

Article

Spatial Distributions, Source, and Coupled Risks of Heavy Metals in Soil-Groundwater Systems of Typical Chemical Industrial Parks, Xinjiang/NW, China

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Abstract

Heavy metal pollution poses a significant threat to industrial and agricultural ecosystems; however, thorough research on the coupled risks and migration mechanisms of heavy metals within soil-groundwater systems in arid-region industrial parks remains limited. This study systematically collected 312 surface soil samples and 239 groundwater samples from typical chemical industrial parks in Xinjiang, northwestern China. The pollution levels of six typical heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) were quantitatively evaluated utilizing the Single Pollution Index (Pi), Nemerow Pollution Index (P_N), and Potential Ecological Risk Index (RI) for soil and the improved Heavy Metal Contamination Index (HCI) for groundwater. Additionally, GIS mapping and the Positive Matrix Factorization (PMF) model were integrated to delineate spatial distributions and primary emission sources. The assessment results indicated overall moderate pollution risks for Cd, Cu, and Ni in the soil, and for Cd, Pb, Cr, and Ni in the groundwater. Notably, Cd emerged as the primary risk contributor across both media. The RI identified Cd as the element posing the highest soil toxicity risk (with a mean RI of 53.57), while the HCI revealed that specific industrial zones face severe contamination levels (HCI > 4500), predominantly driven by Cd and Pb. GIS analysis illustrated a distinct distance–decay diffusion pattern emanating from industrial point sources. Crucially, PMF source apportionment demonstrated divergent contamination pathways: surface soil heavy metals (e.g., Cr, Cu, Pb, Zn) were primarily governed by top-down local industrial emissions (52.5%), whereas groundwater contamination was largely dictated by regional groundwater flow carrying mixed agricultural and natural geogenic inputs (75%). Furthermore, Pearson correlation analysis revealed a prevalent weak or negative correlation between heavy metal concentrations in the two media, suggesting a spatial “decoupling” of their contamination pathways. This phenomenon is likely driven by a dynamic “retention-leaching” mechanism within the arid vadose zone, where alkaline pH and high clay content act as a hydrochemical barrier impeding vertical migration. These findings underscore that soil and groundwater in arid industrial regions should be managed as distinct hydrochemical systems, providing a robust scientific basis for targeted remediation and the sustainable redevelopment of industrial brownfields.

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Keywords: industrial parks; heavy metal pollution; positive matrix factorization; soil; groundwater

1. Introduction

China's new Western Development Strategy and the Silk Road Economic Belt initiative have accelerated the industrialization of key energy and mineral bases in Xinjiang. However, situated in an arid and semi-arid region, Xinjiang possesses an extremely fragile ecological environment. The buildup of heavy metals (HMs) in terrestrial ecosystems due to industrial operations directly compromises both community health and local food security [1,2], but also constitutes a critical bottleneck restricting the region's high-quality economic development and the advancement of ecological civilization. HMs, generally defined as metallic elements with a density exceeding 5 g/cm³ [3], can migrate and be transported into the surrounding environment via pathways such as atmospheric deposition, surface water transport (including acid mine drainage), and groundwater percolation [4], leading to a rapid deterioration in soil quality. A country-wide evaluation of soil quality in China indicated that nearly 16.1% of surveyed locations exhibited pollution, with heavy metals and other inorganic agents representing the vast majority (82.8%) of the affected samples [5]. Soil and groundwater environmental media are inextricably linked. Although soil acts as an effective filter for the adsorption and immobilization of heavy metals, these metals can be released and leached into the groundwater under the influence of precipitation when the soil's retention capacity diminishes. Furthermore, insoluble chemical complexes can be produced through the interaction between these metals and soil organic components [6]. Therefore, systematically analyzing the characteristics of heavy metal pollution in the soil and groundwater of industrial parks, and formulating remediation strategies, accordingly, is of profound significance for improving the region's overall ecological and environmental quality.

To effectively control heavy metal hazards in terrestrial systems, researchers must precisely pinpoint pollution sources, map wide-scale geographic variations, and soundly evaluate ecological threats. Executing these steps establishes a cornerstone scientific framework for targeted soil remediation and post-cleanup land redevelopment. At present, multiple analytical frameworks are widely implemented for quantifying metallic contamination. These consist chiefly of the Potential Ecological Risk Index (RI), the Geoaccumulation Index, the Nemerow Pollution Index (NPI), and the Single Pollution Index (PI) [7–9]. However, these methods predominantly rely on comparing heavy metal concentrations with background or screening values, which introduces limitations when conducting a comprehensive pollution assessment within soil-crop systems. Accurate identification of pollution sources by environmental authorities is essential for formulating effective soil pollution prevention and management strategies. An all-inclusive determination of diverse pollutant inputs is made possible by merging the PMF framework, Pearson correlation tools, and Geographic Information Systems (GIS). This integrated approach significantly enhances the accuracy of source apportionment in regions with multiple co-existing emission sources. For example, Chai et al. successfully leveraged the PMF approach to numerically resolve the source distribution of eight heavy metals within agricultural lands of Lanzhou, thereby unveiling precise origin profiles and fractional inputs for each element [10]. Similarly, Liu et al. utilized a coupled approach of GIS to identify and quantitatively analyze the landscape of soil heavy metal pollution sources in Daye City, China [11]. Bhuiyan et al. applied GIS to analyze the accumulation status, spatial enrichment degree, and ecological risks, alongside the provenances of metallic pollutants found in the terrestrial environments of Dhaka [12]. Furthermore, Tan et al. utilized

Pearson correlation analysis to reveal the relationships between environmental influencing factors and heavy metal concentrations, thereby achieving an accurate estimation of soil heavy metal pollution sources [13].

Fundamentally, the environmental behavior of heavy metals, following their diffusion and deposition from emission sources, is governed by soil physicochemical properties [14]. Among these, soil organic carbon (SOC) and clay minerals—characterized by their high specific surface areas and abundant active sites—can effectively immobilize heavy metals through complexation and electrostatic adsorption [15,16]. Simultaneously, soil pH directly dictates the solubility and mobility of heavy metals: acidic conditions generally promote their release, whereas alkaline environments facilitate precipitation and immobilization [17]. In arid regions, these effects are further amplified. Scarce precipitation and intense evapotranspiration lead to soil compaction and the collapse of pore structures, which significantly reduces saturated hydraulic conductivity. This hinders the vertical migration of heavy metals, causing pollutants to predominantly accumulate in the surface soil and correspondingly decreasing their concentrations in groundwater [18]. In summary, a comprehensive understanding of how soil properties couple with heavy metal transport mechanisms, paired with a structured risk assessment of industrial soil-aquifer systems, provides critical scientific grounding. This approach helps unveil contamination behaviors in arid landscapes and aids the development of joint environmental protection strategies.

With an inland arid climate and a history of long-term industrial operations, Xinjiang is under severe environmental pressure related to heavy metal buildup in soil and groundwater. In such typical arid environments, hydrogeological conditions feature scarce precipitation, strong evaporation and an extremely thick vadose zone. These factors fundamentally change the migration patterns of pollutants relative to humid areas [19]. Specifically, the prevalent alkaline pH and high clay content in arid soils create a robust hydrochemical barrier. This barrier promotes strong adsorption and precipitation of heavy metals, creating a unique “retention-leaching” dynamic that heavily restricts their vertical migration [20]. Consequently, heavy metals tend to accumulate in the surface soil, potentially leading to distinct, decoupled contamination patterns between the topsoil and the underlying groundwater aquifer. For instance, the spatial distribution of soil heavy metals in Xinjiang has been revealed to follow a “high in the north, low in the south” pattern, with socioeconomic factors (e.g., industrial GDP and energy consumption) identified as the primary drivers of this spatial variation in Cd [21]. Furthermore, a comparative analysis across different functional zones on the Northern Slope of the Tianshan Mountains (NSTM) has documented significantly elevated concentrations of Pb, Zn, and Cu near industrial areas, thereby corroborating the dominant role of anthropogenic activities in shaping local heavy metal accumulation [22]. The Monte Carlo (MC) simulation approach has been employed to assess the probabilistic health risks and influencing factors of heavy metals among different populations in the Zhundong region of Xinjiang. According to the outcomes, the potential contamination degrees for Hg, Pb, Cu, and Cr remained moderate. Additionally, adults faced a higher non-carcinogenic risk from dietary exposure to these heavy metals than children did [23]. The APCS-MLR model was applied to apportion heavy metal pollution sources in different grassland soil types in the Altay region, revealing that natural sources, mining activities, industrial coal combustion, wastewater sources, and unidentified sources were the primary contributors to grassland contamination [24]. Some researchers conducted a field survey to assess heavy metal pollution in urban soils of the Dushanzi District, Karamay City, Xinjiang. The mean concentrations of all analyzed metals exceeded the corresponding background values for Xinjiang soils. Due to the influence of industrial activities, the urban soils in Dushanzi exhibited a certain degree of heavy metal pollution, with relatively high ecological risk, and Cd

was identified as the key element of soil metal pollution [25]. By applying the pollution load index (PLI), the researchers assessed As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn in agricultural soils from the Qira-Ruoqiang area. The results indicated slight contamination by Cd and Hg. Moreover, although As posed carcinogenic risks, those risks stayed within acceptable limits for human health [26]. Along the northern Tianshan Mountains (specifically Qitai, Jimusaer, and Fukang counties), researchers gathered 170 surface soil specimens to quantify Hg, Pb, Cr, Cu, and Zn levels. Average Zn and Cr concentrations fell below Xinjiang's baseline metrics. Meanwhile, Cu and Pb slightly surpassed these background figures without breaching national limits, whereas Hg and Pb concentrations violated both regional baselines and national thresholds. Consequently, this research advised targeting industrial facilities to curb Cr discharges [27]. A separate investigation sampled environments across 15 prominent oases in southern Xinjiang to evaluate the geographic distribution and threats of eight metallic pollutants. The data revealed that overall heavy metal accumulations were generally low and distributed evenly, barring minor localized clusters. Excluding Hg and Cd, the majority of these elements presented no comprehensive ecological hazard to the southern oasis soils [28]. However, evaluating current research uncovers a notable void: there is a lack of in-depth investigations focusing on the contamination profiles, source allocations, and environmental hazards of heavy metals, particularly inside the interconnected soil and groundwater networks of representative industrial zones across Xinjiang. Evaluating soil and groundwater in isolation often fails to capture the continuous transport and transformation of pollutants across the subsurface profile. Therefore, integrating both media into a single diagnostic framework is highly essential, as it prevents the misattribution of pollution sources and provides a holistic view of environmental risks that single-medium investigations inherently overlook, especially under the unique hydrogeological conditions of arid regions. Consequently, a core research question emerges: How do heavy metals distribute and interact within the integrated soil-groundwater system under such arid environmental conditions, and what are the key natural and anthropogenic drivers controlling these processes? To answer this question, therefore, this study takes 40 chemical industrial parks in Xinjiang as the research object, with the following objectives: (1) to systematically assess the pollution levels and spatial distribution characteristics of heavy metals in the soil and groundwater of chemical industrial parks in Xinjiang, and to thoroughly identify the sources of heavy metal pollution; (2) to investigate the soil and groundwater as an integrated system and attempt to elucidate the mechanism governing the relationship between heavy metal concentrations in the two media; (3) to screen the key environmental factors affecting heavy metal pollution in soil. The findings of this study can provide scientific support for the overall pollution assessment of soil and groundwater in regional chemical industrial parks, and offer a scientific basis for precision pollution control and heavy metal risk management. Furthermore, the research can provide important theoretical references and practical guidance for the subsequent transformation, upgrading, and redevelopment of industrial land in the arid region of Northwest China.

2. Materials and Methods

2.1. Study Area

The study area is located in the Xinjiang Uygur Autonomous Region, which experiences a temperate continental arid climate characterized by scarce precipitation, abundant sunshine, and significant diurnal temperature variations. The 40 chemical industrial parks were selected as the study area due to their significant regional importance and high industrial representativeness. In terms of representativeness, these parks are geographically widely distributed across both Northern and Southern Xinjiang (such as Aksu, Changji, Bayingolin, Ili, Altay, Hotan, Urumqi, and Karamay). They cover the dominant chemical

industry types in the region, primarily utilizing coal, petroleum, and natural gas to manufacture chemical products, including calcium carbide, polyvinyl chloride (PVC), coal tar, pesticide intermediates, pharmaceutical raw materials, as well as emerging silicon-based, lithium-based, and fluorine-based chemicals. Therefore, they comprehensively reflect the typical industrial structures, production characteristics, and emission patterns of chemical parks in Northwest China. In terms of importance, a modern coal chemical industry system has been established in this region, centered around five major bases including Zhundong and the Ili River Valley. The total output value of these industrial park's accounts for 7.8% of Xinjiang's total industrial output value and 2.98% of the region's Gross Domestic Product [29]. More importantly from an environmental perspective, the complex manufacturing processes of these chemical products involve significant risks of heavy metal emissions and accumulation. Given the high ecological vulnerability of the arid soil-groundwater system, evaluating these specific parks is crucial for regional environmental risk management and pollution control (Figure 1 and Table 1).

