water

MDPI

Article

Groundwater Heavy Metal Contamination and Health Risk Assessment: A Case Study of South Dongting Lake, China

Shun Zhang and Bozhi Ren *

School of Earth Science and Space Information Engineering, Hunan University of Science and Technology, Xiangtan 411201, China; 18390232910@163.com
* Correspondence: bozhiren@126.com

Abstract

To investigate the heavy metal contamination status and associated health risks in the groundwater of South Dongting Lake, China, 88 groundwater samples were collected and analyzed for the contents of heavy metals (Fe, Mn, Cu, Zn, As, Cd, Pb). The heavy metal pollution characteristics and human health risks were comprehensively analyzed using a combined approach of the Heavy Metal Pollution Index (HPI), Heavy Metal Evaluation Index (HEI), Water Quality Index (WQI), and by integrating traditional health risk assessment with Monte Carlo simulation. The results indicated that manganese (Mn) and iron (Fe) were the most prominent pollutants in the regional groundwater, with exceedance rates of 35.3% and 25.0%, respectively. Arsenic (As) showed localized exceedances (13.91 μg/L, 1.39 times the standard limit). Spatially, contamination levels were higher in the north and lower in the south, with Fe, Mn, and As enrichment concentrated in the northern region, correlating with geological structures and industrial discharges. Health risk assessment revealed that the total carcinogenic risk (TCR) for children (1.82×10^{-4}) exceeded the safety threshold by 82%, with arsenic being the primary carcinogen (contribution rate: 74.7%). The non-carcinogenic total hazard index (HI) reached 3.59 for adults and 6.54 for children, significantly exceeding the acceptable level of 1.0. Manganese was identified as the core non-carcinogenic risk source (Hazard Quotient (HQ) for children = 3.35). Monte Carlo simulation confirmed that pollutant concentration and exposure time were the most sensitive risk-driving factors. This study provides a scientific basis for prioritizing the control of As and Mn pollution in the northern region and implementing protective measures against children's exposure.

Keywords: groundwater; heavy metals; health risk assessment; HPI-HEI and WQI; Monte Carlo simulation

check for updates

Academic Editor: Constantinos V. Chrysikopoulos

Received: 26 September 2025
Revised: 5 October 2025
Accepted: 16 October 2025
Published: 22 October 2025

Citation: Zhang, S.; Ren, B. Groundwater Heavy Metal Contamination and Health Risk Assessment: A Case Study of South Dongting Lake, China. *Water* **2025**, *17*, 3036. https://doi.org/10.3390/w17213036

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Heavy metal contamination of groundwater is a global environmental problem [1] and is particularly prominent in industrial-intensive areas, agricultural irrigation areas, and geologically enriched zones [2]. Heavy metals arsenic (As), cadmium (Cd), and lead (Pb) can cause cancer, neurological damage, and developmental toxicity through drinking water exposure, and with long-term exposure, can cause serious harm to humans [3]. Excessive iron and manganese contamination can cause liver and kidney damage, and especially serious effects on children's development [4]; therefore, the health risk assessment of heavy metal contamination in groundwater is particularly important.

This study focuses on the South Dongting Lake Basin, which, as the core part of Dongting Lake, is a typical area affected by the intertwining of hydrological and geological formations as well as human activities [5]. In recent years, the health risk assessment of groundwater contamination has received widespread attention. An example is the arsenic contamination incident in Bangladesh, where excessive arsenic concentrations in the country's groundwater led to a large-scale carcinogenic risk [6]. High fluoride concentrations in groundwater in China's North China Plain have resulted in widespread skeletal fluorosis [7–9]. In the Dongting Lake Basin, many researchers have explored the contamination status of heavy metals in groundwater and health risk analysis through principal component analysis (PCA), self-organized mapping (SOM), and health risk assessment models [10]. The current methods for evaluating heavy metal contamination include the Nemero index method, heavy metal pollution index (HPI), and health risk assessment methods [11]. These were used to evaluate the pollution load of groundwater by the HPI and to predict the health risks by using health risk assessment (HRA) and Monte Carlo simulation [12,13]. Monte Carlo simulation can quantify the traditional health risk assessment, reduce the uncertainty of traditional methods, and improve the accuracy of the results. Monte Carlo simulation is selected to predict the health risk of heavy metals because the traditional health risk assessment relies on a single fixed parameter, which cannot cope with the great spatial difference in heavy metal concentration in groundwater and the uncertainty of human exposure parameters in the study area. The simulation randomly samples the uncertain parameters through 10,000 iterations, which can generate risk probability distribution (such as the quantile of non-carcinogenic risk HI and carcinogenic risk CR), break through the limitations of fixed parameters, and combine sensitivity analysis to identify sensitive factors such as pollutant concentration and exposure time (ED), and quantify the contribution of uncertainty.

In this study, we combine various methods to comprehensively assess the level of heavy metal contamination in groundwater in the South Dongting Lake Basin, and utilize the heavy metal pollution index (HPI), heavy metal evaluation index (HEI), water quality index (WQI), and spatial interpolation techniques to deeply analyze the spatial distribution of Fe, Mn, Cu, Zn, As, Cr, and Pb contaminants in the groundwater and their contamination status; based on the traditional health risk assessment, we introduce Monte Carlo simulation to quantify the traditional health risk assessment, and reduce the uncertainty of traditional methods to improve the accuracy of the results. On the basis of traditional United States Environmental Protection Agency (USEPA) health risk assessment, Monte Carlo simulation is introduced to assess the probability of health risk and analyze the sensitivity, so as to provide a scientific basis for the improvement of groundwater environmental quality and population health in the South Dongting Lake Basin.

2. Materials and Methods

2.1. Overview of the Study Area

The Dongting Lake Plain Basin is a fracture basin on the Jiangnan axis of the Yangzi quasi-terrane, and the former Quaternary strata exposed in its periphery and the basin range from the old to the new, such as the Lengjiaxi Group of the Paleozoic, Banxi Group, Aurora, Paleozoic Cambrian, Ordovician, Devonian, Carboniferous, Mesozoic Triassic, Jurassic, Cretaceous, and Tertiary of the Neoproterozoic, etc. South Dongting Lake is located in the southwestern part of Dongting Lake, with geographic coordinates between longitude 112°14′32.1″ and 112°56′18.3″ East and latitude 28°45′47.5″ and 29°11′08.1″ North, and the administrative area covers four counties and cities in Yiyang City, Hunan Province, including Yuanjiang City, Ziyang District, Xiangyin, Nanxian County, and Miluo. The specific location is shown in Figure 1. During the flood season, it forms a continuous area

of water, and during the dry season, it reveals a continental beach, presenting the typical dynamic geomorphological feature of "water rises to become a lake, and water falls to become a continent". South Dongting Lake is an over-water lake, with an average annual water exchange cycle of about 19 days, the water level dropping to 24–26 m during the dry season, and up to 34 m during the flood season, and the water quality generally reaches the standard of Class II (local Class III), but there is a risk of exceeding the standard of heavy metals (e.g., arsenic, cadmium) and nutrient salts (ammonia, nitrogen, and phosphorus) due to the influence of pollution from industry and agriculture. According to the survey, most of the residents in the study area have been connected to tap water, but in the dry season or sudden water pollution incidents, some rural residents will still temporarily use groundwater as a supplementary water source. In addition, the local tap water source is also partly taken from groundwater.

