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Original Article

Occurrence, Spatial Distribution and Health Risk Assessment of Potentially Toxic Elements (PTEs) in Surface Water Resources, A Case Study in Hamedan, the West of Iran

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Abstract

Background: This study aimed to investigate the concentration of potentially toxic elements (PTEs) including iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd) and lead (Pb) and determine their health risks, and evaluate the water quality of Abbas-Abad, Khako, Moradbeig Valley rivers and Ekbatan Dam inlets and bodies located in Hamadan, Iran.

Methods: In spring 2019, the concentrations of PTEs in water samples collected from 61 stations were quantified using an inductively coupled plasma optical emission spectrometry device. Water quality was evaluated using heavy metal pollution index (HPI), heavy metal evaluation index (HEI), contamination degree , heavy metal toxicity load (HMTL), and environmental water quality index (EWQI) indices. Carcinogenic and non-carcinogenic risks were calculated using cancer risk (CR) and hazard index (HI), respectively.

Results: It was found that the average concentration of Fe and Zn had a statistically significant difference ($P<0.05$). By comparing the metal concentration to the World Health Organization's standard, the concentrations of all elements were below the permissible limit, except for Fe and Cd, in 4 and 5 sampling stations. The quality of water sources revealed a low level of PTE contamination in the studied surface water. According to the HI results, there was no apparent threat to the residents' health. Based on the CR assessment results, the dermal absorption of PTEs for both age groups was classified as low-risk. However, ingestion of these elements was categorized as high-risk.

Conclusion: Since Hamdan's surface water sources are contaminated with PTEs, it is necessary to investigate effective management strategies for preserving the integrity and health of water resources.

Keywords: Potentially toxic elements, Pollution, Heavy metal, Water quality, Hazard, Cancer risk

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Introduction

Population growth, industrial development, urbanization growth, and agricultural modernization have been associated with the discharge of many toxic pollutants into aquatic ecosystems, resulting in ecological threats and diminished water resource quality in many regions of the globe.[1,2] Potentially toxic elements (PTEs), and organic and mineral contaminants frequently contaminate surface water sources, rendering them unusable for domestic, agricultural, and industrial purposes. The discharge of untreated wastewater resulting from urban, industrial, and agricultural practices into surface water sources has contributed to a progressive escalation in the concentration of PTEs within these aquatic ecosystems.[3] PTEs are prevalent toxins in aquatic systems. Some PTEs are considered dangerous and priority pollutants because they have properties of toxicity, resistance, (low biodegradability) and bioaccumulation.[4] The presence of PTEs in aquatic environments may stem from natural phenomena such as soil weathering, volcanic eruptions, and erosion of geological formations. Furthermore, human activities contribute significantly to the introduction of PTEs into water bodies. These activities include the discharge of inadequately treated or untreated wastewater from industrial operations, residential areas, and agricultural activities. Additionally, sources of PTEs include mining activities leading to the deposition of tailings, combustion of fossil fuels, processes involved in metal extraction and refining, drilling operations, transportation activities, and various other anthropogenic endeavors.[1,5,6] Skin/dermal exposure and direct ingestion are the major pathways of PTEs entering the human body. Human exposure to these metals occurs through several pathways: (1) consumption of plants and crops irrigated with water contaminated by PTEs, (2) utilization of industrial products manufactured using polluted water, and (3) consumption of aquatic organisms. Due to their resistance to biodegradation, the long-term accumulation of these elements within human cells, tissues, and organs poses significant health risks, leading to the development of various malignant and non-cancerous diseases. In severe cases, mortality can result.[7,8] Chronic exposure to poisonous PTEs has detrimental impacts on the nervous system, immunity, and endocrine organs, cancer, disability in children and adults,[3,6] stomach diseases, liver and kidney failure, hypertension,[2,9] mutagenicity, and teratogenicity, nutrient deficiency, enzyme dysfunction,[10] anorexia, lung injury, bone fracture, reproductive and hormonal abnormalities.[6,11]

Clinical and epidemiological researches are considered as a reliable tool for public health control and intervention. However, evaluators do not always accept the high economic cost of these studies. In this regard, risk assessment is used as a practical and straightforward method for quantifying the health problems caused by pollutant exposure.[4] Different protection objectives divide risk assessment into health and ecological risk assessments.[12] In general, risk assessment provides information that facilitate decision-making by quantitatively estimating the risk. Also, it can assist the allocating resources to control exposure to environmental hazards.[4] In addition, several indicators for estimating water quality in terms of PTE pollution have been presented. Pollution indicators by showing a combination of the effects of different parameters can be used as important tools by water quality and environment officials as well as decision-makers.[13]

Recent studies have used a variety of indicators to assess and monitor the quality of water resources regarding PTE pollution, including the health risk assessment (HRA), trace element evaluation index (TEI), heavy metal evaluation index (HEI), water pollution index (WPI), environmental water quality index (EWQI), and heavy metal toxicity load (HMTL).[4,8,9,14] To improve environmental protection and administration, it is essential to assess the water quality in areas where PTEs are likely to be contaminated. Conducting exhaustive studies and gaining an adequate comprehension of the water quality in a region is essential for the effective and sustainable management and protection of water resources.[5]

Abbas-Abad (Ganjnameh), Khako, Moradbeig Valley rivers, and Ekbatan Dam inlets and bodies, which are essential rivers and sources of surface water in the densely populated city of Hamadan, as well as the principal sources of drinking and agricultural water supply, have been selected as the focus of this study. Urbanization and anthropogenic activities have exerted a significant impact on the river systems of Hamadan in recent years. This has led to water scarcity issues and a constrained availability of potable water, thereby exacerbating the problem. The close proximity of urban rivers to areas designated for service, welfare, agricultural, and residential purposes, coupled with the inflow of effluents and sewage from diverse sources, has substantially contributed to the pollution of surface water bodies with metals and sediment. Given the presence of PTEs from various sources, compounded by the challenge of water scarcity and the utilization of substandard water for irrigation purposes, it becomes imperative to conduct comprehensive assessments and continuous monitoring of PTE concentrations in the urban rivers of Abbas Abad (Ganjnameh), Khako, and Moradbeig Valley, as well as at the entry points and within the body of the Ekbatan dam. Consequently, the important goals of this research include the following: 1) to evaluate the amount of PTEs pollution and to investigate their spatial changes in the basin of these surface water sources, 2) to use various pollution indices as a quantitative tool to identify high-risk areas based on the PTEs contamination, 3) carcinogenic and non-carcinogenic risk assessment due to PTEs contamination, and 4) comparative analysis following World Health Organization (WHO) drinking water guidelines. Considering the few scattered studies and the lack of a comprehensive study on the contamination of PTEs in the surface water sources of Hamedan County, the results of this study will provide insight into the level of PTE contamination in the surface water sources of Hamadan County. Furthermore, it furnishes essential data that can assist decision-makers in formulating comprehensive regulations and policies aimed at safeguarding the health of individuals.

Materials and Methods

The Study Area

Figure 1 shows the three discrete sources of surface water within Hamadan province. The Khako River stands as a pivotal surface water reservoir for potable consumption in Hamadan. Its diversion occurs primarily during non-agricultural periods. Upon traversing the initial phase of grain collection, the water undergoes refinement processes at the Shahid Beheshti refinery. The Ekbatan Dam, situated approximately 10 kilometers southeast of Hamadan city along the Abshineh River (also known as Yalfan), holds significant prominence as the principal dam within Hamadan province. Positioned below the confluence point of the Yalfan and Eberu rivers, it serves as a critical infrastructure component in the region. The water from the Ekbatan Dam Lake undergoes treatment processes conducted by the Ekbatan and Shahid Beheshti water treatment facilities. Another crucial surface water source within the province is the Abbas Abad River (also known as Ganjnameh). Originating from the Ganjnameh and Tarik Dareh valleys, it merges with the Khako River. The Abbasabad refinery, situated atop Abbasabad Hill, plays a pivotal role in the purification of water derived