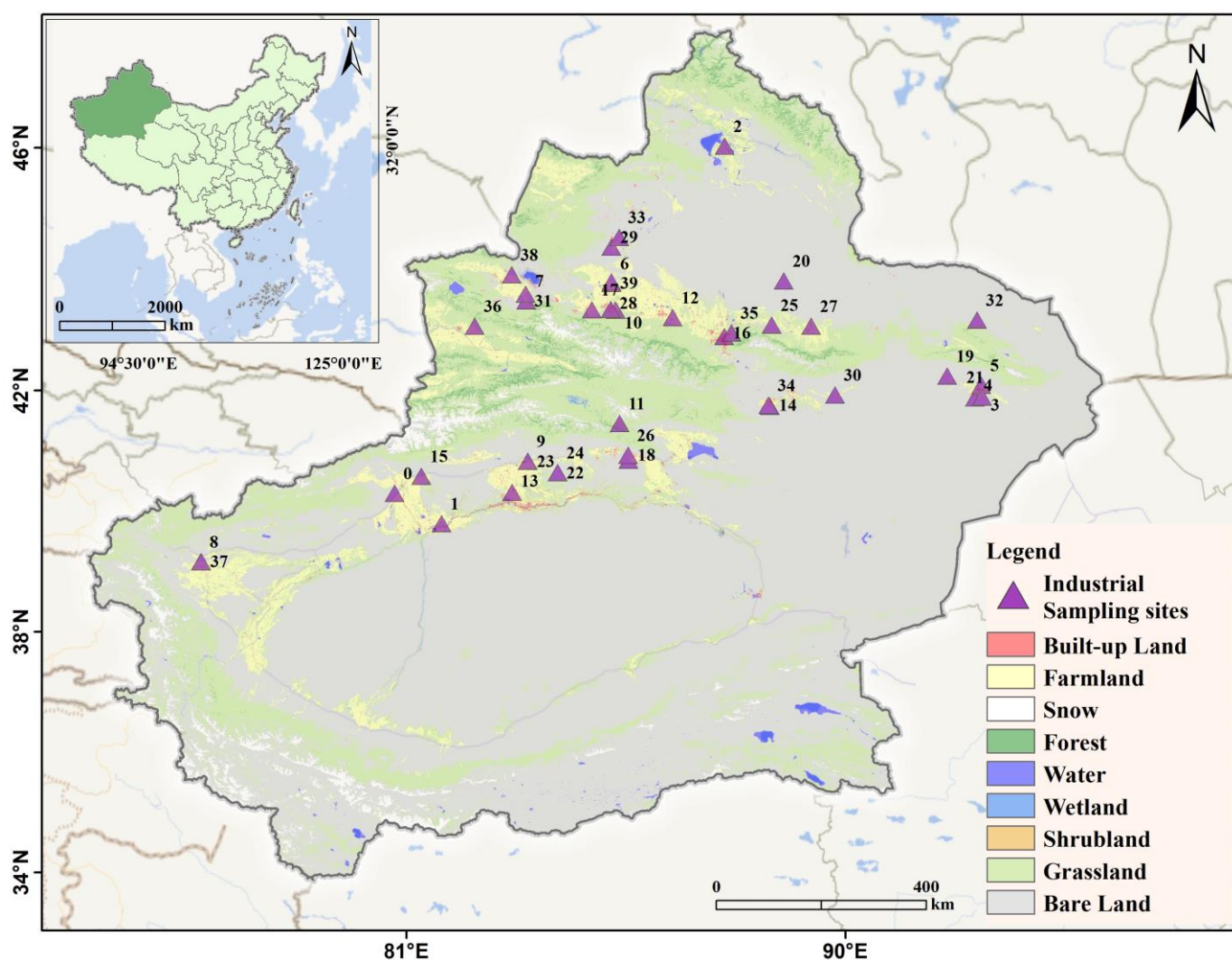


Figure 1. Map illustrating the targeted study zone and the spatial layout of sampling locations. (Note: The numbers represent the IDs of the Industrial Parks)

Table 1. Statistics of Industrial Parks and Sampling Points of soil and groundwater.

Fid	Industrial Park Name	Number of Soil Monitoring Points	Number of Groundwater Monitoring Points
0	Aksu Economic and Technological Development Zone Venous Industrial Park	8	5
1	Textile and Garment Industrial Area of Alar Economic and Technological Development Zone	8	3
2	Chemical Industry Concentration Zone of Fuhai Industrial Park, Altay	8	5
3	Erdaohu Industrial Park	8	5
4	Chemical Industry Concentration Zone of Hami High-tech Industrial Development Zone	8	5
5	Northern Emerging Industrial Park of Hami Industrial Park	3	2
6	South Park of Huyanghe Economic and Technological Development Zone (Fine Chemicals and New Materials Industrial Area)	6	5
7	Jinghe Industrial Park	13	6
9	Kashgar Central and South Asia Industrial Park	5	4
9	Chemical Industrial Park of Kuqa Economic and Technological Development Zone	36	9
10	Chemical Industry Concentration Zone of Kuitun-Dushanzi Economic and Technological Development Zone	7	7
11	Luntai Industrial Park	15	21
12	Tahe Industrial Area of Manas County Industrial Park	5	4
13	Shaya County Circular Economy Industrial Park	7	7
14	Toksun County Heavy Chemical Industrial Park	6	5
15	Chemical Industry Concentration Zone of Wensu Industrial Park	3	3
16	North Industrial Park of Urumqi High-tech Industrial Development Zone (Xinshi District)	3	3
17	Wusu Chemical Industry Concentration Zone	8	3
18	Shuangfeng Circular Economy Industrial Park of Tiemenguan Economic and Technological Development Zone, Second Division of Xinjiang Production and Construction Corps (XPCC)	11	4
19	Chemical Industrial Area of Liushuquan Industrial Park, Xinxing Economic and Technological Development Zone	6	5
20	Zhundong Economic and Technological Development Zone	6	12
21	Shunbei Oil and Gas Field	8	6
22	Yuqixi Block of Tahe Oilfield	7	5
23	Chemical Industry Concentration Zone of Kuqa Economic and Technological Development Zone	6	5
24	Chemical Industry Concentration Zone of Baicheng Industrial Park	9	8
25	Beisantai Circular Economy Industrial Park of Jimsar County	6	5
26	Petroleum and Petrochemical Industrial Park of Korla Shangku High-tech Industrial Development Zone	8	10
27	Chemical Industrial Park of Xinhe County New Materials Zone	6	6
28	Lamahuliang Industrial Park of Qitai County	5	5
29	Chemical Industry Concentration Zone of Dushanzi Industrial Park	11	11
30	Baijiantan District, Karamay City	3	4
31	Shanshan County Stone Industrial Park	3	3
32	Fine Chemicals and Metallurgy Industrial Area of Jinghe Industrial Park	9	7
33	Hongshan Industrial Park of Naomaohu Economic and Technological Development Zone	10	8
34	Karamay Petrochemical Industrial Park	4	4
35	Toksun Energy and Heavy Chemical Industrial Park	6	6
36	Midong District Chemical Industrial Park	22	13
37	Zone B of Yidong Industrial Park	3	3
38	Kashgar Economic Development Zone	3	4
39	Textile Park of Bortala Golden Triangle Industrial Park	3	3
	Total	312	239

2.2. Data Sources

The data used in this study were derived from the Environmental Impact Assessment (EIA) Reports of Industrial Parks and the EIA Reports of Industrial Construction Projects within these parks, published by the Department of Ecology and Environment of Xinjiang Uygur Autonomous Region over the past five years. A total of 40 chemical industrial parks were identified, encompassing 312 soil samples and 239 groundwater samples. This dataset provides a comprehensive representation of the heavy metal pollution status across Xinjiang's chemical industrial zones. In accordance with the Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land (Trial) (GB

15618-2018) [30] and the Soil Environmental Quality Risk Control Standard for Soil Contamination of Development Land (GB 36600-2018) [31], six specific heavy metals—cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn)—were selected as the target pollutants in this study. These elements are designated as priority control contaminants under both national standards due to their persistent toxicity. Furthermore, they are directly correlated with emissions from the dominant local industrial sectors, including petrochemical processing, coal chemical industries, and industrial wastewater discharges. Consequently, the concentrations of these six characteristic heavy metals were systematically determined in both soil and groundwater samples across the study area. The concentrations of heavy metals in the soil were determined using an atomic absorption spectrophotometer (GGX-830, China). Following microwave-assisted acid digestion for soil samples or acidification and filtration for groundwater samples, the concentrations of Cr, Pb, Cd, Cu, Zn, and Ni were quantified via inductively coupled plasma optical emission spectrometry (ICP-OES). For trace levels of Pb and Cd in groundwater, inductively coupled plasma mass spectrometry (ICP-MS) was employed to achieve lower detection limits. Specifically, auxiliary environmental data, including SOC, mean annual temperature (MAT), mean annual precipitation (MAP), pH, and clay content, were sourced from the dataset developed by Chen [32].

2.3. Methods

2.3.1. Environmental Risk Assessment

Both single-factor and comprehensive assessment methods were employed to evaluate the degree of heavy metal pollution. The Single Pollution Index (P_i) was calculated using the following equation:

$$P_i = \frac{C_i}{S_i} \quad (1)$$

where P_i represents the single-factor pollution index for heavy metal i , C_i is the measured concentration of heavy metal i in the sample, and S_i denotes the corresponding soil standard value for heavy metal i [33]. The Class III limits from the Standard for Groundwater Quality (GB/T 14848-2017) [34] were adopted as the legal limits S_i .

The Nemerow Integrated Pollution Index P_N was utilized to evaluate the comprehensive pollution effects of multiple heavy metals. This index accounts for the average value of all single-factor indices while simultaneously emphasizing the weight of the maximum single factor index [35]. The calculation formula is expressed as follows:

$$P_N = \sqrt{\frac{(P_{ia})^2 + (P_{imax})^2}{2}} \quad (2)$$

where P_N is the comprehensive soil pollution index for multiple heavy metals, P_{ia} represents the average value of all single pollution indices, and P_{imax} is the maximum single pollution index among all evaluated metals. Additionally, $P_N \leq 1$, $1 < P_N \leq 2$, $2 < P_N \leq 3$, and $P_N > 3$ indicate no, light, medium, and heavy pollution, respectively.

The Potential Ecological Risk Index for Soil

The Potential Ecological Risk Index (RI) was utilized to analyze the pollution levels of soil heavy metals and evaluate their potential ecological risks proposed by Hakanson [36]. The calculation formulas are as follows:

$$RI = \sum_{i=1}^n E_r^i \quad (3)$$

$$E_r^i = T_r^i \times C_f^i \quad (4)$$

$$C_f^i = \frac{C^i}{C_n} \quad (5)$$

In these equations, RI denotes the comprehensive potential ecological risk, while the specific risk posed by an individual heavy metal i is represented by E_r^i . The term C_f^i stands for the single pollution factor, calculated using the actual measured concentration (C^i) and its corresponding baseline reference level (C_n^i). Additionally, T_r^i acts as the toxic-response parameter, reflecting the biological sensitivity to specific metals. Based on prior studies [37,38], the assigned toxic response factors for the evaluated elements are: Cd = 30; Cu, Pb, and Ni = 5; Cr = 2; and Zn = 1. For the study area, the baseline soil concentrations (C_n^i) in Xinjiang were established at 0.12, 49.30, 26.70, 26.60, 19.40, and 68.80 mg/kg for Cd, Cr, Cu, Ni, Pb, and Zn, respectively [39]. The evaluation categories used to interpret both the E_r^i and RI scores are detailed in Table 2.

Table 2. Ecological risk level and its assessment index.

E_r^i	Criteria	Ecological Risk Level (E_r^i)	RI	Criteria	Ecological Risk Level (RI)
<40		Low risk	<150		Low risk
40~80		Moderate risk	150~300		Moderate risk
80~160		Elevated risk	300~600		Elevated risk
160~320		High risk	>600		High risk
>320		Very high risk			

Evaluation of Groundwater Heavy Metal Risk Based on the Heavy Metal Contamination Index (HCI) Approach

In groundwater heavy metal risk assessment, quantitative indices are widely utilized. Among these, the most commonly used traditional methods include the Heavy Metal Pollution Index (HPI) and the Metal Index (MI) [40]. However, these methods have limitations, such as yielding contradictory evaluation results or underestimating health risks. Therefore, the improved Heavy Metal Contamination Index (HCI) method was proposed and applied to the risk assessment of heavy metals in groundwater [41]. The calculation formula is as follows:

$$HCI = \sum_{i=1}^n MI_i = \sum_{i=1}^n (W_i \times q_i) \quad (6)$$

where MI_i represents the metal sub-index of the i -th heavy metal; W_i is the toxicity weight assigned to the heavy metal based on the Delphi method (ranging from 1 to 4, with higher values indicating greater toxicity and carcinogenic risk); and q_i is the quality rating of the metal, calculated as follows:

$$q_i = \left(\frac{C_i}{S_i} \right) \times 100 \quad (7)$$

where C_i refers to the measured concentration of heavy metal S_i in the water sample, and S_i represents the maximum allowable limit for that heavy metal as specified by the World Health Organization (WHO) or national drinking water standards. In this study, S_i values were derived from the Chinese Standards for Drinking Water Quality (GB 5749-2022) [42], with the limits for Cd, Cr, Cu, Ni, Pb, and Zn set at 0.005, 0.05, 1.0, 0.02, 0.01, and 1.0 mg/L, respectively. Given that cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb) are non-essential elements for humans and pose severe health threats along with high carcinogenicity, they were assigned the maximum weight of 4. In contrast, although copper (Cu) and zinc (Zn) can cause environmental harm at excessive concentrations, they are essential trace elements for the human body with relatively lower overall toxicity; thus, their weights were appropriately assigned a value of 2.

