JAEHR
Journal of Advances in Environmental Health Research
J Adv Environ Health Res. 2025;13(4):245-258. doi: 10.34172/jaehr.1413
http://jaehr.muk.ac.ir

Original Article

Ecological Risk Assessment and Spatial Distribution of Heavy Metals in the Alvand Mountain Ecosystem: A 15-Year Monitoring Study (2008–2022)

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Article history:
Received: January 23, 2025
Revised: March 9, 2025
Accepted: May 5, 2025
ePublished: December 28, 2025

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Abstract

Background: Soil contamination by heavy metals represents a critical environmental issue that endangers both ecological balance and human well-being. This study investigates the ecological risks of arsenic (As) and cadmium (Cd) in the Alvand Mountain ecosystem over a 15-year monitoring period (2008–2022), emphasizing their sources, spatial distribution, and associated health risks.

Methods: Systematic random sampling was performed across the Alvand region. Soil samples were analyzed for As and Cd using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Contamination and ecological risk levels were quantified using the Contamination Factor (Cf), Revised Contamination Degree Index (rCd), and Environmental Risk Potential Index (Eir). Geostatistical interpolation methods (Kriging and IDW) were applied to generate spatial distribution maps for 2008 and 2022, with model accuracy validated via Root Mean Square Error (RMSE) and Mean Absolute Error (MAE).

Results: In 2008, As concentrations were highest in the central and northeastern zones, while Cd pollution dominated the western and eastern borders. By 2022, As contamination expanded westward, and Cd became widespread throughout the region. Cd exhibited an Eir value exceeding 447, indicating a very high ecological risk according to the Hakanson classification.

Conclusion: As contamination appears to stem from natural geogenic sources, whereas Cd accumulation is primarily anthropogenic, driven by agricultural activities. Continuous monitoring and stricter fertilizer management are essential to mitigate heavy metal pollution and safeguard the ecological integrity of mountainous ecosystems.

Keyword: Soil pollution, Environmental risk assessment, Ecosystem, Carcinogenic risk, Arsenic, Cadmium

Please cite this article as follows: Makhfi G, Ildoromi A, Mortazavi S. Ecological risk assessment and spatial distribution of heavy metals in the alvand mountain ecosystem: a 15-year monitoring study (2008–2022). J Adv Environ Health Res. 2025; 13(4):245-258. doi:10.34172/jaehr.1413

Introduction

Soil contamination with heavy metals is one of the most important global environmental challenges.[1] Although numerous studies have examined heavy metal pollution in various environments, a critical gap remains in understanding the long-term spatial and temporal dynamics of arsenic (As) and cadmium (Cd) contamination in mountainous ecosystems, particularly in regions influenced by both natural and anthropogenic sources. Mountainous regions, such as the Alvand Mountain ecosystem, pose unique challenges owing to their complex topography, geological diversity, and susceptibility to erosion, which can exacerbate contaminant dispersion. Soil performs many essential functions in the natural environment[2] and meets the basic needs of human society.[3] It provides essential services, including food production, water filtration, habitat for organisms, and carbon sequestration, which are vital for human survival and development. Heavy metal contamination threatens these functions, undermining ecosystem integrity and human health.[4] As a critical natural resource, soil sustains life by supporting agriculture, regulating water cycles, and maintaining biodiversity. It also plays a vital role in climate regulation by sequestering carbon, making its preservation essential for environmental and public health.[5] As a result, soil contamination with heavy metals has become a major environmental concern in recent decades, attracting growing scientific attention.[6] Natural processes like weathering of parent materials and soil formation, combined with human activities, including the application of chemical fertilizers, sewage sludge, fossil fuels, and atmospheric deposition, have increased heavy metal concentrations in soils, thereby disrupting soil functionality.[7] Heavy metals are an important source of concern in relation to pollution due to their non-biodegradable nature and bioaccumulative tendencies within the food chain.[8] The lack of effective elimination mechanisms in living organisms has made these metals harmful to humans even at low concentrations.[9] Furthermore, heavy metals pose a serious threat to natural ecosystems, as some of them circulate within the ecosystem and accumulate due to the inability of microorganisms to decompose them.[10] In addition to their risks to the environment and human health, excessive levels of heavy metals in contaminated soils diminish biological activity and soil fertility, thereby reducing agricultural productivity.[11] Heavy metals are considered priority pollutants because of their toxicity, persistence, and bioaccumulation potential.[12] Understanding their concentrations is crucial for evaluating environmental and human health risks, predicting disease potential, and establishing soil quality standards.[13] Given the carcinogenic potential of certain metals, such as As and Cd , assessing both carcinogenic and non-carcinogenic risks provides valuable insights for public health management.[14]

To minimize human exposure to soil contaminants, precise monitoring and evaluation are necessary to develop effective remediation strategies and mitigate adverse effects where concentrations exceed permissible limits.[15] As infectious diseases become better controlled and life expectancy increases, non-communicable diseases, including cancer, have emerged as leading causes of mortality. Studies suggest that nearly 30% of human cancers are linked to short-term exposure to dietary carcinogenic pollutants.[16] Once inside the body, heavy metals accumulate in tissues such as fat, bone, muscle, and joints, leading to various diseases and complications.[17]

Air pollution noticeably contributes to the contamination of food and water, making it a primary pathway for pollutant intake.[18] Heavy metals, as a result, can enter the human body through water, air, and skin contact, easily accumulating in organs and living organisms.[19] One such metal is Cd, primarily released from industrial activities and the use of chemical fertilizers. Cd is highly persistent in the environment and can inhibit plant growth by accumulating in plant tissues. Over 40% of Cd can translocate to the aerial parts of plants, posing a severe threat to human health. [20]

As is another hazardous element whose excessive intake can cause gastrointestinal distress, neurological disorders, circulatory dysfunction, and even death.[21] It originates from both natural and anthropogenic sources.[22] Therefore, assessing soil contamination with these metals and understanding their environmental implications are essential.

Studies on heavy metal pollution often start by figuring the spatial distribution of contaminants. For example, Mishra et al analyzed As contamination in agricultural soils in eastern India, collecting 201 soil samples and using pollution indices like Geo-Accumulation Index (Igeo) and CF to assess risks. Geostatistical tools such as Ordinary Kriging (OK) and Inverse Distance Weighting (IDW) were used to Figure As distribution, revealing higher vulnerability to As toxicity in children and emphasizing the need for remediation strategies.[23]

Pollution indices are essential tools for determining the extent of soil contamination by heavy metals and assessing potential environmental risks.[24] Thus, many studies have utilized environmental indices to evaluate contamination levels. Given that these indices represent different aspects of heavy metal behavior, applying multiple indices in soil contamination studies is crucial.[25]

Jing et al studied As variations in the Pearl River Basin, China, across three decades (1990s–2010s). As levels rose from the 1990s (11.40 mg/kg) to the 2000s (14.46 mg/kg) but declined by the 2010s. The Hazard Quotient (HQ) for children peaked in the 2000s (1.54) before dropping to 0.67 in the 2010s, linking trends to geological and human factor.[26]

Zhang et al studied As distribution, bioavailability, and ecological risks in coastal soils of the Tibetan Plateau. The study identified As like as geothermal activity, agriculture, and transportation, focusing on their environmental and ecological impacts in the Lhasa River region.[27]

Previous research has largely emphasized lowland or urban areas, leaving mountainous ecosystems underrepresented in the literature. Furthermore, most studies have relied on short-term data, limiting their ability to capture long-term trends and the cumulative effects of human activities, such as agricultural practices, on heavy metal distribution. This study addresses these gaps by providing a comprehensive 15-year analysis (2008–2022) of As and Cd contamination in the Alvand Mountain ecosystem, integrating spatial analysis, pollution indices, and risk assessment models to monitor temporal and spatial changes. Therefore, the objectives of this study were:

1. To analyze the spatial and temporal changes in As and Cd contamination in the Alvand Mountain ecosystem over a 15-year period (2008–2022).
2. To identify the primary sources of contamination and assess the contributions of natural processes and human activities.
3. To evaluate the ecological and health risks associated with As and Cd contamination and their evolution over time.

