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Assessing the Influence of Proximity to Mining Sites on Water Contamination by Pb, Hg, Cd, and as

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Abstract

Water, an essential element for sustaining life, is increasingly threatened by contamination from anthropogenic activities. Mining plays a key role in mobilizing naturally occurring heavy metals from the Earth's crust into surrounding ecosystems. However, few studies have quantitatively assessed how proximity to mines affects heavy metal levels in local drinking water sources. This study evaluated the influence of distance from an active mining site on heavy metal (Pb, Hg, Cd, As) concentrations in drinking water. Sixty samples were collected from three zones located 0–5 km, 5–15 km, and 15–30 km away and analyzed using inductively coupled plasma–optical emission spectrometry (ICP–OES). Significant differences were found among zones for As ($p<0.001$, $H=48.490$), Cd ($p<0.001$, $F=12.454$), and Hg ($p<0.001$, $H=33.173$), while Pb showed no significant variation ($p=0.181$). Mean As (24.56–1249.89 µg/L), Cd (1.83–8.89 µg/L), and Hg (1.59–4.75 µg/L) levels exceeded WHO/BIS drinking water limits, whereas Pb remained within acceptable ranges (<10 µg/L). The findings suggest that mining activities contribute substantially to heavy metal enrichment in nearby drinking water sources. Regular monitoring and strict control measures are essential to safeguard water quality, particularly in communities located close to mining operations.

Keywords Mining pollution · Heavy metals · Drinking water contamination · ICP-OES analysis · Environmental risk assessment

Introduction

Water is the most essential element for sustaining life on Earth. All living organisms depend on water for their health and the proper functioning of physiological processes. It is also fundamental to ecosystem integrity, serving as the basis for all other natural resources necessary for life. Physiologically, water performs multiple vital functions it transports essential nutrients and oxygen to cells, participates actively in digestion and metabolism, dissolves minerals and nutrients, filters the blood, and facilitates the removal of waste products from the body (Bochynska et al. 2024; Münzel et al. 2025). Beyond its biological importance, water also plays a critical role in economic development, particularly in agriculture, industry, and hydroelectric power generation. The Earth's total water volume is estimated to be approximately 1.39 billion cubic kilometers. Oceans constitute the vast majority of this volume, while glaciers, groundwater, lakes, rivers, and soil moisture account for smaller portions. However, only about 2.5% of global water resources are freshwater, and merely 20–30% of this freshwater is directly accessible for human and animal use. Consequently, water pollution and its sustainable management have become increasingly critical in recent years. Rapid population growth, climate change, and the expansion of mining and industrial activities are among the main drivers of the global water crisis, contributing to growing water stress in future projections. Metals and other pollutants released into the environment from these activities can accumulate in soil, air, and water bodies, posing

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significant risks to both ecosystem and human health (Al-Ansari et al. 2021; NASA, 2024).

Metals with an atomic density greater than 4.5 g/cm³ are classified as heavy metals. Since the beginning of the 21st century, heavy metals have accounted for a substantial portion of water pollutants due to their persistence, bioaccumulation potential, and toxicity even at trace concentrations, posing a significant environmental concern (Masindi & Muedi, 2018; Xiang et al. 2022). Among the major sources of heavy metals, mining activities are particularly critical—not only for the organisms inhabiting mining areas but also for the broader environment through transport and dispersion processes. Toxic metal particles released into the atmosphere from mining operations may settle in water bodies and riverbanks, where they can persist for hundreds or even thousands of years. Today, millions of organisms across North and South America, Asia, and other regions of the world inhabit aquatic ecosystems that may contain dangerously high concentrations of residues derived from current or historical metal mining activities (Macklin et al. 2023; Jomova et al. 2025).

Metal mining operations including ore extraction, crushing and grinding, beneficiation (e.g., flotation, cyanide or thiosulfate leaching), and tailings disposal can significantly increase the transfer of heavy metals to surface and groundwater through acid mine drainage (AMD), fine particle transport, and tailings dam leakage. During these processes, pH reduction and complex formation (e.g., chloride and sulfate complexes) enhance the solubility and mobility of metals, leading to a distance-dependent spatial gradient of contamination, typically showing a peak near the mine source and a gradual decrease with distance. Because heavy metals cannot be degraded or destroyed, they persist as permanent components of the environment. Their toxicity, driven by interactions among ecological, nutritional, and environmental factors, has become an increasing global concern. Understanding metal pollution levels resulting from mining activities provides a better understanding of background metal concentrations, which can vary significantly depending on the geology/lithology, soil type, and dominant biogeochemical processes of the region. This significantly enriches the infrastructure for regional studies (Moulatlet et al. 2023).