2.3.2. Positive Matrix Factorization Model

For a clearer understanding of heavy metal (HM) origins within chemical industrial zones, source apportionment was performed using the Positive Matrix Factorization (PMF) framework. This receptor-based tool, originally developed by the U.S. Environmental Protection Agency (US EPA), mathematically resolves pollutant inputs by constraining factor elements to positive values. It has become a standard approach for identifying and quantifying pollutant contributions within diverse environmental systems, such as aquatic and terrestrial matrices [43,44]. In this work, the EPA PMF 5.0 software was implemented to determine the specific HM contamination sources in both soil and groundwater.

Mechanistically, the tool partitions the empirical concentration dataset (C_{ij}) into two primary matrices: source contributions (G_{ik}) and source profiles (F_{kj}). The fundamental relationship is expressed as follows:

$$C_{ij} = \sum_{k=1}^n G_{ik} \times F_{kj} + E_{ij} \quad (8)$$

In this formulation, n represents the total number of identified pollution sources, while C_{ij} indicates the measured level of a specific analyte j within sample i . The unexplained variance or measurement error for each data point is captured by the residual matrix element E_{ij} .

To achieve the most optimized configurations for the heavy metal concentration matrices G and F , the PMF algorithm iteratively minimizes a target objective function, Q , which is defined by the scaled residuals (E_{ij}) across all datasets:

$$Q = \sum_{i=1}^n \sum_{j=1}^m \left(\frac{E_{ij}}{u_{ij}} \right)^2 \quad (9)$$

Beyond the primary chemical concentration inputs, executing the PMF framework demands the integration of an uncertainty (Unc) profile for each individual species. This parameter is mathematically determined based on two distinct operational scenarios relative to the method detection limit (MDL):

$$Unc = \frac{5}{6} \times MDL, C \leq MDL \quad (10)$$

$$Unc = \sqrt{(Err \times C)^2 + (0.5 \times MDL)^2}, C > MDL \quad (11)$$

Within these conditional expressions, MDL signifies the lower analytical detection threshold for the concentration C , whereas Err represents the designated error proportion unique to each evaluated element [45].

2.3.3. Statistical Analysis

Statistical analysis of the data was performed using OriginPro 2021 (OriginLab Corporation, Northampton, MA, USA). The Pearson product-moment correlation coefficient (PCC) was applied to identify the relationships between environmental influencing factors and the concentrations of various elements, and a correlation heatmap was subsequently generated. Furthermore, the spatial distribution of heavy metals and their associated ecological risks were analyzed and mapped utilizing ArcGIS 10.8 (ESRI, Redlands, CA, USA).

3. Results and Discussion

3.1. Descriptive Statistics of Soil Physicochemical Properties and Heavy Metal Concentrations

The physicochemical properties of the soil samples are summarized in Table 3. The soil pH ranged from 6.29 to 8.78, with a mean value of 7.58, indicating neutral to slightly alkaline conditions. The average concentration of SOC was 8.82 g/kg; the highest values were recorded in north-central Xinjiang, with a spatial distribution that decreased from the northwest to the southeast. Apart from bulk density and SOC, all other measured soil

attributes yielded coefficients of variation (CVs) under 30%. This observation implies that the physicochemical profile within the researched zone remained largely consistent.

Table 3. Statistical description of soil physicochemical properties and climatic factors.

	BD (g/cm ³)	SOC (g/kg)	MAT (°C)	MAP (mm)	pH	Clay (%)
Min	0.58	0.06	15.24	69.86	6.29	52.92
max	1.8	33.64	16.88	133.75	8.78	77.8
mean	1.43	8.82	15.98	101.56	7.58	65.82
S.D.	0.19	6.71	0.43	16.79	0.57	5.72
C.V. (%)	13.44	76.06	2.70	16.53	8.70	8.70

Note: BD, bulk density; SOC, soil organic carbon; MAT, mean annual temperature; MAP, mean annual precipitation; S.D., min, minimum; standard deviation; C.V., coefficient of variation; max, maximum.

The distribution of heavy metals exhibited significant disparities between the two media. In the soil medium, Zn showed the highest absolute concentration, with its inter-quartile range primarily concentrated between 60 and 80 mg/kg (Figure 2). This was followed by Ni, Cu, and Pb, whose median concentrations fluctuated between 15 and 30 mg/kg, with relatively concentrated sample distributions for these three elements. Notably, although the overall median concentrations of Cd and Cr were extremely low, both exhibited distinct extreme high-value outliers. Particularly for Cr, the concentrations at certain sampling points surged to nearly 60 mg/kg, and Cd also presented high values exceeding 60 mg/kg. This strongly implies the presence of point-source pollution or intense anthropogenic inputs in localized areas. For the groundwater samples, almost all of the evaluated heavy metals—namely Ni, Zn, Cd, Cu, and Cr—exhibited extremely low median concentrations. However, Pb demonstrated substantial spatial variability, with its upper quartile being significantly higher than those of the other elements. Furthermore, some elevated outliers were observed for Zn and Cu, whereas Ni maintained the lowest and most stable concentration in the groundwater, showing almost no obvious enrichment.

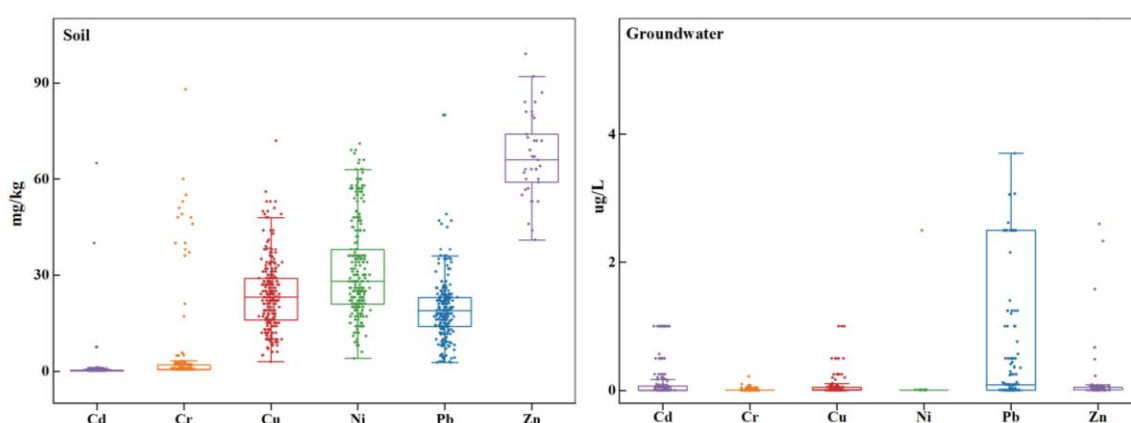


Figure 2. Distribution of heavy metals in soil and groundwater.

The spatial dispersion level of HM concentrations is effectively captured by the coefficient of variation (CV). Generally, a CV > 50% indicates an uneven distribution of pollution, which is likely influenced by external point source contamination [46]. In this study, the CVs of HMs ranged from 15.40% to 50.56% in the soil and from 15.46% to 59.29% in the groundwater, with Pb exhibiting the highest variation in the groundwater. In the soil, Zn displayed the highest variation, whereas the CVs of Cu, Ni, and Pb were all below 30%.

Specifically, the CVs of Ni and Cu in the soil were 21.45% and 22.50%, respectively, implying potential impacts from human activities. Conversely, the relatively low CV of Pb in the soil increases the likelihood that it primarily originates from natural background sources. $CV \leq 20\%$ typically suggests low values with uniform variability [47]. With the exception of Cd, all other HMs exhibited a certain degree of spatial variability. The relatively high CVs of Zn (in soil) and Pb (in groundwater) indicate significant spatial heterogeneity, suggesting the potential existence of point source inputs—such as metal processing or traffic emissions—rather than a uniform distribution originating from the regional geological background. Overall, the groundwater exhibited markedly lower HM accumulation levels when compared to the overlying soil matrix. Utilizing the screening values from the Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land (Trial) (GB 15618-2018) [30] as the soil background baseline, the average concentration of Cd was found to exceed the threshold value (0.6 mg/kg), highlighting a necessary focus on its associated ecological risks.

3.2. Spatial Distribution Characteristics of Heavy Metals in the Soil-Groundwater System

Regarding the spatial distribution of HMs in the soil and groundwater, both media exhibited a “higher in the north and lower in the south” trend. This pattern correlates with the more advanced economic development in northern Xinjiang, which has seen the introduction of a larger number and scale of similar industrial enterprises. Specifically, the highest concentrations of Cd were recorded in Changji, Urumqi, and Karamay in northern Xinjiang, primarily due to the dense distribution of chemical enterprises in these areas. In contrast, HM concentrations in other regions were largely influenced by the local primary geochemical background. In the soil, Cd, Cu, and Pb showed high accumulation consistency within the Economic Belt on the NSTM and the Ili River Valley (IRV) (Figure 3). This is mainly attributed to coal chemical emissions from the Zhundong Industrial Zone and machinery manufacturing in the Toutunhe Industrial Park. Furthermore, the significant enrichment of Cd and Cu in the Ili River Valley is closely linked to the production of agricultural inputs, such as fertilizers and pesticides, in the chemical sector of the Huocheng Economic Development Zone.

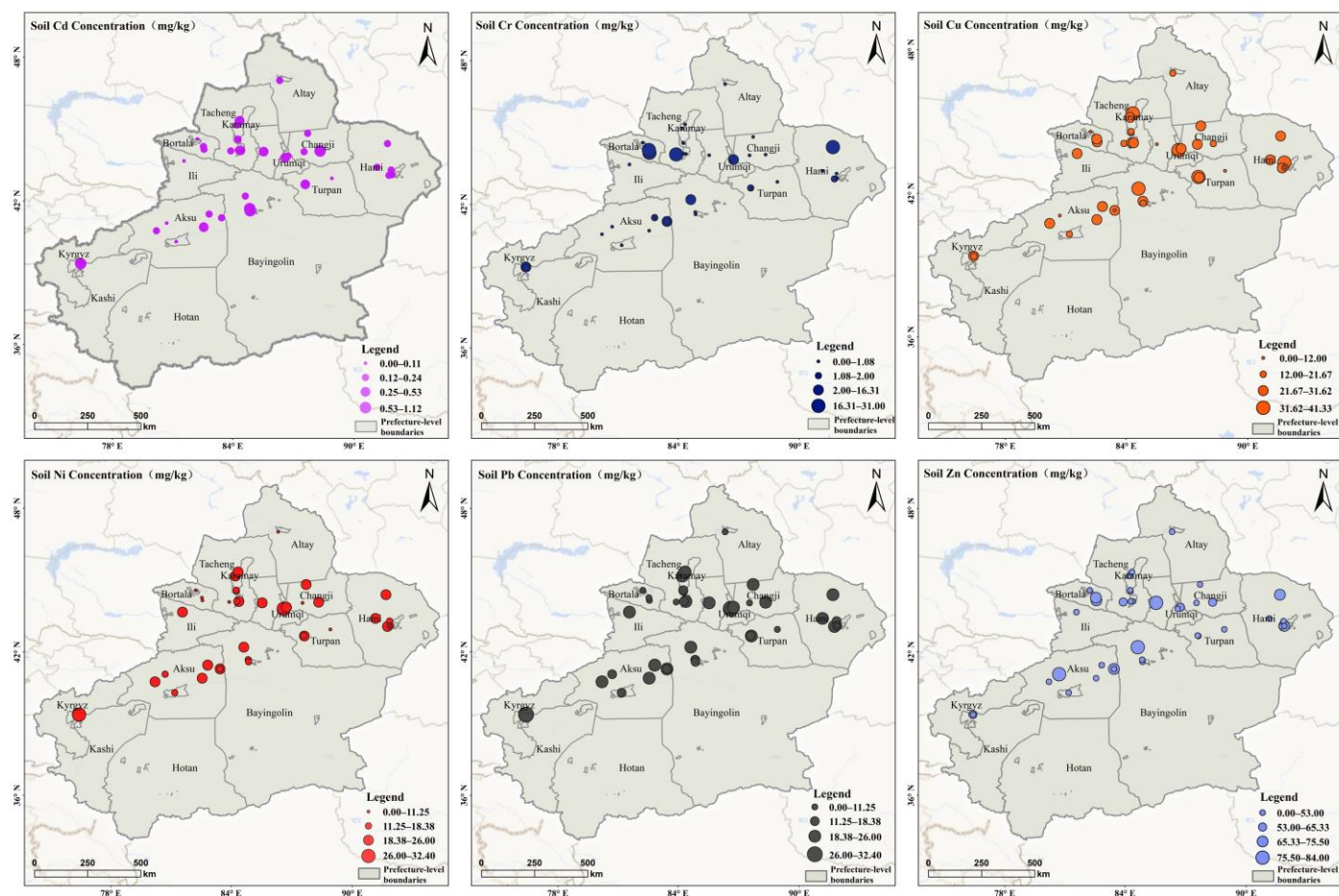


Figure 3. Geographic distribution of heavy metals within the soil.