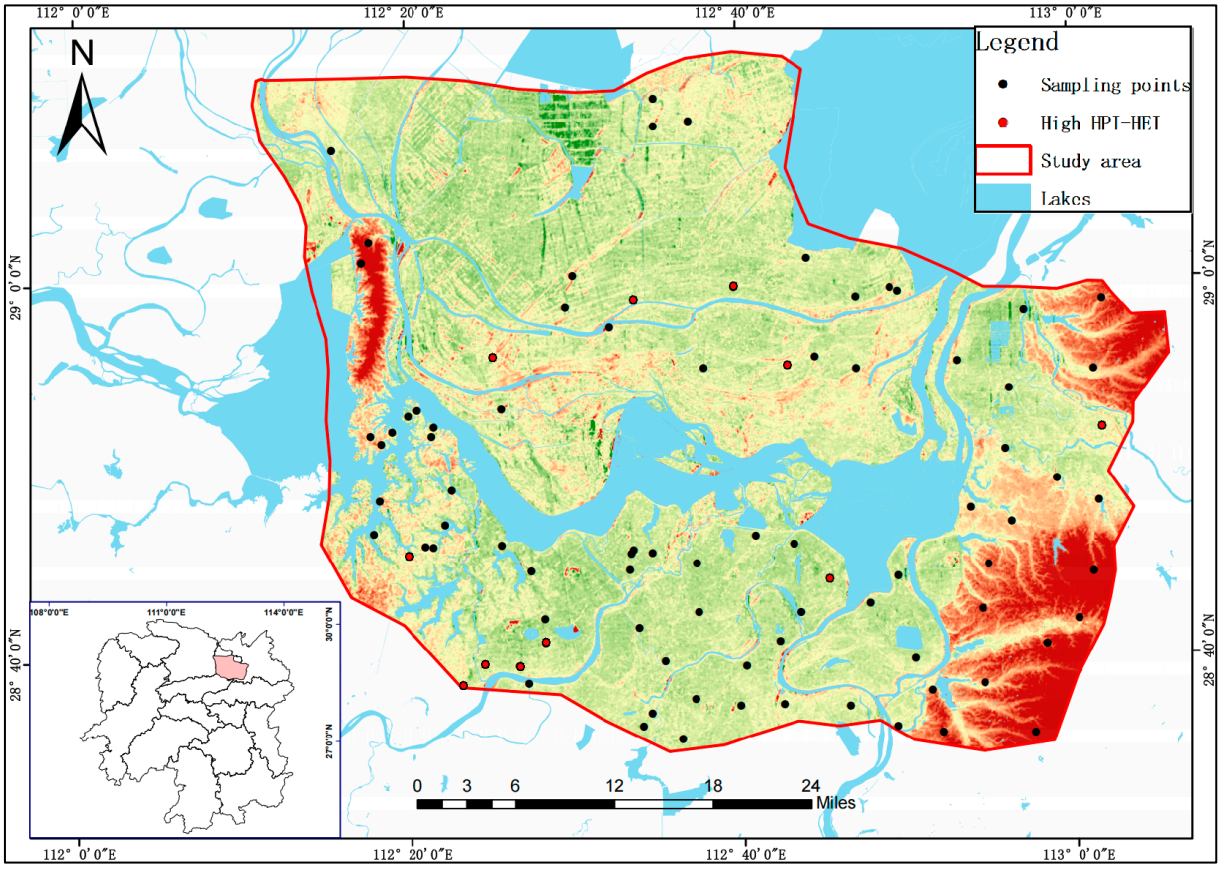


Figure 1. Location of the study area and distribution of sampling points.

2.2. Sample Collection and Testing

In this study, 88 groundwater samples were collected in the South Dongting Lake Basin. The groundwater samples were mainly collected from the phreatic aquifer. The depth range of the sampling borehole is 15 ± 2 m. Groundwater sample sampling requirements refer to the relevant requirements of the Technical Code for Groundwater Environmental Monitoring HJ 164-2020 and HJ1019-2019 [14]. Before collecting groundwater samples on site, wells need to be washed, and pH, turbidity, conductivity, dissolved oxygen, and redox potential are measured using a multi-parameter detector. After the water sample was collected, it was immediately filtered through a 0.45 μm microporous membrane to remove suspended particles. Subsequently, high-grade pure HNO_3 was added and acidified to pH < 2 as a protective agent to prevent the adsorption or precipitation of heavy metals and ensure the stability of the sample during transportation and storage. In this study, Seven

heavy metal elements were analyzed: Fe, Mn, Cu, Zn, As, Cd, and Pb. And the heavy metal elements Fe, Mn, Cu, Zn, As, Cd, and Pb in the water samples were measured by Inductively Coupled Plasma Mass Spectrometry (ICPMS), and the detection limits were 0.02 mg/L, 0.00012 mg/L, 0.00008 mg/L, and 0.00067 mg/L, 0.00012 mg/L, 0.00005 mg/L, and 0.00005 mg/L, respectively.

3. Data Analysis and Evaluation Methods

3.1. Health Risk Assessment

Calculated carcinogenic risk (CR) vs. non-carcinogenic risk (HQ) using USEPA health risk modeling [15,16]. The study was conducted to assess the health risk of Fe, Mn, Cu, Zn, As, Cd, and Pb contaminants detected in the groundwater of South Dongting Lake. The values of each exposure parameter in the model mainly refer to the standard default values recommended by USEPA. Due to the lack of detailed exposure parameter survey data for residents in the South Dongting Lake Basin, this study did not localize the default parameters, which may introduce certain uncertainty. The modeling formulas are as follows [17,18]:

Drinking Water Cancer Risks:

$$CR = SF \times \frac{C_W \times IR \times EF \times ED}{BW \times AT}$$

Drinking Water Non-Cancer Risks:

$$HQ = \frac{C_W \times IR \times EF \times ED}{BW \times AT \times RfD}$$

where CW is the concentration of contaminant in water, mg/L; IR is the intake of drinking water, 2.5 for adults and 1.14 for children, L/d; EF is the exposure frequency, 350 for adults and 350 for children, d/a; ED is the duration of exposure, a; BW is the body weight, 60 for adults and 15 for children, kg; AT is the average exposure time, d; RfD is the daily reference dose, mg/(kg·d); SF is the carcinogenic intensity factor, mg/(kg·d). mg/(kg·d); SF is the carcinogenicity intensity factor, mg/(kg·d).

The values of RfD and SF for the seven pollutants under study in this paper are shown in Table 1 [19]:

Table 1. SF and RfD under different elemental drinking water pathways.