This study was conducted in the same geographical regions as Celebi et al. (2025); however, it addresses a different research question and methodological scope. In the previous study, boron exposure associated with boron mining was investigated through the analysis of boron only, across multiple matrices including water, feed, urine, and serum. In the present study, the focus was shifted—building upon the same regional sampling framework—to the determination of lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) concentrations in environmental water samples. Although both studies employed ICP-OES, differences in target analytes required adjustments in wavelength selection, calibration ranges, quality assurance procedures, and sample preparation protocols to meet the specific analytical requirements of heavy metals. Consequently, while the previous study focused on boron exposure across environmental and biological matrices, the present one evolved toward a quantitative assessment of heavy metal pollution and its distance-dependent spatial distribution. The primary objective of this study is to evaluate the level and spatial variation of heavy metal contamination in surface waters potentially affected by mining activities. The study aims to reveal, in detail, the impact of mining operations on the water quality gradient by considering short-, middle-, and long-distance categories from the mining site.

In this respect, the study is unique as it represents a multi-elemental (Pb, Cd, As, Hg) assessment conducted within a previously characterized mining region. In addition, it provides complementary data to the earlier study conducted by Celebi et al. (2025), which focused solely on boron, thereby contributing to a more comprehensive evaluation of environmental risks in other mining regions as well.

Materials and Methods

Study Areas and Sample Collection

The water samples examined in this study were collected from the same three sampling sites where boron analyses were previously performed (Celebi et al. 2025) during the same field work. However, in this study, arsenic, lead, cadmium, and mercury analyses were performed instead of boron. The present study was conducted to investigate the impact of mining activities on the concentrations of other heavy metals in water, in addition to boron.

The Bigadiç district of Balıkesir, located in the Marmara Region of Turkey, was selected as the study site due to its proximity to active mining operations. The mine in İskele was designated as the central reference point, and sampling zones were defined based on radial distance: 0–5 km (short area, SA), 5–15 km (middle area, MA), and 15–30 km (long area, LA) (Fig. 1). Sampling sites were selected using a stratified purposive sampling strategy, in which the study area was first divided into distance-based zones and, within each zone, drinking-water sources actively used by animals and local residents were

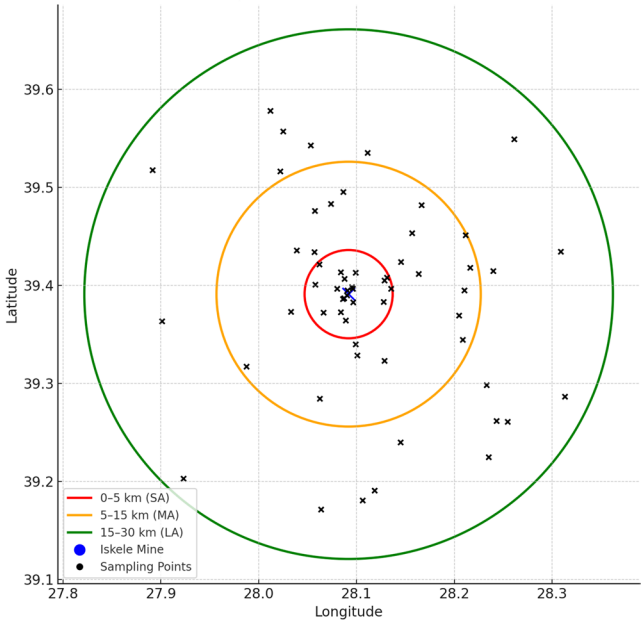

Fig. 1 Sampling locations around İskele Mine (Bigadiç, Balıkesir)

deliberately chosen to represent real exposure conditions. The study area in Bigadiç (Balıkesir) is part of a Neogene volcano-sedimentary lacustrine basin dominated by claystone and tuff formations, which may influence groundwater permeability and trace-metal mobility. These fine-grained lacustrine formations have low permeability, which can slow groundwater movement but enhance the adsorption and accumulation of trace metals within the sediment matrix.

