I | 4.37 ± 0.70$^{aA}$ | 0.00 ± 0.00$^{aB}$ |
| | II | 4.71 ± 0.54$^{aA}$ | 0.00 ± 0.00$^{aB}$ |
| | III | 0.40 ± 0.21$^{aA}$ | 0.00 ± 0.00$^{aB}$ |
| Fe | I | 15.78 ± 2.27$^{aA}$ | 267.33 ± 86.61$^{aB}$ |
| | II | 11.81 ± 0.88$^{bA}$ | 420.57 ± 36.96$^{bB}$ |
| | III | 155.68 ± 53.43$^{cA}$ | 612.04 ± 35.08$^{cB}$ |

*: Different lowercase letters within the same row indicate the differences between periods for each heavy metal at a given station.
**: Different uppercase letters within the same column indicate the differences between stations for the same heavy metal *($p<0.05$)*.
- : Below detection limit

**Correlation analysis**

The presence of a significant relationship among the concentration values of the nine heavy metals examined in this

study was determined using the Spearman correlation coefficient (Table 5). The correlations among heavy metals provide insights into their sources and transport pathways. Positive values indicate that the elements may share a common source, co-occur during transport, and exhibit similar behavior, whereas negative values suggest that these elements originate from different sources (Binici and Pulatsü, 2022). According to the Spearman correlation analysis results ($p<0.05$), during the dry period, moderate (0.671) and strong (0.762) positive correlations were detected for Fe–Ni at stations I and III, respectively, indicating that similar and significant pollutant sources for both heavy metals are present around these stations. During the rainy period, strong positive correlations were observed at station I between Cr–Ni (positive), As–Ni (positive), Cr–Fe (positive), and Ni–Fe. During the dry period, no heavy metals particularly associated with As were observed, whereas the moderate to strong correlations of As with other heavy metals (Ni, Fe) during the rainy period (Table 5) suggest that the levels of these metals also originate from quarry wastewater discharges (Table 4).

**Results regarding the potential sources of heavy metals**

For Stations I and II, the heavy metals in the first principal component exhibited strong positive loadings for Ni (0.978; 0.978), Zn (0.957; 0.976), As (0.884; 0.959), and Fe (0.925; 0.990), whereas Cu (-0.786; -0.702), Cd (-0.983; -0.992), and Pb (-0.971; -0.985) displayed negative loadings. This component accounted for 78% of the total variance for both stations (Table 6). This suggests that Ni, Zn, As, and Fe are likely derived from similar sources. For Station III, the metals grouped in the first factor exhibited strong positive loadings for Ni (0.928), As (0.972), and Fe (0.965), while Cu (-0.925), Cd (-0.977), and Pb (-0.823) displayed negative loadings. These results further support the significant role of agriculture-oriented wastewater in influencing the levels of Ni, As, and Fe at this station (Table 6). In this study, strong positive correlations were detected between Fe–Ni, As–Ni, and Ni–Fe values during both dry and rainy periods, and the PCA results were found to be consistent with the outcomes of the Spearman correlation analysis.

**Results regarding heavy metal pollution indices**

Considering the HPI values calculated based on the maximum environmental quality standard limits, a shift toward “moderate to heavy pollution” was observed at all stations during the dry period. When the values recommended for freshwater quality criteria for the protection of aquatic life were considered, “high pollution” was determined at Stations I and II, while Station III exhibited “moderate to heavy pollution”.

During the rainy period, “low pollution” was observed for all stations in both categories. Regarding HEI values, lake water was classified as “low pollution” based on both the maximum environmental quality standard limits and the freshwater quality criteria for the protection of aquatic life. Considering PER values, during the dry period, a “moderate risk” was identified at Stations I and II, while Station III exhibited a “low risk” according to the maximum environmental quality standard limits. Based on the maximum environmental quality standard limits, a “low risk” was observed at all stations during the rainy period. Similarly, according to the freshwater quality criteria for the protection of aquatic life, “low risk” was determined at all stations during both the dry and rainy periods. The variations of the aforementioned indices according to stations and periods are presented in Figure 3.

