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# Environmental and Ecological Risks Posed by Sediment Heavy Metals in Reservoirs: A Preliminary Study from Northwest Türkiye

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ABSTRACT

Reservoir sediments are an important component of aquatic ecosystems. Concentrations, sources, pollution and ecological risks of heavy metals pose serious risks on sustainable management of these ecosystems. This research focuses on heavy metal contents, physicochemical properties, environmental and ecological risks of sediments in four reservoirs (Ayvacık, Bayramdere, Bayramiç, and Umurbey) in Northwest Türkiye. Bayramiç reservoir had greater sediment Al, Cu, Fe, Mn concentrations, clay and silt contents than the other reservoirs (Ayvacık, Bayramdere, and Umurbey). In all four reservoirs, sediment heavy metals were generally of natural origin. Although sediment pollution index was identified as "considerable contamination" for Mn, such a case was not detected for the other heavy metals (Cd, Co, Cr, Cu, Fe, Ni, Pb, and Zn). An ecological risk assessment was made for reservoir sediments and a "low contamination" was detected.

Keywords: Pollution indices, Reservoirs, Sediment pollution, Ecological risk assessment

## 1. Introduction

Aquatic ecosystems such as oceans, seas, rivers and dams are under pressure of various factors including urbanization, industrialization, domestic and agricultural activities and mining activities (Fang et al. 2019; Githaiga et al. 2021; Muhammad 2023). Direct release of pollutants into the aquatic ecosystems results in serious destruction of existing ecosystems. Heavy metals can intrude into aquatic environments as pollutants and cause toxic effects on living ecosystem through the food chain (Xu et al. 2017; Rezapour et al. 2022; Şavran & Küçük 2022).

Dams and reservoirs have significant contributions to development of humanity. They are mostly constructed on rivers and streams for drinking water supply, irrigation of agricultural fields, flood control, electricity generation, industrial water supply, water quality improvement, recreational activities, river and inland waterway transportation, development and protection of fisheries, sediment retention and control (Alla & Liu 2021). Sediments accumulate in dam reservoirs in time and these dams complete their lifespan.

In aquatic environments, heavy metals enter into various physicochemical reactions. Sediment heavy metal concentrations may vary with the structure of sediment, particle size, specific surface area, and organic matter (Ma et al. 2023; Toller et al. 2022). With their distribution, persistence, non-degradability and toxicity, heavy metals pose a potential threat to aquatic ecosystems (Dong & Li 2023; Kang et al. 2024). Sediments constitute an accumulation site for heavy metals. Pollution loads of heavy metals threaten not only the habitats of aquatic ecosystems but also the entire ecosystem through accumulation and proliferation in the food chain (Li et al. 2024; Wang et al. 2022). Therefore, heavy metal concentrations of aquatic ecosystems should regularly be monitored.

A detailed research has not been conducted on sediment heavy metals of four reservoirs (Ayvacık, Bayramdere, Bayramiç, and Umurbey) in Northwest Türkiye. This study was conducted 1) to determine sediment heavy metal concentrations of four reservoirs used for different purposes (usually drinking and/or irrigation water supply), 2) to determine pollution status and ecological risks of each reservoir with the use of pollution and ecological risk indices, 3) to identify sources of sediment heavy metals. Present hypothesis was set as “There is a low heavy metal pollution and ecological risk since there are no industrial facilities around the reservoirs; pollution sources are not coming from anthropogenic effects”.

## 2. Materials and Method

### 2.1. Study area

Ayvacık, Bayramdere, Bayramic and Umurbey reservoirs are located within the boundaries of Çanakkale Province in Northwest Türkiye (Figure 1).