Heavy Metal Element		SF (kg·d/mg)	RfD (mg/(kg·d))	ED	AT
Carcinogenic	As	1.5	0.0003	70	25,550
	Cd	6.1	0.0005		
Non-carcinogenic	Mn	-	0.046	35	2190
	Zn	-	0.3		
	Fe	-	0.3		
	Cu	-	0.04		
	Pb	-	0.0014		

3.2. Monte Carlo Simulation and Sensitivity Analysis

Modeling of uncertainties (e.g., Cr, Cd, and As concentrations in groundwater) using Monte Carlo simulation [20,21]. By randomly sampling these factors, each possible scenario was modeled and thus assessed for possible carcinogenic and non-carcinogenic risks to the health of the population. In this study, sensitivity analyses were conducted using Crystal Ball software for multiple (10,000 iterations) simulations, and sensitivity analyses were used to determine which variables had the greatest impact on the final health risk assessment

results [22]. This analysis helps to identify the most critical parameters in risk assessment and helps to prioritize these factors in the actual prevention and treatment process, leading to more effective risk reduction.

3.3. Heavy Metal Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI)

The Heavy Metal Pollution Index (HPI) is used to assess the degree of combined heavy metal contamination of groundwater, which helps to assess the overall quality of groundwater, and the HPI is calculated as follows [23,24]:

$$\mathrm{HPI} = \frac{\sum_{i=1}^{n}(W_i \times Q_i)}{\sum_{i=1}^{i=n} W_i}$$

where $W_i = 1/S_i$, S_i is the standard value, $Q_i = C_i/S_i * 100$, C_i is the elemental concentration, The classification criteria are: no pollution (0–25), slight pollution (26–50), moderate pollution (50–100), and heavy pollution (>100).

The formula for the Heavy Metal Evaluation Index (HEI) is as follows [25,26]:

$$\mathrm{HEI} = \sum_{i=1}^{n} \frac{M_i}{\mathrm{MAC}_i}$$

where M_i is the elemental concentration value, MAC_i is the maximum acceptable value. The classification criteria are: HEI < 10 is low pollution, 10–20 is medium pollution, and HEI > 20 is high pollution.

3.4. Water Quality Index Evaluation (WQI)

The Water Quality Index (WQI) is a comprehensive evaluation method that quantifies the overall quality of groundwater by integrating the measured concentrations of multiple contaminants in groundwater into a single value [27]. In this paper, eight heavy metal elements in the groundwater of the South Dongting Lake Basin are targeted to evaluate the water quality index (WQI), and the obtained WQI values are interpolated and analyzed by using the inverse distance weighting (IDW) method, to clarify the risk areas of high pollution and to draw a map of water quality risk areas. When calculating the WQI, different weights are assigned to the parameters according to their importance to human health or ecological hazards [28]. Heavy metals such as As and Cd were assigned the highest weight (5.0) due to high toxicity, followed by Fe, Mn, Cu, Zn, Pb (2.0–4.0). The formula was calculated as follows [29,30]:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$$

where W_i is the relative weight. w_i is the weight.

$$Q_i = \frac{C_i}{S_i} \times 100$$

where Q_i is the quality score normalized, C_i is the concentration of the parameter (mg/L), and S_i is the Groundwater Quality Standard Class III limit value.

$$\mathrm{WQI} = \sum_{i=1}^{n}(Q_i \times W_i)$$

4. Results and Discussion

4.1. Descriptive Statistics and Spatial Distribution of Heavy Metals in Groundwater

In this study, seven indicators, including cadmium (Cd), manganese (Mn), lead (Pb), arsenic (As), iron (Fe), copper (Cu), and zinc (Zn), were analyzed as indicators of heavy metal contamination in the groundwater of the South Dongting Lake Basin, Descriptive statistical analysis was performed in IBM SPSS Statistics 27. And the results of the descriptive statistics and analyses of the seven heavy metals are shown in Table 2.

Table 2. Descriptive statistics of heavy metals in groundwater.

Elemental	Mean (μg/L)	Minimum (μg/L)	Maximum (μg/L)	Standard Deviation (μg/L)	Coefficient of Variation (CV)	Limit of Detection (μg/L)	Groundwater Class III Criteria (μg/L)	Exceedance Rate
Cd	0.104	ND	0.809	0.162	1.058	0.05	5	0
Mn	362.68	ND	8312.28	1080.6	3.433	0.12	100	35.3%
Pb	0.186	ND	1.574	0.24	1.29	0.05	10	0
As	1.245	ND	13.906	0.335	2.168	0.12	10	3.8%
Fe	318.33	ND	8984	1260	2.808	20	300	25.0%
Cu	1.078	ND	13.198	1.71	1.483	0.08	1000	0
Zn	7.73	ND	138.45	19.2	2.406	0.67	1000	0

The analysis of the seven indicators in the groundwater in the study area showed that the pollution status of Mn and Fe was the most significant, with the average values of Mn and Fe being 362.68 μg/L and 318.33 μg/L, respectively, and the maximum concentration of Mn exceeding the standard for Class III water by 83.1 times (8312.28 μg/L), and that of Fe by 29.9 times (8984 μg/L), with an exceedance rate as high as 35.3% and 25.0%, respectively. The maximum concentration of Fe exceeded the standard of Class III water by 29.9 times (8984 μg/L), and the exceedance rates were as high as 35.3% and 25.0%, respectively. The coefficients of variation for Fe and Mn were both greater than 250%, which indicated that the spatial distribution was not uniform. The mean value of carcinogenic pollutant As did not exceed the standard limit, but there was localized exceedance (maximum 13.91 μg/L, 1.39 times exceedance), and As contamination may be affected by arsenic-rich strata as well as industrial emissions [31]. The concentrations of the remaining heavy metals Cd, Pb, Cu, and Zn were not exceeded as a whole, with most of them having values below the detection limit.

According to the Limits for Class III Water of the Groundwater Quality Standards, there are exceedances of Mn and Fe, as well as As. Long-term consumption of water containing high concentrations of manganese and iron may harm human health, especially on children, which may damage their neurological development [32,33]. Localized excesses of arsenic can also lead to cancer risk when exposed for long periods of time.

In order to comprehensively characterize the chemical environment of groundwater, the field conductivity (EC) of water samples was measured simultaneously in this study. The EC value varies greatly (30.1–509 μS/cm), with an average of 212 μS/cm, indicating that the groundwater salinity in the study area is low and belongs to the freshwater environment. From the spatial distribution map in Figure 2, it can be seen that the distribution area of high concentration of Fe, Mn and As is mainly to the north of South Dongting Lake, and the geological structure of Dongting Lake is a faulted basin, and related research shows that tectonic depression and uplift often play the role of separating the groundwater system, and due to the obstruction of vertical alternation of surface water and groundwater, the groundwater has less oxygen, and it is in a reducing environment, which leads to the reduction of elemental Fe. Under anoxic conditions, the iron and manganese oxides in the natural soil/sediment of metal-rich strata (such as the Proterozoic Lengjiaxi Group and Banxi Group) will be reduced and dissolved, thereby releasing the adsorbed heavy metals such as arsenic into groundwater, which is an important natural source process. As

is mainly distributed in the north and southeast of South Dongting Lake; the maximum concentration of As is 0.014 mg/L, which exceeds the risk threshold and causes certain health risks. Cu and Pb are mainly distributed in the more densely populated areas, and the main sources of Cu and Pb pollution are electronics, industrial wastewater, and agricultural runoff, which are the main sources of the pollution of the groundwater. The main source of Pb pollution is industrial wastewater from electronics, electroplating, and battery manufacturing [34]. In heavily trafficked areas, vehicle emissions and pollutants from tire wear, which enter the groundwater system indirectly, may also lead to elevated concentrations of the elements Pb and Zn [35]. The spatial distribution of Pb and Cr is relatively similar. In the study area, especially in hilly areas and densely populated areas, mining is more likely to be the main source of Cu pollution. For the increase in Fe, Mn and As concentrations in the northern region, the specific tectonic geological background provides the basis for the formation of the groundwater reduction environment, which promotes the release of Fe, Mn and As in the primary strata; combined with the additional pollutants emitted by industrial wastewater, the two processes are superimposed on each other, resulting in a significant increase in the concentration of heavy metals in the northern groundwater. This model needs to be verified in the subsequent fine research on this hot spot area.

