

Research Article

Heavy Metal Levels (As, Cd, Hg, Pb, B) in Well and Tap Water from Savaştepe, Balıkesir (Türkiye): An ICP-MS Based Risk Assessment

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ABSTRACT

Heavy metal contamination is an increasing environmental and public health concern, especially in regions where agricultural, domestic, and mining activities overlap. This study evaluated arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb), and boron (B) concentrations in well and tap water from the Savaştepe district of Balıkesir, Türkiye. Twenty samples were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) following American Public Health Association and United States Environmental Protection Agency protocols. Samples were digested with HNO₃/H₂O₂, stored at 4 °C, and quantified using calibration curves between 10–500 ppb (R² ≥ 0.999). Detection and quantification limits were determined using signal to noise ratios of 3 and 10, and values below LOQ were treated using the LOQ/2 method. Clear spatial variation was observed, with well water exhibiting higher As, Pb, and B levels than tap water. Mean concentrations were 2489.20 ± 3270.43 ppb (As), 13.99 ± 20.46 ppb (Cd), 0.0135 ppb (Hg), 504.01 ± 240.93 ppb (Pb), and 12083.32 ± 12913.85 ppb (B). Several well samples exceeded WHO and USEPA limits, particularly for As and Pb, indicating contamination likely linked to geological and mining activities. These findings emphasize the need for regular monitoring and mitigation in Savaştepe.

Keywords: Arsenic, Heavy metals, ICP-MS, Water pollution, Savaştepe (Balıkesir)

ARTICLE INFO

Received:

28.11.2025

Accepted:

02.03.2026

Balıkesir (Türkiye) Savaştepe Kuyu ve Musluk Suyundaki Ağır Metal Düzeyleri (As, Cd, Hg, Pb, B): ICP-MS Tabanlı Bir Risk Değerlendirmesi

Ö Z E T

Ağır metal kirliliği, özellikle tarımsal, evsel ve madencilik faaliyetlerinin örtüştüğü bölgelerde giderek artan bir çevresel sorundur. Bu çalışmada, Türkiye, Balıkesir'in Savaştepe ilçesindeki kuyu ve musluk suyundaki arsenik (As), kadmiyum (Cd), cıva (Hg), kurşun (Pb) ve bor (B) konsantrasyonları değerlendirilmiştir. Çeşitli yerlerden toplanan yirmi örnek, APHA ve USEPA protokollerine uygun olarak endüktif olarak eşleştirilmiş plazma kütle spektrometrisi (ICP-MS) kullanılarak analiz edilmiştir. Örnekler HNO₃/H₂O₂ ile sindirilmiş, 4 °C'de saklanmış ve mükemmel doğrusalığa (R² ≥ 0,999) sahip 10 ila 500 ppb arasında değişen kalibrasyon eğrileri kullanılarak miktarları belirlenmiştir. Tespit sınırları (LOD) ve miktar belirleme sınırları (LOQ), 3 ve 10 sinyal-gürültü oranları kullanılarak hesaplanmış ve LOQ'nun altındaki değerler LOQ/2 yöntemi kullanılarak istatistiksel olarak ele alınmıştır. Metal konsantrasyonlarında belirgin mekansal değişim gözlemlendi. Kuyu suyunda musluk suyuna kıyasla belirgin şekilde daha yüksek As, Pb ve B seviyeleri görüldü. Ortalama konsantrasyonlar 2489.20 ± 3270.43 ppb (As), 13.99 ± 20.46 ppb (Cd), 0.0135 ± 0.0000 ppb (Hg), 504.01 ± 240.93 ppb (Pb) ve 12083.32 ± 12913.85 ppb (B) idi. Birkaç kuyu örneği, özellikle As, Pb ve B için WHO (2022) ve USEPA (2024) kılavuz limitlerini aştı ve bu durum jeolojik kaynaklar, hidrojeokimyasal seferberlik ve yakındaki madencilik faaliyetlerinden etkilenmiş olma ihtimali olan ciddi kirlenmeye işaret etti. Genel olarak, bulgular önemli bir halk sağlığı endişesini düşündürmekte ve Savaştepe'de sistematik izleme ve azaltma stratejilerine duyulan ihtiyacı vurgulamaktadır. Bu çalışma aynı zamanda gelecekteki çevresel değerlendirmeler için ilçe düzeyinde değerli temel veriler sağlamaktadır.