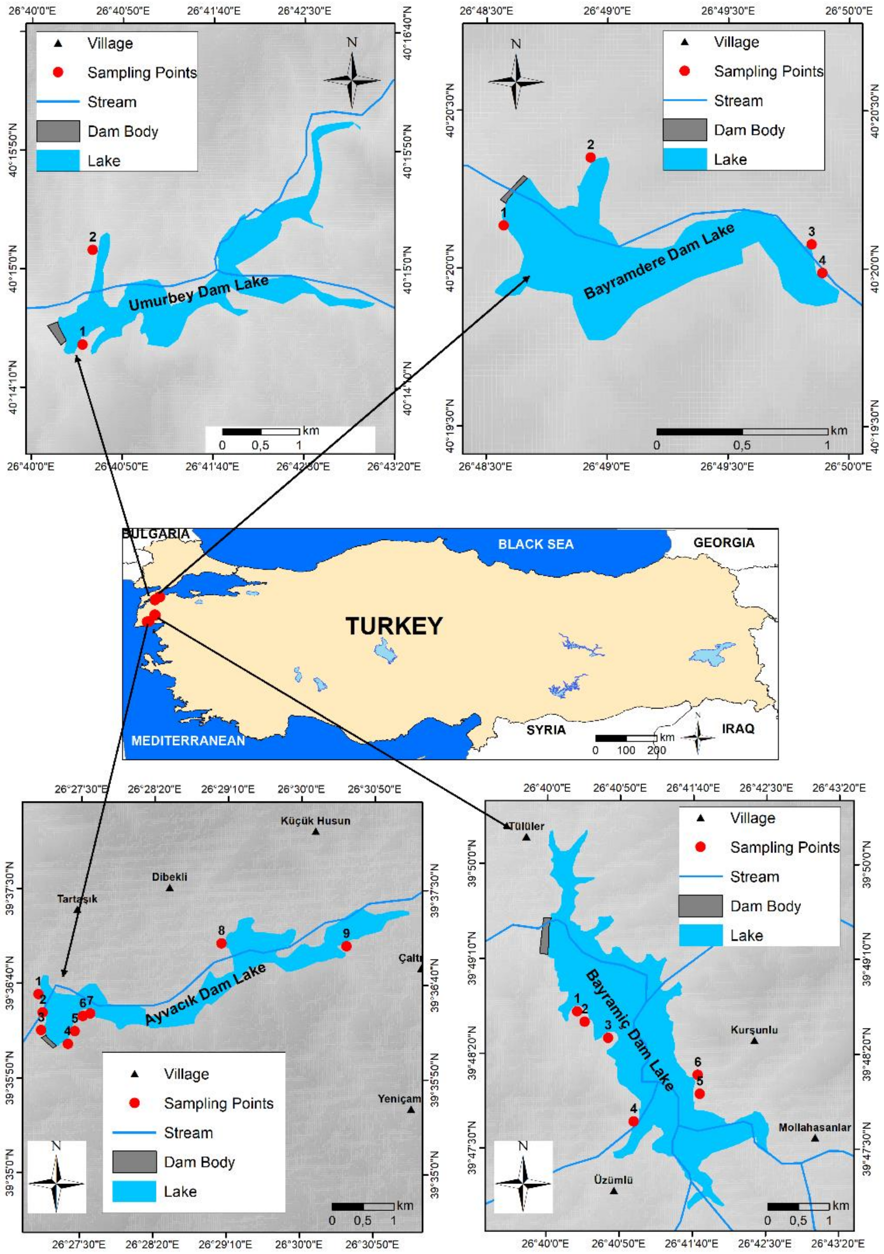

Figure 1- Location of four reservoirs and sediment sampling stations

There are no industrial facilities, but rural settlements and agricultural lands around the reservoirs. Ayvacık Reservoir (AYR) is located 8 km east of Ayvacık district center and was completed in 2008. It has a clay-core inside and sand-gravel embankment, a water storage capacity of 39 hm$^3$ and used for drinking and irrigation water supply (Taş et al. 2023) (Figure 2a). Geology of Ayvacık reservoir consists of melange, volcanic rocks and sedimentary rocks. Melange (complex series) was formed by sedimentary, volcanic and magmatic rocks being moved, torn off, dragged and stored in a certain place as a result of a certain effect. It is composed of radiolarite, mudstone, tuff, serpentinite, diabase, gabbro, marble, meta sand stone and limestone blocks. Volcanic rocks generally consist of altered andesite, agglomerate formed by the loose bonding of andesite blocks and pebbles, mostly with tuff cement and basalt, a product of Plioquaternary basaltic magmatism. Sedimentary rocks include intercalated layers containing clayey limestones, claystone, sandstone, conglomerate and mudstones, old alluviums formed by the cementation of materials such as sand, gravel, silt and clay, slope debris formed by the deposition of andesite blocks and pebbles rolled down from the slopes at the foot of the slopes as a result of the erosion of agglomerates, alluviums formed through erosion and deposition of vegetative soil and rocks along the stream bed at lower elevations (Yağcı 1995).

**Figure 2- Images of reservoirs from which sediment samples were taken (a: Ayvacık Reservoir, b: Bayramdere Reservoir, c: Bayramic Reservoir, d: Umurbey Reservoir) (DSİ 2023)**

Bayramdere Reservoir (BDR) is located 19 km east of Lapseki District center and 7 km downstream of Hacıomerler village. It was completed in 2010 for irrigation and drinking water supply on Karanlık Stream. It has an irrigation area of 1050 ha. It has a clay core inside and rock-fill type embankment. It is 56 m high from the thalweg and 60 m high from the foundation (Taş et al. 2023) (Figure 2b). Geologically, Bayramdere Plain consists of Eocene flysch at the bottom, Neogene-aged sediments and vulcanite and alluviums above them. Bayramdere reservoir contains sedimentary rocks, volcanic rocks and metamorphic rocks. Çanakkale Formation (Cenozoic-Tertiary-Upper Miocene), which is observed in the form of conglomerate-sandstone in sedimentary rocks is composed of alluviums formed by the accumulation of the material carried by Bayramdere, old alluviums (stream terraces, Cenozoic-Quaternary) suspended as the stream bed deepens and slope debris (Cenozoic-Quaternary) formed by the accumulation of material from the stream on the plains and alluviums (Quaternary) formed through the accumulation of material rolling down steep slopes. Although volcanic rocks are found in most of the reservoir area, they are divided into two sections: andesite (plagioclase, hornblende, quartz and biotite) and andesitic tuff (feldspar, mica and glassy paste). Metamorphic rocks include schistosity developed as amphibolite, chlorite, serice and graphite schist (Kırmızı Erdal 2019).

Bayramic Reservoir (BCR), completed in 1975, is located 4 km northeast of Bayramic district center. It is an earth-fill dam with a surface area of 585 ha, an average depth of 8-10 meters and is fed by Küçük Menderes River, Çavuşlu and Ayazma streams. BCR was built for 92% irrigation, 4% energy and 4% drinking water purposes (Taş et al. 2023) (Figure 2c). BCR is located in Evciler Basin in the north of Kaz Mountains region and consists of Paleozoic metamorphic lands. Presence of Paleozoic metamorphics around the Evciler, Çırpılar, Yeşilköy villages and Sakardağı indicates that Evciler basin developed on metamorphics also called Kaz Mountain group. It is also covered by Oligocene volcanics (andesite, dacite, rhyolite-rhyodazite lavas and proclastics). Oligo-Miocene granite-granodiorite terrains are widely observed. Pliocene lands in Evciler basin consist of both volcanic and sedimentary rocks (Koç 2007).

Umurbey Reservoir (UBR) is located 17 km south of Lapseki district center, 6 km downstream from Umurbey Town. UBR, which was built in 2008 as a clay-core sand-gravel, rock fill type on Umurbey stream, irrigates 3661 ha agricultural area (Taş et al. 2023) (Figure 2d). The low areas located in the northern and southern parts of the research area consist of limestones formed in the Miocene and Pliocene and marine sediments deposited in the Tertiary period. While the coastal part of the research area consists of Paleozoic granitoids and metamorphic rocks, upper parts are composed of Quaternary alluvial deposits. There are units consisting of marl, claystone and sandstone located between Umurbey district and southern part of Lapseki district. While the upper part of Umurbey Stream basin consists of Paleocene-Eocene aged volcanics, the lower parts consist of Pliocene sediments (Kırmızı Erdal 2019).

### *2.2. Sediment sampling and analytical procedures*

Reservoir sediment samplings were carried out in August 2023. Since physical facilities were not available in present reservoirs, a small number of sediment samples could be taken. Therefore, every accessible sampling location was chosen a station. For sampling, 9 stations were selected in AYR, 4 stations in BDR, 6 stations in BCR and 2 stations in UBR (Figure 1). Station coordinates were taken with a GPS device (±5 m). A single sediment sampling was done at each station. Surface sediment samples (0-10 cm depth) were taken with a plastic shovel. Three sediment samples taken randomly at each station were mixed and turned into a single sample. Then, sediment samples weighing about 1-1.5 kg were placed into nylon bags and brought to the laboratory. Each sample was air-dried, passed through a 63 µm sieve for heavy metal analysis and stored at +4 ºC until analysis. Sediment samples were sieved through a 63 µm sieve since the particle size at which metal adsorption is most effective is <63 µm (Cüce et al. 2022). For other analyses such as particle size distribution, pH, EC, and organic matter, sediment samples were passed through a 2 mm sieve (El-Radaideh et al. 2017; Parlak et al. 2021).