Drinking-water samples were primarily collected from livestock farms within each sampling zone, including water taken directly from well outlets and from containers or troughs from which animals routinely consume water. In addition, samples were obtained from mosque fountains and other public fountains used by local residents for drinking and water collection. These water sources are supplied predominantly by groundwater (wells and boreholes) and natural springs rather than centrally treated municipal water, and therefore represent drinking-water sources that are directly influenced by local geological conditions and mining-related environmental contamination.

Water sampling was conducted in June, corresponding to the transition between the wet and dry seasons in the study area. During this period, rainfall events are infrequent and dilution effects are minimal, allowing the measured metal concentrations to reflect relatively stable background levels. This period was selected to more accurately represent the baseline heavy metal concentrations in drinking water, independent of seasonal dilution effects. Conducting the sampling at this time minimized the short-term influence of surface runoff while capturing the residual effects of recent precipitation on metal mobility.

Analysis of Heavy Metals

Water samples were collected in pre-cleaned high-density polyethylene (HDPE) bottles. Immediately after collection, samples were acidified to pH < 2 using ultrapure concentrated nitric acid (HNO_3, Merck, ≥ 65%) to prevent metal adsorption onto container walls and precipitation. All samples were stored and transported in ice-filled coolers at approximately 4 °C to minimize chemical changes prior to analysis. The holding time between sampling and digestion did not exceed 7 days, in accordance with the APHA (3030B, 2023) and USEPA Method 200.7 preservation guidelines. The method of Celebi et al. (2025) was then used for the digestion and analysis of the samples. The digestion procedure followed the guidelines of the United States Environmental Protection Agency (USEPA) Method 200.7 and the APHA Standard Methods for the Examination of Water and Wastewater (3030E) for trace metal analysis. A reagent mixture consisting of 65% nitric acid (HNO_3) and 35% hydrogen peroxide (H_2O_2) was used for sample digestion. Prior to digestion, water samples were filtered through 0.45 µm membrane filters to remove suspended solids and particulate matter. The filtrates were subsequently heated under controlled sub-boiling conditions to avoid volatilization losses and maintained for a prescribed period until complete digestion was achieved. The digested samples were then diluted to a final volume of 10 mL with ultrapure deionized water (resistivity ≥ 18.2 MΩ cm) before instrumental analysis. All prepared liquid samples were analyzed using a Perkin Elmer OPTIMA 7300 ICP–OES instrument. Instrument calibration, performance verification, and detection limits were determined in accordance with Celebi et al. (2025) and the referenced standard methods (Tokay and Bagdat, 2022).

For mercury (Hg), several measurements, particularly in the long-area group, were close to the instrumental limit of detection (LOD). Values above the LOD but below the limit of quantification (LOQ) were retained but interpreted with caution, whereas measurements below the LOD were treated as non-detects and excluded from statistical analyses. Group means and medians were well above the LOD, indicating that the observed spatial trends reflect real environmental variation rather than analytical uncertainty.

Table 1 Operating parameters of the ICP-OES (Perkin Elmer OPTIMA 7300 DV) used in this study. Adapted from Celebi et al. (2025).

Parameter	Value	Unit	Notes
Torch viewing	Axial		With Hg lamp recalibration system
RF power	1300	W	Manufacturer-recommended setting
Nebulizer type	Cross-flow		Ensures stable aerosol generation
Spray chamber type	Glass cyclonic		Improves aerosol desolvation
Plasma gas flow rate	15	L min^{-1}	Argon
Auxiliary gas flow rate	0.2	L min^{-1}	Argon
Nebulization gas flow	0.8	L min^{-1}	Argon
Sample uptake rate	1.5	mL min^{-1}	Controlled via peristaltic pump
Delay time	60	s	Time before measurement
Wash rate	1.5	mL min^{-1}	Argon flush
Wash time	30	s	Cleans sample pathway between analyses