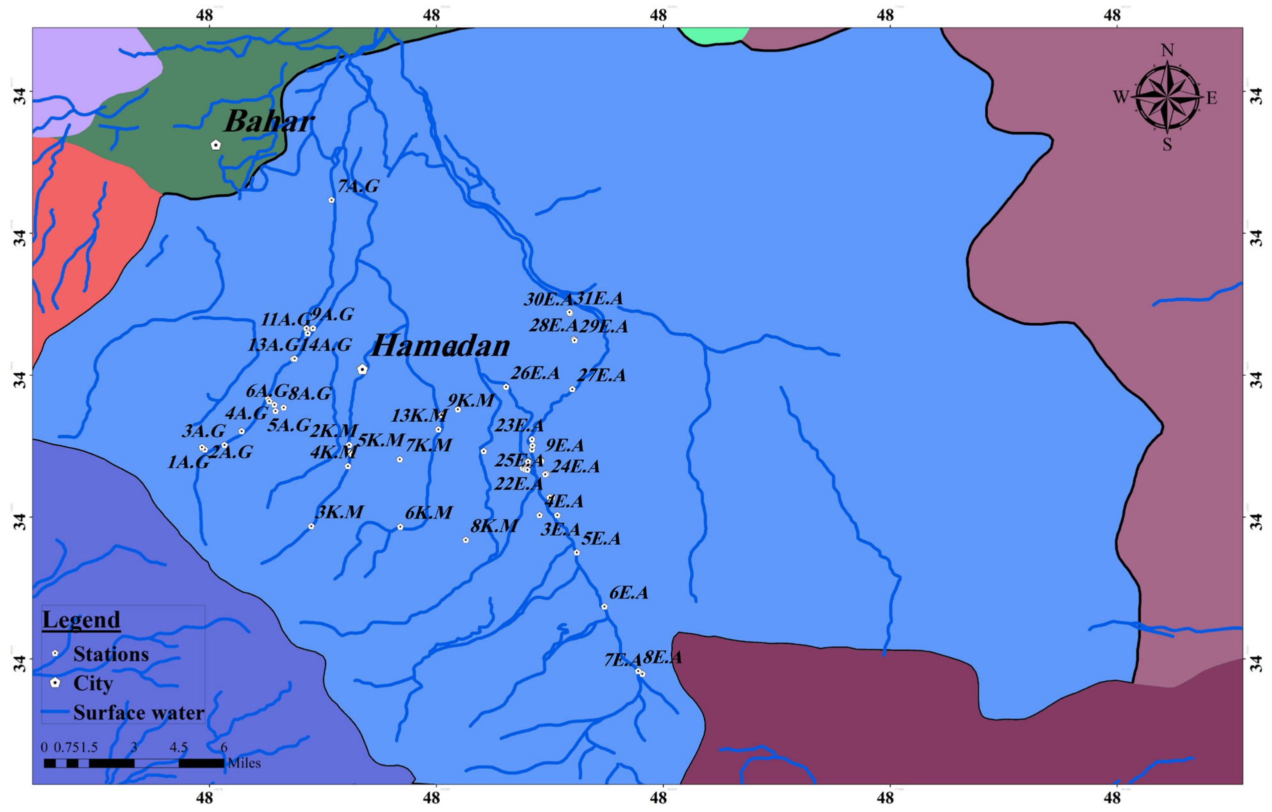

Figure 1. Study Area and SAMPLING SITES

from the Abbasabad River.[15]

Sampling

In spring 2019, a comprehensive sampling campaign was conducted across three primary surface water sources: Abbasabad and Ganjnameh rivers, the Khako and Moradbeig Valley rivers, and the Ekbatan Dam and Abshineh River. A total of 61 sampling stations were strategically selected, considering factors such as proximity, land use patterns, and potential points of contaminant ingress. Specifically, the Abbasabad and Ganjnameh rivers were sampled at 17 stations labeled as 1AG-17AG, while the Khako and Moradbeig Valley rivers were assessed at 13 stations designated as 1KM-13KM. Furthermore, the Ekbatan Dam and Abshineh River were sampled extensively across 31 stations marked as 1EA-31EA (see Figure 1 for reference). The geographical coordinates of each sampling location were recorded using manual GPS devices.

Sampling procedures involved the use of one-liter polyethylene containers, which were meticulously cleaned with distilled water prior to each sampling event. At every designated sampling point, water samples were collected from the water column at depths ranging from 10 to 15 cm. Each individual sample was prepared by combining and thoroughly mixing four subsamples to ensure representative sampling from the respective locations.

Digestion and Analysis of Samples

A 100 mL of the water sample was dispensed into a beaker, to which 5 mL of concentrated nitric acid was added. The resultant mixture was subjected to heating until it reached a final volume of 20 mL, effectively facilitating the digestion of the samples. Following the cooling of the sample, it underwent filtration and was subsequently transferred into a 100 mL container, which was then adjusted to its final volume.[16] The concentration of PTEs was determined utilizing inductively coupled plasma optical emission spectroscopy (ICP-OES).

Validation of the analytical procedure for the quantitative analysis of elements in water samples was conducted through the assessment of detection limit (LOD), recovery, and precision. The perceived LOD values for Lead (Pb), Zinc (Zn), Copper (Cu), Iron (Fe), and Cadmium (Cd) were 0.05 mg/kg, 0.05 mg/kg, 0.05 mg/kg, 0.05 mg/kg, and 0.01 mg/kg, respectively. The average recovery rate ranged between 89% and 101%, with a relative standard deviation (RSD) of 9%.

Pollution Assessment Indices

Heavy Metal Pollution Index

To calculate the combined impact of different heavy metals (HMs) on the quality of surface water resources, the heavy metal pollution index (HPI) was utilized. The HPI index was computed based on equation 1.

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

W_i is the unit weighting of each HM, Q_i is the sub-index for each HM, and n is the number of HMs that are equal to 5 (Fe, Cu, Zn, Cd, and Pb) for this study.

The calculation for the subindex (Qi) is presented in equation 2.

$$2 \quad Qi = \sum_{i=1}^{n} \frac{|M_i - I_i|}{S_i - I_i} \times 100 \tag{2}$$

Where M_i (µg/L) is the measured value of HM. S_i and I_i are the standard and ideal values for drinking water, respectively, according to the WHO for HMs.[14,17]

Heavy Metal Evaluation Index

The HEI indicates the overall health status of the water which is calculated through equation 3.

$$3 \; HEI = \sum_{i=1}^{n} \frac{M_i}{MAC_i} \tag{3}$$

where M_i and MAC_i are the obtained concentration and the maximum acceptable concentration of ith HM, respectively. The quality status of water resources is classified according to HEI as low (<10), moderate (10-20), and high pollution (>20).[5,14]

Contamination degree

Contamination degree is also used to investigate the harmful outcome of HMs on water sources which is determined by equations 4 and 5.

$$Contamination\, degree = \sum_{i=1}^{n} Cf_i \tag{4}$$

$$Cf_i = \frac{M_i}{S_i} - 1 \tag{5}$$

here Cf_i is the HM_i contamination factor, M_i and S_i are the measured and the standard value of ith HM, respectively.[18]

Heavy Metal Toxicity Load

The HMTL index is obtained by multiplying the checked values of HMs with their risk severity and is estimated using equation 6.

$$HMTL = \sum_{i=1}^{n} M_i \times HIS_i \tag{6}$$

where M_i is the concentration of HM; n is the number of HMs and HIS_i is the hazard intensity score of the ith HM based on Agency for Toxic Substances and Disease Registry (ATSDR) HIS values for metals are Zn = 913, Cd = 1318, Pb = 1531, and Cu = 805. Because Fe did not have HIS, it was not included in the HMTL estimation.[14,19,20]

Environmental Water Quality Index

To calculate the EWQI, the heavy metal toxicity index (HMTI) was first obtained, and then the WQI value was divided by the HMTI value. The EWQI was determined by using equation 7.[9]

$$EWQI = \frac{WQI}{HMTI} \tag{7}$$

Human Health Risk Assessment

Human health risk evaluation through ingestion and skin exposure was calculated using equations 8 and 9.[14]

$$ADD_{ing} = \frac{C_i \times IR \times ABS \times EF \times ED \times DI}{BW \times AT} \tag{8}$$

$$ADD_{derm} = \frac{C_i \times SA \times K_p \times ABS \times EF \times ED \times ET}{BW \times AT} \tag{9}$$

ere ADD_i (µg/kg/d) and ADD_d (µg/kg/d) are the mean daily doses with the exposure routes of ingestion and skin contact of water, respectively. Other parameters are as follows: *Ci:* the value of the HMs (µg/L); IR: the amount of ingestion; EF: the exposure frequency; ED: duration of exposure; BW: body weight; AT: meantime for non-carcinogens; SA: skin contact area; Kp: the skin adherence factor; ET: exposure time, and CF is the conversion factor.

The hazard quotient (HQ) was used to obtain non-carcinogenic hazard levels. The hazard index (HI), which expresses the total non-carcinogenic risk of HM through ingestion and dermal absorption, is calculated using equations 10-12.

$$HQ_{ing} = \frac{ADD_{ing}}{RfD_{ing}} \tag{10}$$

$$HQ_{derm} = \frac{ADD_{derm}}{RfD_{derm}} \tag{11}$$

$$HI = HQ_{ing} + HQ_{derm} \tag{12}$$

where RfD_i and RfD_d: are the reference doses of ingestion and dermal absorption (µg/kg/d), respectively. The hazard quotient through ingestion and skin absorption is represented by HQ_i and HQ_d.

The calculation of the carcinogenic risk index (CR) of HMs was carried out to investigate the possibility of humans getting cancer due to contact with potentially carcinogenic substances. The range for CR that was approved according to the United States Environmental Protection Agency (USEPA) is 1×10^{-6} to 1×10^{-4}. The carcinogenic risk index is calculated using equations13-15

$$CR_{ing} = ADD_{ing} \times SF \tag{13}$$

$$CR_{derm} = ADD_{derm} \times SF \tag{14}$$

$$TCR = \sum CR_{ing} + CR_{derm} \tag{15}$$

where TCR is an indicator of cancer, and CR_i and CR_d are the carcinogenic risks for ingestion and skin absorption routes, respectively. SF is a toxicity value that depicts the correlation between dose and reaction.

Data Analysis

IBM SPSS version 22 was employed to calculate the means, standard divisions, minimum and maximum values. The analysis of data was done using one-way ANOVA and one sample *t* test. ArcGIS version 10.3 was utilized to conduct geostatistical analysis aimed at elucidating the spatial distribution of heavy metals. Interpolation was performed using the inverse distance weighting (IDW) method to derive calculated indicators.

Results and Discussion

Statistical Analysis and Distribution Of Physicochemical Parameters and PTEs

A summary of the analysis of physicochemical parameters in Hamadan surface water sources is shown in Table 1. These values were compared with the water quality standards of the WHO[21] and the USEPA.[22] The results of ANOVA revealed significant differences of temperature and pH among the sampling locations ($P<0.05$), indicating variability in these parameters across different sites. Conversely, no significant difference was observed for the total dissolved solids (TDS) and electrical conductivity (EC) parameters ($P>0.05$), suggesting relatively consistent levels of these parameters across the sampled locations. Additionally, comparison of the average parameters with international standards demonstrates that the mean values of all parameters (pH, temperature, TDS, and EC) fall within the optimal ranges defined by the WHO and the USEPA standards (Table 1).