Anahtar Kelimeler: Arsenik, Ağır metaller, ICP-MS, Su kirliliği, Savaştepe (Balıkesir)

MAKALE BİLGİSİ

Geliş:

28.11.2025

Kabul:

02.03.2026

Cite this article as: Celebi, M. ve Dikici, S. (2026). Heavy metal levels (As, Cd, Hg, Pb, B) in well and tap water from Savaştepe, Balıkesir (Türkiye): An ICP-MS based risk assessment. *Manas Journal of Agriculture Veterinary and Life Sciences*, 16(1), 31-41. <https://doi.org/10.53518/mjavl.1832080>

INTRODUCTION

Water is an essential component of all living organisms and one of the natural resources most rapidly and severely impacted by environmental pollution. As the primary constituent of biological systems, it is fundamental to vital physiological functions, including nutrition, respiration, circulation, and excretion. Consequently, water pollution has emerged as one of the most pressing environmental challenges threatening ecosystem integrity and human health. It is broadly defined as the introduction, dissolution, suspension, or accumulation of harmful substances in water bodies such as lakes, rivers, streams, and groundwater, resulting in the deterioration of their chemical, physical, microbiological, or radiological characteristics. Increasing levels of contamination reduce both the quantity and quality of available freshwater, heighten the prevalence of waterborne diseases, and disrupt ecological stability (Bondar et al., 2019; Pásková et al., 2023). Although approximately 71% of the Earth's surface is covered by water, nearly 97% of this is saline and unsuitable for direct consumption or agricultural use. Of the remaining 3% classified as freshwater, the vast majority exists as glaciers and groundwater, leaving only about 0.06% readily accessible at the surface. Lakes and rivers, which constitute merely 0.3% of global freshwater reserves, serve as critical sources for drinking water, agriculture, industry, aquaculture, and transportation. Groundwater, despite being less accessible, represents the largest freshwater reservoir and is particularly indispensable in regions with limited surface water resources (Shaji et al., 2021; Musie and Gonfa, 2023). A visual overview of global water distribution is presented in "Figure 1."

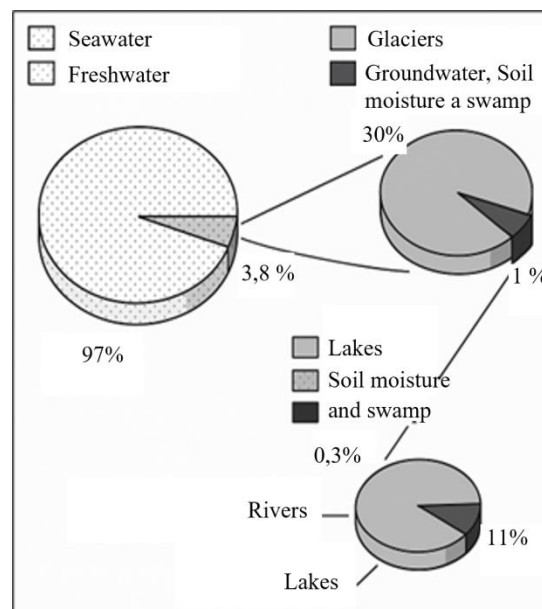


Figure 1. Water resources and rates (Musie and Gonfa, 2023).

Groundwater and surface water function as intrinsically interconnected systems. Groundwater may discharge into surface water bodies and, in turn, be recharged by them. Therefore, any environmental assessment must consider both components simultaneously; contamination introduced at one point in the system can disperse throughout the entire hydrological network. Evaluating only a single component provides an incomplete understanding of the overall impact. Increasing pressures on consumable water resources pose serious threats to ecosystem health and undermine water-dependent livelihoods. The growing mismatch between available freshwater and rising water demand has further intensified concerns regarding water scarcity (Kılıç, 2020; Jones et al., 2022). The quality of freshwater resources is deteriorating due to both natural processes and anthropogenic influences such as industrial development, intensive agriculture, and especially mining-related activities. Water pollutants are generally categorized as chemical (organic and inorganic), physical, and biological agents, among which heavy metals represent a particular concern. Defined as metals with a density greater than 5 g/cm³, heavy metals pose substantial ecological and public health risks due to their chemical stability, environmental persistence, bioaccumulation potential, and long-term toxic effects (Kannan et al., 2021; Ustaoglu et al., 2021). Their impacts on living systems are summarized in "Figure 2."

Lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and boron (B) are of particular importance, as they readily dissolve in water, accumulate in biological tissues, and exert toxic effects even at low concentrations. Chronic exposure has been associated with neurological disturbances, mood changes, cognitive impairment, anxiety, renal and hepatic injury, hematological and immune dysfunction, developmental abnormalities, and various cancers (Aubineau et al., 2022; Dehkordi et al., 2024). Certain pollutants also contribute to early menopause, vasomotor symptoms, decreased bone mineral density, and increased cardiovascular risk. In males, heavy metal contaminated water has been linked to reduced serum LH, FSH, and testosterone levels; increased oxidative stress; enhanced apoptosis in Sertoli and germ cells; impaired spermatogenesis; and altered sperm morphology and concentration. Arsenic may naturally enter groundwater through geochemical mobilization, whereas lead and cadmium frequently originate from metal processing industries, aging pipelines, battery and paint manufacturing, phosphate fertilizers, and mining activities. Mercury is released from coal combustion, industrial effluents, and geothermal regions, and can be transformed into more toxic forms through microbial methylation. Boron contamination, by contrast, is strongly associated with extensive borate deposits and mining operations, particularly in regions such as Balıkesir–Bigadiç, Kütahya–Emet, and Eskişehir–Kırka. Previous studies indicate that proximity to boron mining sites significantly elevates boron concentrations in water and feed sources, with the highest levels observed near active extraction areas (Bochynska et al., 2024; Celebi et al., 2025).

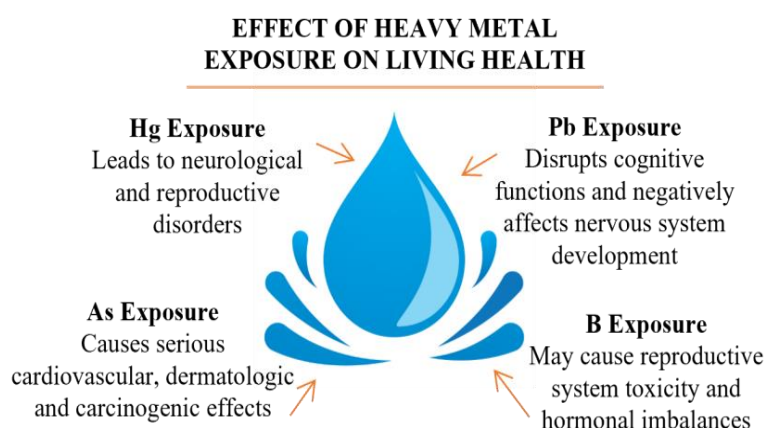


Figure 2. Effects of heavy metal exposure on living health.

Accordingly, determining the concentrations of Pb, Cd, As, Hg, and B in water samples collected from Savaştepe is essential for evaluating regional environmental risks and for comparing the findings with current international water quality standards set by WHO (2022) and USEPA (2024). This study aims to fill a significant gap in the literature by providing up-to-date data on the levels of these contaminants in Savaştepe's water resources and by contributing to a more comprehensive understanding of the region's environmental risk profile.

Table 1. Comparison of WHO (2022) Guideline Values and USEPA (2024) MCLs for Heavy Metals and Boron in Water.

Heavy Metal	WHO 2022 Guideline Value (mg/L)	USEPA 2024-MCL (mg/L)
As	0.01	0.010 (MCL)
Pb	0.01 (Provisional)	0.010 (TT)
Hg	0.006	0.002 (MCL)
Cd	0.003	0.005 (MCL)
B	2.4	No federal MCL; EPA Health Advisory (non-regulatory) suggests longer-term protective levels around ~2 mg/L

¹MCL: Maximum Contaminant Level, TT: Treatment Technique

Balıkesir Province is one of Türkiye's key mining regions and is particularly shaped by the extensive boron reserves located in the Bigadiç district. Savaştepe, a rural district within Balıkesir, depends largely on groundwater and natural springs for drinking and domestic use, underscoring the importance of routine water quality monitoring. The area's geological characteristics, agricultural practices, mining activities, and the dynamic interplay between groundwater and surface water collectively contribute to the potential accumulation of heavy metals and boron in local water sources

Study areas

Sample collection

Sample digestion

Standard preparation and heavy metal analysis

MJAVL Volume 16 (Issue 1) © 2026



to volume with 2% HNO₃. From this stock, calibration standards of 10, 25, 50, 100, 250 and 500 ppb were prepared. Ultrapure water used throughout the preparation was obtained from a Millipore Direct-Q 8 UV system.