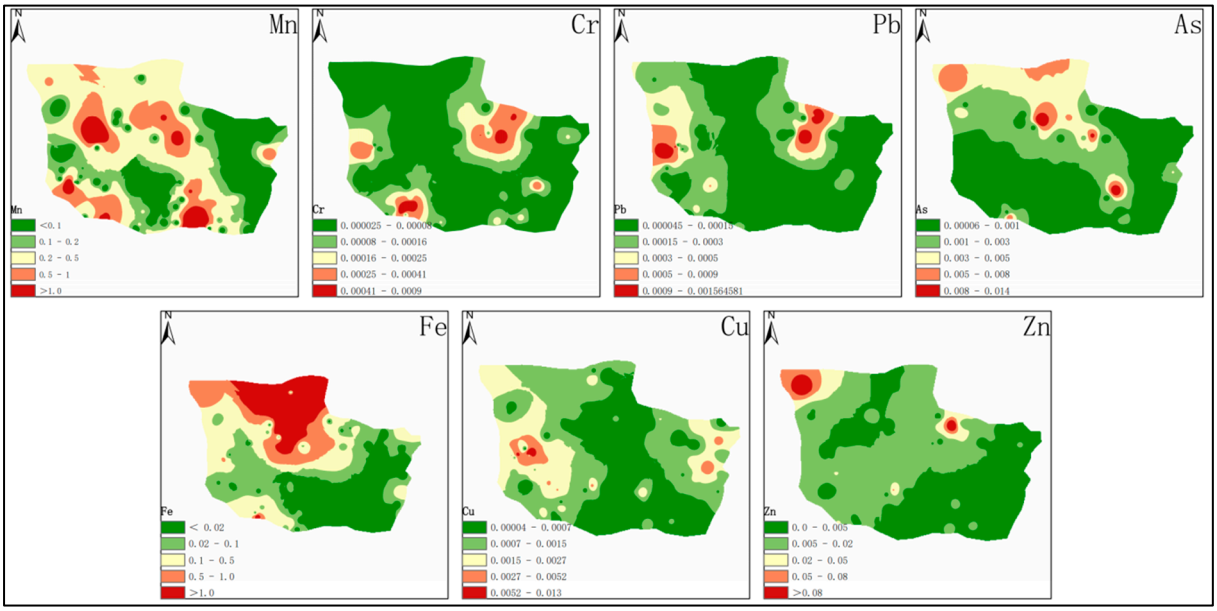


Figure 2. Spatial distribution of pollutants in the study area.

4.2. HPI and HEI Groundwater Contamination Assessment

In this study, the contamination of Fe, Mn, Cu, Zn, As, Cr, and Pb in groundwater of South Dongting Lake was comprehensively assessed based on HPI and HEI indices using USEPA (2009) drinking water guidelines as the standard [36]. The horizontal line in Figure 3 represents the pollution level. The horizontal axis in the figure represents different sampling points or sampling locations of groundwater samples. Each sampling point corresponds to a specific HPI (health pollution index) and HEI (heavy metal element index) value. The results showed that the HPI showed that 72.73% of the points (n = 64) were in a non-polluted state (HPI $\leq$ 25), and 13.64% of the points (12) reached heavy pollution (HPI > 100), with extreme values such as point 23 (HPI = 977.48) indicating the presence of high-intensity sources of contamination in localized areas (e.g., industrial discharges or mining activities). The mean value of the HEI was 7.293 (range 0.039–166.34), 81.82% of the points were low polluted (HEI < 10), and the HEI values of point 23 (HEI = 166.34), point

62 (HEI = 91.63), and point 86 (HEI = 66.44) exceeded the threshold (20) by a factor of 6–8, which is highly overlapping with the HPI-recognized highly overlapping with the heavily polluted areas identified by HPI.

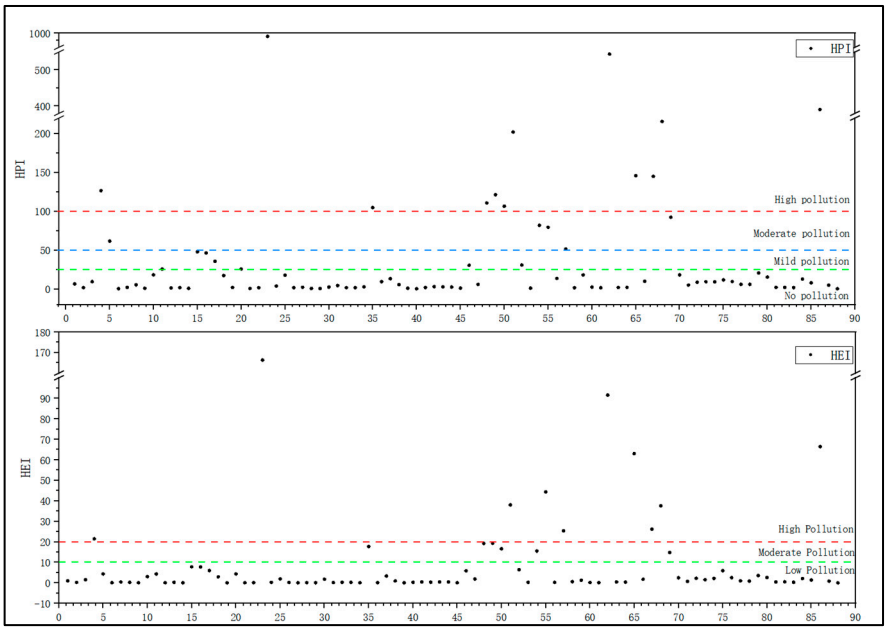


Figure 3. HPI and HEI values in groundwater samples.

The two indices, HPI and HEI, show that although most of the groundwater bodies are of good quality, about 12–14% of the points have serious heavy metal enrichment, with As, Fe, and Mn as the main exceeding elements (As concentration at point 23 exceeds the standard by 47 times). Priority treatment measures are recommended for the eight overlapping points with HEI > 20 and HPI > 100 (e.g., points 23, 62, 86), and monitoring of the moderately polluted area should be strengthened. This study provides a scientific basis for double index validation for groundwater safety control in the South Dongting Lake Basin.