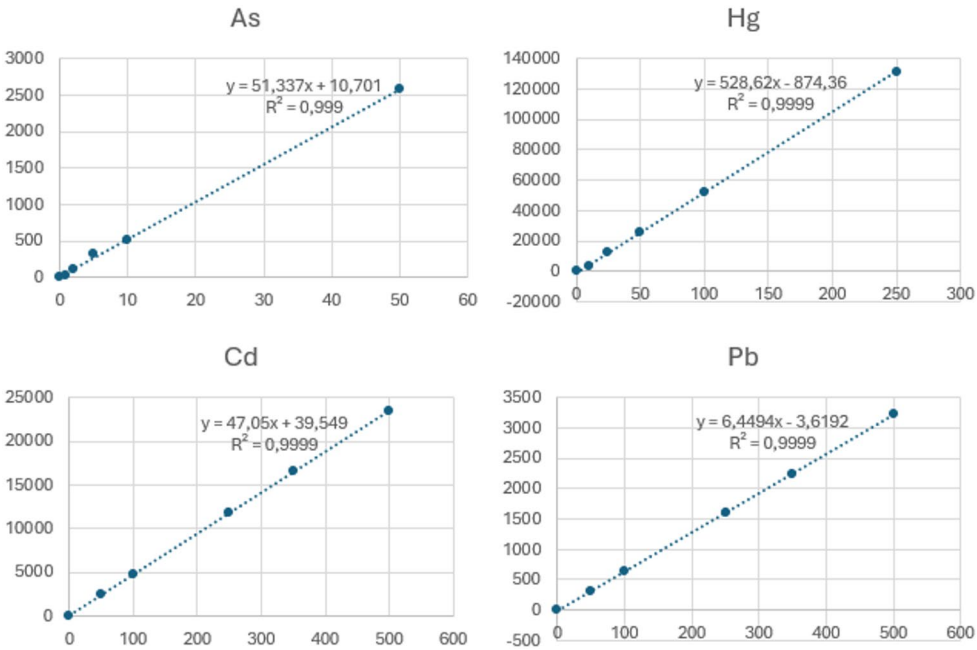

Fig. 2 Calibration curves for arsenic (As), mercury (Hg), cadmium (Cd), and lead (Pb) obtained by ICP-OES. Each curve was constructed using five concentration levels (50, 100, 250, 350, and 500 ppb). All calibration plots demonstrated excellent linearity with correlation coefficients (R^2)≥0.999

Operating Conditions for ICP-OES

A table of operating conditions for ICP-OES has been created (Celebi et al. 2025). The quantification of the analytes was performed using a PerkinElmer 7300 DV ICP-OES instrument (Waltham, MA, USA). The spectrometer was operated under parameters specified by the manufacturer, with detailed operating conditions provided in Table 1.

Linearity

Linearity was evaluated in accordance with the guidelines of the International Council for Harmonisation (ICH Q2(R1)) and the United States Environmental Protection Agency (EPA) method validation protocols. Calibration curves were constructed at concentrations of 50, 100, 250, 350, and 500 ppb. All curves demonstrated excellent linearity with coefficients of determination (R^2)≥0.999 (Fig. 2).

Limit of Determination (LOD) and Limit of Measurement (LOQ)

The limits of detection (LOD) for As, Cd, Pb, and Hg in water samples were 2.65 µg/L, 5.47 µg/L, 5.49 µg/L, and 3.51 µg/L, respectively. The corresponding limits of quantification (LOQ) were 8.02 µg/L, 18.22 µg/L, 18.29 µg/L, and 11.69 µg/L. LOD and LOQ values were determined based on a signal-to-noise ratio of 3:1 and 10:1, respectively.

Quality Assurance/Quality Control (QA/QC)

Method accuracy was verified using a certified reference material (CRM, 250 ppb trace elements in water). Three replicate analyses yielded concentrations of 250.0, 250.9,

and 249.7 ppb, with an average value of 250.2 ppb. The calculated recovery was 100.1%, and the relative standard deviation (%RSD) was <0.5%, demonstrating both the accuracy and precision of the method (Celebi et al. 2025).

To ensure analytical reliability, internal standards (Yttrium for As, Cd, and Pb; and Indium for Hg) were added to all samples and calibration solutions to correct for matrix effects and instrumental drift. Procedural blanks were analyzed after every 10 samples to monitor potential contamination, and no significant background signal was detected.

For mercury (Hg), it should be noted that several measured concentrations were close to the method detection limit. Although certified reference material and internal standards were used to verify accuracy, results at these low levels may carry higher uncertainty.