ICP-MS instrumentation and operating conditions

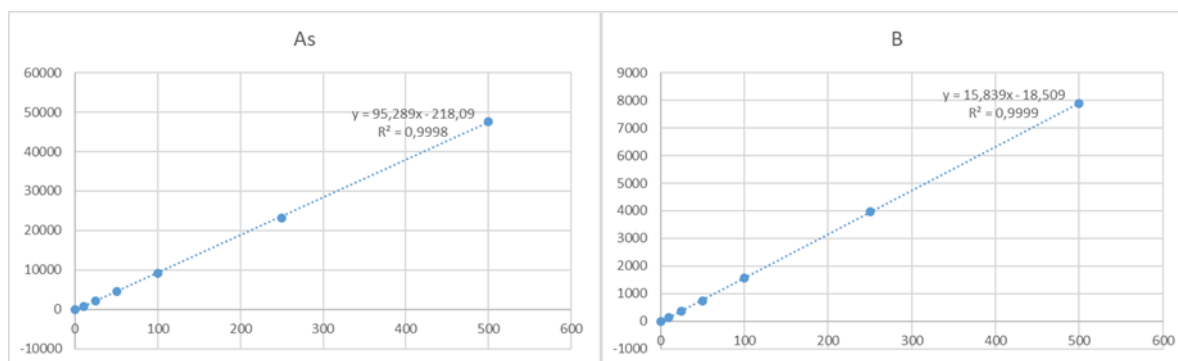
Heavy metal concentrations (As, Pb, Hg, Cd, B) were determined using an Inductively Coupled Plasma–Mass Spectrometer (ICP-MS, Agilent 7800 series, Agilent Technologies, Japan). The system was equipped with a glass MicroMist nebulizer (U-series, Australia), a double-pass quartz spray chamber (USA), and an inert sample introduction kit containing a quartz torch (2.5 mm, Japan). A nickel sample cone and skimmer cone (X-lens type, USA) were used for ion extraction. Prior to analysis, all quartz and glass components were cleaned by soaking in 5–10% HNO₃ overnight, rinsing thoroughly with ultrapure water, and drying in an oven. Nickel components (sample cone and skimmer cone) were cleaned by sequential immersion in ultrapure water, 5% HNO₃, and ultrapure water in an ultrasonic bath for 5 minutes each. After drying, all cleaned components were reassembled. Calibration standards prepared from the stock solution were analyzed to establish and verify calibration curves. Following calibration verification, samples were introduced into the instrument using an autosampler. The autosampler, tubing, and probe were rinsed with 2% HNO₃ and ultrapure water between injections; the probe was additionally rinsed with 1% HCl to prevent carry-over. Instrument control and data processing were performed using MassHunter 4.4 Workstation Software (7800 ICP-MS, TopC.01.04). Selected instrument parameters and operating conditions are summarized in “Table 2.”

Table 2. Operating parameters of the ICP-MS.

Parameter	Value	Unit	Notes
Torch viewing	Axial	–	With Hg lamp recalibration system
RF power	1200	W	Manufacturer-recommended setting
Nebulizer type	MicroMist	–	Ensures stable aerosol generation
Nebulizer pump speed	0.30	rps	-
Spray chamber type	Glass cyclonic	–	Improves aerosol desolvation
Plasma gas flow rate	15	L/min	Argon
Auxiliary gas flow rate	1	L/min	Argon
Carrier gas flow rate	1	L/min	Argon
Device calibration	1	µg/L	Tuning Solution
Nebulization gas flow	0.8	L/min	Argon
Sample uptake rate	0.3-0.4	mL/min	Controlled via peristaltic pump
Delay time	60	s	Time before measurement
Wash rate	1.5	mL/min	Argon flush
Wash time	30	s	Cleans sample pathway between analyses

Linearity

Linearity was assessed in accordance with the International Council for Harmonisation (ICH Q2(R1)) and United States Environmental Protection Agency (EPA) method validation guidelines. Calibration curves were generated at six concentration levels (10, 25, 50, 100, 250, and 500 ppb). All calibration curves exhibited linearity, with coefficients of determination (R^2) of ≥ 0.999 (Figure 4).