In the groundwater, Ni and Zn exhibited extreme high values, primarily concentrated in the Hami region of eastern Xinjiang, which is directly related to the intensive mining of local nickel and copper mineral resources (Figure 4). In certain parts of southern Xinjiang, scattered hotspots of Cr in groundwater were mainly distributed within highly urbanized oases, resulting from the local concentration of coal chemical and textile industries. Overall, Cd was identified as the primary risk factor. In the soil, these risks were heavily localized in both the NSTM and IRV; whereas for groundwater, the risks extended across the NSTM, alongside the Botala and Tacheng regions. These findings are consistent with the research by Li et al. [21], which suggests that anthropogenic activities (particularly industrial emissions in arid regions) are the dominant drivers of Cd accumulation.

Notably, GIS analysis revealed that the pollution diffuses outward in a point-source pattern, which aligns with the description of HM diffusion models in open-pit mining areas by Abliz et al. [48]. Due to the arid climate of Xinjiang, characterized by scarce precipitation and intense evaporation, HMs are prone to accumulating in the surface soil through evaporative concentration.

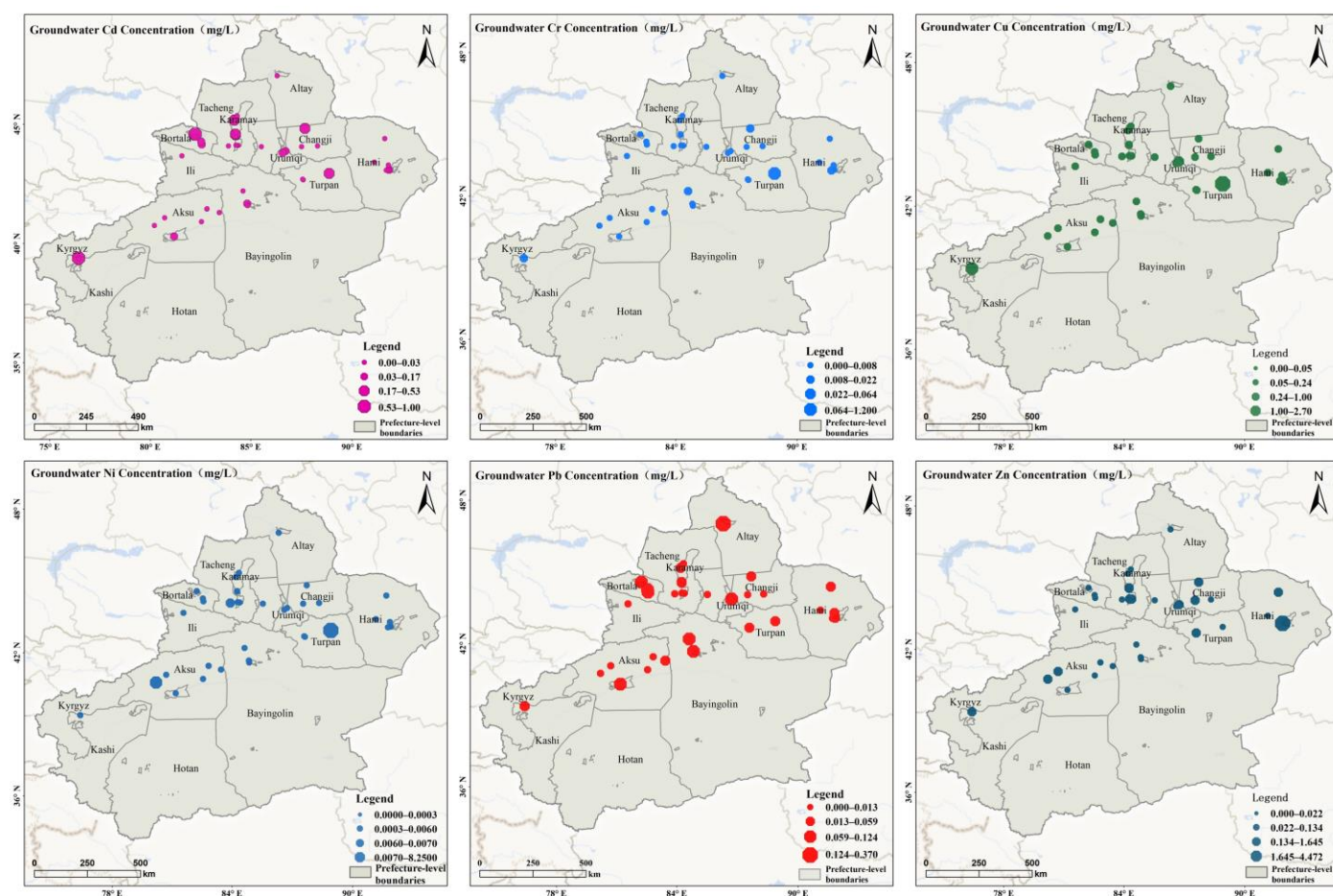


Figure 4. Geographic distribution of heavy metals within the Groundwater.

3.3. Ecological Risk Assessment of HMs in the Soil-Groundwater System

In this study, the single-factor pollution index and the Nemerow integrated pollution index were employed to evaluate the status of heavy metal (HM) pollution. The results indicated that the mean single-factor pollution indices for Cd, Cr, Cu, Ni, Pb, and Zn in the soil were 4.47, 0.07, 2.78, 1.14, 0.93, and 0.11, respectively. In the soil, Cd, Cu, and Ni exhibited a higher pollution risk, categorized as moderate pollution, whereas Cr, Pb, and Zn were classified as light pollution. Regarding the groundwater, the computed single-factor pollution indices revealed that Cd (5.73), Pb (3.87), Ni (2.53), and Cr (2.45) constituted moderate contamination. Meanwhile, identical indices of 0.11 for both Cu and Zn denoted a state of mild pollution. To achieve a more robust evaluation of the overall contamination level pertaining to each sampling location, the Nemerow integrated pollution index (P_N) was adopted, the spatial distribution of which is delineated in Figure 5b. According to the calculation results, 23 sampling sites had a soil $P_N > 3$, indicating the presence of obvious localized point-source pollution in the soil. In contrast, all groundwater P_N values were below 3, suggesting that the overall pollution level of the groundwater is relatively low. According to the evaluation criteria, the comprehensive assessment revealed distinct tracking patterns between soil and groundwater. For instance, Cd, Cr, and Pb exhibited higher frequencies of severe integrated pollution impact in groundwater, while Cu and Zn showed higher risk proportions in soil samples. Within the study area, Cd and Ni in the soil recorded the highest concentrations, the most severe pollution levels, and the most extensive pollution distributions. The spatial distribution characteristics of most other HMs revealed higher concentrations in the central areas of the industrial parks,

with levels gradually decreasing in the outward radiating zones. Overall, the pollution risk in the soil was slightly higher than that in the groundwater.

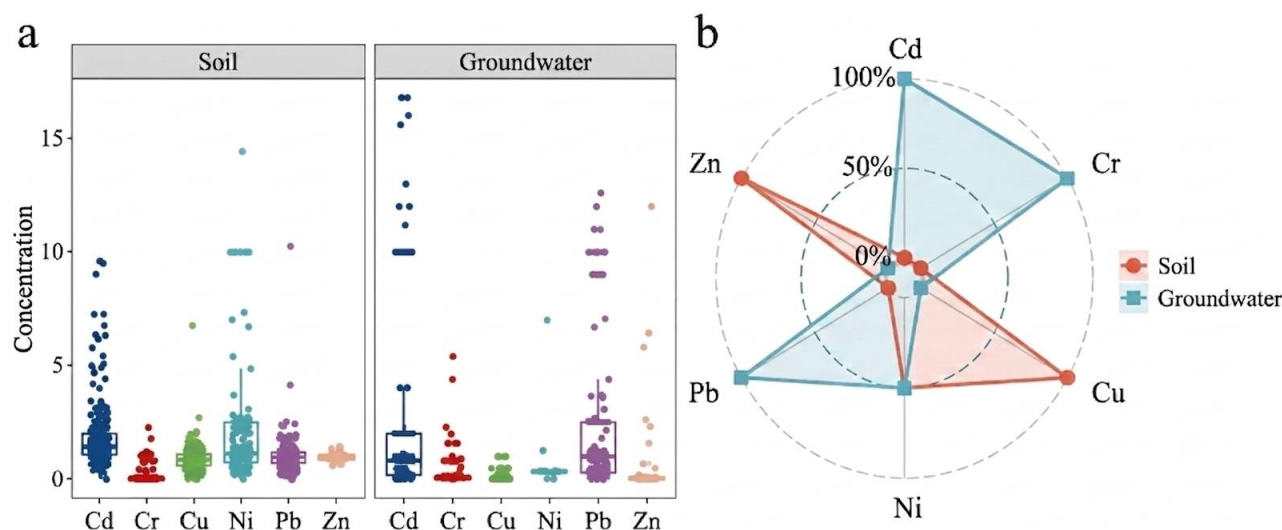


Figure 5. Assessment results of heavy metal (HM) pollution in the soil and groundwater. (a) distribution of single-factor pollution indices; (b) contribution proportions of individual factors to the Nemerow integrated pollution index.

The statistical evaluations pertaining to the potential ecological risk index (E_r) of each discrete heavy metal within the soil matrix are presented in Table 4. The analysis reveals significant differences in the degree of potential ecological hazard among the various HMs within the study area. Based on the mean values, the ecological risk levels of the elements followed a decreasing trend: Cd (53.57) > Ni (6.08) > Pb (5.34) > Cu (4.61) > Zn (0.95) > Cr (0.17). Specifically, the mean E_r values for Cr, Zn, Cu, Pb, and Ni were all substantially below 40, indicating that these five elements remain at a low ecological risk level throughout the study area. Furthermore, the sample distribution showed that nearly 100% of the sampling sites (99.68% for Pb) were within the low-risk interval, suggesting that these elements have not yet exerted significant stress on the local soil ecosystem. The predominant share of the soil's ecological risk was attributed to Cd. The overall assessment for Cd indicated a “moderate” potential ecological risk, with a mean value of 53.57. This finding is consistent with numerous studies on HMs in oasis soils of arid regions in Northwest China, which suggest that the high toxicity coefficient of Cd makes it a core source of risk [49,50]. As presented in Table 4, Cd is identified as the element with the highest soil toxicity risk in the chemical industrial park. This underscores its significant ecotoxic potential, requiring urgent priority and long-term attention.

Table 4. Statistical characteristic values of the potential ecological risk index (E_r^i) for heavy metals in soil.

Element	E_r^i		$E_r^i \leq 40$		$40 < E_r^i \leq 80$		$80 < E_r^i \leq 160$		$160 < E_r^i \leq 320$		$E_r^i > 320$	
	Range	Mean	Samples	Rate (%)	Samples	Rate (%)	Samples	Rate (%)	Samples	Rate (%)	Samples	Rate (%)
Cds	2.50–287.50	53.57	164	52.56	110	35.26	28	8.97	10	3.21	0	0
Crs	0.00–4.54	0.17	312	100	0	0	0	0	0	0	0	0
Cus	0.56–13.48	4.61	312	100	0	0	0	0	0	0	0	0
Nis	0.75–34.77	6.08	312	100	0	0	0	0	0	0	0	0
Pbs	0.70–51.29	5.34	311	99.68	1	0.32	0	0	0	0	0	0
Zns	0.00–1.44	0.95	311	100	0	0	0	0	0	0	0	0

Note: The sample size for Zn and Pb is 311 due to a missing value at one sampling site.

The results of the evaluation of groundwater heavy metal risk are presented in Figure 6. The mean value for all industrial parks was 3370, which, along with equidistant step sizes, was used as the criterion for classifying risk levels. Specifically, 19 parks had HCI values below 1100, 4 parks were in the 1100–2200 range, 2 parks were in the 2200–3400 range, 3 parks were in the 3400–4500 range, 3 parks were in the 4500–5600 range, and 9 parks exceeded 5600. Based on these HCI values, 12 parks fell into the high-risk categories ($HCI > 4500$), accounting for exactly 30% of the studied industrial parks. The Kashgar Central and South Asia Industrial Park and the Altay Fuhai Industrial Park exhibited the highest HCI values in the entire region, both exceeding 15,000.