Sediment samples were passed through acid-digestion process in 1/3 perchloric acid/nitric acid mixture and total heavy metals (Al, Cd, Co, Cu, Cr, Fe, Mn, Ni, Pb, and Zn) were determined in an ICP-OES device (Varian 710-ES model) (USEPA1996). Acid mixture-supplemented sediment samples were kept in a microwave oven (Mars 6 one touch technology model) at 180 ºC for 1 hour. Particle size distribution (clay, silt, fine sand, coarse sand percent) was determined with the use of Bouyoucous hydrometer and sieve (Gee & Or 2002). Sediment pH values were determined in saturation pastes in accordance with (Thomas 1996). Sediment EC values were also determined in saturation pastes with an EC-meter (Rhoades 1996). Organic matter content was determined with the modified Walkley-Black method (Nelson & Sommers 1996). Certified reference material (CRM) (NCS DC73371, sediment) was used to determine analytical accuracy and precision. Recovery percentages of the reference material varied between 93.98 - 100.55% (Table 1).

**Table 1- The certificate values of the certified reference material (NCS DC73371, sediment), and the values (mean ± standard deviation) found in this study and the recovery rates, n = 3**

| *Metals* | *Certified (µg/g)* | *Determined (µg/g)* | *Recovery (%)* |
|---|---|---|---|
| Al | 153600 | 155733±5021 | 98.69 |
| Cd | 0.11 | 0.13±0.01 | 100.55 |
| Co | 20 | 20.66±1.53 | 97.14 |
| Cu | 28 | 29.33±2.08 | 95.78 |
| Cr | 128 | 136.33 ± 5.50 | 93.98 |
| Fe | 65000 | 65833±1412 | 98.76 |
| Mn | 910 | 921±23.3 | 98.84 |
| Ni | 56 | 57±3.60 | 98.51 |
| Pb | 31 | 31.33±2.08 | 99.23 |
| Zn | 90 | 92.33±4.04 | 97.59 |

### *2.3. Sediment quality guidelines (SQG)*

Sediment heavy metals may pose an ecological risk for aquatic organisms (Proshad et al. 2022). Therefore, a comparison was made with Threshold Effect Level (TEL) and Probable Effect Level (PEL) values to assess the harmful effects of heavy metals on benthic organisms. If the heavy metal concentrations are lower than TEL, they don't cause harmful effects; if the concentration is greater than PEL, harmful effects may occur. TEL and PEL values of heavy metals are provided in Table 4.

### *2.4. Evaluation of environmental and ecological risks*

In this study, enrichment factor (EF), geoaccumulation index ($I_{geo}$), contamination factor (CF), and pollution load index (PLI) were used to determine the pollution level of sediments. Ecological risks of sediment heavy metals were calculated with potential ecological risk factor ($Er^1$), potential ecological risk index (RI), and toxic risk index (TRI). The equations, explanations and classifications used in calculation of these indices are given in Table 2.

### *2.5. Statistical analysis*

Data normality was checked with Shapiro-Wilk test. While Cd, Fe, Mn, Pb, fine sand, coarse sand, and pH data showed normal distribution, other data (Co, Cr, Cu, Ni, Zn, clay, silt, and organic matter) did not show normal distribution. Some transformations (logarithmic transformation for Co, Cu, and organic matter; square root transformation for Cr, Ni, clay, and silt; sinus transformation for Zn) were made to make the data that did not show a normal distribution show a normal distribution. One-way

ANOVA test was performed to compare the differences between sediment heavy metal concentrations and physicochemical properties such as particle size distribution, pH, EC**,** and organic matter content. Significant means were compared with the use of Tukey's test ($P<0.05$). Multivariate statistical analyses such as principal component analysis (PCA) and correlation analysis were also performed. Kaiser-Meyer-Olkin (KMO) and Bartlett's tests were applied to determine the suitability of the data for PCA. Those with KMO values greater than 0.6 were used in PCA. Significance levels of 1% and 5% were taken into consideration in correlation tests. Statistical analyses were performed with use of SPSS 22 statistical software.

**Table 2- Environmental and ecological indices used in this study***

| *Index* | *Equation* | *Explanations* | *Classification* | *Contamination degree* |
|---|---|---|---|---|
| Enrichment factor, EF | $EF=\frac{(Cn/Al)Sample}{(Bn/Al)Background}$ | where, $C_n$ is the measured elemental concentration in sediment and $B_n$ is the background heavy metal concentration (Jia et al. 2018) | EF<2 | Minimal enrichment |
| | | | 2≤EF<5 | Moderate enrichment |
| | | | 5≤EF<20 | Significant enrichment |
| | | | 20≤EF<40 | Very high enrichment |
| Geoaccumulation index, $I_{geo}$ | $Igeo = log2(\frac{Cn}{1.5xBn})$ | where, $C_n$ is the measured elemental concentration in sediment and $B_n$ is the background heavy metal concentrations (Jia et al. 2018) | $I_{geo} \leq 0$ | Uncontaminated |
| | | | $0 < I_{geo} \leq 1$ | Uncontaminated to moderate contaminated |
| | | | $1 < I_{geo} \leq 2$ | Moderate contaminated |
| | | | $2 < I_{geo} \leq 3$) | Moderately to heavily contaminated |
| | | | $3 < I_{geo} \leq 4$ | Heavily contaminated |
| | | | $4 < I_{geo} \leq 5$ | Heavily to extremely contaminated |
| | | | $I_{geo} > 5$ | Extremely contaminated |
| Contamination factor, CF | CF=Cn / Bn | where, $C_n$ and $B_n$ are the measured and background elemental concentrations in sediment (Hakanson 1980) | CF < 1 | Low contamination |
| | | | 1 ≤ CF < 3 | Moderate contamination |
| | | | 3 ≤ CF < 6 | Considerable contamination |
| | | | CF ≥ 6 | Very high contamination |
| Pollution load index, PLI | $PLI = (CF_1 \times CF_2 \times CF_n)^{1/n}$ | where, CF is the contamination factor (Pobi et al. 2019) (n=8 in this study). | PLI ≤ 0 | Perfection |
| | | | PLI > 0–1 | Baseline level |
| | | | PLI > 1 | Contaminated |
| Potential ecological risk factor, $Er^i$ | $Er^i = Tr^i \times CF^i$ | where, $Tr^i$ is the biological toxic metal response factor (Cd = 30, Cu = 5, Cr = 2, Ni = 5, Pb = 2 and Zn = 1; Hakanson 1980) and CF is the contamination factor | $Er^i < 40$ | Low risk |
| | | | $40 \leq Er^i < 80$ | Moderate risk |
| | | | $80 \leq Er^i < 160$ | Considerable risk |
| | | | $160 \leq Er^i < 320$ | High risk |
| | | | $Er^i \geq 320$ | Very high risk |
| Potential ecological risk index, RI | $RI = \sum_{i=1}^{n} Er\imath$ | where, $Er^i$ is the potential ecological risk factor | RI < 150 | Low risk |
| | | | 150 ≤ RI <300 | Moderate risk |
| | | | 300 ≤ RI <600 | Considerable risk |
| | | | RI ≥ 600 | High risk |
| Toxic risk index, TRI | $TRIi = \sqrt{\frac{(C_i/TEL)^2 + (C_i/PEL)^2}{2}}$<br>$TRI = \sum_{i=1}^{n} TRI$ | where, $C_i$ is the measured content of heavy metal; TEL and PEL are threshold effect level and probable effect level of heavy metals, respectively; n is the number of heavy metals (Zhang et al. 2016) | TRI ≤ 5 | No toxic risk |
| | | | 5 < TRI ≤ 10 | Low toxic risk |
| | | | 10 < TRI ≤ 15 | Moderate toxic risk |
| | | | 15 < TRI ≤ 20 | Considerable toxic risk |
| | | | TRI > 20 | Very high toxic risk |