4.3. Water Quality Index (WQI)

The study used WQI to assess the water quality condition of the study area of South Dongting Lake as a whole, and the average value of WQI in the groundwater samples of the study area was 81.0, and the results of WQI were divided into five categories in this paper, and the results in Table 3 showed that 75% of the groundwater samples were of high quality, and the spatial distribution of the WQI values showed that the water quality in the southern and eastern parts of the South Dongting Lake was better, and the area of poorer quality was located in the southern part and the northern part of the South Dongting Lake. The main reason for this is the high concentration of Fe, Mn, and As elements, as can be seen in Figure 2.

Table 3. WQI classification.

WQI Range	Classification	Number of Points	Sample
<50	Good quality water	66	75%
50.1–100	Fair	6	6.8%
100.1–200	Poor quality water	7	7.9%
200.1–300	Very poor water	4	4.5%
>300	Unsuitable for drinking	5	5.6%

The analysis of the spatial distribution of WQI values provides a clear picture of the overall status of water quality in the study area of South Dongting Lake and the differences in water quality in specific areas. The high concentration of iron, manganese, and arsenic is the main reason for the poor water quality in the northern region. Based on the results of these analyses, corresponding pollution source control and water quality management measures can be taken to improve regional water quality and ensure the sustainable use of groundwater and the safety of drinking water for residents.

4.4. Health Risks Due to Heavy Metals in Groundwater

This paper evaluated the health risks of heavy metals in groundwater in the South Dongting Lake Basin based on the models recommended by the USEPA [36]. The results are summarized in Table 4, which assessed the health risk of carcinogenic and non-carcinogenic risks caused by oral ingestion for both adults and children, and for both adults and children the non-carcinogenic risk value (HQ < 1) was acceptable, and the carcinogenic risk value (CR) between 1×10^{-6} to 1×10^{-4} is acceptable [19]. The health risk assessment conducted in this study is based on the theoretical calculation values of the USEPA standard model, aiming to quantify the potential population burden of heavy metal pollution in groundwater and identify priority pollutants and areas for control.

Table 4. Health risk values for pollutants.

Item	Elemental	Drinking Water Pathways	
		Adults	Children
CR	Cd	2.54×10^{-5}	4.62×10^{-5}
	As	7.46×10^{-5}	1.36×10^{-4}
TCR		1.00×10^{-4}	1.82×10^{-4}
HQ	Mn	1.84×10^{0}	3.35×10^{0}
	Zn	6.01×10^{-3}	1.10×10^{-2}
	Fe	2.47×10^{-1}	4.51×10^{-1}
	Cu	6.28×10^{-3}	1.15×10^{-2}
	Pb	3.10×10^{-2}	5.65×10^{-2}
THI		2.13×10^{0}	3.88×10^{0}

As shown in Table 4, carcinogenic risk: according to the results of the health risk evaluation of groundwater in South Dongting Lake, the total carcinogenic risk (CR) for adults is 1.00×10^{-4} (close to the upper limit of the USEPA threshold value of 1×10^{-4}), and the total CR for children reaches 1.82×10^{-4} (exceeding the threshold value by 82%), which indicates that the children's group needs to be focused on, and the main carcinogenic pollutants, the arsenic (As) has the highest contribution rate, and the exceedance of its concentration mainly originated from primary release from arsenic-rich strata and industrial wastewater input (e.g., electronics manufacturing, mining wastewater). The CR for Cd is low and does not pose a health risk to humans.

Non-carcinogenic risk: According to the results of risk evaluation, the total hazard index (HI) of non-carcinogenic risk significantly exceeded the standard, with the total HI of adults and children amounting to 3.59 and 6.54, respectively (far exceeding the acceptable threshold value of HI $\leq$ 1), of which manganese (Mn) was the main risk factor, and the manganese contamination was concentrated in the northern part of the South Dongting Lake, with the hazard quotient (HQ) of adults and children amounting to 1.84 and 3.35, respectively; the concentration of Fe in the northern part was abnormal (8984 μg/L exceeding 29.9 times). The concentration of iron (Fe) in the northern part of the lake was abnormal (8984 μg/L, exceeding the standard by 29.9 times), and although the overall HQ was <1, long-term exposure may trigger the risk of localized liver damage, which needs

attention. The non-carcinogenic risk in children was generally 1.8 times higher than that in adults due to differences in metabolic rate and exposure behavior.

In Figure 4, higher non-carcinogenic risk values (HI) were observed in the northwestern part of the study area, which was mainly attributed to higher non-carcinogenic risk values (HQ) for Fe, Mn. Figure 5 shows the spatial distribution of health risk values (CR/HI) in the study area. In the southeast and west of the study area, the cancer risk CR values are higher, mainly because the cancer risk (CR) values of As are higher in children, which is more than the acceptable level of 1.00×10^{-4}, and As is a special hazard for children, which may cause fetal development during pregnancy and affect the neurological development of children. Development, and therefore requires attention [37].

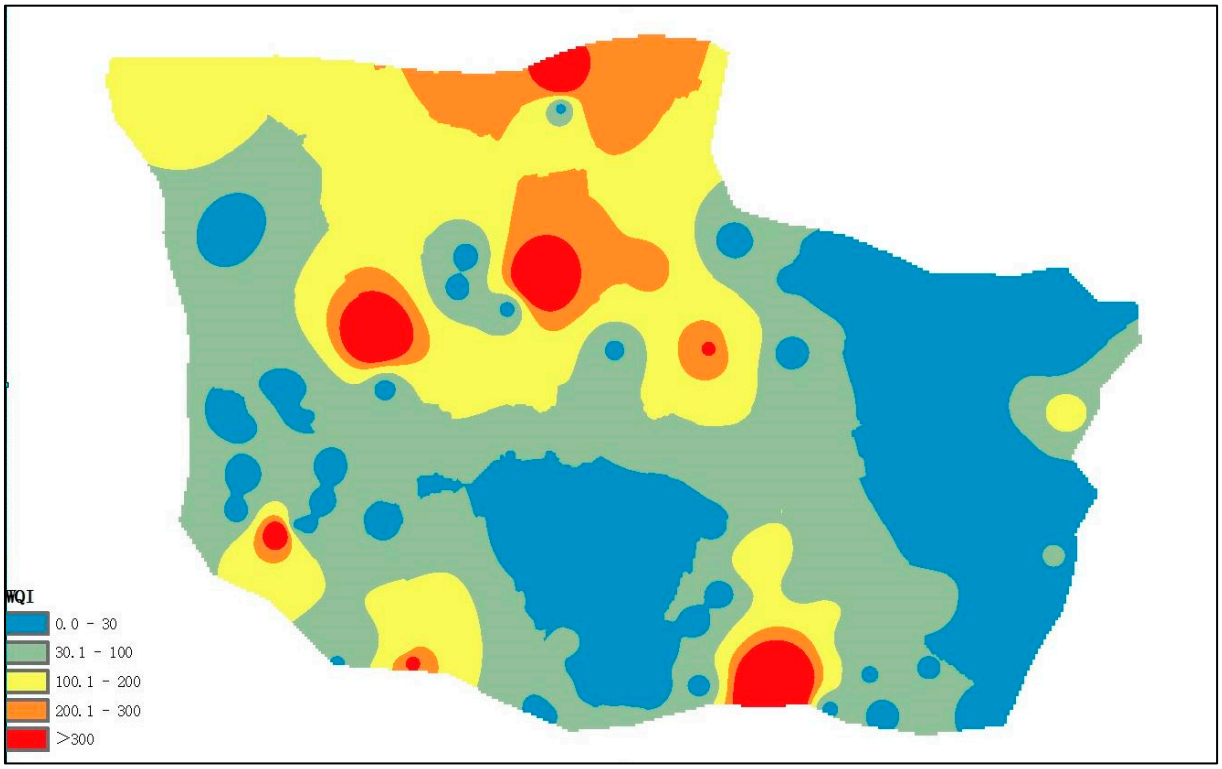


Figure 4. WQI distribution of South Dongting Lake.