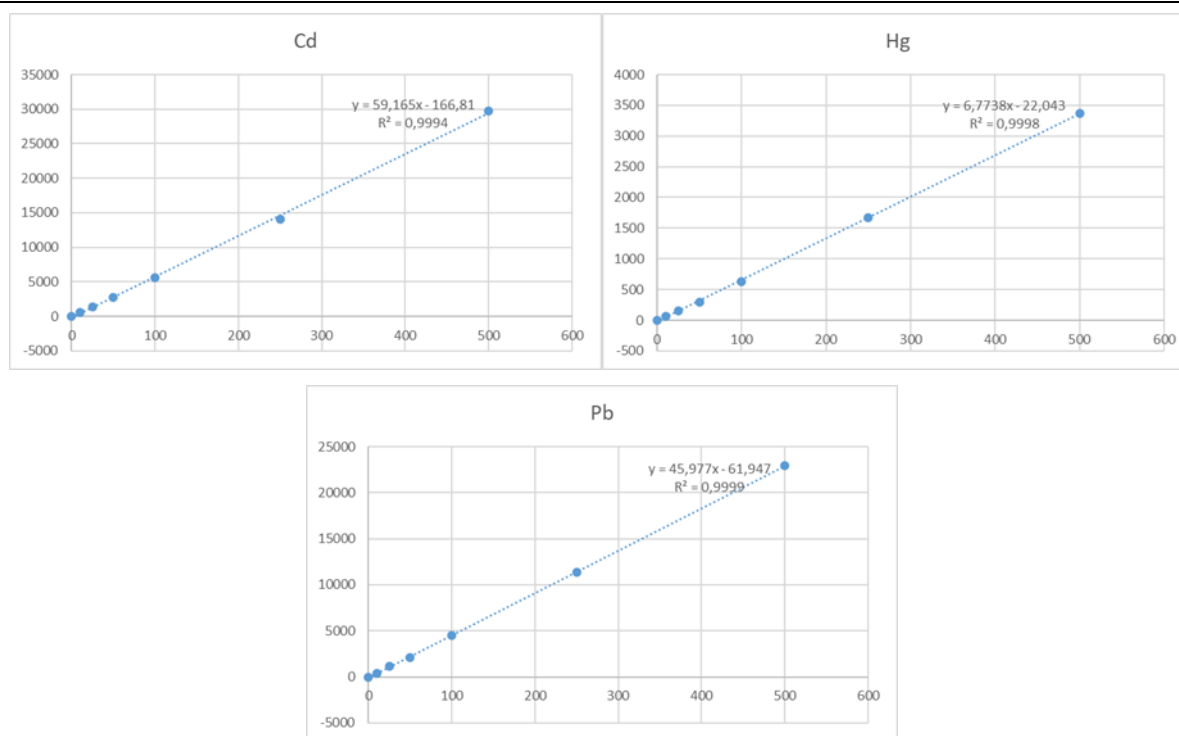


Figure 4. Calibration curves for As, Hg, Cd, Pb and B obtained by ICP-MS. Each curve was constructed using five concentration levels (0, 10, 25, 50, 100, 250, and 500 ppb). All calibration plots demonstrated linearity with correlation coefficients ($R^2 \geq 0.999$).

Limit of determination (LOD) and limit of measurement (LOQ)

LOD values for As, Cd, Pb, Hg, and B were determined as 0.003, 0.001, 0.005, 0.008, and 0.136 ppb, respectively, while the LOQ values were 0.009, 0.002, 0.018, 0.027, and 0.453 ppb. Both LOD and LOQ were established using signal-to-noise ratios of 3 and 10, in accordance with accepted analytical validation criteria for ICP-MS.

Statistical analysis

Differences between well and tap water samples were evaluated using the non-parametric Mann–Whitney U test. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics (Version 20.0; IBM Corp., Armonk, NY, USA)

RESULTS AND DISCUSSION

In this study, the concentrations of As, Cd, Hg, Pb, and B were determined in water samples collected from different sources (tap and well water) in the Savaştepe district. The analytical results revealed substantial variation in element levels across the samples. Notably, several samples exhibited markedly elevated concentrations of As, Pb, and B, whereas Cd and Hg were mostly detected near or below the limit of quantification (LOQ). Mann–Whitney U test results showed that As, Pb, and B concentrations were significantly higher in well water compared to tap water ($p < 0.05$), while no significant differences were observed for Cd and Hg ($p > 0.05$). The sampling locations, source types, and measured concentrations for each sample are presented in detail in “Table 3.”