**Table 5.** Correlation analysis of heavy metals based on stations and periods

| **Dry period** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Station I** | **Cr** | **Ni** | **Cu** | **Zn** | **As** | **Cd** | **Hg** | **Pb** | **Fe** |
| Cr | 1.000 | | | | | | | | |
| Ni | -.441 | 1.000 | | | | | | | |
| Cu | .123 | .531 | 1.000 | | | | | | |
| As | .438 | -.259 | .259 | | 1.000 | | | | |
| Cd | -.285 | .046 | -.358 | | -.168 | 1.000 | | | |
| Pb | -.427 | .217 | .476 | | .182 | .263 | | 1.000 | |
| Fe | -.018 | .671* | .510 | | -.035 | -.028 | | -.098 | 1.000 |
| **Station II** | **Cr** | **Ni** | **Cu** | **Zn** | **As** | **Cd** | **Hg** | **Pb** | **Fe** |
| Cr | 1.000 | | | | | | | | |
| Ni | .192 | 1.000 | | | | | | | |
| Cu | -.297 | -.291 | 1.000 | | | | | | |
| As | -.247 | -.368 | .196 | | 1.000 | | | | |
| Cd | -.073 | .063 | .399 | | -.294 | 1.000 | | | |
| Pb | -.352 | .095 | .242 | | .018 | -.525 | | 1.000 | |
| Fe | -.051 | -.630* | .042 | | .378 | -.266 | | -.224 | 1.000 |
| **Station III** | **Cr** | **Ni** | **Cu** | **Zn** | **As** | **Cd** | **Hg** | **Pb** | **Fe** |
| Cr | 1.000 | | | | | | | | |
| Ni | .613* | 1.000 | | | | | | | |
| Cu | .708* | .098 | 1.000 | | | | | | |
| As | .172 | .161 | -.217 | | 1.000 | | | | |
| Cd | .455 | .580* | .189 | | .427 | 1.000 | | | |
| Pb | -.417 | -.371 | -.371 | | -.028 | -.063 | | 1.000 | |
| Fe | .525 | .762** | .189 | | .336 | .650* | | -.399 | 1.000 |
| **Rainy period** | | | | | | | | | |
| **Station I** | **Cr** | **Ni** | **Cu** | **Zn** | **As** | **Cd** | **Hg** | **Pb** | **Fe** |
| Cr | 1.000 | | | | | | | | |
| Ni | .826** | 1.000 | | | | | | | |
| Cu | .262 | .474 | 1.000 | | | | | | |
| Zn | -.577* | -.371 | .101 | 1.000 | | | | | |
| As | .413 | .741** | .467 | -.203 | 1.000 | | | | |
| Fe | .911** | .825** | .291 | -.524 | .364 | | | | 1.000 |
| **Station II** | **Cr** | **Ni** | **Cu** | **Zn** | **As** | **Cd** | **Hg** | **Pb** | **Fe** |
| Cr | 1.000 | | | | | | | | |
| Ni | .266 | 1.000 | | | | | | | |
| Cu | -.087 | .268 | 1.000 | | | | | | |
| Zn | .098 | .545 | .529 | 1.000 | | | | | |
| As | -.287 | .552 | .203 | .119 | 1.000 | | | | |
| Fe | .392 | .371 | .080 | -.112 | .175 | | | | 1.000 |
| **Station III** | **Cr** | **Ni** | **Cu** | **Zn** | **As** | **Cd** | **Hg** | **Pb** | **Fe** |
| Cr | 1.000 | | | | | | | | |
| Ni | .580* | 1.000 | | | | | | | |
| Cu | | | | | | | | | |
| Zn | | | | | | | | | |
| As | .196 | .294 | | | 1.000 | | | | |
| Fe | -.028 | 0.000 | | | -.161 | | | | 1.000 |

*(p<0.05) **(p<0.01)