Materials and Methods

Study Area

The study area is the Alvand Mountain ecosystem, located in Hamadan Province, Iran. Alvand Mountain is an isolated range in the eastern branch of the Central Zagros, covering a total area of 4,593.51 km^2. The mountain's highest elevation is 3,574 meters, and its lowest point is 1,460 meters above sea level. It extends between 47°40′–48°54′ E longitude and 34°23′–35°13′ N latitude. The region includes parts of Hamadan, Tuyserkan, Bahar, and Asadabad counties, with approximately 265 villages situated within this area (Figure S1). This geographic diversity, combined with its ecological and agricultural importance, makes the Alvand Mountain ecosystem a key area for assessing environmental risks associated with heavy metal contamination. The region features a semi-arid climate with cold winters and mild summers, characterized by limited rainfall and significant temperature fluctuations. The soils are primarily derived from weathered parent materials and exhibit a mix of loamy and rocky textures, influenced by the area's complex topography and geological diversity.[28]

Sampling and Sample Preparation

The sampling method employed was systematic-random sampling, chosen over stratified or grid-based approaches for its ability to balance spatial coverage with practicality in complex mountainous terrain. In such regions, stratified sampling can be challenging because defining homogeneous strata across diverse landscapes is difficult, while grid-based sampling may fail to capture variations in elevation and slope.[29] The collected soil samples were air-dried until a constant weight was achieved. The dried samples were then ground into powder and sieved sequentially through a 10-mesh (2 mm) sieve and a 230-mesh (63 µm) sieve. For digestion, 2 grams of each dried soil sample were treated with a mixture of nitric acid, perchloric acid, and hydrochloric acid in a ratio of 4:4:12. The digestion was performed using a Hot Block Digester, initially at 40°C for 1 hour, followed by heating at 140°C for 3 hours. The digested samples were then filtered through Whatman No. 1 filter paper, and the filtrates were stored in polyethylene containers under refrigeration.[15] Finally, the samples were analyzed using ICP–MS.30 The detection limits for As and Cd were established as three times the standard deviation of blank measurements, resulting in detection limits of 0.01 mg/kg for As and 0.005 mg/kg for Cd.

Pollution Factor

To assess the contamination levels and ecological risks of As and Cd, several pollution indices were selected based on their widespread use, reliability, and ability to address specific aspects of heavy metal behavior in soil. The CF was selected because it provides a simple yet effective measure of the degree of contamination relative to background levels, making it suitable for identifying localized pollution hotspots.[31] The mCd was included to offer a more comprehensive assessment by considering the average contamination level across multiple elements, which is particularly useful for evaluating overall soil quality.[32] The Eir was selected due to its ability to integrate both contamination levels and the toxicity of heavy metals, providing a holistic view of ecological risks. Additionally, the Nemerow Pollution Index (PI) and Modified Pollution Index (MPI) were applied to account for both average and maximum contamination levels, ensuring a balanced evaluation of pollution severity.[33] These indices were chosen over others because they collectively address the key aspects of heavy metal contamination, including spatial distribution, toxicity, and cumulative ecological impacts, making them well-suited for the objectives of this study. Furthermore, their widespread use in similar research allows for meaningful comparisons with other studies and regions

CF

The CF and degree of contamination are commonly used to describe the pollution level of heavy metals and environmental contamination. In this calculation, M_x represents the concentration of the element in the sample, and M_b denotes the concentration of the same element in the reference material (mean shale values). The relationship is expressed in Equation 1, and the classification of contamination degree is presented in Table 1:[32]

$$C_f = \frac{M_x}{M_b} \tag{1}$$

Cd

The Cd is calculated using Equation 2:

$$C_d = \sum_{i=1}^{8} C_f^i \tag{2}$$

Where, n is number of parameters analyzed.[34]

mCd

The relationship is expressed in Equation 3, and the classification of Revised mCd is presented in Table 2:

$$mC_d = \frac{\sum_{i-1}^{n} C_f^i}{n} \tag{3}$$

Table 1. Classification of Contamination Degree[34]

Class	Pollution Degree	CF Value	Cd Value
1	Low contamination	1 > Cf	Cd < 6
2	Moderate contamination	3 > Cf ≥ 1	6 ≤ Cd < 12
3	High contamination	6 > Cf ≥ 3	12 ≤ Cd < 24
4	Very high contamination	Cf ≥ 6	Cd ≥ 2 4

Environmental Risk Potential Index

The Eir was first introduced by Hakanson in 1980 and has been widely used to assess sediment pollution. The index evaluates the potential ecological risk of heavy metals using Equation 4 and the classification of the Environmental Risk Potential Index presented in Table 3:

$$E_r^i = T_r^i \times C_f^i = T_r^i \left(C_s^i / C_n^i \right) \quad (4)$$

Where, Csi is concentration of the element in the sample, and Tri is biological toxicity factor of a single element.

PI and MPI

The PI was introduced by Nemerow in 1991. In subsequent years. The MPI improves upon the original index by using the enrichment factor instead of the Contamination Factor (Cf). The calculations for these indices are shown in Equations 5 and 6:

$$PI = \sqrt{\frac{\left(Cf_{average}\right)^2 + \left(Cf_{max}\right)^2}{2}} \quad (5)$$

Where, Cfaverage is average Cf, and Cfmax is maximum Cf.

$$MPI = \sqrt{\frac{\left(Ef_{average}\right)^2 + \left(Ef_{max}\right)^2}{2}} \quad (6)$$

Where, Efaverage is average enrichment factor, and Efmax is maximum enrichment factor.[37]

Health Risk Assessment of Heavy Metals

In this study, the health risk assessment of heavy metals was conducted using the model developed by the United States Environmental Protection Agency (USEPA). However, to ensure the relevance of the model to local conditions, key assumptions such as exposure frequency, ingestion rate, and soil-to-human transfer factors were carefully evaluated and adjusted where necessary.