Table 2 shows the statistical results of PTEs (Fe, Pb, Zn, Cu, and Cd) in surface water sources in Hamadan. The results of ANOVA revealed that the average concentration of metals Cd, Pb and Cu has no significant difference in the three studied surface water sources ($P>0.05$), whereas the average concentration of metals Fe and Zn had a statistically significant difference ($P<0.05$). Based on the findings, the highest and lowest concentrations of metals in the analyzed surface water sources are as follows: for Fe, the highest concentration was observed at station 8AG (501 µg/L), while the lowest was recorded at station 1EA (12.5 µg/L); for Zn, the highest concentration was detected at station 31EA (435 µg/L), whereas the lowest was found at station 6KM (5.18 µg/L); for Cd, the highest concentration was measured at station 4KM (5.08 µg/L), while the lowest was identified at station 10EA (0.002 µg/L); for Pb, the highest concentration was recorded at station 31EA (12.4 µg/L), whereas the lowest was observed at station 26EA (0.004 µg/L); and for Cu, the highest concentration was found at station 7KM (21.8 µg/L), while the lowest was noted at station 2KM (0.340 µg/L). The One Sample T-Test was employed to assess the average concentration of HMs across various stations in comparison to standard values. The analysis revealed a statistically significant difference ($P<0.01$) between the average concentration and their corresponding standard values as per the WHO. Through the comparison of metal concentrations across various stations in the three studied surface water sources with the standard values outlined by the WHO in 2011, it was established that the concentrations of all PTEs fall below the permissible limits, with the exception of Fe at stations 1AG, 3AG, 8AG, and 9AG, and Cd at stations 9AG, 16AG, 2EA, 20EA, and 30EA. The spatial distribution pattern and the comparison of PTE concentrations with the maximum allowable limits for drinking water are depicted in Figure 2.

The findings showed that Hamadan's surface water sources had an average concentration of elements as follows: Fe > Zn > Cu > Pb > Cd in Ganjnameh and Abbas Abad and Zn > Fe > Cu > Pb > Cd in Khako and Moradbeig Valley rivers and Ekbatan Dam. Numerous factors, with proximity to pollutant sources being foremost among them, influence the fluctuation in pollutant concentrations within aquatic environments.[23] Due to the rugged

Table 1. Physicochemical Parameters of the Water Samples Analyzed From Surface Water Sources of Hamadan Province

Parameters	Abbas Abad and Ganjnameh		Khako and Moradbeig Valley		Ekbatan and Abshineh Dam		WHO (2011)	EPA (2018)
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD		
T (°C)	11.7-17.8	$14.7^{b} \pm 1.84$	13.7-22.5	$17.7^{a} \pm 2.19$	12.3-27.1	$19.2^{a} \pm 3.35$	26.3-32.3	-
pH	6.35-7.50	$6.96^{C} \pm 0.269$	6.78-7.98	$7.33^{b} \pm 0.417$	7.0-8.82	$8.16^{a} \pm 0.547$	6.5-8.5	6.5-9
EC (µS/cm)	52.4-735	$142^{a} \pm 97.1$	56.7-501	$246^{a} \pm 161$	94.5-603	$220^{a} \pm 107$	500	-
TDS (mg/L)	34.9-485	$93.7^{a} \pm 61.5$	37.2-330	$162^{a} \pm 106$	62.2-397	$145^{a} \pm 70.3$	1000	500

WHO, World Health Organization; EPA, Environmental Protection Agency.

Table 2. Average and Range of PTEs (µg/L) in Surface Water Sources of Hamadan Province

Heavy metals (µg/L)	Abbas Abad and Ganjnameh		Khako and Moradbeig Valley		Ekbatan and Abshineh Dam	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
Fe	68.6-501	$217^{a} \pm 113$	18.5-249	$104^{b} \pm 77.3$	12.5-281	$142^{b} \pm 68.9$
Zn	8.48-402	$129^{b} \pm 120$	5.18-384	$148^{b} \pm 140$	51.1-435	$231^{a} \pm 91.9$
Cd	ND-4.58	$1.30^{a} \pm 1.32$	ND-8.70	$1.03^{a} \pm 1.37$	ND-12.4	$1.10^{a} \pm 1.27$
Pb	ND-9.48	$2.60^{a} \pm 2.84$	ND-6.48	$1.99^{a} \pm 2.13$	ND-12.4	$1.64^{a} \pm 2.96$
Cu	2.45-75.1	$20.9^{a} \pm 21.3$	0.34-89.2	$23.3^{a} \pm 28.3$	0.82-73.0	$15.1^{a} \pm 19.3$

terrain, mountainous topography, and rocky substrates, there is an absence of an urban sewage collection infrastructure along the Abbas Abad and Ganjnameh rivers. Consequently, residents are reliant on septic tanks for sewage disposal. However, these septic systems are insufficient in fully treating sewage, particularly during periods of heavy rainfall when their limited capacity may lead to overflow into the rivers if not promptly emptied. Furthermore, establishments within the Abbasabad and Ganjnameh complexes, such as entertainment venues and restaurants, lack septic tanks, resulting in direct discharge of untreated sewage into the rivers, particularly during nighttime hours. While sewage from sanitary facilities in Ganjnameh and Abbasabad is directed to septic tanks and removed via sewage tankers, the capacity of these tanks may prove inadequate during peak tourist seasons, resulting in overflow into the rivers. Rainfall exacerbates this issue, further contributing to sewage leakage into the environment.[24] Throughout the Ganjnameh and Abbas Abad river corridors, various establishments such as restaurants, canteens, coffee shops, cable cars, camps, museums, gardens, residential villas, and fish breeding ponds are present. Consequently, the direct discharge or inadvertent leakage of sewage from these establishments

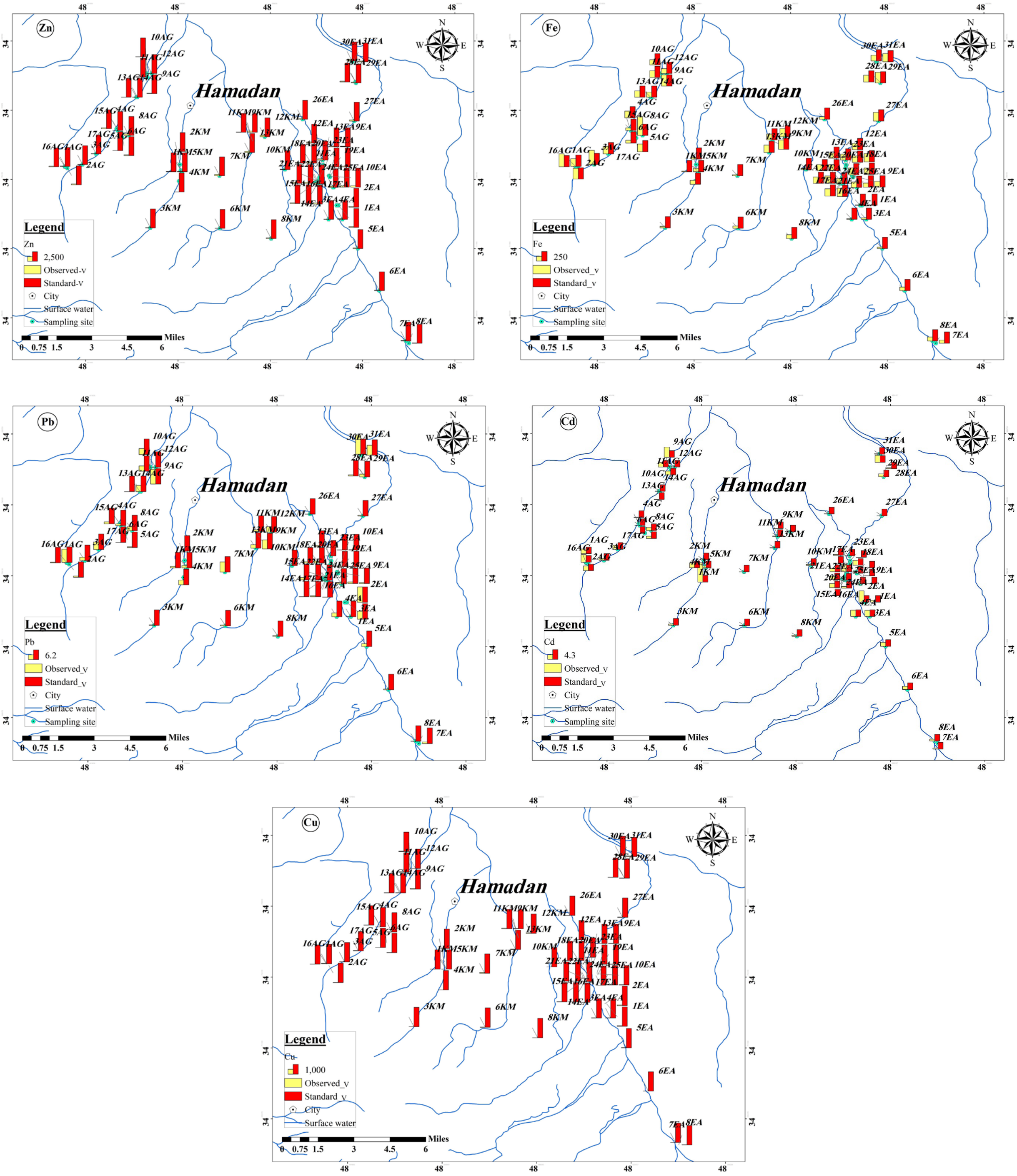

Figure 2. Spatial Distribution of PTEs in Sampling Stations of the Surface Water Sources of Hamadan Province (Zn, Fe, Pb, Cd, and Cu)

along the riverbanks, along with vehicular washing activities, nomadic settlements, heightened vehicular traffic particularly during holidays, and the underlying geological characteristics have collectively influenced the concentration of PTEs. Moreover, the Ekbatan Dam Reservoir is notably impacted by the influx of agricultural runoff from the surrounding lands, compounded by the geological features of the area. Similarly, the rivers leading to the dam, as well as the Abshineh River, are subject to contamination from domestic sewage originating from nearby villages, agricultural runoff, and nomadic settlements in the vicinity. Furthermore, the Khako and Moradbeig Valley rivers are adversely affected by a combination of domestic, industrial, and agricultural effluents.