**Table 6.** Principal component analysis of various heavy metals in selected stations

| Parameters | Station I (PC1) | Station II (PC1) | Station II (PC2) | Station III (PC1) | Station III (PC2) |
|---|---|---|---|---|---|
| Cr | -0.525 | -0.011 | 0.996 | 0.126 | 0.978 |
| Ni | 0.968 | 0.978 | -0.038 | 0.928 | 0.313 |
| Cu | -0.786 | -0.702 | -0.097 | -0.925 | 0.167 |
| Zn | 0.957 | 0.976 | -0.057 | - | - |
| As | 0.884 | 0.959 | -0.015 | 0.972 | 0.167 |
| Cd | -0.983 | -0.992 | 0.043 | -0.977 | -0.113 |
| Pb | -0.971 | -0.985 | -0.009 | -0.823 | -0.243 |
| Fe | 0.925 | 0.990 | -0.047 | 0.965 | 0.226 |
| Eigenvalues | 6.294 | 6.261 | 1.007 | 5.454 | 1.020 |
| Variance (%) | 78.676 | 78.258 | 12.594 | 77.914 | 14.574 |

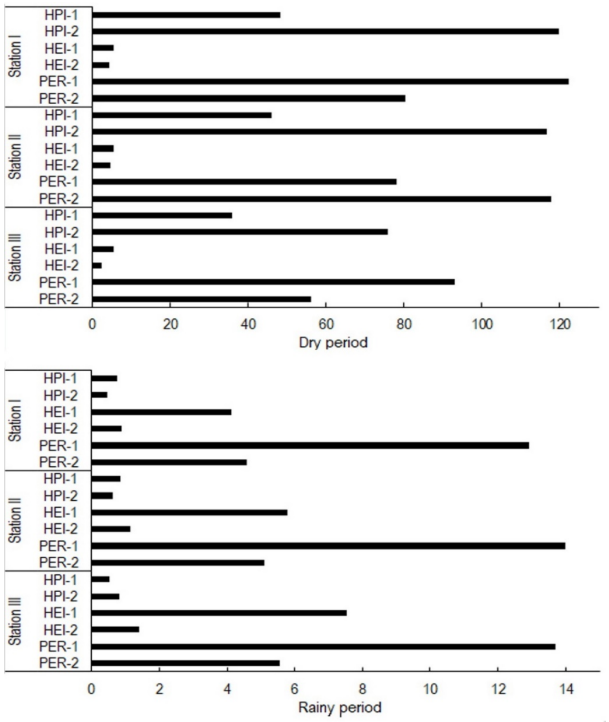



**Figure 3.** Variations of Heavy Metal Pollution Index (HPI), Heavy Metal Evaluation Index (HEI) and Potential Ecological Risk (PER) values according to stations and periods

During the dry period, no significant differences were observed among stations for the HPI, HEI, and PER indices ($p>0.05$). However, during the rainy period, statistically significant differences were detected for the HPI-2, HEI-1, HEI-2, and PER-2 indices ($p<0.05$). While the PER and HPI indices were significantly higher during the dry period, the HEI-1 index was found to be higher in the rainy period (7.54) compared to the dry period (5.57) (Figure 3). This indicates that rainfall differently affects pollution sources specific to each station and that basin dynamics (flow, erosion, transport) during the rainy season accentuate the characteristic differences among stations. Similarly, during the rainy period, at Station II, which is located closest to residential areas, no significant difference was observed between HPI-1 and HPI-2 measurements ($p>0.05$). In contrast, at the other stations, significant differences were detected between HPI and HEI measurements assessed in the two different categories ($p<0.05$).