Table 2. Classification of Revised mCd [35]

Class	Contamination Degree	mCd Value
1	Very low degree of contamination	mCd ≤ 1.5
2	Low degree of contamination	1.5 < mCd ≤ 2
3	Moderate degree of contamination	2 < mCd ≤ 4
4	High degree of contamination	4 < mCd ≤ 8
5	Very high degree of contamination	8 < mCd ≤ 16
6	Extremely high degree of contamination	16 < mCd ≤ 32
7	Ultra-high degree of contamination	mCd > 32

Table 3. Classification of Environmental Risk Potential Index[36]

Class	Environmental Risk Index (RI)	Classification
1	RI < 150	Low
2	150 ≤ RI < 300	Moderate
3	300 ≤ RI < 600	High
4	RI ≥ 600	Very high

Exposure Frequency

The USEPA default value for exposure frequency (350 days/year) was used, as it aligns with the agricultural and residential activities observed in the Alvand Mountain region. This assumption is supported by local surveys indicating that residents in the study area are frequently exposed to soil due to farming and outdoor activities.[38]

Ingestion Rate

The ingestion rate for soil was set at 100 mg/day for adults and 200 mg/day for children, based on USEPA recommendations. These values were deemed appropriate for the study area, as they reflect typical soil ingestion patterns in rural and agricultural communities.[38]

Soil-to-Human Transfer Factors

Soil-to-human transfer factors for As and Cd were derived from USEPA guidelines, but their applicability to local conditions was verified using regional data on soil properties and bioavailability. For example, the alkaline nature of the soil in the Alvand Mountain region may reduce the bioavailability of certain heavy metals, potentially lowering the actual transfer factors compared to USEPA defaults.

Sensitivity Analysis

To account for uncertainties in these assumptions, a sensitivity analysis was conducted by varying key parameters (e.g., exposure frequency, ingestion rate) within plausible ranges.[38]

Exposure to heavy metals in soil is calculated based on the Average Daily Dose (ADD) using Equation 7:

$$ADD = \frac{\left(Ci \times InhR \times EF \times ED\right)}{\left(PEF \times BW \times AT\right)} \quad (7)$$

Where, ADD (mg/kg/day) is average daily dose of pollutants via inhalation, Ci is concentration of heavy metals in soil, InhR is inhalation rate (100 for adults and 200 for children), EF is exposure frequency (days/year), assumed to be 350 days/year for both children and adults, ED is exposure duration (years), BW is average body weight (kg), assumed to be 15 kg for children and 55.9 kg for adults, AT is averaging time (days), calculated as ED × 365 time, and PE is particulate emission factor from soil to air, equal to 1.36×10^9 for both age groups.

Cancer Risk (CR) Assessment

The probability of developing cancer over a lifetime due to carcinogenic exposure is represented by CR, (Equation 8):

$$CR = \sum ADD_i \times CSF \quad (8)$$

Where, CR is cancer risk (unit less), CSF is cancer slope factor for each metal (mg/kg/day), 15.1 for As and 6.3 for Cd (via inhalation), and ADD is average daily dose of pollutants via inhalation.

Non-Carcinogenic Risk Assessment (HQ)

The potential for non-carcinogenic diseases caused by each metal was evaluated using the HQ, (Equation 9):

$$HQ = ADDi/RFDi \quad (9)$$

Where, HQ is hazard quotient (unit less), and RfD is reference dose of the metal (mg/kg/day), 0.3 for As and 0.001 for Cd (via inhalation).

These metrics (ADD, CR, and HQ) provide a comprehensive understanding of both carcinogenic and non-carcinogenic health risks posed by heavy metals in contaminated soils, helping to prioritize interventions and remediation strategies.[39]

Spatial Analysis and Statistical Validation

Spatial distribution Figures were generated using geostatistical interpolation methods, including OK and Inverse IDW. The accuracy of the interpolation was assessed through cross-validation, with RMSE and MAE used as statistical metrics. These methods ensured the reliability of the spatial analysis and provided a robust basis for interpreting the distribution patterns of As and Cd.

Results and Discussion

So as to analyze pollution trends over a 15-year period (2008–2022) in the mountainous ecosystem of Hamadan Province, the concentrations of the heavy metals As and Cd were examined. This study was highly relevant to the Alvand Mountain ecosystem, as it investigated the long-term dynamics of As and Cd contamination in a mountainous region characterized by complex topography and high susceptibility to erosion. The study identifies growing ecological and health risks from these heavy metals, offering key insights for designing effective management approaches. The integration of spatial analysis, pollution indices, and risk assessment models establishes a replicable framework for monitoring and mitigating pollution in similar mountainous ecosystems worldwide. Pollution indices were employed to assess concentration levels and pollution trends, and the results were presented as spatial distribution figures. The key findings of the index evaluations have been summarized as follows:

Pollution Degree Index

It was found that the lowest pollution levels were in the southwestern region, categorized as "low pollution degree" according to the pollution factor classification (Figure 1). However, in other parts of the region, pollution levels increased, with the central and southern areas showing the highest contamination levels, classified as "high pollution degree. By 2022, pollution levels had increased across the entire study area. The entire region fell into the "high pollution degree" category. The contamination gradient was seen to shift from the northern and southern areas toward the northwest, illustrating an upward trend in pollution over time.

Revised Pollution Degree Index

Pollution density was primarily concentrated in the northern and central parts of the region (Figure S2). However, noticeable pollution loads were also observed in the southern areas. Most of the contamination levels fell under the "high pollution degree" category. In contrast, the eastern and southwestern parts showed the lowest

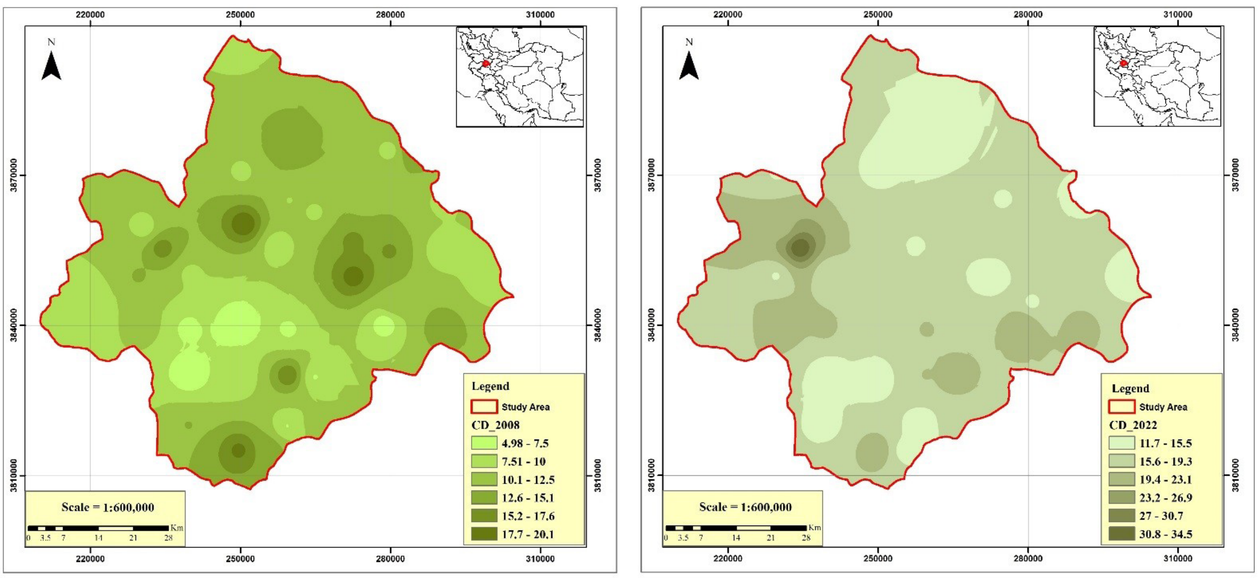

Figure 1. Pollution Degree Index in the Study Area for 2008 and 2022

pollution loads, categorized as "moderate pollution degree."