Statistical Analysis

The data collected during the study were digitized and organized using Microsoft Excel, after which statistical analyses were performed with SPSS (Statistical Package for the Social Sciences) software, version 29.0 (IBM Corp., Armonk, NY, USA). Prior to hypothesis testing, the distributional characteristics of the numerical variables were evaluated through skewness and kurtosis statistics, as well as visual assessments using histogram plots and Q–Q plots. The results indicated that the numerical data did not conform to the assumption of normality. Categorical variables were summarized as frequencies and percentages, whereas numerical variables were described using mean, standard deviation, median, minimum, and maximum values. For comparisons involving three independent groups, the non-parametric Kruskal–Wallis test was applied. When the Kruskal–Wallis test indicated statistical significance, Dunn–Bonferroni post-hoc tests were used for pairwise comparisons between the sampling zones. Statistical significance was determined at a p-value threshold of <0.05 for all analyses. All graphical representations were prepared using GraphPad Prism (version 10.0; GraphPad Software, San Diego, CA, USA).

Results

Heavy metal levels in water samples are shown in Fig. 3.

Table 2 shows the As concentrations in water samples obtained from 3 different locations. According to the data presented in the table, there are statistically significant differences in arsenic (As) concentrations among water samples collected from short, middle, and long area. The Kruskal-Wallis H test yielded an H value of 48.490 with a p value of <0.001, indicating that the observed differences among the groups are statistically significant and not due to random variation. Post-hoc comparisons reveal significant differences between all three groups ($3<1$, $3<2$, $2<1$). Mean and median values show a clear and significant decrease in arsenic concentrations from short to long areas. These findings indicate that arsenic pollution is much higher near the source, and levels decrease substantially as the areas increases.

Table 3 compares the mean Cd concentrations in water samples taken from short, middle, and long areas. The One Way ANOVA test results show an F-value of 12.454 and a p-value of <0.001, indicating statistically significant differences among the groups. The mean values indicate that Cd concentration is highest in the short areas group (8.89 µg/L), lower in the middle group (3.68 µg/L), and lowest in the long areas group (1.83 µg/L). According to the statistical comparisons, both the middle and long areas groups have significantly lower Cd concentrations compared to the short areas group. In summary, Cd concentration decreases significantly as the areas from the contamination source increases.

Table 4 compares the lead (Pb) concentrations in water samples collected from short, middle, and long areas. The mean values are 7.03, 5.20, and 8.24 µg/L for the short, middle, and long areas groups, respectively. According to the One Way ANOVA test results, the F value is 1.759 and the p value is 0.181. Since the p value is greater than 0.05, there is no statistically significant difference among the groups. In other words, lead concentrations do not significantly differ based on sampling areas.

Table 5 shows the Hg concentrations in water samples obtained from 3 different locations. According to the data in the table, there are statistically significant differences in mercury (Hg) concentrations among water samples collected from short, middle, and long areas. The Kruskal-Wallis H test yielded an H value of 33.173 with a p value of <0.001, indicating that the differences between the groups are statistically significant. Post-hoc analysis shows that mercury levels are highest in the short areas group (mean 4.75 µg/L), lower in the middle group (mean 2.89 µg/L), and lowest in the long areas group (mean 1.59 µg/L). In summary, mercury concentration in water samples significantly decreases as the areas from the pollution source increases.

The measured concentrations of several metals exceeded the guideline limits set by the World Health Organization (WHO, 2022) and the U.S. Environmental Protection Agency (USEPA, 2024), approaching levels considered critical for drinking-water safety and public health. As showed particularly high concentrations, especially in SA, where the mean value exceeded international standards by approximately 125-fold. Cadmium and mercury also surpassed WHO and EPA limits in certain samples, whereas Pb remained within the permissible range across all sampling zones. These findings highlight the potential health