Similar sources of PTEs release have been documented in analogous studies on water sources. For instance, Seleem et al[25] attributed the elevated levels of arsenic (As) and other HMs to several factors including the influx of substantial volumes of agricultural wastewater (resulting from the use of fertilizers and pesticides), weathering processes of source rocks, and the presence of mafic/ultramafic rock formations. Sadeghi et al[26] identified urban and industrial development, along with a multitude of human activities within the Moradbeig Valley River watershed, as the primary sources of HMs pollution in the region of Hamadan. These activities include the discharge of urban, rural, and industrial wastewater, as well as the utilization of various chemical fertilizers and pesticides, and the improper disposal of solid waste materials into the river.

Furthermore, natural factors such as low precipitation levels, seasonal variations in precipitation patterns, expansion of agricultural lands, degradation of vegetation quality, sudden and intense rainfall events, erosion, and habitat destruction have collectively exacerbated the physical and chemical pollution load within the Moradbeig Valley River.

In a study conducted by Yarimoghadam et al,[27] the findings indicated that the levels of HMs present in the Abshineh River, located in Hamadan, comply with the WHO standards for drinking water, with the exception of Pd during the spring season. The elevated Pb concentration observed during this period is attributed to the runoff of rainwater, which facilitates the transport of soil contaminants originating from sewage and agricultural discharges in rural vicinities, coupled with the geological composition and soil characteristics of the river basin.

Given the recorded concentrations of Fe surpassing permissible limits at primary monitoring stations along the Ganjnameh River and its upstream areas, originating from Alvand Mountain, it is evident that both natural factors inherent to the region's geological makeup and human activities collectively contribute significantly, potentially to a greater extent, to the observed concentrations of measured elements. Notably, the flood event in March 2019 exerted a substantial and influential impact by redistributing and depositing elements within the water sources. Consequently, the elevated levels of Fe can be attributed to a combination of natural phenomena and anthropogenic activities. Common sources of Fe release encompass a spectrum of industries and practices, including but not limited to Fe and steel production, metallurgical operations, pigment manufacturing, dyeing processes, textile production, refinery activities, fuel consumption, mineral waste disposal, fertilizer application, herbicide usage, corrosion of Fe infrastructure, and geological reservoirs.[28] The permissible maximum concentration of Fe in drinking water stands at 0.3 mg/L. Initially, the presence of Fe concentrations exceeding this threshold in drinking water may not manifest immediate adverse health effects. However, it is crucial to acknowledge the potential for Fe enrichment, a condition that may arise with sustained consumption of water containing elevated Fe levels.[29]

In addition to the associated health concerns, elevated concentrations of Fe can induce a metallic taste and impart a crimson hue to water, leading to the formation of stains and streaks on washing machines and plumbing fixtures. Furthermore, such conditions provide an ideal substrate for bacterial proliferation, potentially resulting in pipe blockages, diminished water flow rates within pipelines, and the development of unpleasant odors and tastes within the water distribution network. The demise of these bacteria further contributes to the emergence of undesirable odors and tastes in the water system.[29,30] The results of the study by Farzan and Sobhanardakani[31] also indicated that the surface runoff of high-traffic areas in Hamadan is contaminated with Fe, Pb, and Cd. In this study, the high amount of Fe in the surface runoff samples of Hamadan is attributed to the presence of car washes, oil changes, and car repair businesses. In contrast, the high amount of Pb is attributed to the high volume of vehicle traffic.

The permissible limit of Cd has been exceeded in Ganjnameh and Ekbatan Dam stations. These stations are impacted by domestic sewage, agricultural effluents, sediment washed away by flooding, and surface runoff. Also, the high traffic of vehicles due to the large number of tourists has contributed to the release of Cd. Similarly, Farzan and Sobhanardakani[31] found that Cd has accumulated more than Fe and Pb in the surface runoff of Hamadan city, which is due to the high volume of urban traffic, the high consumption of fossil fuels, depreciation of vehicle brake pads, the geological structure and climatic conditions of the studied area are described. According to Kianpoor and Sobhanardakani study,[32] the average Cd level in bread and wheat samples consumed in Hamadan city exceeded the standard limit, which was due to soil pollution owing to geological origin, excessive use of chemical fertilizers, especially phosphate fertilizers as the most common source of Cd pollution in agricultural soils, use of insecticides, use of municipal wastewater for land irrigation and vehicle traffic along the Hamadan-Saveh road and near wheat fields.

Considering that these three sources of surface water are among the most important sources of drinking and agricultural water, exposure to these PTEs from different routes, such as consumption of aquatic animals grown in polluted water, vegetables and grains grown in polluted water, and cattle meat, in addition to direct ingestion and skin absorption, can cause many health problems for humans. In this regard, Ghobadi and Jahangard[33] demonstrated the contamination of spinach and tomato consumption vegetables in Hamadan with the studied heavy metals, to the extent that the concentration of Cd and manganese (Mn) metals in all samples was determined to be hazardous for consumers. The utilization of substandard water for irrigation, soil contamination, and excessive application of chemical fertilizers and insecticides constitute the primary pathways for the introduction of PTEs into spinach and tomato plants. The discernible repercussions of these PTEs are multifaceted: Cu is linked to conditions such as Wilson's disease, gastrointestinal inflammation, insomnia, and liver impairment; Cd, classified as a carcinogen, is implicated in kidney disorders and damage; Zn exposure may result in symptoms such as lethargy, nervous system disturbances, melancholy, and increased thirst; and Pb adversely affects various physiological systems including the circulatory system, nervous system, embryonic brain development, and kidney function.[3,28] Given the health implications stemming from prolonged exposure to PTEs, it is imperative to implement rigorous monitoring protocols to assess the quality of Hamadan's surface water resources. This initiative is particularly crucial as the region is concurrently confronted with the challenge of water scarcity.

Correlation Results of Physicochemical Parameters and PTEs

The current study conducted a comparison of heavy metal concentrations alongside physicochemical parameters, utilizing Pearson's correlation coefficient (Table 3). Analysis of the correlation coefficients among PTEs in water samples revealed a positive association between Pb and Cu, Pb and Cd, as well as Fe and Zn. The examination of element concentrations across different monitoring stations and their respective correlations suggests the likelihood of contributions from both natural phenomena and anthropogenic activities. Notably, the presence of Zn and Pb in the environment can be attributed to significant sources such as car tires and gasoline emissions, implicating traffic-related pollution as a notable contributor to the levels of Zn and Pb.[34] Generally, Cd indicates agricultural activity, and pesticides and fertilizers contain Zn, Pb, Cu, and Fe. Therefore, agricultural activities can also contribute to the presence of Zn, Cd, Pb, Fe, and Cu in water systems.[2] In addition, Cd is typically present in vehicle tires and gasoline, and tire wear can lead to the release of Cd into the environment.[35] Therefore, PTEs such as Pb, Cd, As, Cu, and Zn can be released into rivers due to surface runoff, which can lead to contamination of the water system.[6] Concerning the natural origins of these elements, it is important to note that the predominant geological formations in the province of Hamadan are alluvial terraces, shale and marl, metamorphosed sandstone, and reef limestone.[36] Shales, characterized by their fine sedimentary composition, are known reservoirs of heavy metals, encompassing elements such as Cu, Zn, Mn, Pb, As, silver, Cd, molybdenum, uranium, and vanadium. Owing to their inherent capacity for metal ion absorption, clays and shale formations often exhibit elevated concentrations of heavy metals. It is estimated that approximately half of the Cd influx into surface water reservoirs occurs as a result of rock weathering processes, particularly during periods of increased rainfall.[31]

The correlation analysis of physicochemical factors pertaining to water revealed a statistically significant positive correlation between TDS and both temperature and EC. Furthermore, a positive correlation was observed between temperature and both pH and EC. The EC serves as a measure of water's ability to conduct an electric current, thus functioning as a valuable indicator of TDS. This relationship arises from the fact that water's EC predominantly hinges upon the concentration of ionic species within the water.[37] The higher the dissolved substance in the water sample, the higher the EC level in the sample. The EC is also affected by temperature; The warmer the water, the higher the conductivity. The correlation results in this study have also shown the validity of this relationship. The streams that run via regions with clay soils have a tendency to have higher conductivity due to the presence of substances that ionize whilst washed into the water. Discharge effluents, sewage, and runoff into the water stream can change the EC depending on their composition. The leakage of sewage systems into surface water sources due to the presence of chloride, phosphate, and nitrate causes the EC of water to 1rise.[38]