By 2022, there was not only a significant increase in pollution levels but also a change in the distribution pattern. The contamination exhibited a gradient flow from the northern and eastern parts toward the west. The highest pollution level was recorded in the western region, with a value of 15.4, placing it in the "very high pollution" category.

Environmental Risk Potential Index

The values of Eri for As in 2008 and 2022 have been presented in Figure 2a. The highest concentrations of As were observed in the central region, while the lowest concentration (19.1) was found in the southwestern area. The distribution pattern of As concentrations shifted greatly, with the highest concentrations observed in the western region and the lowest concentrations in the northern to central parts. The distribution pattern for Cd differed considerably from that of arsenic. Also, the highest concentrations of Cd were recorded in the western and eastern border areas, while the lowest concentrations were observed in the central and parts of the northern region. A considerably increase in Cd concentrations was noted, with the highest accumulation observed in the western region, reaching a value of 447. Overall, all areas were classified under the "high environmental risk potential" category (Figure 2b).

PI and MPI

The PI in 2008 was stupendously lower compared to 2022. During this year, the distribution of pollution was concentrated primarily in the central and southern regions of the study area. The southwestern region showed the lowest PI . By 2022, both the PI values and the overall distribution patterns had changed notably. The pollution levels increased noticeably, with a gradient of pollution spreading toward the northwest. The lowest pollution levels were observed in the northern and northeastern regions, as well as partially in the southwestern area

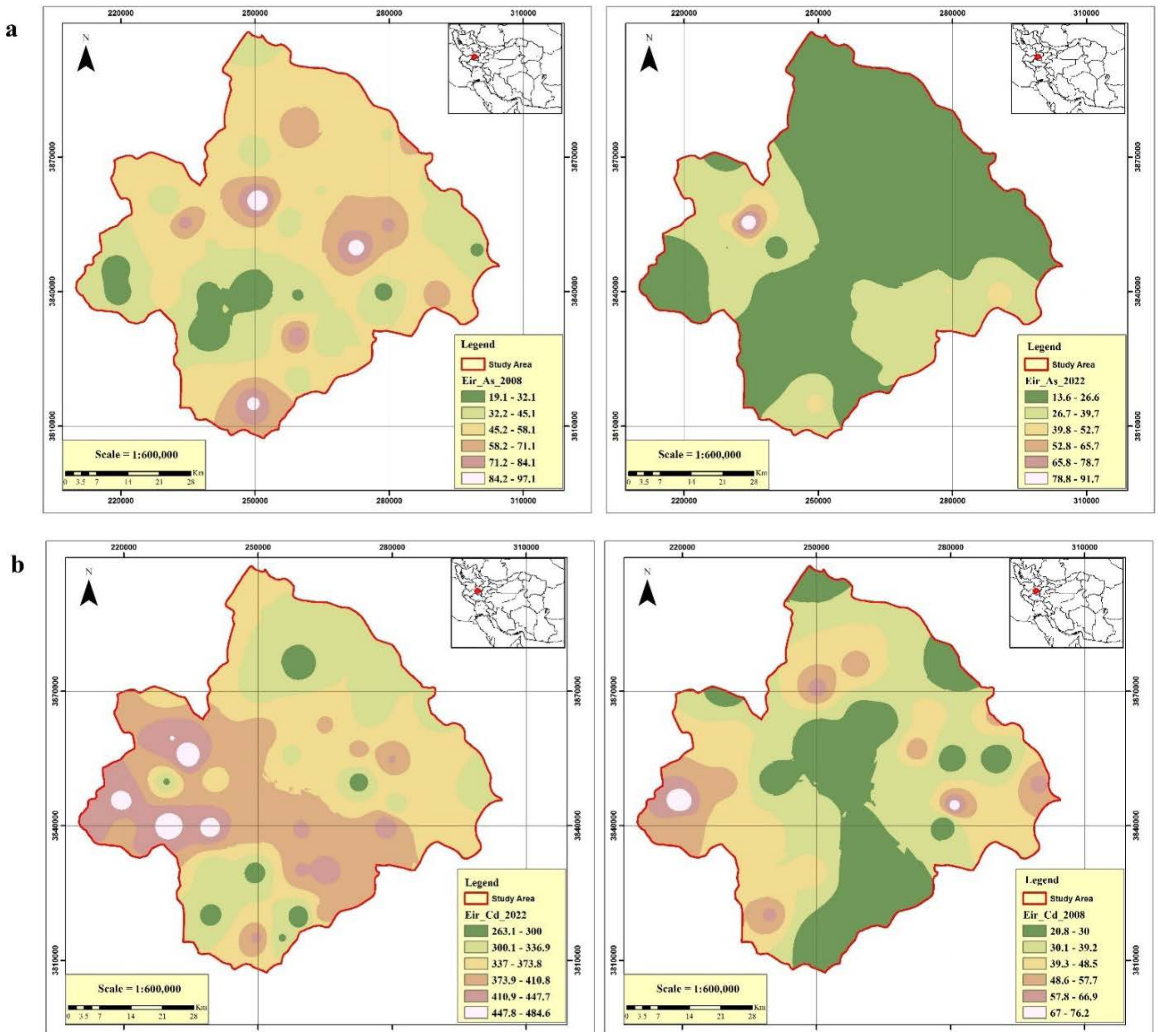

Figure 2. Eir in the Area Studied for 2008 and 2022

(Figure 3a).

Modified Nemerow Pollution Index (MPI)

The MPI for 2008 indicated a non-uniform distribution of pollution (Figure 3b). The central region of the study area showed the lowest pollution levels, whereas higher levels were observed along the southern, northern, northwestern, and northeastern borders. The pollution gradient appeared to move from the southwestern region toward the northern and northeastern parts of the area studied. By 2022, both the average pollution levels and the direction of the gradient had changed. Pollution levels increased from the eastern region toward the west, with the highest concentrations recorded in the western part of the area studied. In other regions, pollution displayed a relatively uniform distribution.

Carcinogenic and Non-Carcinogenic Risk

Based on Figure S3a, it can be stated that in 2008, the carcinogenic risk level for Cd in adults was negligible. However, as the distance from the center of the area studied increased, the risk level also rose. In 2022, the carcinogenic risk for Cd showed an increase, placing the region within the controlled risk threshold, with a gradient flowing from the north and northeast toward the west. It is worth noting that the values in all the carcinogenic and non-carcinogenic risk figures are multiplied by 10^{-6}.