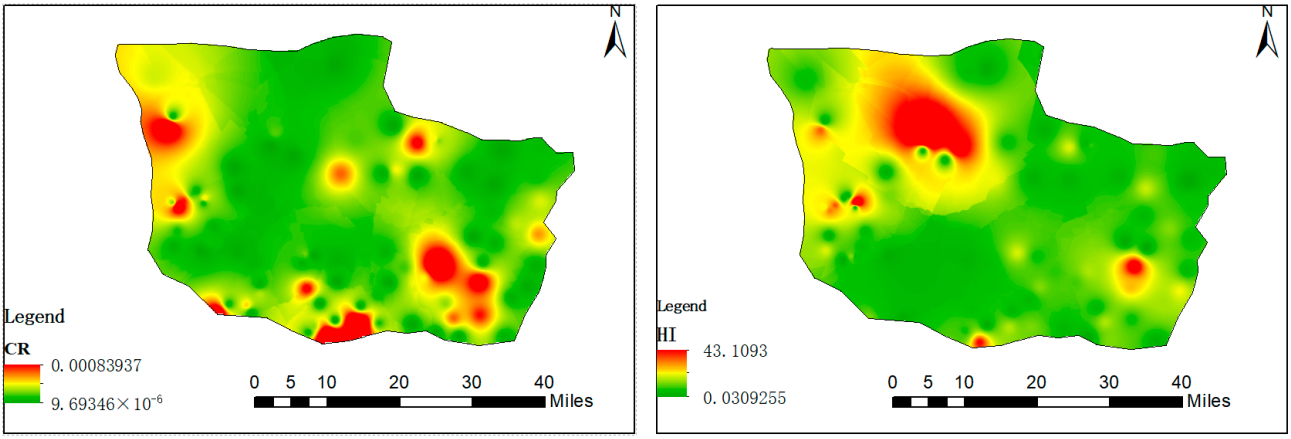


Figure 5. Spatial distribution of CR and HQ in the study area.

4.5. Health Risk Assessment Based on Monte Carlo Simulation

Monte Carlo simulation is a probabilistic analysis method for quantifying uncertainty in risk assessment [38]. In this study, the probability distribution of the health risk of groundwater contaminants was based on Monte Carlo simulations, and the data were processed using Oracle Crystal Ball software, with the number of iterations set to 10,000 for each run. The simulated values for the health risk assessment were at the 95th percentile, which is the most severe or worst possible outcome [39]. The probability distribution of the input parameters is shown in Table 5.

Table 5. Parameter probability distribution function of the health risk assessment model.

Parameter	Unit	Probability Distribution	Adult	Children	References
Daily ingestion rate (IR)	L/d	Triangular distribution	TR (0.43, 2.3, 3.6)	TR (0.33, 1.14, 1.62)	[40]
Exposure frequency (EF)	d/a	Triangular distribution	TR (180, 345, 365)		[40]
Means the body weight (BW)	kg	Lognormal distribution	LN (60, 1.18)	LN (19.6, 1.96)	[40]
Duration of carcinogenic exposure (ED)	a	Uniform distribution	UN (0, 70)		[41]
Non-carcinogenic exposure duration (ED)	a	Uniform distribution	UN (0, 35)		[41]
Average carcinogenic exposure time (AT)	d	Single point distribution	25550		[42]
Average non-carcinogenic exposure time (AT)	d	Single point distribution	2190		[43]

Figure 6 shows the probability distribution of non-carcinogenic risks simulated by Monte Carlo, and the results show that among the non-carcinogenic pollutants, the order of non-carcinogenic risks is: Mn > Fe > Zn > Cu > Pb, and the mean value of HI of Mn to children is greater than 1, and the mean value of HI of the remaining non-carcinogenic pollutants is less than 1. The predicted value of Mn falls in the unacceptable risk interval of carcinogenicity, and the HI value is 397, so the health risk caused by Mn needs to be taken into account. The HI value of Mn was 3.97, so the health risk caused by Mn should be emphasized. 95% quantile values of Fe, Cu, Pb, and Zn fell in the acceptable cancer risk interval, and the health risk caused by these pollutants was small. The THI values for adults and children were 0.796 and 1.2, respectively, and the THI for children was greater than 1, and the 95% quantile values for both adults and children exceeded the risk value of 1, which indicated that the health risks caused by non-carcinogenic heavy metals to human beings should not be neglected, especially the health risks caused by Mn to children.

The probability distribution of non-carcinogenic risk was simulated by Monte Carlo. The mean values of carcinogenic risk of As for adults and children were 2.67×10^{-5} and 4.02×10^{-5}, respectively, and the 95% values for children fell in the unacceptable carcinogenic risk interval, with a certain carcinogenic risk, and the risk of children's exposure was significantly higher than that of adults. The mean values of carcinogenic risk of Cd for adults and children were less than the maximum acceptable level (1.0×10^{-4}), the 95% values of Cd for both adults and children fall in the acceptable carcinogenic risk interval, and the health effects caused by Cd are negligible. From Figure 7c, the 95% TCR values for children exceeded the risk threshold, indicating that the carcinogenic risk to children in groundwater in the study area needs to be emphasized, especially for As contamination.