The pH value of water is subject to influence from various sources, including dissolved minerals, suspended particles, airborne particulate matter, anthropogenic waste, biological processes such as photosynthesis and respiration by flora and fauna, bacterial activity, hydrodynamic conditions, chemical constituents in runoff, sewage discharge, and other human-induced factors both within and external to the watershed (e.g., discharge from coal mines, accidental releases, and precipitation of acidic compounds like acid rain). Additionally, an elevation in temperature augments the ionization propensity of water, thereby inducing alterations in its pH. These fluctuations in water chemistry, particularly deviations in pH, can have adverse implications for indigenous aquatic species. Even minor fluctuations in pH can affect the solubility of certain metals, such as Fe and Cu, with potential consequences for aquatic biota. Indirectly, aquatic

Table 3. Pearson Correlation Between Physicochemical Parameters and PTEs

	TDS	T	pH	EC	Fe	Zn	Cd	Pb	Cu
TDS	1	0.288*	0.106	1.00**	0.073	0.037**	0.045	0.517**	0.602**
T		1	0.699**	0.288**	0.105	0.577**	-0.034	-0.069	0.047
pH			1	0.106	-0.023	0.564**	-0.142	-0.172	-0.089
EC				1	0.073	0.037*	0.044	0.517**	0.602**
Fe					1	0.319*	0.044	0.060	0.064
Zn						1	-0.159	0.093	0.180
Cd							1	0.385**	0.220
Pb								1	0.877**
Cu									1

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

ecosystems may suffer repercussions, as lowered pH levels can lead to resuspension of toxic metals from estuarine sediments into the water column, exacerbating ecological stressors.[39]

The correlation analysis between water physicochemical factors and PTEs revealed a noteworthy positive association between TDS and EC with Zn, Pb, and Cu, along with temperature and pH with Zn. The highest temperatures and pH levels were observed at the Ekbatan dam and Abshineh stations, attributed to the stagnant nature of the water in these locations. Conversely, the highest TDS and EC levels were documented at the Ganjnameh and Abbas Abad stations, situated in the Hasar Gasaban area characterized by sewage inflow and low water flow rates.

PTE Pollution Assessment Indicators

The results of the assessment and computation of the HPI across three surface water sources investigated within the city of Hamadan are presented in Tables 4-6, with Figure 3 illustrating the HPI values. The highest and lowest HPI values were observed in the Abbas-Abad and Ganjnameh rivers, registering at 107 and 1.96, respectively, at stations 16AG and 6AG. Similarly, in the Khako and Moradbeg valley rivers, HPI values reached 228 and 0.120 at stations 4KM and 2KM, while in the Ekbatan dam and Abshineh river, they amounted to 152 and 0.470 at stations 2EA and 22EA, respectively.

The HEI and contamination degree indices were additionally computed to assess the quality of the investigated surface water resources based on PTE concentrations, as detailed in Tables 7-9. Spatial distribution of these indexes is depicted in Figure 4. Analysis of HEI values revealed the highest and lowest indices at stations 4KM (3.55) and 2KM (0.163), respectively. Similarly, for the contamination degree index, the highest and lowest values were recorded at stations 4KM (-1.44) and 6KM (-4.71), respectively.

According to the findings presented in Table 10, Zn exhibited the highest quantity of HMTL, while Cd displayed the lowest amount. Furthermore, upon comparing the concentrations of HMTL for all metals across the three investigated surface water sources, it was determined that the highest concentration was associated with Ekbatan Dam and Abshineh River (HMTL = 228), whereas the lowest concentration was linked to Abbas Abad and Ganjnameh River (HMTL = 141), as illustrated in Figure 5.

The spatial distribution of EWQI index values in the sampling stations of the three studied surface water sources is shown in Figure 6. According to the findings, the calculated EWQI values in the studied surface water sources range from 0.001 to 7.10, with an average of 0.324. According to this index, the higher the EWQI value, the lower the water quality.

The HPI index is a useful technique which is often used by researchers to survey the general quality of water for drinking and residential use.[5] The HMTL index determines the loading or pollution level of water system and indicates the rate at which HMs are removed from a river to make it secure for human use. This index refers to a regulatory authority that determines the level of purification necessary to make river water suitable for human consumption. Therefore, this index facilitates the development of an effective treatment and management strategy.[14] The average results of HPI, HMTL, HEI, and contamination degree indices for all three investigated surface water sources indicated a low pollution level. However, the HPI index exceeded the permissible limit at some stations. In addition, the quality of surface water resources as measured by the EWQI index, except for one station in the Khako and Moradbeig Valley rivers, the entry point for domestic sewage, is adequate in other stations and does not exhibit a high number.

Various studies have used the indicators to investigate the quality of water resources in terms of heavy metals. For instance, in Sobhanardakani and colleagues’ study[40] evaluating heavy metal pollution in the underground water resources of Asadabad Plain of Hamadan, employing HPI and HEI indicators, and in Sobhanardakani and colleagues’ investigation[41] in the underground water resources of Rezen Plain of Hamadan, utilizing Cd, HPI, and HEI indicators, findings revealed minimal pollution levels which were similar to our results. In the

Table 4. HPI of Water Sample of Abbas Abad and Ganjnameh River

Heavy Metals	M_i (μg/L)	S_i	W_i	Q_i	$W_i = K/S_i$	$W_i \times Q_i$
Fe	217	300	0.003	72.4	0.003	0.241
Zn	129	5000	0.0002	2.57	0.0002	0.0008
Cd	1.38	3	0.333	46.0	0.333	15.3
Pb	3.16	10	0.1	31.6	0.1	3.16
Cu	20.9	2000	0.0005	1.49	0.0005	0.0007

$\Sigma W_i = 0.437$; $\Sigma W_i \times Q_i = 18.7$; HPI = 42.8.

M_i: Mean Concentration (μg/L); S_i: Standard value; W_i: Unit weightage; Q_i: Subindex.

Table 5. HPI of water sample of Khako and Moradbeig Valley River

Heavy Metals	M_i (μg/L)	S_i	W_i	Q_i	$W_i = K/S_i$	$W_i \times Q_i$
Fe	104	300	0.003	34.5	0.003	0.115
Zn	148	5000	0.0002	4.93	0.0002	0.0009
Cd	1.22	3	0.333	40.8	0.333	13.5
Pb	2.15	10	0.1	21.5	0.1	2.15
Cu	23.3	2000	0.0005	1.36	0.0005	0.0006

$\Sigma W_i = 0.437$; $\Sigma W_i \times Q_i = 15.8$; HPI = 36.2.

Table 6. HPI of Water Sample of Ekbatan Dam and Abshineh River

Heavy Metals	M_i (μg/L)	S_i	W_i	Q_i	$W_i = K/S_i$	$W_i \times Q_i$
Fe	142	300	0.003	47.2	0.003	0.157
Zn	231	5000	0.0002	7.71	0.0002	0.0015
Cd	1.31	3	0.333	43.7	0.333	14.5
Pb	1.89	10	0.1	18.9	0.1	1.89
Cu	15.1	2000	0.0005	1.78	0.0005	0.00089

$\Sigma W_i = 0.437$; $\Sigma W_i \times Q_i = 16.6$; HPI = 38.0.

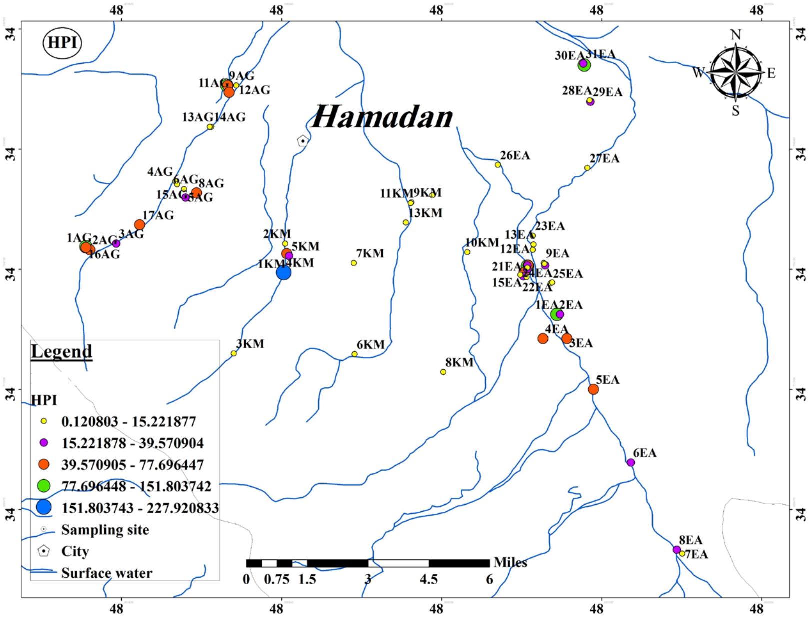

Figure 3. Spatial Distribution of HPI in Surface Water Sources of Hamadan Province

investigation conducted by Nejatijahromi et al[42] on the underground water resources of the Varamin aquifer, findings from the HEI and HPI indices affirmed that the heavy metal contamination of the Varamin aquifer is generally not hazardous across most areas; however, significant fluctuations in metal concentrations were noted in select regions. Rezaei et al,[13] in their research on the underground waters of northern Isfahan, categorized

Table 7. HEI and Contamination Degree for PTEs of Abbas Abad and Ganjnameh River Surface Water

Heavy Metals	M_i (μg/L)	MAC	M_i/MAC	S_i	$Cf = \frac{Mi}{Si}\ 1$
Fe	217	300	0.724	300	- 0.275
Zn	129	5000	0.025	5000	- 0.957
Cd	1.38	3	0.460	3	- 0.539
Pb	3.16	10	0.316	10	- 0.683
Cu	20.9	2000	0.010	2000	- 0.989

HEI = $\Sigma \frac{Mi}{MAC}$ = 1.53; Contamination degree = Σ Cf = - 3.44.