Table 3. Sampling locations, water sources, and measured concentrations of As, Cd, Hg, Pb, and B in Savaştepe, Balıkesir.

Sample No	Sample Location	Sample Source	As (ppb)	Cd (ppb)	Hg (ppb)	Pb (ppb)	B (ppb)
1	Savaştepe (district center-1)	Well Water	15494.33	<LOQ	<LOQ	383.57	4635.05
2	Savaştepe (district center-2)	Well Water	5124.17	50.88	<LOQ	550.24	6651.28
3	Savaştepe (district center-3)	Tap Water	374.59	<LOQ	<LOQ	<LOQ	7375.59
4	Yeşilhisar 1	Tap Water	882.99	<LOQ	<LOQ	<LOQ	6193.44
5	Savaştepe (district center-4)	Tap Water	2461.69	<LOQ	<LOQ	<LOQ	5788.72
6	Yeşilhisar 2	Tap Water	2756.02	<LOQ	<LOQ	<LOQ	17564.54
7	Savaştepe (market area-1)	Well Water	1873.01	<LOQ	<LOQ	<LOQ	46087.16
8	Savaştepe (market area-2)	Well Water	2394.79	3.63	<LOQ	668.56	4770.0
9	Savaştepe (market area-3)	Tap Water	1658.95	<LOQ	<LOQ	<LOQ	8128.23
10	Savaştepe (public fountain-1)	Well Water	387.96	69.06	<LOQ	496.85	10017.22
11	Savaştepe (market area-4)	Tap Water	709.07	<LOQ	<LOQ	<LOQ	6182.85
12	Yeşilhisar 3	Well Water	1939.91	39.98	<LOQ	<LOQ	3864.94
13	Savaştepe (public fountain-2)	Tap Water	923.11	36.35	<LOQ	<LOQ	5053.94
14	Savaştepe (Ceylanpark-1)	Tap Water	869.6	18.17	<LOQ	<LOQ	5788.75
15	Yeşilhisar 4	Well Water	2394.78	25.44	<LOQ	912.6	7286.79
16	Savaştepe (Ceylanpark-2)	Well Water	2060.32	21.81	<LOQ	260.18	5717.74
17	Savaştepe (district center-5)	Tap Water	2247.61	<LOQ	<LOQ	<LOQ	5362.77
18	Savaştepe (district center-6)	Well Water	3170.77	7.27	<LOQ	150.45	16971.6
19	Savaştepe (district center-7)	Well Water	1739.23	10.9	<LOQ	609.62	16616.06
20	Savaştepe (district center-8)	Tap Water	321.08	3.63	<LOQ	<LOQ	5664.52

In the present study, several measurements for Cd, Hg, and Pb fell below the analytical limit of quantification (LOQ). Because excluding these values from statistical analyses may bias the dataset and artificially underestimate true environmental concentrations, values reported as "<LOQ" were treated using the widely accepted LOQ/2 substitution method. This approach is recommended by major regulatory and scientific bodies, including the World Health Organization (WHO), the United States Environmental Protection Agency (USEPA), and the OECD environmental monitoring guidelines, particularly for trace-level contaminant datasets. Accordingly, each <LOQ measurement was replaced with half of the LOQ value (LOQ/2) for use in subsequent statistical analyses (mean, standard deviation, and data visualization). The LOQ/2 values applied in this study were as follows: As: 0.0045 ppb, Cd: 0.001 ppb, Pb: 0.009 ppb, Hg: 0.0135 ppb and B: Not applicable (no measurements <LOQ). This substitution method preserves the relative distribution and variance of the dataset while preventing overestimation (as would occur if LOQ were used directly) or underestimation (as would occur if LOQ values were set to zero). The LOQ/2 approach is therefore considered an appropriate and scientifically robust strategy for handling censored environmental data in trace-metal analysis.

Table 4. Mean Heavy Metal Concentrations (As, Cd, Hg, Pb, B) in Water Samples Compared with WHO (2022) and USEPA (2024) Limits.