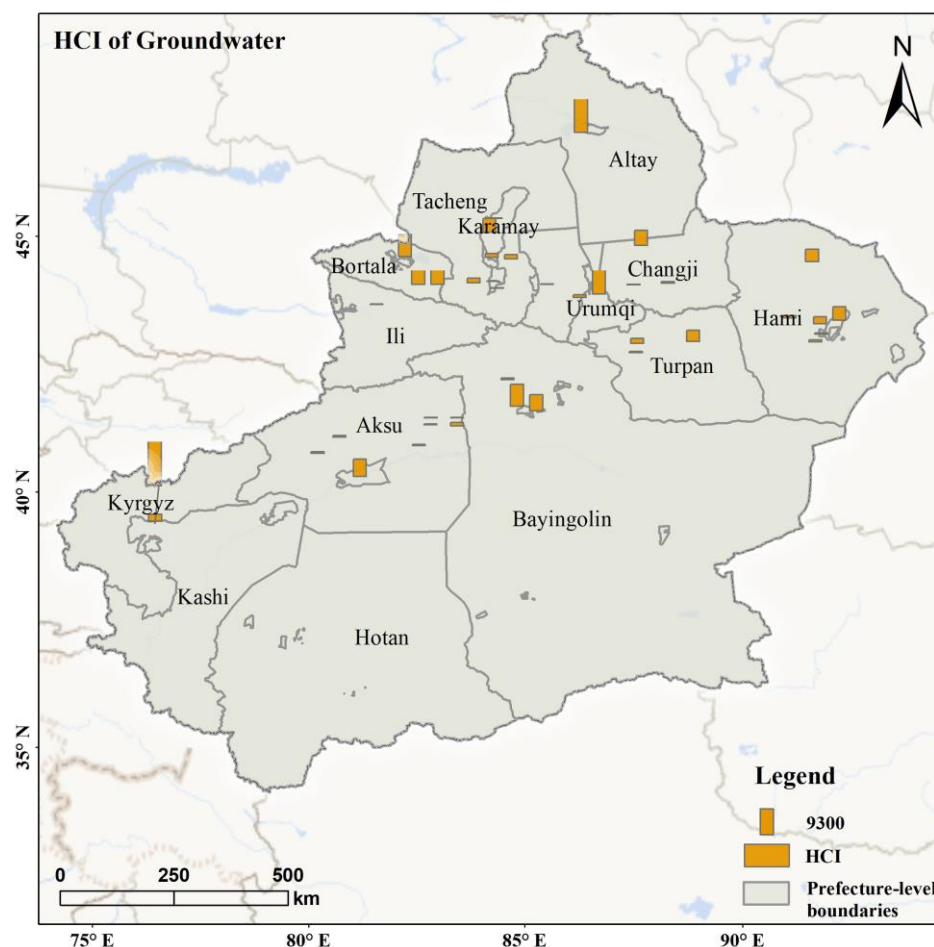


Figure 6. Spatial mapping of heavy metal HCI values within the groundwater.

Figure 7 visually presents the RI assessment outcomes regarding HMs across the investigated region. Overall, the soil system was affected by varying degrees of multi-element HM contamination, with risk levels exhibiting distinct differences between the two media. Regarding the soil environment, approximately half (50.96%) of the sampling sites had RI values below 150, categorized as an overall “low” ecological risk level. However, 35.26% of the areas were at “moderate” risk, while sites reaching “high” and “very high” ecological risk levels accounted for 10.58% and 3.21%, respectively. This is primarily attributed to the intense enrichment of Cd driven by industrial activities. The assessment results of groundwater heavy metal risks are illustrated in Figure 6, where the high-risk and above levels ($HCI > 4500$) observed in specific industrial parks were predominantly triggered by Cd and Pb contamination. This is ascribed, on one hand, to the highly sensitive weights assigned to these two highly toxic elements within the HCI framework (80,000 and 40,000). On the other hand, it reflects that the management of cadmium-

containing residues, lead-bearing wastewater, or heavy metal point-source emissions from industrial activities—such as chemical, metallurgical, and textile processes—in relevant parks (e.g., Kashgar, Altay, and Zhundong) still needs to be further strengthened. By contrast, elements like Cu and Zn posed no substantial threat to the overall safety of the regional aquatic environment due to their lower environmental toxicity and smaller weights. Consequently, these two elements should be prioritized as key HMs for pollution control and management in this region [51]. This phenomenon suggests that in arid regions such as Xinjiang, groundwater systems (characterized by slow recharge and limited self-purification capacity) endure more intense and concentrated HM ecological stress in localized areas [52]. Consequently, regions exhibiting extremely high HCI values should be precisely identified and designated as primary target zones for groundwater environmental remediation and management.

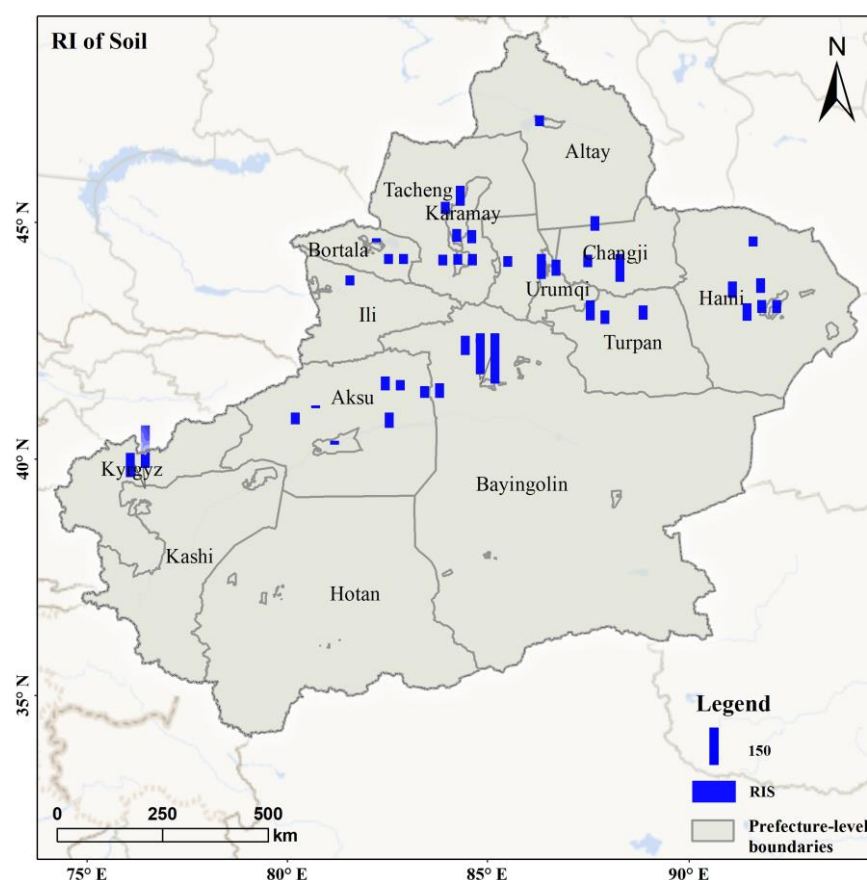


Figure 7. Spatial mapping of heavy metal RI values within the soil.

3.4. Correlation Analysis Between Heavy Metal Concentrations and Physicochemical Properties

3.4.1. Correlation Analysis in Soil

The linear relationships connecting the 6 targeted HMs to 6 distinct soil physicochemical and climatic variables within the study site were quantified via Pearson correlation. A significant positive correlation between elements suggests they are influenced by identical or similar factors, while a significant negative correlation may indicate different control mechanisms or potential antagonistic effects. According to Figure 8a, remarkably robust positive linear associations ($p < 0.01$) linked Cd with Cu, and similarly connected Ni with Pb, displaying r values above 0.9. This strong symbiotic phenomenon implies a high degree of spatial co-variability, suggesting they are likely driven synergistically by similar geochemical environments or anthropogenic activities within the region. It is noteworthy that although the Pearson analysis showed a significant statistical correlation

between Cd and Cu, likely due to their similar geochemical migration behaviors during specific pedogenic or leaching processes, the aforementioned PMF model, based on absolute concentration contribution matrices, further revealed their distinctions at the initial emission sources (e.g., industrial emissions vs. agricultural non-point sources). This combined analysis highlights that a high statistical correlation does not necessarily equate to a single identical pollution source. In contrast, Cr and Zn showed weaker correlations with other elements, further confirming their relatively independent pollution sources.

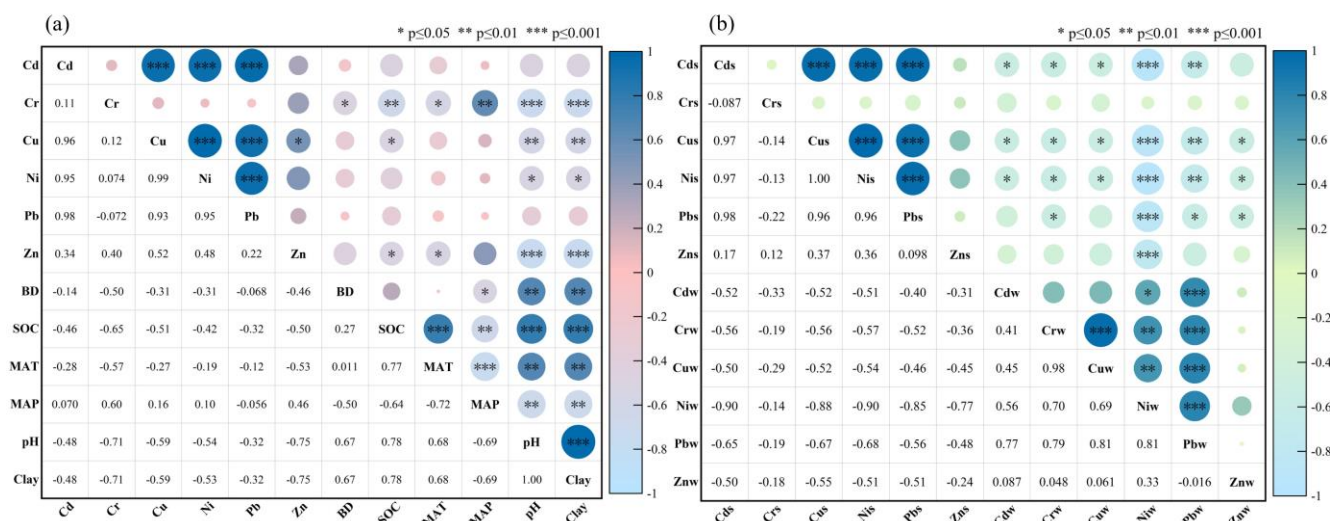


Figure 8. Heatmaps of correlation analysis. (a) correlation between soil heavy metal concentrations and physicochemical factors; (b) correlation between heavy metal concentrations in soil and groundwater.

Environmental and physicochemical properties profoundly dictate the enrichment of HMs within the soil matrix. Notably, soil pH and clay content exhibited significant negative correlations with most HMs (e.g., r values for pH with Zn, Cr, and Cu were -0.75 , -0.71 , and -0.59 , respectively). This suggests that the anthropogenic pollution sources (such as industrial atmospheric deposition or wastewater) responsible for HM enrichment in the region may be inherently acidic, thereby lowering the local soil pH. MAP was significantly positively correlated with Cr ($r = 0.60$), indicating that precipitation runoff may be a major driver for the migration and accumulation of agricultural-source Cr. Soil BD was negatively correlated with Zn and Cr, which may be related to the limitation of HM migration and diffusion by soil structure. SOC showed a significant negative correlation with Cr; this could be due to the inhibitory effect of Cr on microbial biomass carbon, microbial respiration, and the bacterial Shannon index, leading to a reduction in SOC. Additionally, clay content was significantly negatively correlated with Cr and Zn and negatively correlated with Cu, as increased clay content influences the migration and distribution of HMs through adsorption or physicochemical interactions [53]. Overall, the concentrations of the six HMs are primarily influenced by pH, BD, clay, MAT, and MAP, which in turn affect the SOC content.

This study identified pH and clay content as the most critical physicochemical factors influencing soil HM distribution, which complements the findings of Liu et al. [54] on arid oasis soils. In alkaline or neutral soil environments, minor fluctuations in pH can significantly alter the speciation and bioavailability of HMs. The negative correlation between pH and multiple HMs suggests that as soil acidifies (potentially due to acidic industrial wastewater), HM mobility increases. Research indicates that higher pH enhances the adsorption of HM ions onto soil particles, thereby reducing the concentration of active HM

ions. Soil texture, specifically clay content, strongly influences the pollution behavior of Cr and Zn. SOC can adsorb HMs to form stable complexes under low pH conditions, enhancing the adsorption of Zn [55,56]. The negative correlation between SOC and HM concentrations may arise from the complexation and fixation of metals by organic matter, or from the simultaneous input of HMs and organic matter from external sources [57]. Although pH fundamentally constrains the geochemical behavior of HMs at the microscopic scale, its low spatial variation in the study area suggests it may not be the primary driver of regional spatial distribution differences. In contrast, cation exchange capacity (CEC) and climatic factors may exert more critical control. Abundant cations in the soil compete with HMs for adsorption sites on particle surfaces; meanwhile, a higher CEC increases the number of negatively charged surface functional groups, effectively promoting the adsorption and immobilization of HMs such as Cu [58,59]. Furthermore, Pb pollution appears more independent of soil physicochemical properties, as its sources are diverse and anthropogenic emissions far exceed natural background levels. The primary transport pathways for Pb are atmospheric deposition and soil erosion; thus, its pollution levels are comprehensively regulated by macro-climatic factors such as temperature, precipitation, and air pressure [60].

Clay content acts as a physical barrier; by increasing specific surface area and providing more adsorption sites, it effectively intercepts HMs, which are subsequently stabilized through encapsulation or lattice substitution [61]. In areas with higher clay content, HMs tend to accumulate in the surface soil, whereas in sandy soil areas, HMs exhibit a stronger tendency for downward leaching. This difference in vertical migration, determined by soil structure, is the fundamental reason for the localized variations in HM enrichment levels.