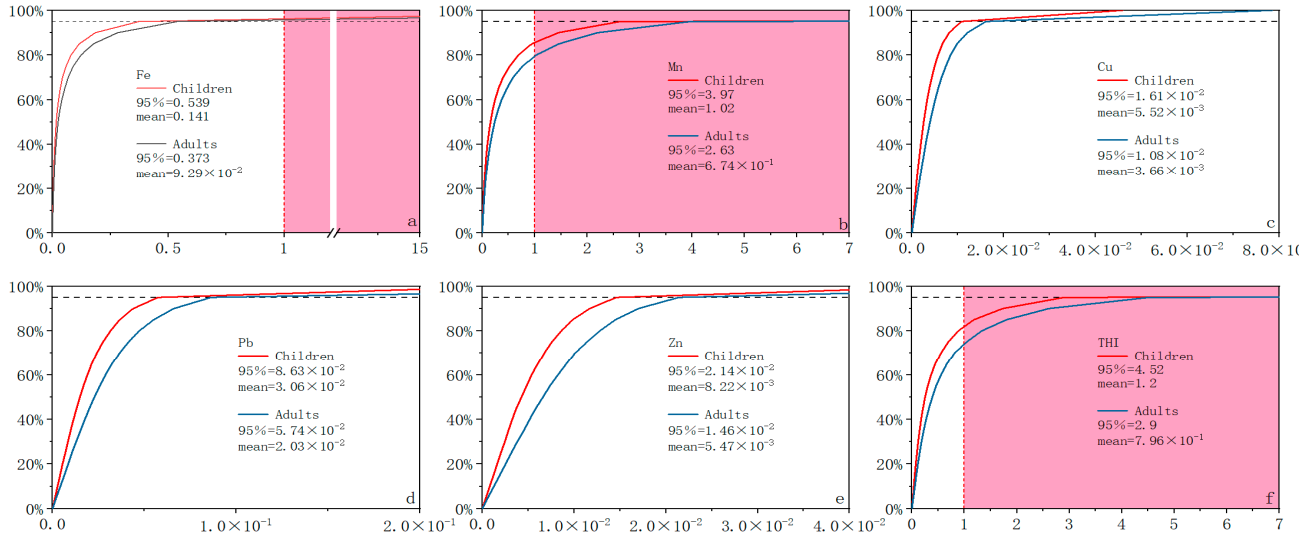


Figure 6. Cumulative probability of predicted non-carcinogenic risk (**a**) Fe; (**b**) Mn; (**c**) Cu; (**d**) Pb; (**e**) Zn; (**f**) THI.

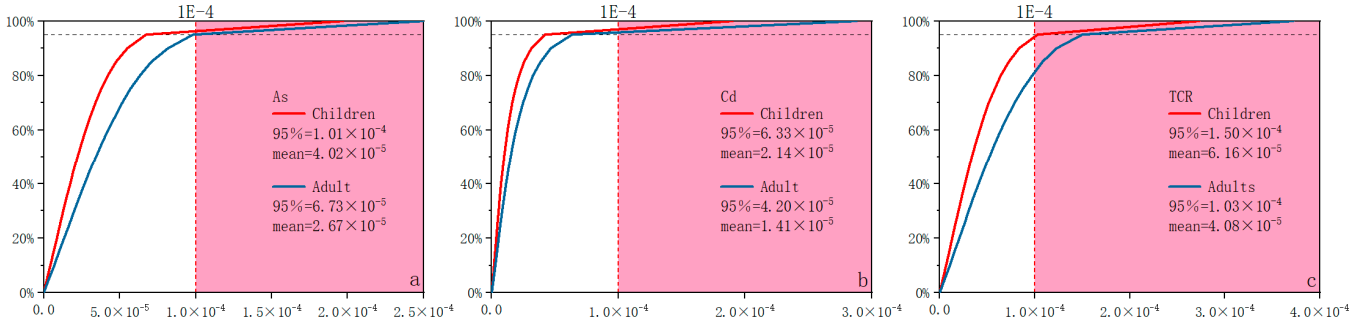


Figure 7. Cumulative probability of predicted cancer risk (**a**) As; (**b**) Cd; (**c**) TCR.

4.6. Sensitivity Analysis

Sensitivity analysis is a method used in risk assessment to determine the magnitude of the effect of different parameters on the outcome of a carcinogenic or non-carcinogenic risk assessment. The analysis shows that children are slightly more sensitive than adults overall, and that this difference is related to differences in body weight and metabolic rate. As analyzed in Figure 8, the highest sensitivities were found for pollutant concentration (Mn) and exposure duration (ED) for non-carcinogenic risk in both adults and children. Among carcinogenic risks in adults and children, exposure time (ED) had the highest sensitivity, followed by drinking water intake (IR) and exposure frequency (EF). In summary, heavy metal concentrations as well as exposure time (ED) were the most sensitive factors, and long-term exposure can have a cumulative effect on the human body, especially in areas with highly polluted water sources. Therefore, lowering pollutant concentrations and reducing exposure time can reduce carcinogenic and non-carcinogenic risks in the population.

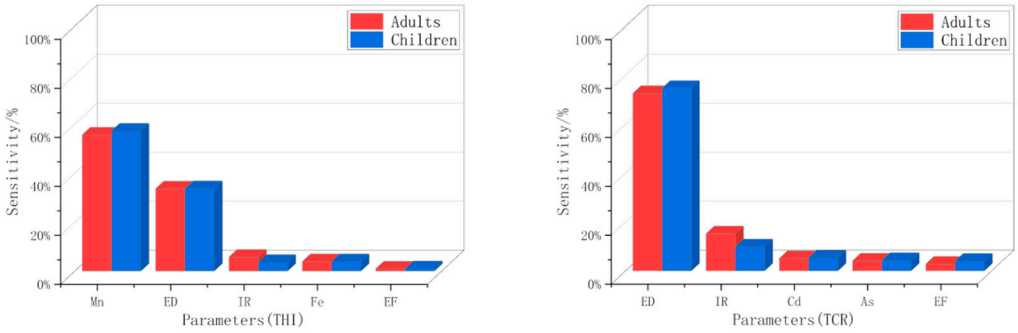


Figure 8. Sensitivity analysis of contaminants under the drinking water pathway.

5. Conclusions

1. Groundwater in the South Dongting Lake Basin is mainly contaminated with Mn and Fe, with the maximum concentration of Mn exceeding the standard for Type III water by 83.1 times (8312.28 μg/L) and Fe by 29.9 times (8984 μg/L). As exceeded the standard locally (maximum concentration of 13.91 μg/L, exceeding the standard by 1.39 times), Cr, Pb, Cu, and Zn as a whole did not exceed the standard.

2. Uneven spatial distribution, Mn, Fe, and As pollution are mainly concentrated in the north, related to geological structure, groundwater redox environment, and industrial activities. Pb, Cu, and Zn are mainly distributed in densely populated industrial areas and transportation hubs.

3. HPI and HEI double validation: 72% of the points are not polluted, but 12–14% of the points reach heavy pollution. As, Fe, and Mn are the main exceeding elements. WQI shows that the water quality in the north is the worst (75% of the points are of good quality, 5.6% of the points are not suitable for drinking), which coincides with the high concentration area of heavy metals.

4. According to the health risk assessment, the total carcinogenic risk (CR = 1.82×10^{-4}) for children exceeded the threshold value, and As contributed the most to the carcinogenic risk for children. The total non-carcinogenic index (THI) for adults and children amounted to 2.13 and 3.88, respectively (well above the threshold HI = 1), with Mn as the core risk source (HQ = 3.35 for children), followed by iron (HQ = 0.45 for children). The child population was generally 1.8 times more at risk than adults due to metabolic differences.

5. Monte Carlo simulations and sensitivity analyses showed that pollutant concentration (Mn) and exposure duration (ED) were the most sensitive variables to health risks, and that lowering the concentration of Mn and As and reducing the duration of exposure (especially in the children's group) were the priority directions for risk control.

This study combined Monte Carlo simulation with traditional assessment models to quantify uncertainty and identified pollutant concentration and exposure time as the most sensitive risk drivers. Although this study preliminarily explored the sources, future work can conduct in-depth and accurate source analysis to distinguish the contribution of natural background and human activities, so as to provide a more reliable basis for the precise management and risk control of heavy metal pollution in groundwater in the South Dongting Lake Basin.