Table 8. HEI and Contamination Degree for PTEs of Khako and Moradbeig Valley River Surface Water

Heavy Metals	M_i (μg/L)	MAC	M_i/MAC	S_i	$Cf = \frac{Mi}{Si} - 1$
Fe	217	300	0.345	300	- 0.654
Zn	129	5000	0.029	5000	- 0.950
Cd	1.38	3	0.408	3	- 0.591
Pb	3.16	10	0.215	10	- 0.784
Cu	20.9	2000	0.011	2000	- 0.988

HEI = $\Sigma \frac{Mi}{MAC}$ = 1.01; Contamination degree = Σ Cf = - 3.96.

Table 9. HEI and Contamination Degree for PTEs of Ekbatan Dam and Abshineh River surface water

Heavy Metals	M_i (μg/L)	MAC	M_i/MAC	S_i	$Cf = \frac{Mi}{Si} - 1$
Fe	217	300	0.472	300	- 0.527
Zn	129	5000	0.046	5000	- 0.922
Cd	1.38	3	0.437	3	- 0.562
Pb	3.16	10	0.189	10	- 0.810
Cu	20.9	2000	0.007	2000	- 0.992

HEI = $\Sigma \frac{Mi}{MAC}$ = 1.15; Contamination degree = Σ Cf = - 3.81.

samples based on HPI classification, revealing that 51% exhibited low pollution levels, 46% demonstrated moderate pollution levels, and 3% indicated high pollution levels. Chandran et al,[43] examining the Vaigai River in South India, employed the Cd, HPI, HEI, and MI indices, while Mishra et al,[44] studying the Kali River in India, utilized principal component analysis, cluster analysis, and the HPI index, both studies underscoring the poor water quality and heightened pollution levels of the investigated water sources. In an investigation by Njuguna et al[45] concerning Kenya's Tana River, the HPI value of 98.6 fell marginally below the critical threshold of 100 for potable water. Kumar and colleagues' study,[14] analyzing the heavy metal content in surface water sources worldwide from 1994 to 2019, highlighted that the examined waters are extensively contaminated with heavy metals, as indicated by the HPI, HEI, WPI, and HMTL indices. Furthermore, Enyigwe and colleagues' research[8] revealed that, based on the results of the HEI, HPI, and Cd indices, the majority of samples are enriched with PTEs, rendering them unsuitable for human consumption. These studies underscore the importance of employing water quality indicators that consider all environmental factors contributing to water pollution, facilitating informed decision-making in resource management.

Human Health Risk Assessment

Non-Carcinogenic Health Risks (HI)

The initial step in non-carcinogenic risk assessment involves computing the chronic daily intake (CDI). The mean CDI and risk quotients (RQ) of PTEs for both children and adults in Abbas-Abad and Ganjnameh, Khako and Moradbeig Valley, and Ekbatan Dam and Abshineh are presented in Tables 11, 12, and 13, respectively. Analysis of HQ revealed that the contribution of PTEs to non-carcinogenic health risks associated with water consumption for adults and children follows the order: Cd > Pb > Cu > Zn > Fe. Conversely, the contribution of PTEs to non-carcinogenic health risks via dermal exposure for adults and children ranks as: Cd > Zn > Cu > Pb > Fe.

Figure 7 depicts the non-carcinogenic health risk (HI) caused by the studied PTEs for adults and children via ingestion and dermal exposure in the studied surface water sources. According to Figure 7, both children and adults had HI values less than 1 for the studied PTEs. The highest levels of HI (from the dermal exposure route) were found in Ekbatan Dam and Abshineh River for both adult (0.149) and children (0.318) populations and the lowest amounts were observed in Khako and Moradbeg Valley rivers for both adult (0.128) and children (0.272) groups.

The non-carcinogenic health risk of the studied PTEs indicates that there is no obvious risk to the resident's health. The findings indicate that the HI of metals in the studied surface water sources, concerning both adults and children, is notably higher through dermal exposure compared to water ingestion. Moreover, the HI via dermal exposure is markedly elevated for children in comparison to adults, suggesting that children are more vulnerable to PTEs in the analyzed water resources. Consequently, the results highlight the heightened susceptibility of children to PTE-related threats in the examined water sources. Additionally, the calculated risk (CR) via dermal absorption for both age groups across all investigated surface water sources falls within the low-risk category ($10^{-6} < CR < 10^{-4}$), while through ingestion, it falls within the high-risk category ($10^{-3} < CR < 0.1$).

Carcinogenic Risks for Health (CR)

In this study, Cd and Pb were investigated as carcinogenic factors, and since the carcinogenic slope factor (CRF) was available, the CR index was calculated only for Cd and Pb. Figure 8 shows the average carcinogenic risks of these PTEs from the ingestion route in the three analyzed surface water sources, while Figure 9 depicts the risks from the dermal absorption route. The results of the CR index indicated that the probability of carcinogenicity of PTEs investigated for both age groups of adults and children through the ingestion route is significantly

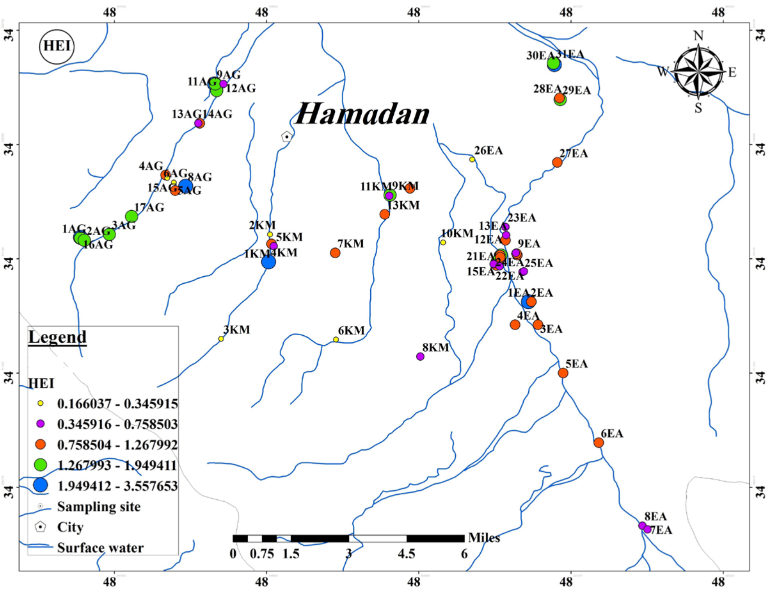

Figure 4. Spatial distribution of HEI and contamination degree for heavy metals in surface water sources of Hamadan province

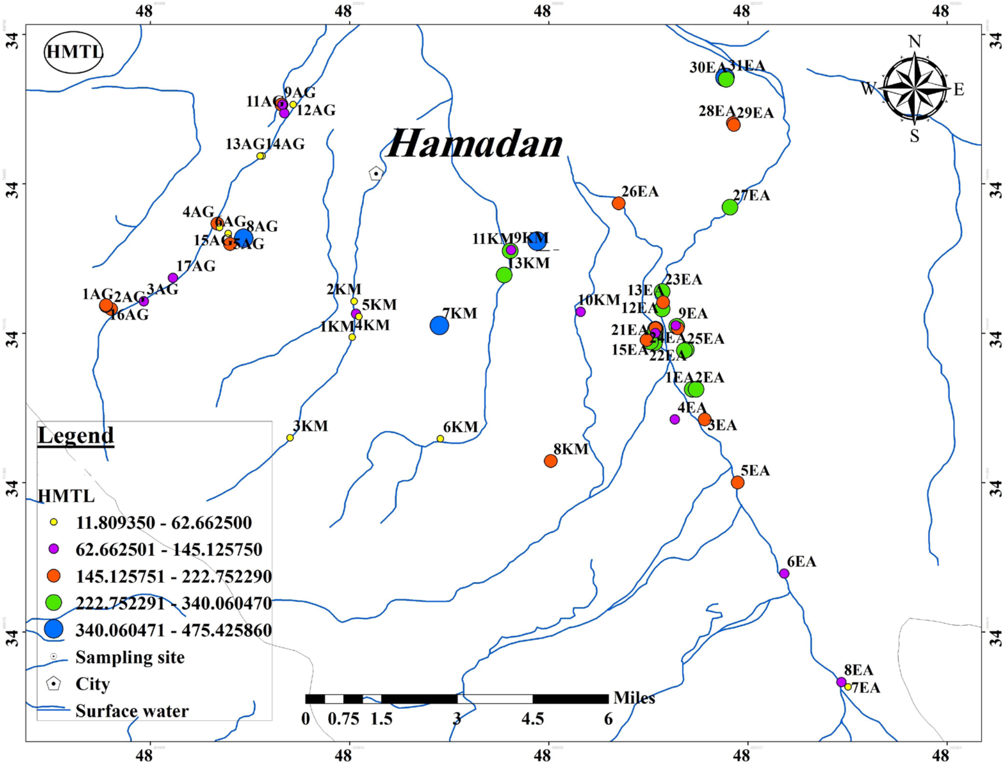

Figure 5. Spatial Distribution of HMTL in Surface Water Sources of Hamadan Province