3.4.2. Correlation Analysis of Heavy Metal Concentrations Between Soil and Groundwater

Soil leaching is often recognized as a potential source of HMs in groundwater [62], Figure 8b illustrates the correlation between HM concentrations in soil and groundwater; however, this study observed a prevalent and significant negative correlation between soil HMs (Cds, Cus, Nis, Pbs) and their corresponding elements in groundwater (Cdw, Cuw, Niw, Pbw). For instance, the correlation coefficients of soil Cd (Cds) with groundwater Ni (Niw) and Pb (Pbw) exhibited robust inverse relationships of -0.90 and -0.65 , respectively. While Pearson correlations alone cannot definitively prove specific metal retention or leaching mechanisms, this distinct negative correlation suggests a potential decoupling between surface soil HM accumulation and groundwater contamination. This hypothesized decoupling aligns with Li et al. [44], who reported distinct source profiles and negative soil-groundwater correlations in an arid zone due to separate pathways (soil dominated by local industry; groundwater by lateral agricultural recharge). We hypothesize that regional soil physicochemical conditions (e.g., higher clay content or high soil viscosity) may favor the interception and immobilization of HMs in the surface soil, thereby reducing the risk of seepage into the groundwater. Similarly, Tang et al. [18] observed a spatial mismatch between soil and groundwater pollution in a semi-arid region, attributing it to alkaline conditions ($\text{pH} > 8$) that restricted vertical metal migration. Consequently, this finding suggests that HM sources in the groundwater of Xinjiang's industrial parks may not be entirely dominated by recent, widespread surface soil leaching. Instead, groundwater HM concentrations are likely governed by a more complex combination of factors, including specific localized contamination sources, lateral groundwater transport, and water-rock interactions. This is likely coupled with the regional hydroclimatic characteristics—scant precipitation and intense evaporation—which collectively restrict the vertical migration of HMs. These insights provide a critical theoretical basis for the synergistic management of groundwater anti-seepage and soil pollution control.

In locations characterized by strong adsorption capacity and high clay content in the vadose zone, HMs are physically and chemically immobilized within the soil matrix, hindering vertical transport [63]. This aligns with Zhang et al. [64], who attributed negative soil-groundwater metal correlations to clay-mediated immobilization in the vadose zone. Our robust inverse correlation between soil Cd and groundwater Ni (-0.90 , $p < 0.01$) similarly reflects the trapping capacity of clay-rich horizons. If such mechanisms are active in the study area, they could explain the observed trend of high soil concentrations paired with low groundwater concentrations. In contrast, in areas with high permeability or poor water-holding capacity, HMs penetrate the vadose zone and enter the aquifer under the rinsing action of precipitation runoff or industrial irrigation, leading to intensified groundwater pollution and relatively lower surface soil concentrations. Therefore, the observed negative correlation indicates that groundwater pollution risk likely depends not merely on surface input loads but, more critically, on the transport efficiency of the vadose zone media. Xiang et al. noted that the relatively stable soil-groundwater environment and low active component content in decommissioned industrial parks limit the vertical migration and release of HMs from soil to groundwater [65]. HM sources in groundwater primarily include water-rock interactions, water-soil interactions, atmospheric deposition, and industrial activities. While precipitation initially increases HM concentrations in groundwater during the early leaching stages, further precipitation enhances the dilution effect, causing concentrations to gradually decrease [66]. Furthermore, many industrial zones in Xinjiang are characterized by soil salinization. Intensified anthropogenic activities and the resulting increase in exchangeable sodium percentage (ESP) promote the dispersion of colloidal particles and the collapse of pore structures. This significantly reduces saturated hydraulic conductivity and weakens the leaching capacity of natural rainfall and irrigation for salts and pollutants, leading to soil compaction. This process is highly likely to further exacerbate the pronounced disparity in HM concentrations between soil and groundwater [67]. Beyond the vadose zone retention, lateral transport from localized sources and seasonal variability also play critical roles. This seasonal modulation echoes Wei et al. [66], where soil-groundwater correlations inverted dynamically due to seasonal flushing. In hyper-arid Xinjiang, the annual spring snowmelt may similarly generate transient leaching pulses that temporarily synchronize concentration profiles. However, further mechanistic investigations, such as column leaching experiments and multi-seasonal 3D hydrogeological monitoring, remain necessary to definitively confirm these complex dynamics.

3.5. Source Apportionment of Heavy Metals in the Soil-Groundwater System

3.5.1. Source Apportionment of Heavy Metals in the Soil

Quantitative source apportionment of soil heavy metals was performed using Positive Matrix Factorization (PMF). The model, implemented in EPA PMF 5.0, was evaluated with 3, 4, and 5 factor solutions, each run with a minimum of 100 iterations to ensure convergence stability. A 3-factor solution was ultimately selected as the most interpretable and geochemically meaningful configuration. The relative contributions of the resolved factors, visualized in Figure 9, followed the order: Factor 2 (52.5%) > Factor 3 (29.7%) > Factor 1 (17.7%).

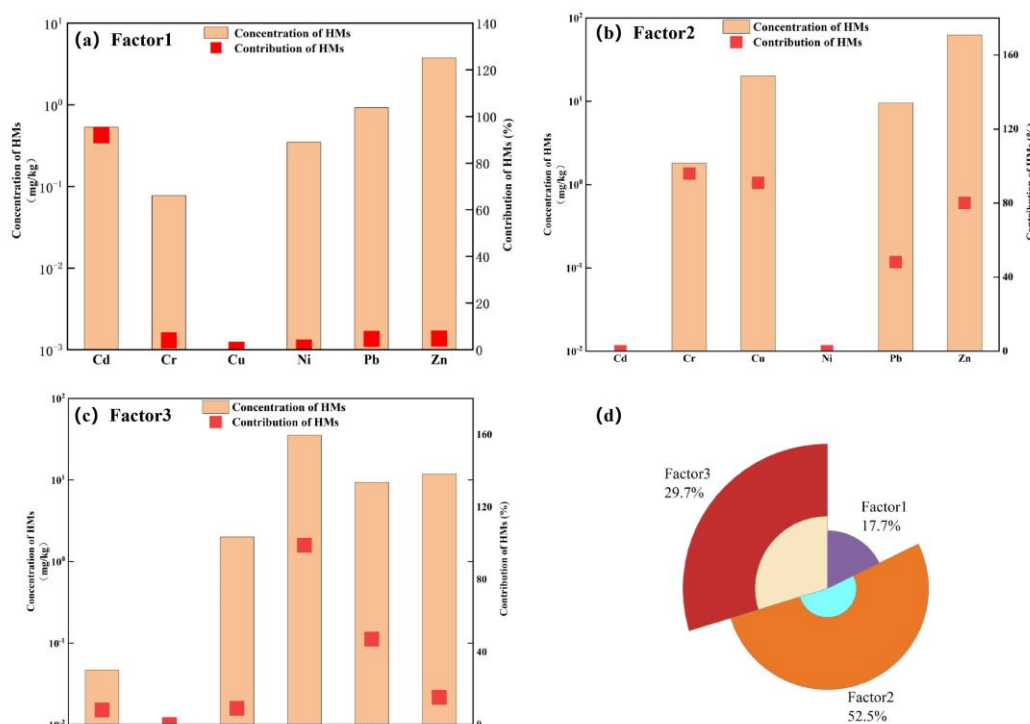


Figure 9. Factorial contribution profiles for individual soil heavy metals (a–c) and the total contributions of factors to soil heavy metals (d).

Among the three factors, Factor 2 was the dominant source, accounting for 52.5% of total soil HM concentrations, heavily loaded with Cr (95.91%), Cu (90.93%), Zn (80.07%), and Pb (48.14%). Previous studies in Northwest China have indicated that Cr and Cu in soil near industrial zones serve as typical indicator elements for smelting, chemical production, and industrial wastewater treatment [65]. While Cu can originate from soil parent material (natural factors) as well as agricultural activities like irrigation and fertilization [49]. Considering the enrichment characteristics of these elements in soil, Factor 2 was designated as the industrial activity source.

Factor 3 was responsible for 29.7% of the soil HM levels, with Ni was the dominant element (contribution rate of 99.02%). Its spatial distribution was primarily concentrated at the boundaries of multiple administrative districts at the northern foot of the Tianshan Mountains (Figure 3). with concentrations closely aligning with local soil background values and exhibiting a moderate coefficient of variation. At a regional scale, Ni enrichment is primarily controlled by soil parent material and rock weathering [68]. Consequently, Factor 3 represents the natural geogenic source.

Factor 1 accounted for 17.7% of the soil HM concentration, with Cd as the core loading element (91.92%). In this region, Cd is typically influenced by non-point source pollution from intensive agricultural practices (e.g., application of phosphate fertilizers and pesticides) [69], as well as overlapping atmospheric deposition from adjacent industrial point sources. Due to these overlapping emission characteristics, Factor 1 was defined as a mixed industrial-agricultural source.

3.5.2. Source Apportionment of Heavy Metals in the Groundwater

For groundwater HM source apportionment, a 3-factor PMF solution was similarly identified as optimal, visualized in Figure 10, With the contribution rates following the order of Factor 1 (75.0%) > Factor 2 (15.1%) > Factor 3 (9.9%).

Factor 1 was the overwhelmingly dominant contributor (75.0%), characterized by exceptionally high loadings of Zn (99.99%), Pb (97.23%), and Cu (96.30%). The Zn-Cu association is a well-established geochemical fingerprint of agricultural activities, primarily derived from phosphate fertilizers, livestock manure, and Cu-based agrochemicals. Pb in this factor likely originates from historical atmospheric deposition and pH-Eh-driven reductive release from aquifer media [70]. Considering the study area is zoned as industrial land surrounded by extensive agricultural fields, the absolute dominance of this factor suggests significant lateral groundwater recharge from adjacent cultivated areas. Therefore, Factor 1 is interpreted as a mixed agricultural non-point and natural geogenic release source, transported into the study area via regional groundwater flow.

Factor 2 contributed 15.1%, with Cd (95.22%) as the primary tracer and a notable secondary contribution from Ni (57.19%). Cd in groundwater systems is predominantly associated with phosphorus fertilizer application [71]. The co-loading of Cd and Ni suggests that vadose-zone leaching from historically fertilized soils in adjacent agricultural zones is transmitted into the study aquifer. Factor 2 is primarily attributed to agricultural fertilizer leaching, with a minor contribution from historical industrial deposition.

Factor 3 accounted for 9.9%, dominated by Cr (94.96%) and partially by Ni (42.81%). Cr (VI) mobilization is favored under the oxidizing and slightly alkaline conditions typical of arid-zone aquifers [64]. The partial loading of Ni further supports a lithogenic provenance from the weathering of mafic/ultramafic minerals. Factor 3 is interpreted as a natural geogenic source.

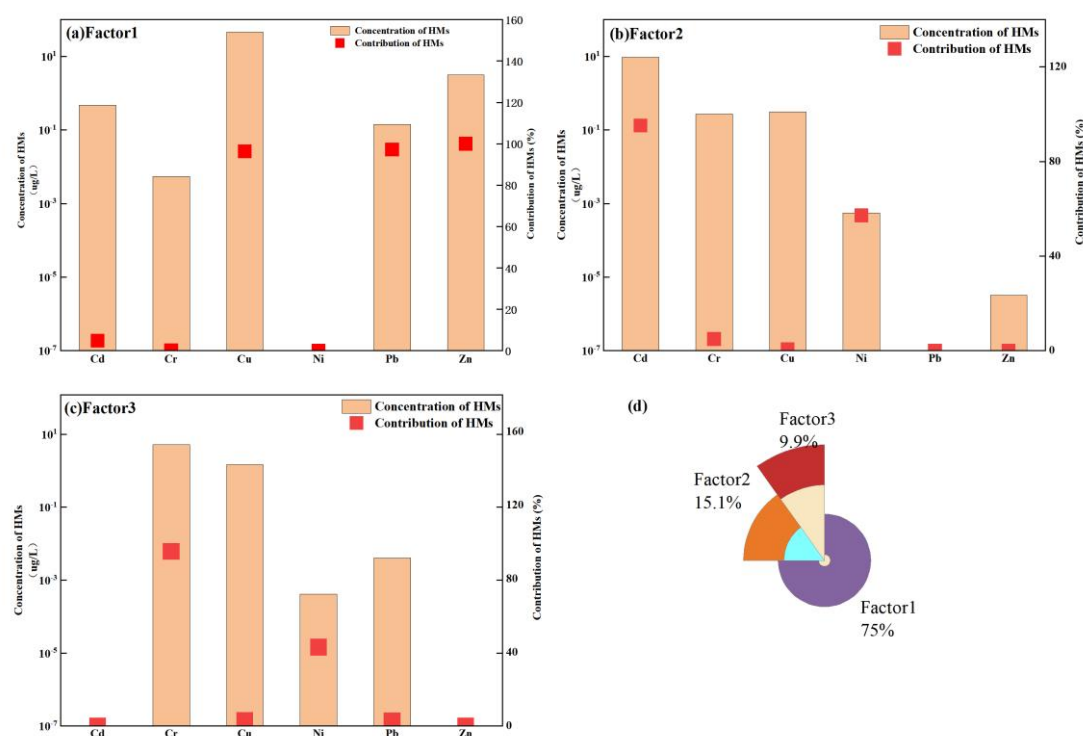


Figure 10. Factorial contribution profiles for individual groundwater heavy metals (a–c) and the total contributions of factors to groundwater heavy metals (d).