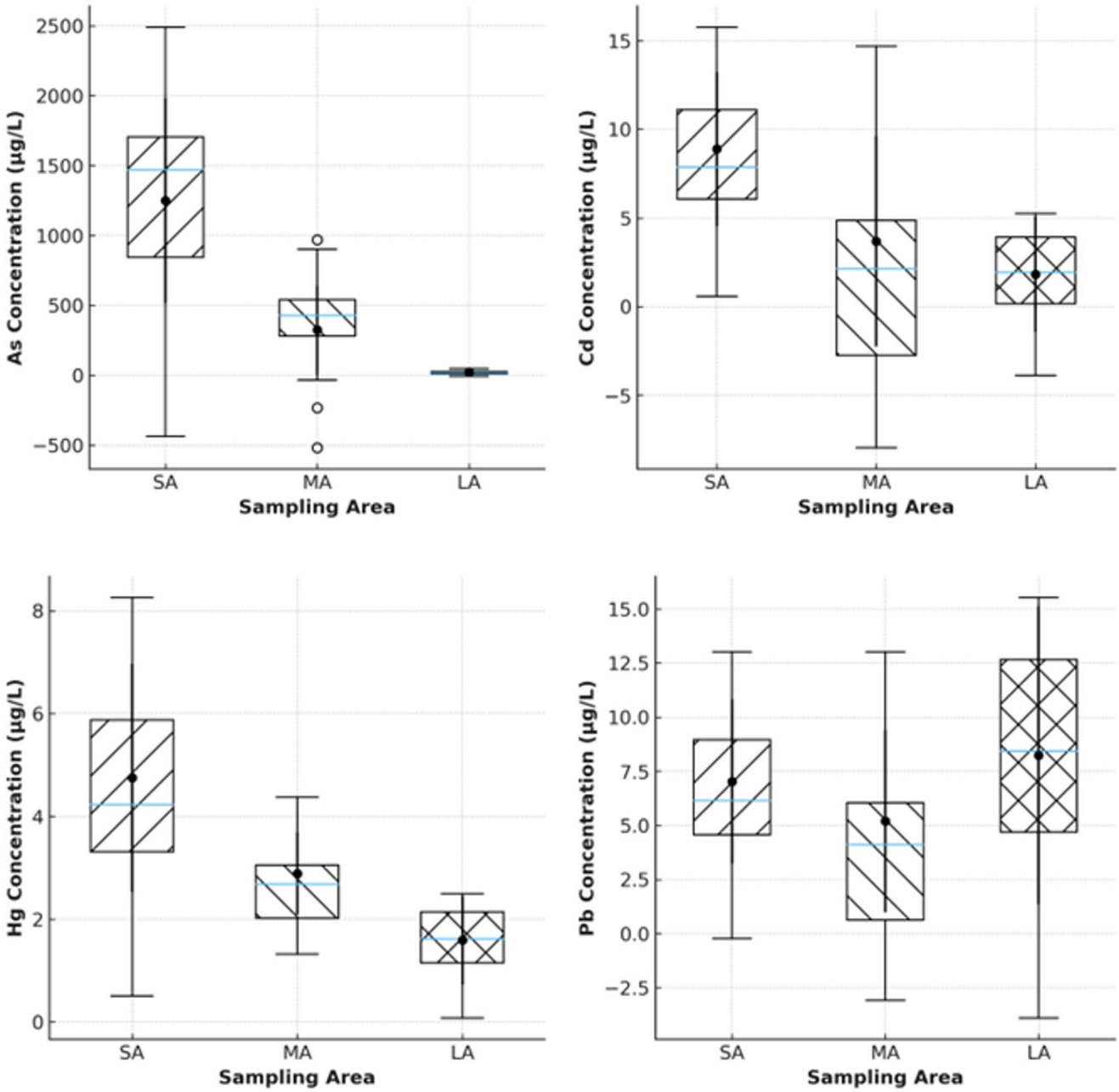

Fig. 3 Heavy metal levels in water samples (SA, short area; MA, middle area; LA, long area)

Table 2 As concentrations in water samples according to area and statistical comparison

	Area	N	$\bar{x}$±SD	Median (min-max)	H	*p*	Difference
As (µg/L)	(1) SA	20	1249.89 ± 730.99	986.50 (353.00-3244.00)	48.490	**< 0.001**	**3 < 1**
	(2) MA	20	324.08 ± 317.15	198.56 (174.28-1081.60)			**3 < 2**
	(3) LA	20	24.56 ± 13.85	21.96 (10.87–62.28)			**2 < 1**

± SD, Mean ± standard deviation, H, Kruskal Wallis H Test, $p < 0.05$

SA: short area, MA: middle area, LA: long area

Table 3 Cd concentrations in water samples according to area and statistical comparison

	Area	N	$\bar{x}$±SD	F	p	Difference
Cd (µg/L)	(1) SA	20	8.89±4.34	12.454	**<0.001**	**2<1**
	(2) MA	20	3.68±5.94			**3<1**
	(3) LA	20	1.83±3.24			

± SD, Mean ± standard deviation; H, Kruskal Wallis H Test, $p<0.05$

SA, short area; MA, middle area; LA, long area

Table 4 Pb concentrations in water samples according to area and statistical comparison

	Area	N	$\bar{x}$ ± SD	F	p
Pb (µg/L)	(1) SA	20	7.03±3.79	1.759	0.181
	(2) MA	20	5.20±4.22		
	(3) LA	20	8.24±6.89		

± SD, Mean ± standard deviation; H, Kruskal Wallis H Test, $p<0.05$

SA, short area; MA, middle area; LA, long area

risk associated with As, Cd, and Hg contamination, while Pb concentrations indicate a relatively lower environmental concern. Concentrations of As, Cd, Hg, and Pb showed clear spatial variation across distance zones, with descriptive statistics presented in Table 6.