Heavy Metal	Mean $\pm$ SD ($\mu\text{g/L}$)	Comparison with Guideline Limits
As	2489.20 $\pm$ 3270.43	Exceeds both WHO (10 $\mu\text{g/L}$) and USEPA (10 $\mu\text{g/L}$) limits by a very large margin
Cd	13.99 $\pm$ 20.46	Above WHO (3 $\mu\text{g/L}$) and USEPA (5 $\mu\text{g/L}$) limits
Hg	0.0135 $\pm$ ~0.0000	Below WHO (6 $\mu\text{g/L}$) and USEPA (2 $\mu\text{g/L}$) limits
Pb	504.01 $\pm$ 240.93	Extremely exceeds WHO (10 $\mu\text{g/L}$) and USEPA (15 $\mu\text{g/L}$) limits
B	12083.32 $\pm$ 12913.85	Exceeds WHO limit (2. 400 $\mu\text{g/L}$); no federal USEPA MCL (health advisory $\approx$ 2. 000 $\mu\text{g/L}$)

Environmental pollution represents the combined effect of contamination occurring in interconnected components of the ecosystem such as soil, air, and water. Pollutants accumulated in soil can enter the food chain by affecting crop quality and plant health, and may also infiltrate surface and groundwater, contributing to the deterioration of water quality. Processes such as deforestation, climate change, and soil erosion further exacerbate this problem by remobilizing previously bound contaminants. Given that heavy metals tend to adsorb onto soil particles and organic matter, the migration of highly toxic elements such as As, Pb, and Cd into water systems can be particularly pronounced. In addition, the extraction and processing of ores in mining areas directly introduce metals into surrounding environments, further elevating regional contamination levels. However, clean, uncontaminated, and accessible water is essential not only for human health but also for ecosystem sustainability (Mohammad et al., 2025; Münzel et al., 2025).

In this study, levels of As, Pb, B, Cd, and Hg were measured in tap and well water samples collected from different locations in the Savaştepe district, and the findings were evaluated in the context of both regional environmental conditions and international drinking water guidelines. The results revealed that As, Pb, and B concentrations in certain samples markedly exceeded the limits set by WHO (2022) and USEPA (2024), indicating a significant pollution burden at the regional scale. Conversely, the majority of Cd and Hg measurements fell below the LOQ, suggesting that these two elements may not represent a major contaminant source for local water resources. The observation that well waters contained higher concentrations of As, Pb, and B compared to tap waters highlights the potential influence of geological structure, groundwater–rock interactions, and aquifer characteristics on metal mobilization. The higher concentrations observed in well water compared to tap water may also reflect the effect of treatment and dilution processes in distribution systems, whereas groundwater is directly influenced by aquifer geochemistry and local contamination sources. The Balıkesir region is known for its substantial borate deposits, particularly around Bigadiç. Previous studies have reported that geochemical processes such as mineral dissolution, ion exchange, and redox reactions can facilitate elevated concentrations of boron and heavy metals in groundwater (Shaji et al., 2021; Celebi et al., 2025). The fact that boron levels in some sampling points exceeded WHO limits in the present study is consistent with the region's natural boron reserves and the district's proximity to Bigadiç borate fields.

Other research conducted in the Balıkesir region similarly supports these findings. Studies at Pb–Zn mining sites have demonstrated elevated transfer of heavy metals into soil and water, posing a significant public health risk. The elevated As, Pb, and B concentrations recorded in Savaştepe likewise point to combined geological and anthropogenic pressures. However, the substantial variation and high concentrations observed in well waters suggest that site-specific hydrogeochemical conditions may play an even more prominent role (Şimşek et al., 2012). The extremely high Pb concentrations detected in some samples likely indicate localized contamination and strong spatial heterogeneity, possibly related to site-specific geological conditions, old infrastructure, or point-source inputs. Recent investigations around the Balya and Kuru Pb–Zn mining areas have confirmed that heavy metal accumulation persists in soil and mine waste, continuing to present environmental risks (Parlak et al., 2024). Similarly, studies conducted in Ayvalık Saltpan reported elevated heavy metal accumulation in both water and sediment, emphasizing that Pb, Cd, and As enrichment results from geological factors combined with anthropogenic inputs (Ay et al., 2021). Together, these findings align with the results of the present investigation, indicating that metal concentrations in Savaştepe are shaped by regional environmental dynamics. International studies likewise demonstrate that mining and energy production activities play a major role in water contamination. A study from India reported significant Hg, Pb, Cd, and As pollution in groundwater and surface waters located near coal mines, thermal power plants, and ash ponds (Bhardwaj et al., 2020). Another investigation from Nigeria highlighted that groundwater quality is adversely affected by both geogenic and anthropogenic pressures, with Pb and Cd