3.5.3. Decoupling of Soil and Groundwater Contamination Pathways

It is noteworthy that Pearson correlation analysis revealed a weak negative correlation between HM concentrations in the topsoil and the underlying groundwater. This

inverse relationship suggests a potential “decoupling” of the contamination pathways between these two environmental compartments.

While the soil PMF results indicate that surface HMs (e.g., Cr, Cu, Zn, Pb) are primarily governed by “top-down” local industrial emissions (Factor 2, 52.5%), the groundwater HMs appear to be largely dictated by lateral hydrogeological inputs from adjacent agricultural zones (Factor 1, 75.0%). Such a decoupling phenomenon is corroborated by the recent observations of Xiang et al. [62], regarding distinct source mismatches between soil and groundwater in a retired industrial park, and similarly by Li et al. [44], who attributed groundwater metal loading primarily to lateral agricultural recharge. In the arid climate of Xinjiang, characterized by high evaporation and low precipitation, the vertical leaching of HMs is likely restricted. Furthermore, the slightly alkaline nature of the local soils may promote the precipitation and adsorption of industrial HMs within the shallow topsoil, potentially acting as a hydrochemical barrier, as conceptually described by Ke et al. [63] as a “retention-leaching” mechanism, which restricts vertical migration and leads to the observed weak negative correlations. Conversely, in shallow aquifer settings with higher permeability, such as the industrial park investigated by Pan et al. [65], vertical leaching dominated the soil-groundwater transfer. Consequently, surface industrial pollutants may be impeded from penetrating the thick vadose zone to reach the aquifer, leaving the groundwater predominantly influenced by lateral agricultural recharge. This hypothesized decoupling phenomenon provides a plausible explanation for the weak negative correlation and highlights that, in arid industrial regions, soil and groundwater remediation should perhaps be managed as relatively independent hydrological systems.

3.6. Risk Control and Sustainable Management Recommendations

Monitoring the spatial distribution and deciphering the source-sink dynamics of HMs in chemical industrial parks are vital components of sustainable environmental management. This study underscores the necessity of adopting differentiated management strategies for soil and groundwater, guided by their decoupled contamination pathways. The quantitative assessment reveals that the ecological vulnerability of the groundwater system in these arid regions far exceeds expectations, with approximately 30% of the evaluated industrial parks falling into high-risk categories based on the HCI, compared to 13.79% attaining high ecological risk (RI) in the soil. Given that groundwater pollution in this region is primarily driven by lateral agricultural inputs rather than vertical industrial leaching, traditional source control measures focusing solely on industrial surface emissions are insufficient to protect the aquifer. For high-risk, highly toxic elements like Cd and Pb, cross-regional synergistic management must be implemented, combining industrial point-source reduction with stringent control over agrochemical applications in adjacent agricultural zones. Furthermore, leveraging the natural “interception” capacity of the vadose zone—by applying amendments to maintain optimal soil pH or enhance the stability of clay structures—can serve as an effective proactive measure to minimize any potential downward migration of HMs.

As the socio-economic structure evolves, an increasing number of traditional chemical industrial parks are facing relocation, upgrading, or functional transformation. Effectively managing HM legacies in these areas is a prerequisite for safe land redevelopment. The findings of this study confirm that while surface soils bear the brunt of localized industrial emissions, the pollution remains largely confined to the upper horizons due to the region’s unique arid pedogenic environment. This provides an optimistic outlook for the environmental reclamation of industrial brownfields. By conducting precise, site-specific risk assessments and implementing environment-oriented restoration—rather than adopting a “one-size-fits-all” deep excavation approach—these former industrial sites can be safely and economically repurposed into commercial zones, public parks, or even

modern agricultural lands [72]. Ultimately, recognizing the independent yet interconnected nature of soil and groundwater systems will provide invaluable practical guidance for sustainable land resource management within the arid zones of Northwestern China.

4. Conclusions

In this work, a systematic integration of multiple pollution and ecological risk assessment indices with GIS and the PMF model was employed to examine the contamination characteristics, spatial distribution patterns, and potential origins of heavy metals (HMs) within the soil–groundwater systems of representative chemical industrial parks in Xinjiang. The principal findings are summarized as follows:

(1) The soil and groundwater in the 40 industrial parks within the study area generally exhibited low to moderate pollution levels. Specifically, Cd was identified as the predominant pollutant and the primary contributor to ecological risk in both media. The P_i and P_N assessment results revealed that Cd posed substantial ecological risks in both soil and groundwater, whereas Pb exhibited elevated risk levels primarily in groundwater. For soil, the RI indicated a “moderate” risk for Cd, with a mean value of 53.57. Furthermore, the HCI demonstrated that groundwater in specific industrial parks is currently at a high-risk level ($HCI > 4500$). Cd and Pb were identified as the predominant triggering factors, highlighting them as priority targets for future groundwater management and remediation. Notably, except for Cd, the concentrations of all other HMs in the soil remained within the risk control standards for agricultural land.

(2) HM pollution exhibited significant spatial heterogeneity driven by point sources. Spatially, the northern region showed higher pollution loads and potential ecological risks compared to the southern region. Pollution hotspots were highly concentrated in the core industrial zones and displayed a sharp attenuation trend with increasing distance (distance–decay effect), confirming that regional HM dispersion is primarily controlled by emissions from typical industrial point sources.

(3) The PMF source apportionment successfully quantified the divergent input pathways for the two environmental media. In the soil, Cr, Cu, Zn, and Pb were primarily driven by local industrial activities (52.5%), while Cd exhibited characteristics of mixed industrial-agricultural emissions. Conversely, in the groundwater, the dominant heavy metals (Zn, Pb, Cu) were overwhelmingly dictated by lateral regional groundwater recharge influenced by adjacent agricultural non-point sources (75.0%). Ni in both media was largely attributed to the natural geological background.

(4) Key environmental variables, notably soil pH, clay content, MAT, MAP, and SOC, emerged as the primary factors shaping heavy metal spatial patterns. Crucially, pronounced inverse relationship between heavy metal levels in the surface soil and the subjacent groundwater indicates a possible separation of their contamination pathways. We hypothesize that under the specific physicochemical conditions of arid regions (e.g., alkaline pH, high clay content, and limited precipitation), a dynamic “interception-leaching” mechanism is formed within the vadose zone. This hydrochemical barrier restricts vertical migration, effectively isolating surface industrial inputs from the underlying aquifer. These findings provide a critical theoretical foundation for the independent, targeted management and synergistic remediation of soil and groundwater pollution in chemical industrial parks.

(5) Owing to the difficulty in acquiring detailed internal operational data from the chemical industrial parks, a comprehensive coupling analysis between heavy metal distribution and specific microscopic industrial activities or distinct industrial sectors was not conducted in this study. This is recognized as a key limitation of the current work and will be systematically investigated in our next stage of research.

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References

1. Liu, X.M.; Gu, S.B.; Yang, S.Y.; Deng, J.S.; Xu, J.M. Heavy metals in soil-vegetable system around E-waste site and the health risk assessment. *Sci. Total Environ.* **2021**, *779*, 146438.
2. Peng, C.; Zhang, K.; Wang, M.E.; Wan, X.X.; Chen, W.P. Estimation of the accumulation rates and health risks of heavy metals in residential soils of three metropolitan cities in China. *J. Environ. Sci.* **2022**, *115*, 149–161.
3. Mishra, S.; Lin, Z.Q.; Pang, S.M.; Zhang, Y.M.; Bhatt, P.; Chen, S.H. Biosurfactant is a powerful tool for the bioremediation of heavy metals from contaminated soils. *J. Hazard. Mater.* **2021**, *418*, 126253.
4. Liu, X.; Bai, Z.; Shi, H.; Zhou, W.; Liu, X. Heavy metal pollution of soils from coal mines in China. *Nat. Hazards* **2019**, *99*, 1163–1177.
5. Chen, N.; Zheng, Y.; He, X.; Li, X.; Zhang, X. Analysis of the Report on the national general survey of soil contamination. *J. Agro-Environ. Sci.* **2017**, *36*, 1689–1692.
6. Rajendran, S.; Priya, T.A.K.; Khoo, K.S.; Hoang, T.K.A.; Ng, H.S.; Munawaroh, H.S.H.; Karaman, C.; Orooji, Y.; Show, P.L. A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. *Chemosphere* **2022**, *287*, 132369.
7. Li, Z.Y.; Jia, C.; Du, J.Y.; Ye, L.; Yang, X.W.; Yang, X. A bidirectional feedback model for enhancing heavy metal pollution sensitivity Assessment: Case study of Queshan Longhu Wetland. *J. Clean. Prod.* **2025**, *513*, 145764.
8. Veluchamy, C.; Sharma, A.; Thiagarajan, K. Assessment of heavy metal pollution and human health risk along the Southeast coast of India: A comprehensive ecotoxicological study. *Mar. Pollut. Bull.* **2025**, *221*, 118512.
9. Guo, G.H.; Wang, Y.T.; Zhang, D.G.; Li, K.; Lei, M. Human health risk apportionment from potential sources of heavy metals in agricultural soils and associated uncertainty analysis. *Environ. Geochem. Health* **2023**, *45*, 881–897.
10. Chai, L.; Wang, Y.H.; Wang, X.; Ma, L.; Cheng, Z.X.; Su, L.M. Pollution characteristics, spatial distributions, and source apportionment of heavy metals in cultivated soil in Lanzhou, China. *Ecol. Indic.* **2021**, *125*, 107507.
11. Liu, H.W.; Zhang, Y.; Yang, J.S.; Wang, H.Y.; Li, Y.L.; Shi, Y.; Li, D.C.; Holm, P.E.; Ou, Q.; Hu, W.Y. Quantitative source apportionment, risk assessment and distribution of heavy metals in agricultural soils from southern Shandong Peninsula of China. *Sci. Total Environ.* **2021**, *767*, 144879.
12. Bhuiyan, M.A.H.; Karmaker, S.C.; Bodrud-Doza, M.; Rakib, M.A.; Saha, B.B. Enrichment, sources and ecological risk mapping of heavy metals in agricultural soils of dhaka district employing SOM, PMF and GIS methods. *Chemosphere* **2021**, *263*, 128339.
13. Tan, C.; Wang, H.; Yang, Q.C.; Yuan, L.Y.; Zhang, Y.L.; Martín, J.D. An integrated approach for quantifying source apportionment and source-oriented health risk of heavy metals in soils near an old industrial area. *Environ. Pollut.* **2023**, *323*, 121271.
14. Chen, W.; Peng, L.; Hu, K.R.; Zhang, Z.; Peng, C.H.; Teng, C.Y.; Zhou, K.G. Spectroscopic response of soil organic matter in mining area to Pb/Cd heavy metal interaction: A mirror of coherent structural variation. *J. Hazard. Mater.* **2020**, *393*, 122425.