The carcinogenic risk for children based on Cd in 2008 was within acceptable limits (Figure S3b). However, the risk level increased at the edges of the studied area. By 2022, this risk had greatly risen, indicating the presence of a carcinogenic risk, although it remained under control. The gradient flows from the northeast toward the west.

The spatial distribution of arsenic's carcinogenic risk in 2008 indicates an increase from the southwest toward the north and northeast for adults (Figure 4a). However, overall, this risk remains low. In 2022, the risk pattern shifted, showing an increasing trend from the north and northeast toward the northwest. Overall, the carcinogenic risk level has increased but remains under control. According to Figure 4b, the carcinogenic risk of As for children in 2008 was low and negligible, with changes

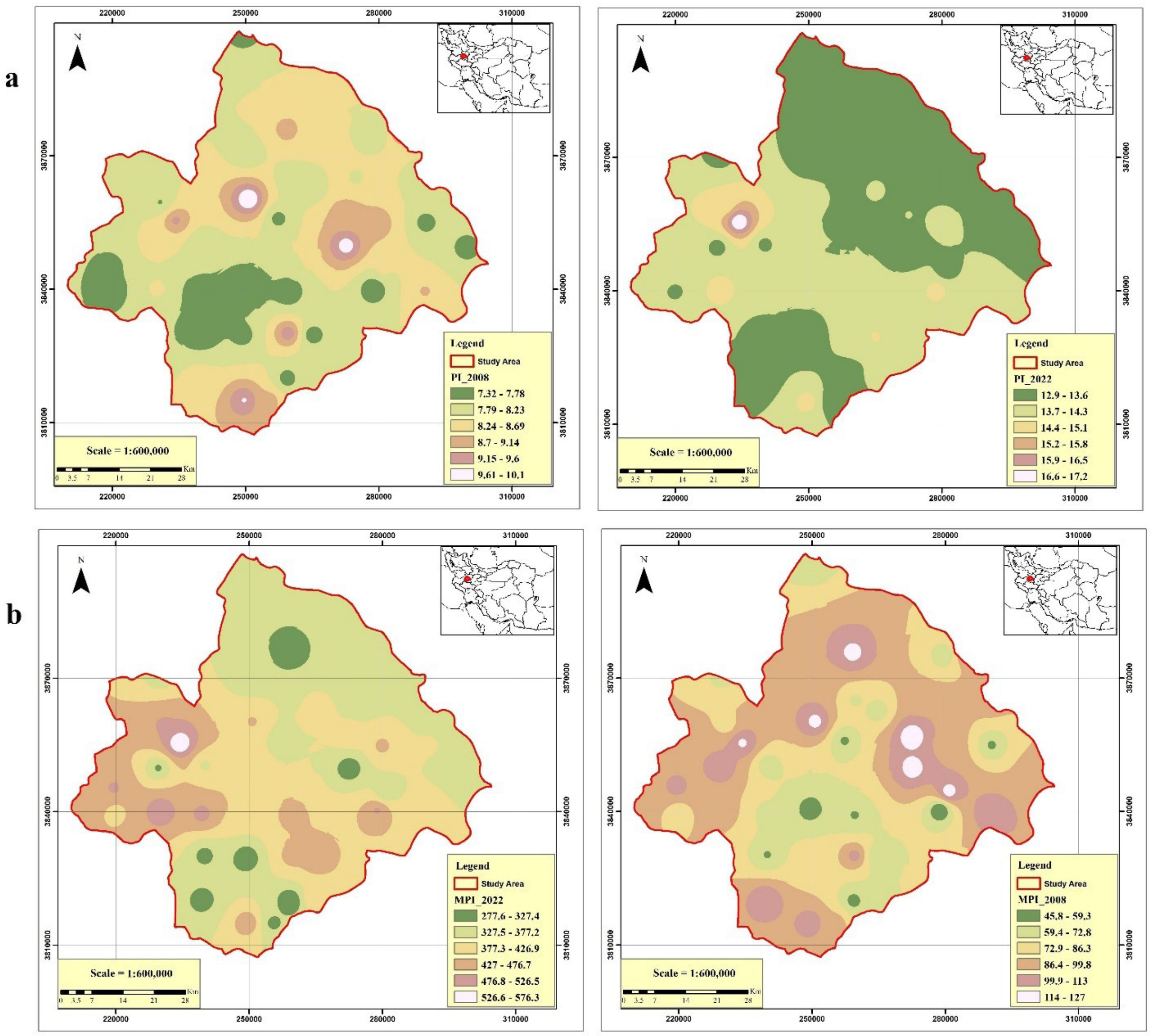

Figure 3. PI and MPI in the Study Area for 2008 and 2022

radiating from the southwest outward. In 2022, the carcinogenic risk remained low, but the gradient shifted from the northern and southwestern regions toward the northwest.

The non-carcinogenic risk of Cd for adults in both 2008 and 2022 was within a low and negligible range. In 2008, the risk index increases from the center toward the edges, whereas in 2022, the non-carcinogenic risk increased from the north and northeast toward the west (Figure 5a). For children, the spatial distribution of Cd in 2008 showed an increasing trend from the center to the edges. In 2022, this trend shifted, with the risk rising from the north and northeast toward the west. In both years, the non-carcinogenic risk remains negligible (Figure 5b).

In 2008, the non-carcinogenic risk of As for adults was extremely low, with a distribution pattern moving from the north and northeast toward the southwest. Similarly, in 2022, the risk remained very low, with the trend shifting from the east toward the northwest (Figure 6a). Moreover, the non-carcinogenic risk for children in both 2008 and 2022 was negligible. The highest risk in 2008 was observed in the northern and northeastern regions, while in 2022, the highest risk was concentrated in the northwest (Figure 6b).

As naturally occurs in many mountainous regions within mineral deposits. The weathering of arsenic-rich rocks, along with runoff and soil erosion, can contribute to the dispersion of this element in the environment. Also, mining activities (such as metal extraction) in mountainous areas can significantly increase As levels.[40]

According to the PI and the RPI, the high patterns of As pollution in central and northeastern areas in 2008 may result from the breakdown of natural mineral deposits. The increase in the index in 2022, particularly in the western regions, emphasizes the role of water flows and erosion as primary factors in As distribution. Furthermore, considering the Eir, the As concentration distribution in 2022, with the highest accumulation in the