***** In our study, Al was chosen as the heavy metal used for background due to its abundant content and stability in sediment (Canpolat et al. 2022).

## 3. Results and Discussion

### *3.1. Sediment heavy metal concentrations and physicochemical characteristics*

Sediment heavy metal concentrations for studied 10 heavy metals and some physicochemical properties of 4 reservoirs are given in Table 3.

**Table 3- Reservoir sediment heavy metal concentrations (in mg kg$^{-1}$) and some physicochemical characteristics***

| | *Al* | *Cd* | *Co* | *Cr* | *Cu* | *Fe* | *Mn* | *Ni* | *Pb* | *Zn* |
|---|---|---|---|---|---|---|---|---|---|---|
| AYR | | | | | | | | | | |
| Mean±std.dev. | 6264±1843$^{ab}$ | 0.005±0.002 | 0.39±0.94 | 11.99±8.31$^{a}$ | 7.82±2.18$^{b}$ | 8788±1726$^{ab}$ | 1275±550$^{b}$ | 13.63±14.45 | 5.25±1.81 | 15.48±2.09$^{b}$ |
| Min.-Max. | 3665-8915 | 0.003-0.008 | 0.01-2.89 | 5.53-31.30 | 4.97±11.95 | 6375-11233 | 77-2080 | 1.91-47.81 | 3.48-12.27 | 12.27-19.28 |
| BDR | | | | | | | | | | |
| Mean±std.dev. | 2888±1136$^{b}$ | 0.008±0.003 | 0.08±0.02 | 0.93±0.92$^{b}$ | 5.65±0.74$^{b}$ | 6363±1759$^{b}$ | 1865±611$^{ab}$ | 0.002±0.001 | 2.07±2.01 | 13.74±5.93$^{b}$ |
| Min.-Max. | 2015-4434 | 0.005-0.011 | 0.06-0.11 | 0.07-2.18 | 4.88-6.41 | 5300-8980 | 1241-2662 | 0.001-0.003 | 0.01-4.77 | 7.14-21.01 |
| BCR | | | | | | | | | | |
| Mean±std.dev. | 10158±5220$^{a}$ | 0.008±0.005 | 0.10±0.07 | 9.10±4.72$^{ab}$ | 19.32±9.04$^{a}$ | 11522±3056$^{a}$ | 3047±1034$^{a}$ | 5.09±6.71 | 5.01±3.33 | 23.56±9.63$^{ab}$ |
| Min.-Max. | 4979-19505 | 0.003-0.014 | 0.03-0.22 | 5.17-18.15 | 13.02-35.22 | 7696-15549 | 1546-4167 | 0.98-18.47 | 0.01-9.46 | 15.10-38.83 |
| UBR | | | | | | | | | | |
| Mean±std.dev. | 4763±317$^{ab}$ | 0.060±0.003 | 0.09±0.03 | 3.75±0.34$^{ab}$ | 15.42±7.90$^{ab}$ | 7124±214$^{ab}$ | 2380±892$^{ab}$ | 1.76±2.48 | 6.76±4.85 | 47.78±45.63$^{a}$ |
| Min.-Max. | 4538-4987 | 0.040-0.080 | 0.07-0.11 | 3.51-3.99 | 9.83-21.01 | 6973-7275 | 1749-3010 | 0.002-3.51 | 3.32-10.19 | 15.51-80.05 |

**Table 3 (Continue)- Reservoir sediment heavy metal concentrations (in mg kg$^{-1}$) and some physicochemical characteristics***

| | *C* | *Si* | *F.S* | *C.S* | *pH* | *EC* | *O.M* |
|---|---|---|---|---|---|---|---|
| AYR | | | | | | | |
| Mean±std.dev. | 5.69±3.34$^{b}$ | 12.28±9.44$^{b}$ | 74.47±14.67$^{a}$ | 7.29±2.89 | 7.75±0.16 | 0.40±015$^{b}$ | 0.72±0.53 |
| Min.-Max. | 2.04-12.25 | 2.04-28.57 | 46.96-86.77 | 3.72-12.25 | 7.46-7.92 | 0.22-0.68 | 0.15-1.78 |
| BDR | | | | | | | |
| Mean±std.dev. | 12.22±6.19$^{ab}$ | 18.15±6.67$^{ab}$ | 64.42±10.70$^{ab}$ | 5.21±1.85 | 7.49±0.42 | 1.07±0.68$^{a}$ | 1.22±0.98 |
| Min.-Max. | 8.16-21.28 | 12.25-24.44 | 52.74-73.94 | 2.58-6.53 | 7.02-7.87 | 0.27-1.92 | 0.36-2.49 |
| BCR | | | | | | | |
| Mean±std.dev. | 23.92±11.38$^{a}$ | 33.64±20.87$^{a}$ | 34.69±27.66$^{b}$ | 7.73±2.83 | 7.34±0.32 | 1.02±0.33$^{a}$ | 1.76±1.75 |
| Min.-Max. | 6.12-34.69 | 8.16-64.58 | 8.96-78.75 | 4.37-12.31 | 6.87-7.70 | 0.42-1.39 | 0.25-4.40 |
| UBR | | | | | | | |
| Mean±std.dev. | 15.62±7.36$^{ab}$ | 12.50±2.95$^{ab}$ | 61.69±12.35$^{ab}$ | 10.18±2.04 | 7.57±0.08 | 0.73±0.07$^{ab}$ | 0.65±0.52 |
| Min.-Max. | 10.42-20.83 | 10.41-14.59 | 52.96-70.43 | 8.74-11.63 | 7.52-7.63 | 0.68-0.78 | 0.28-1.02 |