identified as the major contaminants (Shuaibu et al., 2025). These findings mirror the contamination patterns observed in the present study and show that the pollution profile of Savaştepe is consistent with global trends linking mining-related activities to water degradation. Overall, this study demonstrates that groundwater resources in the Savaştepe district may pose significant risks due to elevated levels of heavy metals and boron. The exceedance of international drinking water standards in some locations indicates potential health risks for the local population. The elevated concentrations of As and Pb detected in several sampling locations may pose significant health concerns for the local population through long-term exposure via drinking water. Chronic arsenic exposure has been associated with increased risks of skin, bladder, and lung cancers, as well as cardiovascular and metabolic disorders. Similarly, lead exposure is well known for its neurotoxic effects, particularly in children, and has been linked to cognitive impairment, developmental delays, and hypertension in adults. Although boron is an essential micronutrient at low levels, excessive intake may adversely affect the reproductive system and endocrine function. In contrast, cadmium and mercury, which were mostly below the LOQ in the present study, are primarily associated with renal toxicity and neurological disorders when present at elevated levels. Although a quantitative human health risk assessment (e.g., hazard quotient or cancer risk estimation) was not performed in this study, the exceedance of international drinking water standards suggests a potential risk under chronic exposure conditions. Recent studies have similarly emphasized that long-term consumption of metal-contaminated groundwater may result in significant non-carcinogenic and carcinogenic health risks, particularly in mining-influenced regions (Wu et al., 2022; Li et al., 2023; WHO, 2022).

The marked spatial variability observed in the groundwater further emphasizes the need for more comprehensive hydrogeochemical investigations. Strengthening periodic monitoring programs, revising water treatment strategies, and developing localized water-protection policies are essential steps for safeguarding public health. This study has several limitations. The sample size was limited and sampling was conducted during a single season, which may not fully represent temporal variability. In addition, a quantitative human health risk assessment (e.g., HQ or cancer risk) was not performed. Future studies including seasonal monitoring and detailed risk modeling are recommended. In conclusion, this research fills an important gap in the literature regarding heavy metal and boron contamination in Savaştepe, and provides an integrated perspective on how natural geochemical processes and anthropogenic influences collectively shape local water quality. The findings offer a valuable basis for future risk assessments and water-management strategies.

CONCLUSION

The findings of this study demonstrate that groundwater and tap water resources in the Savaştepe district exhibit significant variation in heavy metal and boron concentrations, with As, Pb, and B levels in several sampling points exceeding internationally accepted limits. These results indicate that both natural geochemical processes and potential anthropogenic influences play a decisive role in shaping regional water quality. The elevated concentrations particularly observed in well waters highlight the importance of understanding local hydrogeochemical dynamics for effective water-resource management.

From a public-health perspective, evaluating the condition of surface and groundwater environments is essential for clarifying the importance and value of pollution-control strategies. As emphasized in environmental health frameworks, assessing the health benefits of surface-water pollution control can provide more directive and actionable information for water-management policies by measuring the effectiveness of related interventions and regulatory practices. In this regard, the outcomes of the present study underline the need for systematic monitoring programs, improved water treatment processes, and region-specific protection strategies to reduce exposure risks for local communities.

Overall, this research fills a critical gap in the literature by providing up-to-date data on heavy metal and boron contamination in the Savaştepe region. The results serve as an important reference for future environmental risk assessments and contribute valuable evidence to support informed water-management decisions, public-health planning, and sustainable use of regional water resources.

Compliance with Ethical Standards

This research study was conducted in accordance with research and publication ethics.

Ethical approval

This research study complies with research and publication ethics.

Conflict of interest

The authors declared no conflict of interest.

Author contributions

All authors contributed equally.

Funding

This research was supported within the scope of TÜBİTAK-2209 University Students Research Projects Support Programme with Project number 1919B012448883.

Data availability

The original data collected during the study are included in the article. Further inquiries can be directed to the corresponding author.

Statement of Use for Artificial Intelligence and Its Types

Artificial intelligence and its various types were not used in the writing of this article.

Approval for Publication

All authors declare that they have seen and approved the final version of the submitted manuscript

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