Discussion

The Bigadiç region, known for hosting the world's largest colemanite and ulexite deposits, has been extensively studied for the environmental impacts of borate mining. Gemici et al. (2008) reported that borate-bearing formations significantly influence groundwater quality by increasing the concentrations of certain contaminants. In that study, arsenic (As) and boron (B) were identified as the two primary pollutants in groundwater samples collected around the Bigadiç borate mines. Arsenic concentrations ranged from 33 to 911 µg/L and B from 0.05 to 391 mg/L, with the highest B levels detected at mining sites. All samples exceeded the drinking-water limit for As, and the groundwater quality was concluded to be directly related to the borate zones through water–rock interaction processes. These findings indicate that geogenic sources, together with mining activities, play a dominant role in shaping the hydrogeochemical characteristics of the Bigadiç aquifer system.

In a complementary study conducted by our group, water samples collected at near, intermediate, and distant zones from the Bigadiç borate mining area also exhibited high B concentrations, with the highest levels measured in samples closest to the mine (Celebi et al. 2025). The same investigation revealed elevated B concentrations in feed, blood, and urine samples from local livestock, indicating that mining-derived boron contamination has entered the biological exposure pathway. Further support for the heavy-metal risk in this region was provided by Kobya et al. (2022), who used groundwater collected from the Bigadiç colemanite mining area as experimental material in an electrocoagulation study for As removal. Their choice of sampling location highlights the recognized contamination of local waters. Likewise, Parlak et al. (2024) found that soil and waste samples from the Balya and Koru mining sites within Balıkesir Province posed the highest carcinogenic risk for Cd and Pb. They attributed the contamination mainly to nearby mining operations and emphasized the necessity of environmental management plans to mitigate the health impacts of metal exposure. The absence of water and sediment sampling in that work was also noted as a limitation.

Comparable metal contamination has been documented in other mining- and industry-affected areas of Türkiye. Katip (2022) investigated temporal and spatial variations of As in the Nilüfer River, which flows through the industrialized and agriculturally intensive province of Bursa. As concentrations exceeded the limits established by the World Health Organization (WHO) and Turkish National Standards for drinking water, although they remained below irrigation-water thresholds. However, hazard quotient (HQ) values exceeded 1 at all monitoring stations, indicating potential health risks and confirming that mining and industrial discharges substantially contribute to aquatic pollution. Similarly, Pulatsü and Latifi (2023) assessed heavy-metal contamination in Lake Mogan and evaluated associated

Table 5 Hg concentrations in water samples according to area and statistical comparison

	Area	N	$\bar{x}$±SD	Median (min-max)	H	p	Difference
Hg (µg/L)	(1) SA	20	4.75±2.22	3.55 (2.67–11.01)	33.173	**<0.001**	**3<1**
	(2) MA	20	2.89±0.80	3.22 (1.39–3.66)			**3<2**
	(3) LA	20	1.59±0.86	1.49 (0.07–3.27)			

± SD, Mean ± standard deviation; H, Kruskal Wallis H Test, $p<0.05$

SA, short area; MA, middle area; LA, long area

Table 6 Mean concentrations (±SD) of heavy metals (As, Cd, Hg, Pb) in drinking-water samples from different distance zones and their comparison with WHO (2022) and USEPA (2024) guideline limits

Heavy metal	Area	Mean±SD (µg/L)	Comparison with guideline limits (µg/L)
As (Arsenic)	SA	1249.89±730.99	Exceeded WHO (10) and USEPA (10) limits by approximately 125-fold
	MA	324.08±317.15	About 30-fold higher than WHO and USEPA limits
	LA	24.56±13.85	Within 2–6× the permissible range; elevated but below extreme-risk level
Cd (Cadmium)	SA	8.89±4.34	About 3× higher than WHO limit (3) and 1.8× higher than USEPA limit (5)
	MA	3.68±5.94	Slightly above WHO limit; close to USEPA threshold
	LA	1.83±3.24	Within safe range; below both WHO and USEPA limits
Hg (Mercury)	SA	4.75±2.22	Exceeded USEPA limit (2); some samples approached WHO limit (6)
	MA	2.89±0.80	Above USEPA limit; below WHO threshold
	LA	1.59±0.86	Within WHO and USEPA safe limits
Pb (Lead)	SA	7.03±3.79	Below WHO/EPA action level (15); acceptable for drinking water
	MA	5.20±4.22	Within permissible range
	LA	8.24±6.89	Below the 10 safety threshold; minor local variations observed