* C (Clay) (%), Si (Silt) (%), F.S (Fine sand) (%), C.S (Coarse sand) (%), EC (Electrical conductivity) (dS m$^{-1}$), O.M (Organic matter) (%): Means in the same column followed by the different letter for each criterion are significantly different at the 0.05 level (Tukey's test).

There were significant differences in average Al, Cr, Cu, Fe, Mn, Zn, clay, silt, fine sand, and EC of reservoir sediments ($P<0.05$). BCR had a higher Al concentration than BDR; AYR had a higher Cr concentration than BDR; BCR had a higher Cu concentration than AYR and BDR. BCR had a greater Fe concentration than BDR. BCR had a higher Mn content than AYR, UBR had a higher Zn content than AYR and BDR. Such differences in some heavy metal concentrations (Al, Cr, Cu, Fe, Mn, and Zn) were attributed to lithogenic properties. Buccione et al. (2021) indicated the reasons of Cr, Cu, and Zn in the Pietro del Pertusillo (Italy) reservoir sediments as geogenic/lithogenic processes. BCR had greater clay and silt contents than AYR. AYR had higher fine sand content than BCR. BDR and BCR had greater EC values than AYR. AYR sediments were classified as 55.56% sandy, 22.22% loamy-sand, 22.22% sandy-loam; BDR sediments were classified as 50% loamy sand, 25% sandy clay loam**;** BCR sediments were classified as 16.67% sandy loam, %16.67 loamy sand, 33.32% silt loam, 16.67% clay loam, 16.67% silt clay loam; UBR sediments were classified as 50% sandy-loam and 50% sandy-clay-loam. There were no significant differences in Cd, Co, Ni, Pb, coarse sand, pH, and organic matter contents of reservoir sediments. Sediment pH value was measured as 7.75 for AYR, 7.49 for BDR, 7.34 for BCR and 7.57 for UBR and they were all slightly alkaline.

### *3.2. Comparison of reservoir sediment heavy metal concentrations with the other studies*

In this study, heavy metal concentrations of sediments taken from four reservoirs were compared with the other reservoirs of Türkiye and the reservoirs of the other countries (Table 4). While Al concentration of AYR, BDR and UBR was lower than in the other reservoirs of Türkiye, Al concentration of BDR was found to be higher than Süreyyabey reservoir and lower than the others (Çubuk II, Atıkhisar, and Değirmendere) and the average shale value. Present Cd concentrations were found to be lower than the average shale value of reservoirs and water bodies of Türkiye and other countries. Co concentrations were lower than Süreyya Bey, Çubuk II, Atıkhisar, Değirmendere, Wadi Al-Aqiq Reservoirs and the average shale value. While Cr concentrations of AYR and BCR were higher than reservoirs of Algeria and Poland and lower than the others (Çubuk II, Süreyyabey, Atikhisar, Alemşah, Değirmendere, Hammaz Grouz Dam, Wadi Al-Aqiq Water Reservoir Dam, Lake Nasser), Cr concentrations of BDR and UBR were lower than the reservoirs of other countries and higher than the average shale value of Türkiye. Fe concentrations of 4 reservoirs were lower than the other reservoirs (Süreyyabey, Çubuk II, Alemşah, Değirmendere, Wadi al-Aqiq, Konsin River, and Lake Nasser) and average shale value. Mn concentration of AYR was higher than the reservoirs of others countries, except for Nigeria. Mn concentrations of BDR, BCR and UBR were higher than the other studies. While Ni concentration of AYR was higher than Alemşah Earth Fill Dam and Jezewoir Reservoirs and lower than the other water bodies, Ni concentrations of three reservoirs (BDR, BCR, and UBR) were lower than the mean values of the other reservoirs. Present Pb concentrations were lower than the values of the other reservoirs of Türkiye and the other countries, except for Algeria, and the average shale value. Zn concentrations of present reservoirs were lower than the other studies and the average shale value. Present findings revealed that there was no significant heavy metal contamination, except Mn, in the sediments of AYR, BDR, BCR and UBR. Mn, which makes up approximately 0.1% of the Earth's crust, is usually found in olivine, clay minerals, feldspar, apatite, anorthite and biotite minerals (Atabey 2015; Post 1999). Parlak et al. (2023) stated that Mn was formed by geochemical weathering of rocks (pedogenic processes). It is also estimated that sediment heavy metal concentrations of different reservoirs varied greatly with natural factors such as anthropogenic sources and rock weathering (Table 4). Heavy metal concentrations (Cd, Cu, Cr, Ni, Pb, and Zn) of the sediments sampled from reservoirs were determined to be lower than TEL and PEL. This result shows that heavy metals in sediments do not have a harmful effect on benthic organisms. Ustaoğlu et al. (2022) reported that TEL and PEL values for Pb, Cd, Zn, Cu, Ni, and Cr in Sera Lake Nature Park sediments did not pose a risk to sediment biota. Kankılıç et al. (2013) found that Zn, Cu, Pb, and Cd in Kapulukaya Dam Lake sediments did not have a negative effect on aquatic organisms.