Table 10. HMTL for PTEs in surface water sources of Hamadan province

Heavy Metals	Hazard Intensity Score (HIS)	Abbas Abad and Ganjnameh		Khako and Moradbeig Valley		Ekbatan and Abshineh Dam	
		M_i	HMTL	M_i	HMTL	M_i	HMTL
Fe	-	217	-	104	-	142	-
Zn	913	129	118	148	135	231	211
Cd	1318	1.30	1.82	1.03	1.61	1.10	1.73
Pb	1531	2.60	4.84	1.99	3.30	1.64	2.89
Cu	805	20.9	16.8	23.3	18.8	15.1	12.2
HMTL (µg/L) =		141		159		228	

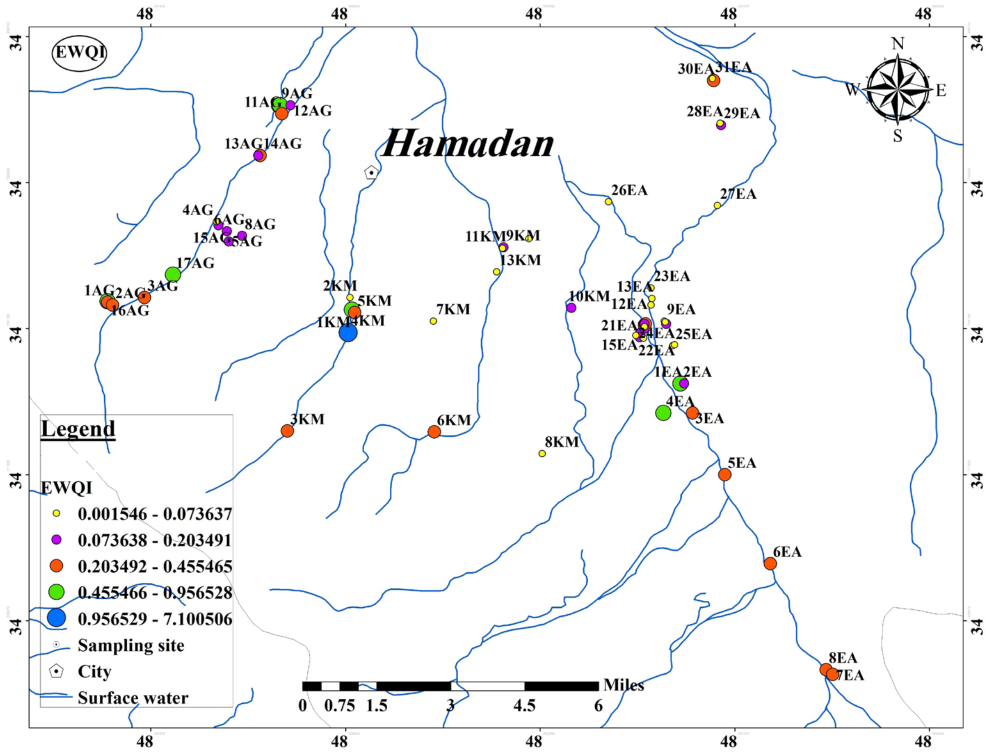

Figure 6. Spatial Distribution of EWQI in Surface Water Sources of Hamadan Province

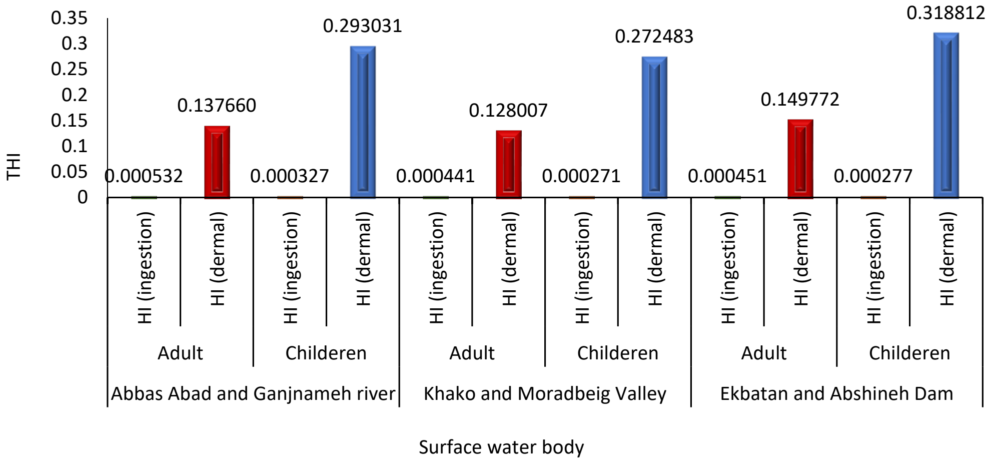

Figure 7. Total HI distribution between adults and children at all the Hamadan surface water bodies

higher than through dermal absorption. So, the amount of CR through dermal absorption for both age groups in all investigated water sources is related to the low-risk category ($10^{-6} < CR < 10^{-4}$). However, through ingestion, it was in the high-risk category ($10^{-3} < CR < 0.1$). Figure 10 illustrates the spatial distribution of CR amount for two age groups, adults and children, via the two routes of dermal absorption and ingestion at the stations of the three examined water sources.

The results indicated a statistically significant elevation in the concentration of CR in children compared to adults following ingestion. Additionally, children exhibit a heightened susceptibility to CR associated with the water sources under investigation, mirroring findings reported in studies conducted by Eze et al,[3] Xie and Ren,[46] Bhatti et al,[6] and Jin et al.[2] This heightened vulnerability in children can be attributed to their accelerated respiratory rate, efficient gastrointestinal absorption, and specific behavioral patterns such as hand-to-mouth contact. According to the World Health Organization[21], children are inherently more susceptible to health hazards compared to adults due to their higher consumption of water and calories, as well as increased oxygen intake. Prolonged exposure of children to these PTEs through ingestion and dermal contact manifests in adverse effects on their gastrointestinal, renal, and pulmonary systems during early stages of development.

In investigations across rivers and surface water sources in diverse urban areas, the HI and CR indices reliably depicted the health status of these water bodies. They

Table 11. Chronic Daily Intake and Non-carcinogenic Human Health Risk of PTEs for Children and Adults in Surface Water (Abbas Abad and Ganjnameh River)

Heavy metals	Children		Adults		Children		Adults	
	CDI (Ingestion)	CDI (Dermal)	CDI (Ingestion)	CDI (Dermal)	HQ (Ingestion)	HQ (Dermal)	HQ (Ingestion)	HQ (Dermal)
Fe	0.011	0.974	0.018	0.457	1.61E-05	0.007	2.63 E-05	0.003
Zn	0.006	3.46	0.010	1.62	2.24E-05	0.058	3.64 E-05	0.027
Cd	0.00007	0.006	0.0001	0.003	1.44E-04	0.206	2.34 E-04	0.097
Pb	0.0001	0.014	0.0003	0.007	1.18E-04	0.010	1.91 E-04	0.005
Cu	0.001	0.094	0.001	0.044	2.72E-05	0.012	4.43 E-05	0.006

Table 12. Chronic Daily Intake and Non-carcinogenic Human Health Risk of PTEs for Children and Adults in Surface Water (Khako and Moradbeig Valley)

Heavy Metals	Children		Adults		Children		Adults	
	CDI (Ingestion)	CDI (Dermal)	CDI (Ingestion)	CDI (Dermal)	HQ (Ingestion)	HQ (Dermal)	HQ (Ingestion)	HQ (Dermal)
Fe	0.005	0.46	0.008	0.218	7.70 E-06	0.003	1.25E-05	0.002
Zn	0.007	3.9	0.012	1.86	2.57 E-05	0.066	4.18E-05	0.031
Cd	0.0001	0.01	0.0001	0.003	1.27 E-04	0.183	2.07E-04	0.086
Pb	0.0001	0.01	0.0002	0.005	8.02 E-05	0.007	0.1.30E-04	0.003
Cu	0.001	0.10	0.002	0.049	3.04 E-05	0.013	4.95E-05	0.006

Table 13. Chronic Daily Intake and Non-carcinogenic Human Health Risk of PTEs for Children and Adults in Surface Water (Ekbatan Dam and Abshineh River)

Heavy metals	Children		Adults		Children		Adults	
	CDI (Ingestion)	CDI (Dermal)	CDI (Ingestion)	CDI (Dermal)	HQ (Ingestion)	HQ (Dermal)	HQ (Ingestion)	HQ (Dermal)
Fe	0.007	0.635	0.012	0.298	1.05 E-05	0.005	1.71 E-05	0.002
Zn	0.012	6.21	0.019	2.92	4.01E-05	0.104	6.52 E-05	0.048
Cd	0.00007	0.006	0.0001	0.003	1.37 E-04	0.196	2.22 E-04	0.092
Pb	0.00001	0.008	0.0002	0.004	7.03 E-05	0.006	1.14 E-04	0.002
Cu	0.0007	0.068	0.001	0.032	1.97 E-05	0.008	3.21 E-05	0.004

proved effective in assessing the carcinogenic and non-carcinogenic risks posed by PTEs. Kumar et al[14] reported HI values exceeding 1 for chromium, Mn, cobalt, As, and Cd, indicating potential health risks associated with these elements. Similarly, the CR index for chromium, nickel, As, and Cd indicated a CR via ingestion for both children and adults. The study by Liu and Ma[47] demonstrated that both the carcinogenic and non-carcinogenic risks associated with Ni and Cr exceeded the recommended standard values. In a separate investigation by Seleem et al,[25] the HI for ingestion surpassed that for dermal contact by over 200-fold, while the carcinogenic risk associated with Fe, Mn, Cu, and Zn remained below acceptable limits. Xie and Ren[46] reported a total HI of 47.70 for adults and 90.10 for children, with antimony (Sb) and As identified as the most significant non-carcinogenic risk factors. Moreover, the average carcinogenic risk exceeded 1×10^{-4} for both adults and children, indicating a high carcinogenic risk. Bhatti et al.[6] found that the HI index for ingestion of all selected PTEs, except in the Mohmand region, remained below the threshold value (HIing < 1). Furthermore, the carcinogenic risk values associated with Ni and Cr exceeded the threshold established by the USEPA. Enyigwe et al[8] reported that all samples exhibited risk index values greater than 4, indicating a very high risk to the health of both adults and children. Similarly, the carcinogenic risk assessment revealed that all contaminated samples containing As, Ni, and Cd posed an elevated carcinogenic risk to both populations. Consequently, based on the review of literature, water quality indicators and health risk assessment parameters can be utilized for the quantitative and qualitative evaluation of water concerning PTEs, facilitating decision-making for the optimal and effective management of water resources to preserve ecosystem, organism, and human health.