SA, short area; MA, middle area; LA, long area

health risks for adults and children. Their results showed higher HQ values for children, suggesting greater vulnerability to metals such as Hg, As, Cd, Cr, Pb, Ni, Cu, and Zn, with As posing the greatest risk. These findings collectively underscore the widespread and persistent nature of As contamination in Turkish freshwater systems.

The results of the present study align with previous research, confirming that mining operations play a significant role in the contamination of surface and groundwater resources. Together with the earlier investigation conducted in the same area (Celebi et al. 2025), the present findings indicate a multi-element contamination pattern with potential ecological and health implications. The observed decrease in As, Cd, and Hg concentrations with increasing distance from the mining area likely reflects the combined effects of hydrogeochemical attenuation processes. Dilution by uncontaminated groundwater reduces metal concentrations downgradient, while adsorption onto clay minerals and Fe/Mn oxides immobilizes trace metals near the source zone. Furthermore, co-precipitation and pH buffering in the slightly alkaline aquifers of the region enhance metal removal from solution. Hydrogeological dispersion and changes in redox potential may also contribute to the decline in dissolved metal mobility away from the mine. In contrast, Pb concentrations did not differ significantly among sampling zones ($p > 0.05$). The relatively uniform Pb distribution is likely attributed to geogenic background levels associated with local lithology and to widespread atmospheric deposition from regional industrial and vehicular emissions rather than direct mining influence. Moreover, the presence of a Pb mine within Balıkesir Province and additional local sources such as industrial facilities, traffic, and air-pollution zones may have contributed to the overall Pb burden, resulting in a spatially homogeneous distribution. Such patterns are consistent with observations from other mining regions worldwide (Fisher et al. 2021; Cipriani-Avila et al. 2020).

Overall, the elevated metal concentrations recorded in this study some exceeding WHO guideline values indicate potential risks to both environmental and public health. Heavy metals such as As, Cd, Pb, and Hg are recognized as priority pollutants due to their toxicity, persistence, and bioaccumulation potential. High levels of these elements in groundwater may lead to long-term ecological degradation and adverse health outcomes. Therefore, preventive measures, including continuous groundwater monitoring, stricter regulation of mining discharges, and comprehensive environmental-management strategies, are urgently required. The exceedance of WHO limits in multiple samples indicates a high potential frequency of standard violations, implying chronic exposure risks. Based on the elevated and spatially heterogeneous concentrations of Hg and As observed in drinking and domestic water sources from the Bigadiç mining region, groundwater monitoring should be stratified according to contamination risk, with high-risk sources located near mining and tailings areas sampled more frequently than background locations. In addition, water-quality data from the Bigadiç region should be integrated into a regional early-warning system to identify emerging Hg or As contamination and enable timely regulatory or public-health interventions, such as restricting contaminated sources from potable use or providing alternative water supplies. Expanded and more frequent investigations of water resources surrounding mining areas are essential to better evaluate contamination dynamics and to protect ecosystem and human health in the Bigadiç region.

This study revealed the impact of borate mining conducted in the Bigadiç region one of the world's most important borate deposits on groundwater quality and provided new data on the spatial distribution of a multi-element contamination profile for As, Cd, Pb, and Hg. The study is among the first in Türkiye to quantitatively evaluate such gradients associated with borate mining and serves as a valuable reference for future environmental assessments. The focus on water samples alone, without analyzing seasonal variations and different environmental media (soil, sediment, biological material), is considered a limitation. It is therefore recommended that future studies address these aspects through more comprehensive investigations. The results confirm that mining activities are the primary source of heavy metal pollution in drinking water resources. Therefore, strengthening environmental policies, improving analytical quality control processes, and strictly enforcing water quality standards are critically important for protecting ecosystem and public health in mining-affected regions.

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Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical Approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Human and Animal Participants This article does not contain any studies with human participants or animals performed by any of the authors.

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