**Table 4- Comparison of present heavy metal concentrations with the heavy metal concentrations of the sediments in various parts of the world and sediment quality**

| *Study location* | *Al* | *Cd* | *Co* | *Cu* | *Cr* | *Fe* | *Mn* | *Ni* | *Pb* | *Zn* | *References* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ADL,Türkiye | 6264 | 0.005 | 0.39 | 7.82 | 11.99 | 8788 | 1275 | 13.63 | 5.25 | 15.48 | This study |
| BDL,Türkiye | 2888 | 0.008 | 0.08 | 5.65 | 0.93 | 6363 | 1865 | 0.02 | 2.07 | 13.74 | This study |
| BcDL,Türkiye | 10158 | 0.08 | 0.10 | 19.31 | 9.10 | 11522 | 3048 | 5.09 | 5.01 | 23.56 | This study |
| UDL,Türkiye | 4763 | 0.06 | 0.09 | 15.42 | 3.75 | 7124 | 2380 | 1.76 | 6.76 | 47.78 | This study |
| Süreyyabey Dam Lake, Türkiye | 8455 | 0.10 | 105.5 | 61.70 | 201.5 | 52651 | 721 | 628.60 | 12.40 | 182.70 | Erdoğan et al. 2023 |
| Çubuk II Dam Lake, Türkiye | 20725 | - | 21.14 | 31.23 | 48.81 | 37510 | 696 | 61.21 | 10.94 | 66.45 | Fikirdeşici Ergen et al. 2021 |
| Atıkhisar Dam Lake, Türkiye | 22742 | 0.37 | 12.80 | 40.26 | 24.50 | 28021 | 732 | 29.10 | 35.51 | 74.40 | Fural et al. 2021 |
| Alemşah Earth Fill Dam, Türkiye | - | - | - | 23.03 | 21.52 | 18505 | 296 | 9.44 | 8.39 | 30.99 | Parlak et al. 2021 |
| Degirmendere Dam Lake, Türkiye | 20397 | 0.11 | 7.10 | 16.00 | 41.00 | 16161 | 387 | 22.00 | 9.00 | 26.00 | Varol et al. 2022 |
| Hammam Grouz Dam, Algeria | - | 1.59 | - | 2.85 | 5.60 | - | - | - | 1.86 | 68.00 | Aissaoui et al. 2017 |
| Wadi Al-Aqiq Water Reservoir Dam, Saudi Arabia | - | - | 14.20 | 50.29 | 50.58 | 22670 | 482 | 30.04 | 6.81 | 37.07 | Alghamdi et al. 2019 |
| Konsin River and Igboho Dam Reservoir, Nigeria | - | 0.86 | - | 32.17 | 33.43 | 33850 | 1536 | - | 44.20 | 119.24 | Asomba et al. 2023 |
| Hussain Sagar Lake, India | - | 19.89 | - | 90.11 | 90.00 | - | - | 47.04 | 79.89 | 273.14 | Ayyanar & Thatikonda 2020 |
| Lake Nasser, Egypt | - | 0.18 | - | 21.78 | 30.79 | 12418 | 280 | 27.56 | 10.91 | 35.38 | Goher et al. 2014 |
| Jezewo Reservoir, Poland | - | 0.40 | - | 10.10 | 6.50 | - | - | 5.90 | 17.6 | 903.70 | Sojka et al. 2018 |
| Mean Sediment Values | - | 0.17 | - | 33.00 | 72.00 | - | - | 52.00 | 19.00 | 95.00 | Salomons & Förtsner 1984 |
| Average Shale Values | 80000 | 0.30 | 19.00 | 45.00 | 90.00 | 47200 | 850 | 68.00 | 20.00 | 95.00 | Turekian & Wedepohl1961 |
| Threshold Effect Level (TEL) | - | 0.59 | - | 35.70 | 37.30 | - | - | 18.00 | 35.00 | 123.00 | Mac Donald et al. 2020 |
| Probable Effect Level (PEL) | - | 3.53 | - | 197.00 | 90.00 | - | - | 36.00 | 91.30 | 315.00 | Mac Donald et al. 2020 |

### *3.3. Determination of sediment heavy metal sources*

Correlation analysis and factor analysis were performed to determine the sources of heavy metals in reservoir sediments. Table 5 shows the correlation coefficients between heavy metals and some physicochemical properties (particle size distribution, pH, and organic matter) of reservoir sediments. Significant positive correlations was seen between Cd and silt (r= 0.44) ($P<0.05$); highly significant positive correlations between Co and Cr (r= 0.74), between Co and Ni (r= 0.82) ($P<0.01$); highly significant positive correlations between Cu and Fe (r= 0.71), between Cu and Mn (r= 0.68), between Cu and Zn (r= 0.64), between Cu and clay (r= 0.57), between Cu and silt (r= 0.68), between Cu and organic matter (r=0.67) ($P<0.01$); significant positive correlations between Cu and Pb (r= 0.43) ($P<0.05$); significant negative correlations between Cu and fine sand (r= 0.69) ($P<0.01$); significant negative correlations between Cu and pH (r= 0.53) ($P<0.05$); significant positive correlations between Cr and Ni (r= 0.96) ($P<0.01$); significant positive correlations between Fe and Mn (r= 0.64) ($P<0.01$); significant positive correlations between Fe and silt (r=0.53), between Fe and organic matter (r=0.60) ($P<0.05$); significant negative correlations between Fe and fine sand (r= 0.47) ($P<0.05$); significant positive correlations between Mn and clay (r= 0.79), between Mn and silt (r= 0.78), between Mn and organic matter (r=0.65) ($P<0.01$); significant negative correlations between Mn and fine sand (r= 0.82) ($P<0.01$); significant negative correlations between Mn and pH (r=0.49) ($P<0.05$); significant positive correlations between Pb and Zn (r= 0.56)

(P<0.01); highly significant negative correlations between clay and silt (r= 0.73) (P<0.01); significant positive correlations between clay and pH (r= 0.50), between clay and organic matter (r= 0.51), (P<0.05); significant negative correlations between silt and fine sand (r= 0.95), between silt and organic matter (r= 0.69), and between pH and organic matter (r= 0.69) (P<0.01). Fikirdeşici Ergen et al. (2021) worked on sediments of reservoirs in Ankara and reported highly significant positive correlations between Co and Ni (P<0.01); significant positive correlations between Cu and Fe (P<0.05); between Cu and Zn (P<0.01); between Pb and Zn (P<0.01); highly significant positive correlations between Ni and Cr (P<0.01) and significant positive correlations between Fe and Mn (P<0.05). Sojka et al. (2023) conducted research on the sediments of reservoirs in Poland and reported a strong relationship between Ni and Cr (r= 0.94). Researchers reported that no correlation was detected between heavy metals and pH, EC, and organic matter of the sediments.