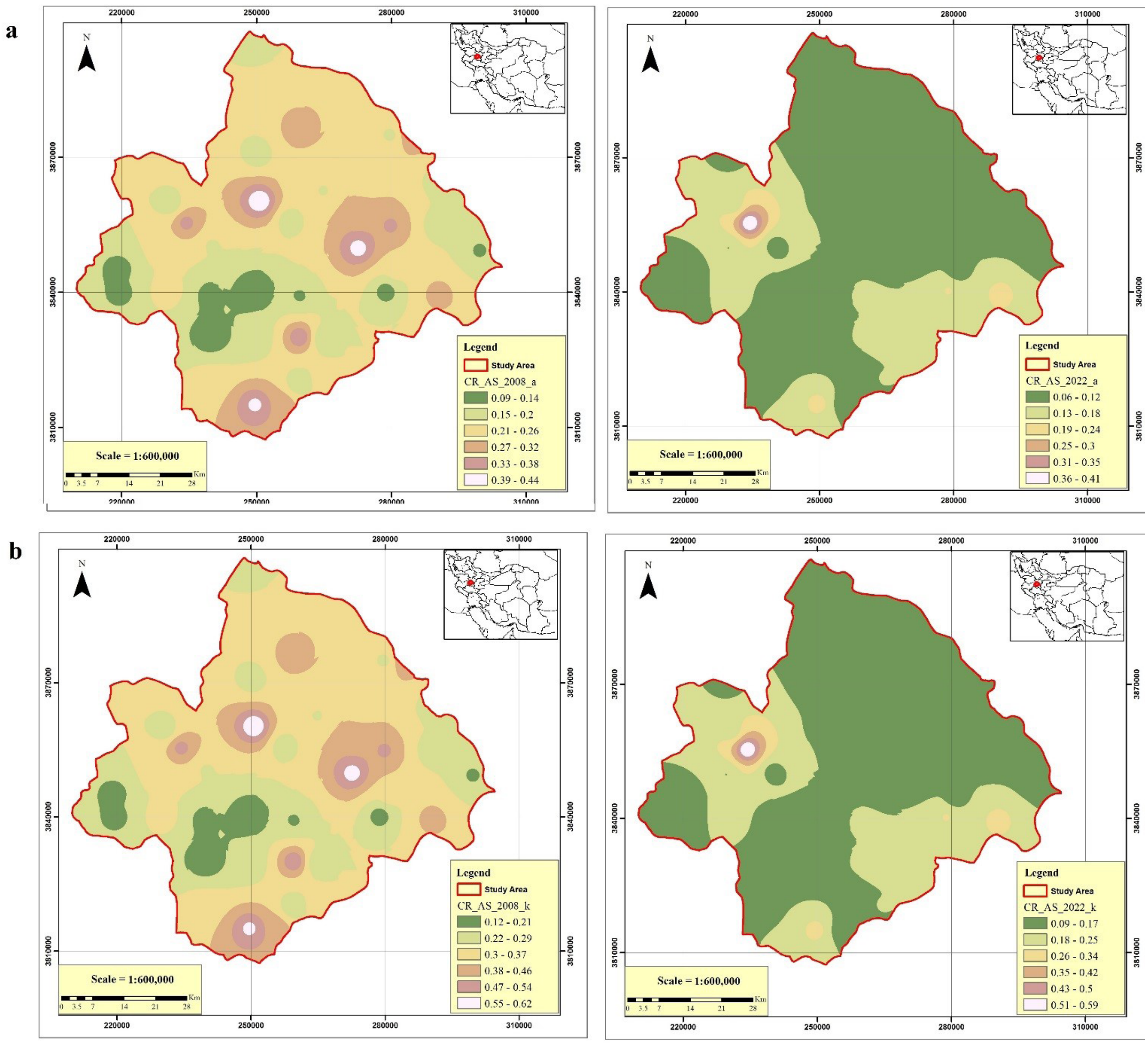

Figure 4. Carcinogenic Risk Index of Arsenic for Adults and Children in the Area Studied (2008 and 2022)

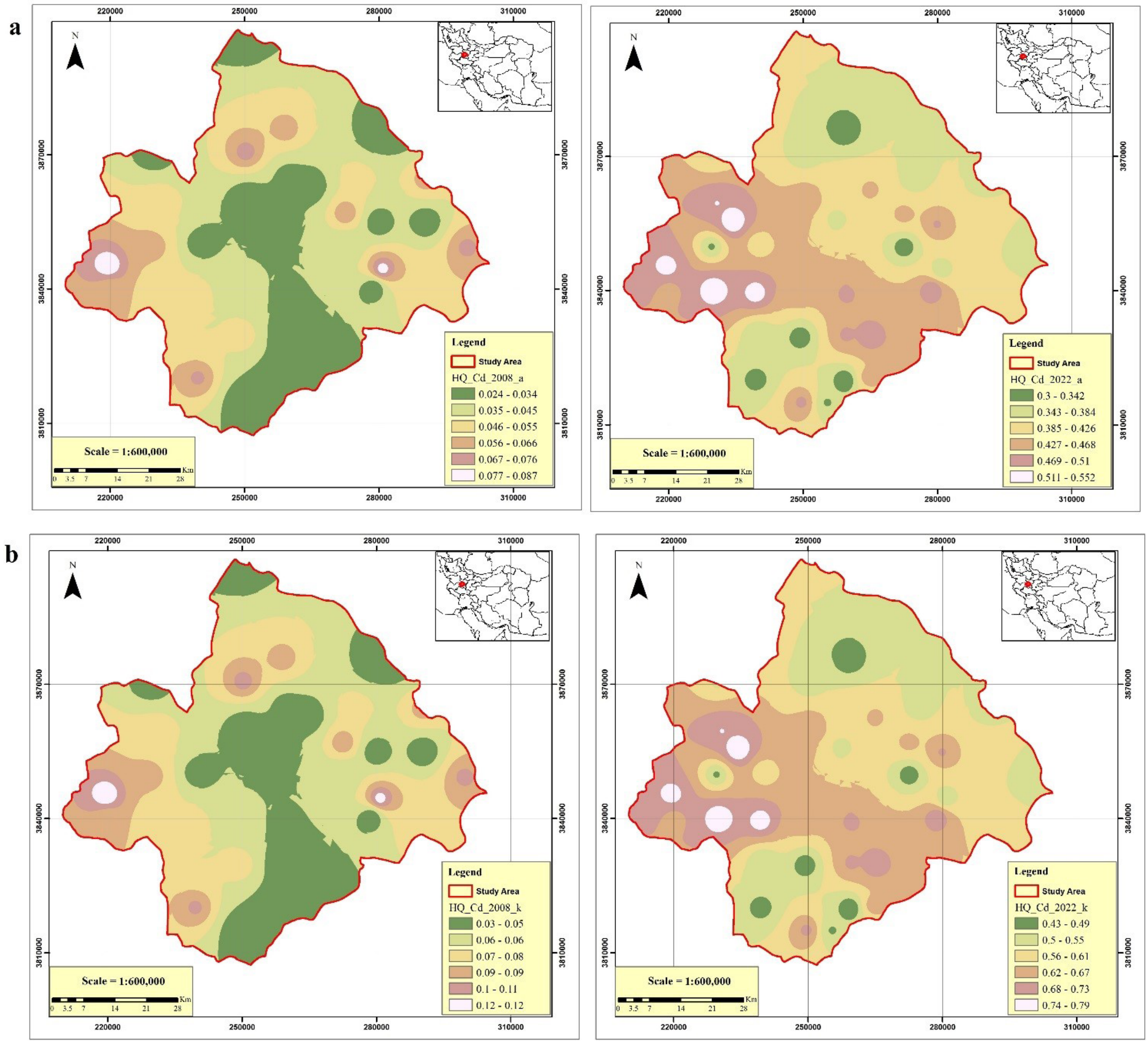

Figure 5. Non-Carcinogenic Risk Index of Cadmium for Adults and Children in the Area Studied (2008 and 2022)

western areas, is likely associated with changes in surface or groundwater flow, which transported the element to lower regions. As exhibited low carcinogenic risk in 2008, with a gradual increase up to 2022. This trend suggests that, in addition to natural influences, human activities have played a role in increasing As accessibility in the soil. Studies conducted in regions with high geological potential for As, such as volcanic areas or those with mineral reserves) indicate that As pollution levels are often dependent on the local geological structure. For example, Jing et al examined the spatial and temporal variations in As concentration and distribution in surface soils over three monitoring periods (1990s, 2000s, and 2010s) based on geochemical properties. Their findings revealed a decline in soil As content from 1990 to 2010, with the most significant changes occurring in mining regions. This study attributed the high values and variations in soil As to geological background and human activities.[26]
To contextualize the contamination levels observed in the Alvand Mountain ecosystem, it is important to compare them with findings from other regions in Iran and worldwide. This comparison marks the extent of As and Cd contamination in the study area and provides valuable perspectives on the performance of existing management practices.