## DISCUSSION

Regarding OPI values, which are among the indicators of organic pollution in surface waters, some studies have reported no significant seasonal variation (Bahroun et al., 2022), while others have indicated higher values during the summer months (Biedunkova et al., 2025; Tokatlı et al., 2025; Özşeker et al., 2026). Within the scope of this study, the OPI value was determined to be at the level of "Beginning to be polluted" ($1 \leq OPI < 2$) during the rainy period for all stations, reaching its maximum at Station II (1.89), which is located in close proximity to densely populated areas. This result supports the notion that rainfall triggers an increase in organic load transported to the lake through urban surface runoff—potentially including sewage leakages—as well as from agricultural lands. Furthermore, the relatively higher OPI and NPI values observed during the rainy period, along with their variation among stations, are thought to be influenced by the inflowing creeks (Başpınar, Gölcük, Sukesen, and Yavrucak Creeks), which feed the lake and are characterized by high TP, TN, and TOC concentrations during the rainy period (Latifi and Pulatsü, 2024). The seasonal variation of EI values in Lake Mogan was found to be consistent with those reported for the habitats of Lake Uluabat in Türkiye (Tokatlı et al., 2025) and Borçka Dam Lake (Özşeker et al., 2026), exhibiting an approximately sixfold increase during the dry period compared to the rainy period. In this context, not only water temperature and dissolved oxygen values, but also the applied organic pollution risk assessment indicators demonstrated notable seasonal variations in this study. The particularly high EI values observed during the dry period are consistent with the findings of Coşkun and Demir (2025), who reported significant seasonal variations in the trophic status of Lake Mogan and indicated that increased biological activity during the spring–summer period accelerates the eutrophication process. Moreover, our EI values are in line with the results of Özdemir et al. (2024), who classified the trophic status of Lake Mogan as eutrophic/hypertrophic based on TN and TP levels in surface waters.

Among the heavy metals considered in this study (Cr, Ni, Cu, Zn, As, Cd, Hg, Pb, Fe), the sources of arsenic include mine wastes, landfill leachates, industrial effluents, as well as natural processes such as volcanic eruptions and rock weathering. In contrast, the sources of nickel include battery production, the paper industry, fertilizer manufacturing, the iron and steel industry, and thermal energy production (Pulatsü et al., 2014). Within the scope of the study, arsenic (As) concentrations ranged between 53.15 and 67.51 µg/L, while iron (Fe) concentrations varied from 155.68 to 612.04 µg/L (except at Stations I and II during the dry period) (Table 4). The concentrations of both metals were found to exceed the environmental quality standards established for lakes (53 µg/L for As and 101 µg/L for Fe) under the "Surface Water Quality Regulation" (TSWQR, 2023). During the dry period, except for

Cd and Pb, the levels of Cr, Ni, Zn, As, and Fe were not considered to pose critical significance in terms of the freshwater quality criteria for the protection of aquatic life. The detection of cadmium (Cd) and lead (Pb) at maximum levels during the dry period, while remaining below detection limits in the rainy period, appears to be attributable to both the increased activity of quarry processing facilities during the summer season and the lower lake water levels, which may have contributed to elevated concentrations of these pollutants.

Within the scope of the study, the highest heavy metal concentration detected in surface waters was Fe (612.04 µg/L), followed by As and Ni. While this finding is consistent with the results reported by Kuçukosmanoglu and Filazi (2020), who identified iron as the metal with the highest concentration in lake waters, it does not align with their reported mean As concentration of 12.4 ± 4.8 µg/L. In the present study, As concentrations were determined to be considerably higher (53.15–67.51 µg/L), indicating an approximately fivefold increase over time. It has been reported that andesite stone deposits, which are volcanic in origin, are located to the east of Gölbaşı District and constitute an economic asset for the region (Anonymous, 2026). It has been reported that discharges from andesite-processing facilities are released into Sukesen Creek in an uncontrolled manner (Anonymous, 2013), thereby triggering elevated concentrations of Ni and As in the creek (Pulatsü and Latifi, 2023). This situation also explains the relatively higher levels of Fe, As, and Ni detected at Station I, where Sukesen Creek discharges, compared to other heavy metal concentrations.