Conclusion

Both human activities and the geological characteristics of the region contribute to the concentration of PTEs in the surface water resources of the Hamadan province. The occurrence of extensive flooding, two months prior to sampling, played a significant role on the overflow of sewage and the leaching of PTEs from soil, rocks, agricultural lands, and gardens, consequently contaminating surface water sources. Furthermore, the proximity of these urban surface water sources to various human activities and densely populated areas, coupled with the discharge of untreated or inadequately treated urban sewage, as well as agricultural and industrial

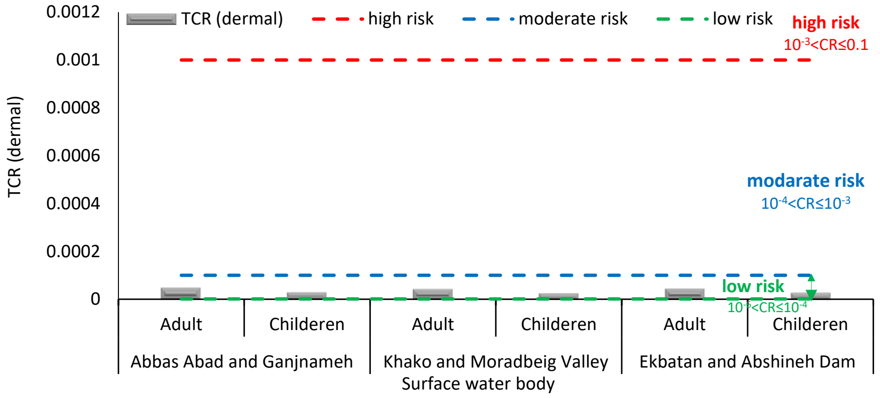

Figure 8. The CR of PTEs Through Dermal Absorption for Adults and Children at All the Hamadan Surface Water Bodies

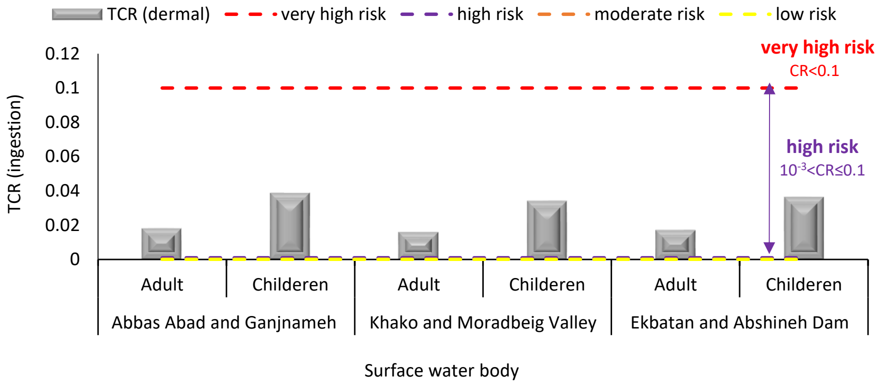

Figure 9. The CR of PTEs Through Ingestion Route for Adults and Children at All the Hamadan Surface Water Bodies.

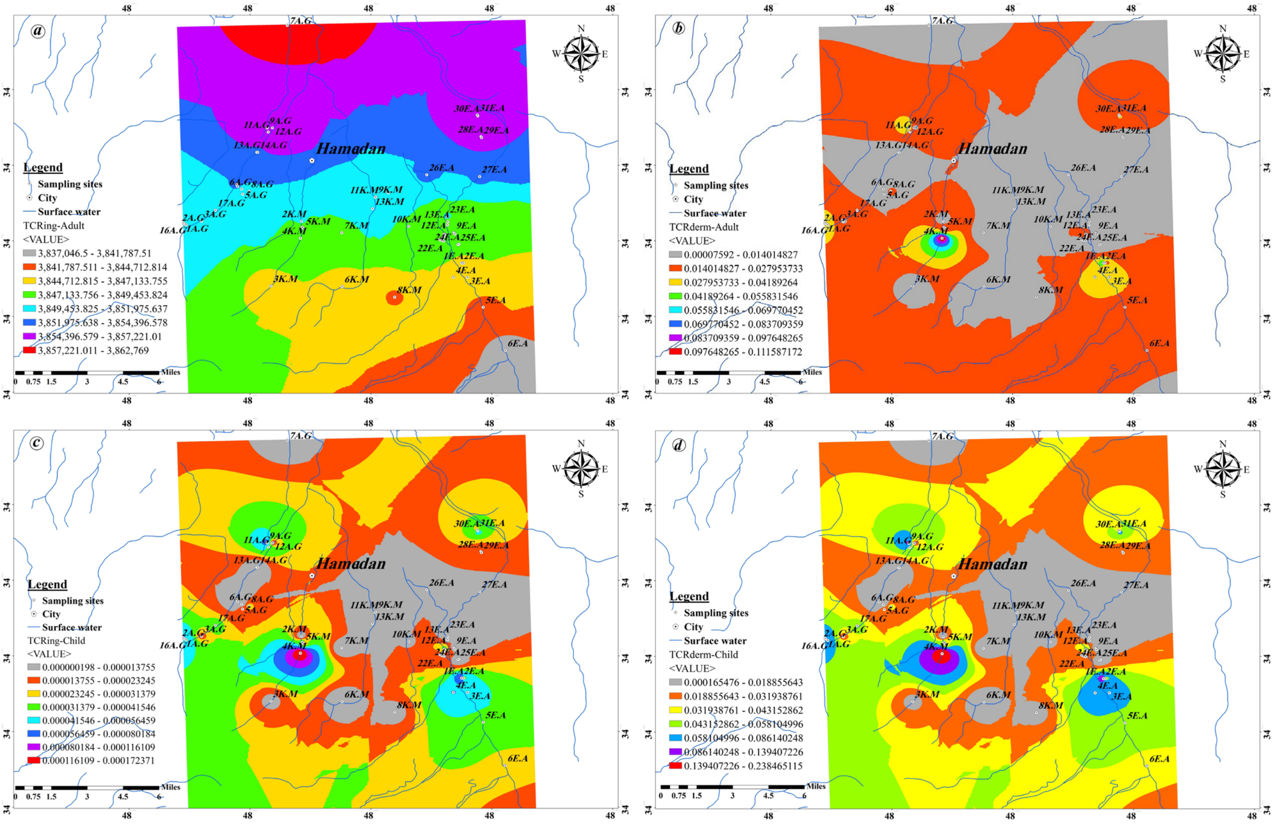

Figure 10. Spatial Distribution of Total Cancer Risks of PTEs Through Ingestion Route and Dermal Absorption for Adults (a, b) and Children (c, d) at All the Hamadan Surface Water Bodies

effluents, has adversely impacted the health and quality of these water sources. However, the results of the indicators suggest that the studied surface water sources exhibit low pollution levels. However, considering the health impacts associated with PTEs even at low concentrations, their potential for bioaccumulation and carcinogenicity, and the significant role of these water resources in tourism, aesthetics, drinking water supply, agriculture, and irrigation, alongside the prevailing challenges of water scarcity and intermittent availability of drinking water in the province leading to frequent water outages, it becomes imperative to implement measures aimed at protecting and cleaning these invaluable rivers. No comprehensive study regarding PTE contamination in surface water sources of Hamedan was found in the literature. Therefore, this study holds fundamental importance and has the potential to draw significant attention. It is crucial to note that this study is cross-sectional and short-term. To obtain more precise and comprehensive results, it is highly recommended to conduct seasonal and long-term studies assessing the concentration, ecological risk, and health effects of PTEs in surface water sources, sediments, underground waters, and consumer products throughout Hamadan County. Such extended research efforts would provide a deeper understanding of the situation and facilitate the development of effective strategies for managing and mitigating PTE contamination in the region.

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Funding acquisition: Malayer University.
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Methodology: Nasrin Hassanzadeh, Faezeh Jafari, Fariba Hedayatzadeh.
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Supervision: Nasrin Hassanzadeh.
Validation: Nasrin Hassanzadeh.
Visualization: Fariba Hedayatzadeh.
Writing–original draft: Faezeh Jafari, Fariba Hedayatzadeh.
Writing–review & editing: Nasrin Hassanzadeh.

Competing Interests

The authors declared that there is no conflict of interest.

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