The As levels in the Alvand Mountain ecosystem are comparable to those reported in other mountainous regions of Iran, such as the Kerman Province, where As concentrations in soil range from 10 to 50 mg/kg due to natural geological processes.[2] However, the As levels in the Alvand Mountain are noticeably lower than those in highly polluted areas like the Zarshuran gold mining region, where concentrations can exceed 500 mg/kg owing to mining activities.[34] However, they are much lower than those in severely polluted areas like Bangladesh, where As concentrations in soil can exceed 1000 mg/kg because of groundwater contamination.[40] The presence of As in the Alvand Mountain ecosystem can be attributed to

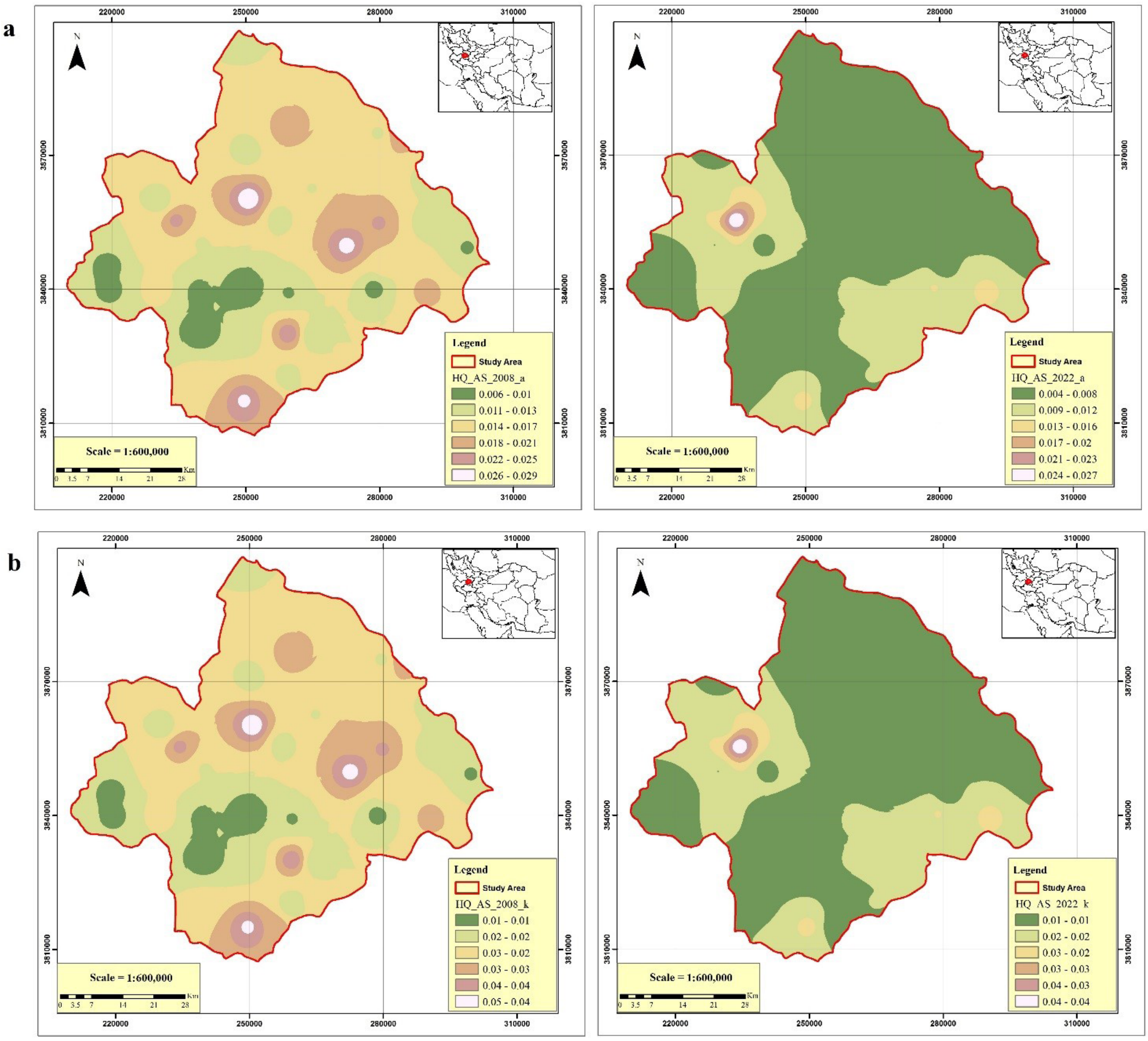

Figure 6. Non-Carcinogenic Risk Index of Arsenic for Adults and Children in the Area Studied (2008 and 2022)

both natural geological processes and human activities. The region's complex geology, characterized by arsenic-bearing minerals such as arsenopyrite, contributes to the natural release of As through weathering. Also, agricultural practices, including the use of phosphate fertilizers, have been shown to introduce As into the soil over time.[41] The mountainous terrain further facilitates the distribution of As through erosion and runoff, spreading it across the ecosystem. These findings align with previous studies in similar regions, confirming that As contamination in the study area is influenced by both natural and anthropogenic factors.