Due to the unique physicochemical and biological characteristics of each lake, the temporal variation of pollutants causing water quality deterioration may differ seasonally and even daily. Aliagha and Mustafa (2022) reported higher concentrations of heavy metals (Al, Fe, Ba, Cu, Ni, Cd) during the rainy season compared to the dry season in Varsity Lake, Malaysia, whereas Tavakoli and Bayati (2026) observed increased concentrations of Cu, Cr, and As in surface waters of the Dehloran Basin (Ilam, Iran) during the dry season. In the present study, among the heavy metals detected in the surface waters of Lake Mogan, Ni, As, and Fe exhibited higher concentrations during the rainy period, whereas Cu, Cd, and Pb were found at higher levels during the dry period (Table 4). Owing to its geological formation, the Lake Mogan basin constitutes a natural source of arsenic, and the transport of weathered rocks via surface runoff appears to increase the concentration of this metal during the rainy period. Our finding that As concentrations increase during the rainy period is consistent with the results reported by Tokatlı and Varol (2021).

According to the HPI and HEI values of Mogan Lake, its surface waters were found to have low pollution levels in terms of heavy metals. This finding is consistent with studies reporting that the waters of Karataş Lake in Türkiye (Tekin-Özan et al., 2024) and pond water samples in the Meriç-Ergene River Basin (Tokatlı and Varol, 2021) also fall within the low pollution category. Furthermore, the low levels of heavy metal contamination detected in the lake's surface waters are consistent with the results of studies on the creeks feeding the lake (Pulatsü and Latifi, 2023). Considering the HPI values calculated based on the EQS values specified for lakes, the dry period appears to have triggered increased heavy metal pollution. When the standard values reported for the protection of aquatic life – Freshwater Quality Criteria – are taken into account, the lake's HPI values fall within the "high pollution" category. However, according to the HEI and PER values, the lake represents a "low to moderate risk" both in terms of environmental quality standards (EQS) and the freshwater quality criteria for the protection of aquatic life.

Previous studies have demonstrated that most heavy metals, which constitute a significant component of pollutants in aquatic ecosystems, originate from various anthropogenic sources. In this study, iron was identified as the heavy metal with the highest concentration during both the dry and rainy periods, with mean values ranging from 61.09 to 433.31 µg/L. Wastewaters originating from andesite rock deposits of volcanic origin in the basin appear to be the primary factor contributing to the elevated levels of this metal. Additionally, the spatial variation of nickel (Ni), identified as the metal with the second-highest concentration after arsenic (As), further supports the anthropogenic origin of this metal. In other words, these three metals (Fe, Ni, and As) are influenced both by the basin's geology and by agricultural activities, with surface runoff playing a significant role in their environmental transport.

## CONCLUSION

Mogan Lake is not only an important wetland and recreational area in its region, but also one of Türkiye's significant natural habitats in terms of its flora and fauna. Within the scope of this study, the lake's recreational status was evaluated with respect to organic pollution and heavy metal levels. In this context, it is anticipated that the OPI and EI indices, applied for the first time in the lake, could serve as indicators shedding light on its eutrophication status. The ranking of the average concentrations of the heavy metals considered in the study (Fe > As > Ni) remained consistent across both stations and periods, and these three metals were identified as the primary metals threatening the lake's health when evaluated against environmental quality standards. Based on the statistical findings, it was determined that all three metals are influenced by a combination of wastewater from andesite processing facilities, settlements, and discharges from agricultural activities. In particular, the HPI and PER indices are considered to be effective tools for monitoring heavy metal pollution in the lake during the dry period. In light of the study results, which indicate warning signs of eutrophication, the management of wastewater originating from settlements and agricultural activities (e.g., limiting the number of households, promoting organic farming and livestock practices, and providing farmer education) is crucial

for the sustainable management of the lake. Furthermore, administrative measures addressing anthropogenic sources that threaten heavy metal levels, particularly mining activities, should not be overlooked, as they constitute a priority for maintaining the lake's ecological health.


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## AUTHOR CONTRIBUTIONS

All authors took part in designing the research, collecting and writing the manuscript.

## CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

## ETHICAL APPROVAL

There are no ethical issues with the publication of this manuscript.

## DECLARATION OF AI USE

We have not used AI-assisted technologies in creating this article.

## DATA AVAILABILITY

The authors confirm that the data that supports the findings of this study are available within the article.

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