15. Wang, S.; Ma, Z.; Yue, G.; Wu, H.; Wang, P.; Zhu, L.; Liang, C.; Xie, C.; Wang, S.; Jiao, W.; et al. Spatial Distribution and Assessment of the Human Health Risks of Heavy Metals in a Retired Pharmaceutical Industrial Area, Southwest China. *Bull. Environ. Contam. Toxicol.* **2022**, *109*, 808–816.
16. Sharma, P.; Ngo, H.H.; Khanal, S.; Larroche, C.; Kim, S.H.; Pandey, A. Efficiency of transporter genes and proteins in hyperaccumulator plants for metals tolerance in wastewater treatment: Sustainable technique for metal detoxification. *Environ. Technol. Inno* **2021**, *23*, 101725.
17. Reyes, A.; Cuevas, J.; Fuentes, B.; Fernández, E.; Arce, W.; Guerrero, M.; Letelier, M.V. Distribution of potentially toxic elements in soils surrounding abandoned mining waste located in Taltal, Northern Chile. *J. Geochem. Explor.* **2021**, *220*, 106653.
18. Tang, L.; Liu, J.; Zeng, J.; Luo, X.; Ke, W.; Li, C.; Gao, W.; Jiang, J.; Xue, S. Anthropogenic processes drive heterogeneous distributions of toxic elements in shallow groundwater around a smelting site. *J. Hazard. Mater.* **2023**, *453*, 131377.
19. Scanlon, B.R.; Keese, K.E.; Flint, A.L.; Flint, L.E.; Gaye, C.B.; Edmunds, W.M.; Simmers, I. Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrol. Process. Int. J.* **2006**, *20*, 3335–3370.
20. Bradl, H.B. Adsorption of heavy metal ions on soils and soils constituents. *J. Colloid Interface Sci.* **2004**, *277*, 1–18.
21. Li, Y.W.; Xue, J.P.; Cai, J.X.; Zhang, Y.C.; Li, F.X.; Zha, X.H.; Fang, G.D. The Spatial Distribution and Influencing Factors of Heavy Metals in Soil in Xinjiang, China. *Sustainability* **2023**, *15*, 16379.
22. Abliz, A.; Shi, Q.; Abulizi, A. Contamination status and health risk assessment of soil heavy metals in the northern slope of eastern Tianshan mountains industrial belt in Xinjiang, Northwest China. *Forests* **2022**, *13*, 1914.
23. Zhang, H.; Zhang, F.; Song, J.; Tan, M.L.; Kung, H.-T.; Johnson, V.C. Pollutant source, ecological and human health risks assessment of heavy metals in soils from coal mining areas in Xinjiang, China. *Environ. Res.* **2021**, *202*, 111702.
24. Hu, Q.; Li, J.; Wang, Y.; Huang, P.; He, X. Evaluation and source analysis of heavy metal pollution in grassland soils under different management modes in Altay, Xinjiang. *Agronomy* **2023**, *13*, 2621.
25. Wang, W.; Lai, Y.; Ma, Y.; Liu, Z.; Wang, S.; Hong, C. Heavy metal contamination of urban topsoil in a petrochemical industrial city in Xinjiang, China. *J. Arid. Land.* **2016**, *8*, 871–880.
26. Fan, W.; Zhou, J.; Zhou, Y.; Wang, S.; Du, J.; Chen, Y.; Zeng, Y.; Wei, X. Heavy metal pollution and health risk assessment of agricultural land in the Southern Margin of Tarim Basin in Xinjiang, China. *Int. J. Environ. Health Res.* **2021**, *31*, 835–847.
27. Panqing, Y.; Abliz, A.; Xiaoli, S.; Aisaiduli, H. Human health-risk assessment of heavy metal-contaminated soil based on Monte Carlo simulation. *Sci. Rep.* **2023**, *13*, 7033.
28. Xu, X.; Liu, Y.; Liu, Q.; Gui, D.; Cui, B.; Chen, X.; Abd-Elmabod, S.K. Spatial distribution characteristics and risk assessment of heavy metals in soils of Southern Xinjiang oases. *Environ. Monit. Assess.* **2025**, *197*, 395.
29. Statistics Bureau of Xinjiang Uygur Autonomous Region Statistical Communiqué of the Xinjiang Uygur Autonomous Region on the 2025 National Economic and Social Development. Available online: <https://tjgb.hongheiku.com/sjtjgb/68172.html> (accessed on 17 April 2026).
30. Soil Environmental Quality—Risk Control Standard for Soil Contamination of Agricultural Land. Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2018.
31. Soil Environmental Quality—Risk Control Standard for Soil Contamination of Development Land. Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2018.
32. Chen, Z.; Chen, L.; Lu, R.; Lou, Z.; Zhou, F.; Jin, Y.; Xue, J.; Guo, H.; Wang, Z.; Wang, Y. A national soil organic carbon density dataset (2010–2024) in China. *Sci. Data* **2025**, *12*, 1480.
33. Wan, M.X.; Hu, W.Y.; Wang, H.F.; Tian, K.; Huang, B.A. Comprehensive assessment of heavy metal risk in soil-crop systems along the Yangtze River in Nanjing, Southeast China. *Sci. Total Environ.* **2021**, *780*, 146567.
34. Standard for Groundwater Quality. Standardization Administration of the People's Republic of China: Beijing, China, 2017.
35. Yi, S.T.; Liu, W.L.; Lin, J.J.; Li, B.; Zhao, L.; Li, W. Migration patterns and pollution assessment of heavy metals in seawater, sediments, and marine organisms in the Xisha coral reef ecosystem of the South China Sea. *Mar. Pollut. Bull.* **2026**, *227*, 119482.
36. Hakanson, L. An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Res.* **1980**, *14*, 975–1001.
37. Xu, Z.Q.; Ni, S.J.; Tuo, X.; Zhang, C.J. Calculation of heavy metals' toxicity coefficient in the evaluation of potential ecological risk index. *Environ. Sci. Technol.* **2008**, *31*, 112–115.
38. Mei, W.L.S.L. Yuan Y Y, Optimization of potential ecological risk index method for soil heavy metals—A case study of Chengkou County, Chongqing City. *Chin. J. Soil. Sci.* **2023**, *54*, 473–480. (In Chinese)
39. Li, Y.; Zhuang, Z.; Xia, Q.; Shi, Q.; Zhu, J.; Wang, P.; Li, D.; Zhakypbek, Y.; Tursbekov, S. Health risk assessment of heavy metals in coal mine soils of Northwest China. *J. Arid. Land.* **2025**, *17*, 933–957.

40. Baskaran, P.; Abraham, M. Evaluation of groundwater quality and heavy metal pollution index of the industrial area, Chennai. *Phys. Chem. Earth Parts A/B/C* **2022**, *128*, 103259.
41. Rajkumar, H.; Naik, P.K.; Rishi, M.S. A new indexing approach for evaluating heavy metal contamination in groundwater. *Chemosphere* **2020**, *245*, 125598.
42. Standards for Drinking Water Quality. Standardization Administration of the People's Republic of China: Bei-jing, China, 2022.
43. Zhu, T.T.; Wu, Q.X.; Gao, S.L.; Zeng, J.; Linghu, K.; Zhang, X.D. Comparative assessment of health risks and water quality of groundwater in urban and rural Guiyang, Southwest China: Insights from PMF and Monte Carlo Simulation. *Ecotox Environ. Safe* **2025**, *299*, 118359.
44. Li, Z.; Alemu, C.; Yang, F.; Wei, C. Integrated PMF-GeoDetector approach for source apportionment and spatial drivers of heavy metals in coupled surface-groundwater systems. *Environ. Earth Sci.* **2025**, *84*, 611.
45. Huo, B.Y.; Shen, Y.J.; Ning, Y.B.; Shen, W.; Ma, P.H.; Jia, Z.J.; Zhao, L.Q.; Zhao, J.Y.; Chen, X.; Ding, T.; et al. Accumulation pattern, source apportionment and risk assessment of soil heavy metals across diverse land use types: Insights from the northern foothills of Qinling mountains, China. *Catena* **2026**, *266*, 109938.
46. Wang, Y.Z.; Duan, X.J.; Wang, L. Spatial distribution and source analysis of heavy metals in soils influenced by industrial enterprise distribution: Case study in Jiangsu Province. *Sci. Total Environ.* **2020**, *710*, 134953.
47. Reed, G.F.; Lynn, F.; Meade, B.D. Use of coefficient of variation in assessing variability of quantitative assays. *Clin. Diagn. Lab. Immun.* **2002**, *9*, 1235–1239.
48. Abliz, A.; Imin, B.; Asaiduli, H. Spatial Patterns, Possible Sources, and Risks Assessment of Soil Potentially Toxic Elements in an Open Pit Coal Mining Area in a Typical Arid Region. *Sustainability* **2023**, *15*, 1163–1177.
49. Guan, Q.; Wang, F.; Xu, C.; Pan, N.; Lin, J.; Zhao, R.; Yang, Y.; Luo, H. Source apportionment of heavy metals in agricultural soil based on PMF: A case study in Hexi Corridor, northwest China. *Chemosphere* **2018**, *193*, 189–197.
50. Wei, B.G.; Yang, L.S. A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. *Microchem. J.* **2010**, *94*, 99–107.
51. Zhang, W.; Long, J.H.; Zhang, X.R.; Shen, W.N.; Wei, Z.Y. Pollution and Ecological Risk Evaluation of Heavy Metals in the Soil and Sediment around the HTM Tailings Pond, Northeastern China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 7072.
52. Wang, Z.Y.; Su, Q.; Wang, S.; Gao, Z.J.; Liu, J.T. Spatial distribution and health risk assessment of dissolved heavy metals in groundwater of eastern China coastal zone. *Environ. Pollut.* **2021**, *290*, 118016.
53. Acosta, J.A.; Martínez-Martínez, S.; Faz, A.; Arocena, J. Accumulations of major and trace elements in particle size fractions of soils on eight different parent materials. *Geoderma* **2011**, *161*, 30–42.
54. Liu, J.; Li, C.B.; Wang, J.; Li, L.L.; He, J.L.; Zhao, F.N. Spatial Heterogeneity of Heavy Metals in Arid Oasis Soils and Its Irrigation Input-Soil Nutrient Coupling Mechanism. *Sustainability* **2025**, *17*, 7156.
55. Ortner, M.; Seidel, M.; Semella, S.; Udelhoven, T.; Vohland, M.; Thiele-Bruhn, S. Content of soil organic carbon and labile fractions depend on local combinations of mineral-phase characteristics. *Soil* **2022**, *8*, 113–131.
56. Schweizer, S.A.; Seitz, B.; van der Heijden, M.G.A.; Schulin, R.; Tandy, S. Impact of organic and conventional farming systems on wheat grain uptake and soil bioavailability of zinc and cadmium. *Sci. Total Environ.* **2018**, *639*, 608–616.
57. Bai, J.; Xiao, R.; Cui, B.; Zhang, K.; Wang, Q.; Liu, X.; Gao, H.; Huang, L. Assessment: Of heavy metal pollution in wetland soils from the young and old reclaimed regions in the Pearl River Estuary, South China. *Environ. Pollut.* **2011**, *159*, 817–824.
58. Hailegnaw, N.S.; Mercl, F.; Pracke, K.; Praus, L.; Száková, J.; Tlustos, P. The Role of Biochar and Soil Properties in Determining the Available Content of Al, Cu, Zn, Mn, and Cd in Soil. *Agronomy* **2020**, *10*, 885.
59. Bonatotzky, T.; Ottner, F.; Erendsson, E.; Gísladóttir, G. The weathering of volcanic tephra and how they impact histosol development. An example from South East Iceland. *Catena* **2019**, *172*, 634–646.
60. Hu, Y.L.; Wang, S.G. Formation mechanism of a severe air pollution event: A case study in the Sichuan Basin, Southwest China. *Atmos. Environ.* **2021**, *246*, 118135.
61. Wu, J.; Liu, H.; Wang, D.L.; Zhao, X.Y.; Zeng, X.; Huang, C.M. Two-stage heavy metal enrichment during carbonate rock weathering-pedogenesis: Micro-scale evidence from soil-rock interface. *J. Hazard. Mater.* **2025**, *498*, 139910.
62. Xiang, Z.; Wu, S.; Zhu, L.; Yang, K.; Lin, D. Pollution characteristics and source apportionment of heavy metal(loid)s in soil and groundwater of a retired industrial park. *J. Environ. Sci.* **2024**, *143*, 23–34.
63. Ke, H.; Fei, M.L.; Zhang, C.S.; Zhan, L.T.; Zhang, G.B.; Lan, J.W.; Zhang, X.Q.; Zheng, S.N.; Chen, Y.M. Heavy metal distribution in MSW-derived soils and migration within the subjacent soil strata of landfills. *Waste Manag.* **2026**, *209*, 115181.
64. Zhang, Y.; Zhang, Q.; Chen, W.; Shi, W.; Cui, Y.; Chen, L.; Shao, J. Source apportionment and migration characteristics of heavy metal (loid) s in soil and groundwater of contaminated site. *Environ. Pollut.* **2023**, *338*, 122584.

65. Pan, Z.; Bai, Y.; Guo, J.; Ma, X.; Ma, L.; Wang, Y. Pollution characteristics and quantitative source apportionment of soil heavy metals using PMF and APCS-MLR models in an industrial park in Northwest China. *J. Mt. Sci.-Engl.* **2025**, *22*, 3183–3199.
66. Wei, D.; Yang, S.; Zou, L.; Torres-Martínez, J.A.; Zheng, Y.; Hu, Q.; Zhang, Y. Appraisal of potential toxic elements pollution, sources apportionment, and health risks in groundwater from a coastal area of SE China. *J. Environ. Manag.* **2025**, *377*, 124691.
67. Lei, S.H.; Jia, X.X.; Zhao, C.L.; Shao, M.A. A review of saline-alkali soil improvements in China: Efforts and their impacts on soil properties. *Agr. Water Manag.* **2025**, *317*, 109617.
68. Zhang, W.H.; Yan, Y.; Yu, R.L.; Hu, G.R. The sources-specific health risk assessment combined with APCS/MLR model for heavy metals in tea garden soils from south Fujian Province, China. *Catena* **2021**, *203*, 105306.
69. He, X.; Zhang, F.; Zhou, T.; Wang, B.; Zhang, X.; Liu, X.; Ahmed, Z.; Tan, M.L.; Feng, Z.; Li, Z. Risk assessment, source apportionment and driving mechanism of soil heavy metals in coal mining areas of Xinjiang, China. *Gondwana Res.* **2026**, *154*, 64–81.
70. Li, S.; Shuai, H.; Yu, H.; Liu, Y.; Jing, Y.; Kong, Y.; Liu, Y.; Wu, D. Source Apportionment and Health Risk Assessment of Heavy Metals in Groundwater in the Core Area of Central-South Hunan: A Combined APCS-MLR/PMF and Monte Carlo Approach. *Sustainability* **2026**, *18*, 1225.
71. Zhu, S.; Li, S.; Shao, M.A.; Qiao, J.; Zhu, Y. Source identification and migration fate of heavy metals of soil-groundwater system in a thousand-year cultivation region. *Environ. Geochem. Health* **2024**, *46*, 345.
72. Department of Natural Resources of Anhui Province from Industrial “Rust Belt” to Living “Showcase”: A Case Study of Land Redevelopment in the Anqing Petrochemical Port Tank Farm Area. Available online: <https://zrzyt.ah.gov.cn/xwdt/ywlb/150268481.html> (accessed on 23 April 2026).

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