**Table 5- Correlation matrix for correlations between sediment heavy metals, particle size distribution, pH, and organic matter**

| | *Cd* | *Co* | *Cu* | *Cr* | *Fe* | *Mn* | *Ni* | *Pb* |
|---|---|---|---|---|---|---|---|---|
| Cd | 1 | | | | | | | |
| Co | 0.12 | 1 | | | | | | |
| Cu | 0.15 | -0.01 | 1 | | | | | |
| Cr | -0.12 | 0.74** | 0.30 | 1 | | | | |
| Fe | -0.04 | -0.13 | 0.71** | 0.37 | 1 | | | |
| Mn | 0.27 | -0.17 | 0.68** | 0.05 | 0.64** | 1 | | |
| Ni | -0.12 | 0.82** | 0.14 | 0.96** | 0.16 | -0.10 | 1 | |
| Pb | -0.14 | -0.07 | 0.43* | 0.20 | 0.33 | 0.17 | 0.11 | 1 |

| | *Zn* | *C* | *Si* | *F.S* | *C.S* | *pH* | *O.M* |
|---|---|---|---|---|---|---|---|
| Zn | 1 | | | | | | |
| C | 0.17 | | | | | | |
| Si | 0.19 | 0. 073** | 1 | | | | |
| F.S | -0.20 | 0.0.90** | 0.95** | 1 | | | |
| C.S | 0.09 | 00.12 | 0.03 | -0.19 | 1 | | |
| pH | -0.22 | 0 0.50* | -0.41 | 0.49* | -0.17 | 1 | |
| OM | 0.23 | 0 0.51* | 0.75** | 0.69** | 0.01 | -0.69** | 1 |

Heavy metals (mg $kg^{-1}$), C: Clay (%), Si: Silt (%), F.S: Fine sand (%), C.S: Coarse sand (%), O.M: Organic matter (%): * P<0.05: ** P<0.01

In PCA, 3 components with eigenvalues values greater than 1 were identified (Table 6). These 3 components explained 74.83% of the total variance. Component 1, which is responsible for 35.62% of the total variance, consists of Cu, Fe and Mn. Of these 3 heavy metals, Fe and Mn are the most abundant in Earth's crust (Kabata-Pendias 2011; Algül & Beyhan 2020). Although Cu was generally of anthropogenic origin (Bhuyan et al. 2023), it showed a significant positive correlation with Fe. Such a case shows that Cu is of natural origin. Low CF values of Cu also support this phenomenon. The second component explained 21.16% of the total variance and showed strong positive loading values for Cr and Ni. The EF and CF values of Cr and the EF, $I_{geo}$ and CF values of Ni, except for AYR, were found to be low (Table 7). In addition, Cr and Ni concentrations in sediments of 4 reservoirs did not exceed PEL values. Varol et al. (2022) indicated that Cr and Ni in sediments of three stagnant water bodies in Northern Türkiye were of natural origin. Furthermore, Tumuklu et al. (2023), working on Gümüşler Reservoir sediments, indicated the origin of Cr and Ni as the weathering of mafic rocks in the research area. Component 3, which showed strong positive loading values for Co and Zn, explained 18.06% of the total variance (Table 7). In sediments of all reservoirs, EF, $I_{geo}$ and CF values were determined to be low for Co and only CF values were determined to be low for Zn (Table 7). Additionally, Zn concentrations of the sediments did not exceed PEL values (Table 4). Therefore, it was concluded that Co and Zn were of geogenic origin. Cüce et al. (2022) indicated the terrestrial origin of Co & Bhuyan et al. (2023) stated that Zn is naturally present in Earth's crust. Additionally, Canpolat et al. (2022) reported that heavy metals (Co, Cr, Cu, Fe, Mn, Ni, and Zn) in Keban reservoir (Türkiye) sediments originate from lithological units of the study area.

**Table 6- Varimax rotated component matrix for heavy metals***

| | *Component 1* | *Component 2* | *Component 3* |
|---|---|---|---|
| Cd | 0.310 | -0.551 | 0.520 |
| Co | 0.037 | 0.318 | **0.699** |
| Cu | **0.895** | 0.171 | 0.071 |
| Cr | 0.289 | **0.895** | 0.235 |
| Fe | **0.807** | 0.336 | -0.072 |
| Mn | **0.882** | -0.178 | 0.094 |
| Ni | 0.097 | **0.921** | 0.260 |
| Pb | 0.427 | 0.386 | -0.504 |
| Zn | 0.035 | 0.155 | **0.759** |
| Eigenvalues | 3.206 | 1.904 | 1.625 |
| % of variance | 35.622 | 21.158 | 18.052 |
| % cumulative variance | 35.622 | 56.780 | 74.832 |
| Kaiser- Meyer- Olkin measure of sampling adequacy | | | 0.667 |
| Bartlett's test of sphericity | | | 0.000 |

*: Bold values are factor loadings of the principal components

**Table 7- Enrichment factor (EF), geoaccumulation index ($I_{geo}$), contamination factor (CF), potential ecological risk factor ($Er^i$), pollution load index (PLI), potential ecological risk index (RI), and toxic risk index (TRI) values of sediment heavy metals**

| | *Cd* | *Co* | *Cu* | *Cr* | *Mn* | *Ni* | *Pb* | *Zn* |
|---|---|---|---|---|---|---|---|---|
| EF values | | | | | | | | |
| AYR | 0.65 | 0.33 | 4.22 | 1.41 | 22.42 | 3.25 | 4.64 | 3.19 |
| BDR | 2.44 | 0.10 | 6.68 | 0.19 | 74.98 | 0.001 | 4.43 | 6.19 |
| BCR | 0.79 | 0.03 | 6.45 | 0.57 | 35.99 | 0.55 | 2.55 | 3.02 |
| UBR | 0.98 | 0.06 | 10.15 | 0.50 | 56.36 | 0.55 | 7.46 | 11.91 |
| $I_{geo}$ values | | | | | | | | |
| AYR | -3.41 | 0.16 | 1.06 | 1.54 | 2.67 | 1.30 | 0.75 | 1.49 |
| BDR | -3.27 | 0.11 | 0.97 | 0.60 | 2.67 | -1.23 | 0.07 | 1.44 |
| BCR | -3.36 | 0.10 | 1.30 | 1.50 | 2.67 | 0.99 | 0.49 | 1.57 |
| UBR | -3.42 | 0.15 | 1.25 | 1.31 | 2.64 | -0.02 | 0.80 | 1.65 |
| CF values | | | | | | | | |
| AYR | 0.05 | 0.16 | 0.31 | 0.09 | 1.77 | 0.24 | 0.35 | 0.24 |
| BDR | 0.08 | 0.003 | 0.23 | 0.008 | 2.60 | 0.0001 | 0.14 | 0.21 |
| BCR | 0.07 | 0.004 | 0.77 | 0.07 | 4.25 | 0.09 | 0.34 | 0.36 |
| UBR | 0.06 | 0.004 | 0.62 | 0.025 | 3.32 | 0.03 | 0.45 | 0.74 |
| $E_r$ values | | | | | | | | |
| AYR | 1.4 | - | 1.56 | 0.19 | - | 1.23 | 0.71 | 0.24 |
| BDR | 2.5 | - | 1.14 | 0.02 | - | 0.0002 | 0.28 | 0.21 |
| BCR | 2.3 | - | 3.85 | 0.14 | - | 0.45 | 0.68 | 0.36 |
| UBR | 1.8 | - | 3.08 | 0.05 | - | 0.15 | 0.91 | 0.74 |
| | | AYR | | BDR | | BCR | | UBR |
| PLI values | | 2.49 | | 3.04 | | 5.38 | | 4.78 |
| RI values | | 47.94 | | 16.47 | | 46.73 | | 13.44 |
| TRI values | | 10.95 | | 1.09 | | 6.37 | | 1.83 |