The Cd levels in the Alvand Mountain ecosystem are higher than those reported in non-agricultural regions of Iran, such as the central deserts, where Cd concentrations typically range from 0.1 to 0.5 mg/kg.[42] However, they are lower than those in heavily industrialized areas like the Ahvaz region, where Cd levels can reach up to 10 mg/kg owing to industrial emissions and oil extraction activities.[43] The Cd levels in Alvand Mountain are comparable to those in agricultural regions of China, where Cd concentrations range from 0.5 to 5 mg/kg due to the extensive use of phosphate fertilizers.[44] But they are lower than those in heavily industrialized regions of Europe, such as the Ruhr Valley in Germany, where Cd levels can exceed 20 mg/kg due to historical industrial activities.[45] In another study, Raju conducted a review of the sources, geochemical processes, toxicity, and removal technologies of As. He stated that erosion, dissolution, and weathering release As into the soil and water environment.[46] The geochemistry and mobilization of As is a complex phenomenon influenced by various biogeochemical processes in mountainous regions, agriculture is more limited, but the concentrated use of fertilizers in certain areas, such as the plains bordering mountains can exacerbate Cd pollution. Phosphate fertilizers typically contain Cd as an accompanying contaminant. Long-term use of these fertilizers can lead to the gradual accumulation of Cd in the soil. The PI and Revised Pollution Index (RPI) indicated an increase in Cd concentration along the western and eastern borders in 2008, which expanded to cover the entire region by 2022. This widespread and continuous use of chemical fertilizers is the primary cause. Furthermore, the significant increase in the Cd Eir in 2022 (exceeding 447) in western areas is attributed to the infiltration of contaminated fertilizers and the transfer of Cd to lower areas through erosion and surface waters. According to the Hakanson classification, an Eir value above 447 indicates a very high ecological risk, highlighting the severe environmental and health implications of Cd contamination in these areas.[31] In 2008, the Cd carcinogenic risk index reflected the limited impact of chemical fertilizers, but by 2022, the sharp increase in risk, particularly in western regions, was likely caused by prolonged fertilizer use and the gradual accumulation of Cd in the soil. Studies conducted in other regions demonstrate that the duration of agricultural activities significantly impacts heavy metal accumulation. For instance, Shahbazi in 2020 examined the effects of agricultural activities on the accumulation of Cd, cobalt, and chromium in soils. The study revealed that fields cultivated for 65 years exhibited significantly higher concentrations of these metals compared to fields farmed for 35 or 20 years. The increasing concentration trend was linked to the use of chemical fertilizers and the possible presence of metals in the chemical composition of urea, phosphate, and potash fertilizers.[47] Another study by Vaziri conducted in 2021 found that environmental indices for Cd showed that the main sources of metal pollution were human activities such as excessive use of chemical fertilizers, urban wastewater discharge into soils, and the presence of oil industries in the study area.[40]

These comparisons indicate that As and Cd pollution in soils is highly dependent on local characteristics (natural or human sources). Moreover, the health impacts identified in this study align with global patterns, particularly in areas where chemical fertilizer use or natural pollutant sources are predominant.

While the study identified the widespread use of phosphate fertilizers as the primary source of Cd contamination in the Alvand Mountain ecosystem, it is important to consider other potential sources, such as industrial activities and atmospheric deposition. However, several lines of evidence support the conclusion that fertilizers are the dominant contributor to Cd pollution in this region. The highest concentrations of Cd were observed in regions with intensive agricultural activity, particularly in the western parts of the study area where fertilizer use is prevalent. The significant increase in Cd levels from 2008 to 2022 coincides with the expansion of agricultural practices and increased fertilizer application in the region. Phosphate fertilizers commonly used in the study area are known to contain Cd as a contaminant, which accumulates in the soil over time with repeated application. While there are limited industrial facilities in the Alvand Mountain region, the possibility of Cd from industrial sources cannot be entirely ruled out. However, the spatial distribution of Cd does not correlate with known industrial sites, suggesting that industrial contributions are minimal.

Overall, As is more influenced by the geological features and natural processes of the region, whereas Cd is directly linked to human activities. In 2008, As exhibited a more uniform distribution, while Cd showed a more localized distribution pattern due to external sources (fertilizers). By 2022, both elements had accumulated in western regions, reflecting the convergence of geological (arsenic) and human (cadmium) factors. Arsenic's carcinogenic risk has remained relatively stable and within controlled limits, as its changes are primarily influenced by natural factors. In contrast, cadmium's carcinogenic risk has significantly increased, indicating the direct impact of contaminated fertilizer use. This study emphasizes that in mountainous regions, the management of natural and human resources must be integrated. As management depends on controlling natural processes such as weathering and runoff, while Cd pollution control requires agricultural policies and regulation of human activities. The increasing trend of risk indices and the spread of pollution in 2022 underscore the urgent need for management measures and preventive policies to protect the environment and public health.

The pollution indices used in this study, including the CF, mCd, and Eir, are widely applied in environmental studies because of their ability to provide a quantitative assessment of contamination levels and ecological risks. However, it is important to acknowledge their limitations, particularly in capturing long-term trends and complex interactions within ecosystems. These indices are useful for comparing contamination levels across different time periods, they may not fully capture the dynamic nature of heavy metal behavior in soil, such as changes in bioavailability, leaching, or interactions with organic matter. For example, the CF and mCd do not consider the potential for heavy metals to migrate vertically or horizontally over time, which can significantly influence long-term contamination patterns. Additionally, the Eir index, while comprehensive, may underestimate risks in regions with complex topography or variable hydrological conditions, such as mountainous ecosystems.

While this study presents a comprehensive assessment of long-term trends in As and Cd contamination from 2008 to 2022, it is essential to acknowledge the potential impacts of seasonal variations and climate change on heavy metal dispersion. Seasonal fluctuations in rainfall, temperature, and soil moisture can markedly influence the mobility and spatial distribution of heavy metals in the environment. In the Alvand Mountain region, seasonal rainfall patterns play a crucial role in transporting heavy metals through surface runoff and erosion. For instance, intense rainfall during the spring and winter months may enhance the leaching of As and Cd from higher elevations to low-lying areas, particularly in the western part of the study area. Likewise, temperature variations can affect the bioavailability of heavy metals by altering microbial activity and organic matter decomposition in the soil. Elevated temperatures during the summer months may promote the release of heavy metals from soil particles, thereby increasing their mobility and potential for wider dispersion.

Conclusion

This study delivers a comprehensive long-term assessment of heavy metal contamination in the Alvand Mountain ecosystem, revealing a dual-source pattern: As originating from natural geological formations and Cd primarily from anthropogenic activities, notably fertilizer application. Spatial analyses and pollution indices (PI, RPI, Eir) consistently demonstrate a westward expansion of As and widespread Cd contamination over the 15-year monitoring period, with Cd posing pronounced ecological and health risks. These findings emphasize the dynamic interactions between natural processes, such as erosion and weathering, and human interventions in determining soil contamination patterns.

By combining spatial mapping, pollution indices, and ecological and health risk models, this study establishes a rigorous and replicable framework for understanding contamination mechanisms and guiding evidence-based management strategies. It highlights the urgent need for proactive measures to protect ecosystem integrity and public health in mountainous regions.

While this study relies on established models and indices, further validation through biomonitoring and field studies is advisable. Future research incorporating dynamic geochemical modeling, sequential extraction, or isotopic analysis could provide deeper insights into the mobility, bioavailability, and long-term behavior of heavy metals. Effective mitigation should include regulating fertilizer use, controlling erosion through reforestation and terracing, implementing continuous monitoring and early warning systems, and enhancing public awareness of contamination risks to ensure sustainable management.

In summary, this research consolidates critical insights on the sources, distribution, and ecological and health risks of heavy metal contamination in mountainous environments, offering a scientifically robust foundation for targeted management interventions and long-term ecosystem protection.

Acknowledgments

The professors of the Environmental Science department of Malayer University are sincerely thanked and appreciated.

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Competing Interests

There is no conflict of interest between the authors and other.

Ethical Approval

There were no ethical considerations to be considered in this research.

Funding

The authors did not receive any financial support for the research, authorship, or publication of this article

Supplementary Files

Supplementary file 1 contains Figures S1-S3.

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