### *3.4. Contamination degree and ecological risk indices of heavy metals*

The average EF, $I_{geo}$, CF, PLI, Er, RI and TRI values calculated for the sediments of each reservoir are given in Table 7. EF and $I_{geo}$ indices were used to detect natural and anthropogenic sources of sediment heavy metals (Aykır et al. 2023; Kükrer et al. 2020). While the EF values of Cd, Co and Cr in AYR were below 2 (‘minimal enrichment’ level), the EF values of Cu, Ni, Pb and Zn varied between 2–5 (‘moderate enrichment’ level), and the EF value of Mn was determined at a very high enrichment level. The EF values of Co, Cr and Ni in BDR were determined at 'minimal enrichment' level, the EF values of Cd and Pb were between 2-5 (‘moderate enrichment’ level) and the EF of Mn was determined ‘very high enrichment’ level. While the EF values of Cd, Co, Cr and Ni in BCR and UBR were <2 (‘minimal enrichment’ level), the EF values of Cu were between 5-20 (‘significant enrichment’ level) and the EF values of Mn were determined ‘very high enrichment’ level. In four reservoirs, the $I_{geo}$ values of Cd were found to be negative (‘uncontaminated’ level), the $I_{geo}$ values of Co and Pb were determined to be between 0-1 (‘uncontaminated to moderate contaminated’ level), and the $I_{geo}$ values of Mn were determined to be between 2–3 (‘moderately to heavily contaminated’ level). The $I_{geo}$ values of Cu, Cr, Ni and Zn in AYR were determined to be between 1–2 (‘moderate contaminated’ level). The $I_{geo}$ values of Cr and Pb in BDR were between 0–1 ('uncontaminated to moderately contaminated' level), the $I_{geo}$ value of Ni was <0 (‘uncontaminated’ level) and the $I_{geo}$ values of Zn were between 1–2 (‘moderate contaminated’ level). In BCR and UBR, the $I_{geo}$ values of Cu, Cr and Zn were determined to be between 1–2 (‘moderate contaminated’ level), while the $I_{geo}$ values of Pb were between 0–1 (‘uncontaminated to moderate contaminated’ level). CF was used to determine the degree of contamination of each heavy metal of the sediment (Hakanson 1980). Except for Mn, CF values of other heavy metals were found to be <1 (‘low contamination’ level). The CF values of Mn varied between 1–3 (‘moderate contamination’ level), in AYR and BDR and between 3–6 (‘considerable contamination’ level) in BCR and UBR. Yüksel et al. (2024) determined EF, CF, and Igeo values in the sediments of Almus Dam Lake (Turkey) as low to no contamination.

The Er value is used to determine the potential ecological risk of each heavy metal in the sediment (Hakanson, 1980). Er values varied between 1.56 (Cu) and 0.19 (Cr) in AYR, between 2.5 (Cd) and 0.0002 (Ni) in BDR, between 3.85 (Cu) and 0.14 (Cr) in BCR, between 3.08 (Cu) and 0.05 (Cr) in UBR. Er values are determined in the low-risk class for heavy metals. PLI provides an overall assessment of heavy metal contamination in sediment (Zoidou & Sylaious 2021). PLI values were >1 in all reservoirs, indicating that they were 'contaminated'. Potential ecological risk index (RI) was used to determine the total ecological risk of heavy metals (Aykır et al. 2023). RI values were determined as 47.94 for AYR, 16.47 for BDR, 46.73 for BCR, and 13.44 for UBR. Such a case showed that four reservoirs were in the low-risk class. Toxic risk index (TRI) is used to determine the toxic effects of elements (Zhang et al. 2016). TRI values were determined as 1.09 for BDR and 1.83 for UBR. In BDR and UBR, heavy metals were detected in the "no toxic risk" class. TRI values were determined as 10.95 (moderate toxic risk) in AYR 6.37 in BCR (low toxic risk). Fural et al. (2020) reported TRI values in the sediments of İkizcetepeler Dam Lake (Turkey) as between 4 - 6.6. The researchers reported that TRI in sediment samples were in no toxic risk and low toxic risk class.

## 4. Conclusions

In this study, which is important in terms of determining and risk assessment of heavy metal-containing sediments, which are one of the risks of ecological diversity, sediment sources, sediment heavy metal concentrations, physicochemical characteristics, contamination status of heavy metals and potential ecological risks were investigated in four reservoirs used for drinking and irrigation water supply in northwest Türkiye. There were significant differences in sediment Al, Cr, Cu, Fe, Mn, and Zn concentrations, particle size distribution, and EC values. Except for Mn, sediment heavy metal concentrations were generally lower than the other water bodies. Multivariate statistical analyses (correlation analysis and PCA) were also performed in this study. Correlation analyses revealed significant and highly significant (1% and 5% level) correlations between majority of the heavy metals. Such a case indicated that contamination sources were coming from the same and similar transport processes. PCA revealed the natural sources of heavy metals. Except for Mn, EF values of heavy metals were within the range of minimal enrichment and moderate enrichment, $I_{geo}$ values of heavy metals were within the range of uncontaminated ile moderate uncontaminated, and CF values were determined to be low contamination. Er, RI and TRI values of reservoir sediments indicate low ecological risk; PLI values were determined as “contaminated degree”. For better risk assessment of heavy metals in similar ecosystems, chemical fractionation of sediments should be performed. For sustainable management of reservoirs, sediment heavy metal concentrations should be monitored regularly.

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