Author Contributions: S.Z.: Methodology, investigation, software, formal analysis, writing—original draft. B.R.: Conceptualization, supervision, writing—review and editing, validation. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Natural Science Foundation of China (Grant No. 41973078), the Key Research and Development Program of Hunan Province (Grant

No. 2022SK2073), and the Postgraduate Research and Innovation Project of Hunan Province (Grant No. CX20231049).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We sincerely thank the reviewers and editor for their constructive comments.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Fernandez, F.; Lopez-Valdez, F.; Gamero-Melo, P.; Luna-Suarez, S.; Aguilera-Gonzalez, E.N.; Martínez, A.I.; García-Guillermo, M.; Hernandez-Martinez, G.; Herrera-Mendoza, R.; Álvarez-Garza, M.A. Heavy metal pollution in drinking water-a global risk for human health: A review. *Afr. J. Environ. Sci. Technol.* **2013**, *7*, 567–584.
2. Vetrimurugan, E.; Brindha, K.; Elango, L.; Ndwandwe, O.M. Human exposure risk to heavy metals through groundwater used for drinking in an intensively irrigated river delta. *Appl. Water Sci.* **2017**, *7*, 3267–3280. [CrossRef]
3. Balali-Mood, M.; Naseri, K.; Tahergorabi, Z.; Khazdair, M.R.; Sadeghi, M. Toxic mechanisms of five heavy metals: Mercury, lead, chromium, cadmium, and arsenic. *Front. Pharmacol.* **2021**, *12*, 643972. [CrossRef]
4. Rushdi, M.I.; Basak, R.; Das, P.; Ahamed, T.; Bhattacharjee, S. Assessing the health risks associated with elevated manganese and iron in groundwater in Sreemangal and Moulvibazar Sadar, Bangladesh. *J. Hazard. Mater. Adv.* **2023**, *10*, 100287. [CrossRef]
5. Wei, R.; Tang, S.; Ouyang, Q.; Lu, T.; Hu, B.X. Study on the groundwater system of the Dongting Lake Plain, central-south China: A tectonic perspective. *Hydrogeol. J.* **2022**, *30*, 707–721. [CrossRef]
6. Tasnim, F.; Hasan, M.; Sakib, N.; Zahid, A.; Rahman, M.; Islam, S.; Muktadir, G. An assessment of the spatial and temporal distribution of nitrate and trace element concentrations in groundwater in coastal districts of Bangladesh. *Sci. Total Environ.* **2025**, *970*, 178988. [CrossRef]
7. Li, J.; Wang, Y.; Zhu, C.; Xue, X.; Qian, K.; Xie, X.; Wang, Y. Hydrogeochemical processes controlling the mobilization and enrichment of fluoride in groundwater of the North China Plain. *Sci. Total Environ.* **2020**, *730*, 138877. [CrossRef] [PubMed]
8. Wu, C.; Wu, X.; Qian, C.; Zhu, G. Hydrogeochemistry and groundwater quality assessment of high fluoride levels in the Yanchi endorheic region, northwest China. *Appl. Geochem.* **2018**, *98*, 404–417. [CrossRef]
9. Zhang, L.; Zhao, L.; Zeng, Q.; Fu, G.; Feng, B.; Lin, X.; Liu, Z.; Wang, Y.; Hou, C. Spatial distribution of fluoride in drinking water and health risk assessment of children in typical fluorosis areas in north China. *Chemosphere* **2020**, *239*, 124811. [CrossRef]
10. Deng, X.; Zou, H.; Ren, B.; Wang, J.; Chen, L. Study on Pollution Characteristics, Sources, and Health Risks of Potentially Toxic Elements in Groundwater of Dongting Lake Basin, China. *Sustainability* **2025**, *17*, 3554. [CrossRef]
11. Chen, L.; Ren, B.; Deng, X.; Yin, W.; Xie, Q.; Cai, Z.; Zou, H. Potential toxic elements (PTEs) in rhizosphere soils and crops under a black shale high geological background: Pollution characteristics, distribution and risk assessment. *Ecol. Indic.* **2024**, *165*, 112236. [CrossRef]
12. Mobarok, H.; Pulak Kumar, P. Contamination zoning and health risk assessment of trace elements in groundwater through geostatistical modelling. *Ecotoxicol. Environ. Saf.* **2020**, *189*, 110038. [CrossRef]
13. Yadav, S.K.; Attry, B.; Shukla, S.; Dutta, S.; Sharma, K.; Rajak, R.; Gupta, A.; Baruah, B.; Ranjan, R.K. Distribution, toxicity load and risk assessment of heavy metals in the groundwater of Dhemaji, Assam, India. *Chemosphere* **2024**, *358*, 141979. [CrossRef]
14. Zhou, Y.; Wei, A.; Li, J.; Yan, L.; Li, J. Groundwater quality evaluation and health risk assessment in the Yinchuan Region, Northwest China. *Expo. Health* **2016**, *8*, 443–456. [CrossRef]
15. Gao, S.; Li, C.; Jia, C.; Zhang, H.; Guan, Q.; Wu, X.; Wang, J.; Lv, M. Health risk assessment of groundwater nitrate contamination: A case study of a typical karst hydrogeological unit in East China. *Environ. Sci. Pollut. Res.* **2020**, *27*, 9274–9287. [CrossRef] [PubMed]
16. Li, J.; Zou, S.-Z.; Liang, Y.-P.; Lin, Y.-S.; Zhou, C.-S.; Zhao, Y. Metal distributions and human health risk assessments on waters in the Huixian Karst Wetland, China. *Huan Jing Ke Xue = Huanjing Kexue* **2020**, *41*, 4948–4957.
17. Ravindra, K.; Thind, P.S.; Mor, S.; Singh, T.; Mor, S. Evaluation of groundwater contamination in Chandigarh: Source identification and health risk assessment. *Environ. Pollut.* **2019**, *255*, 113062. [CrossRef]
18. Luo, X.; Ren, B.; Hursthouse, A.S.; Jiang, F.; Deng, R.-j.; Wang, Z. Source identification and risk analysis of potentially toxic elements (PTEs) in rainwater runoff from a manganese mine (south central Hunan, China). *Water Supply* **2021**, *21*, 824–835. [CrossRef]
19. Cai, Z.; Ren, B.; Xie, Q.; Deng, X.; Yin, W.; Chen, L. Potential toxic heavy metals in village topsoil of antimony mining area: Pollution and distribution, environmental safety—A case study of Qilijiang village in xikuangshan mining area, central Hunan Province, China. *Ecol. Indic.* **2023**, *155*, 111033. [CrossRef]

20. Giri, S.; Singh, A.K.; Mahato, M.K. Monte Carlo simulation-based probabilistic health risk assessment of metals in groundwater via ingestion pathway in the mining areas of Singhbhum copper belt, India. *Int. J. Environ. Health Res.* **2020**, *30*, 447–460. [CrossRef] [PubMed]
21. Jiang, C.; Zhao, Q.; Zheng, L.; Chen, X.; Li, C.; Ren, M. Distribution, source and health risk assessment based on the Monte Carlo method of heavy metals in shallow groundwater in an area affected by mining activities, China. *Ecotoxicol. Environ. Saf.* **2021**, *224* (Suppl. C), 112679. [CrossRef]
22. Mallongi, A.; Rauf, A.U.; Daud, A.; Hatta, M.; Al-Madhoun, W.; Amiruddin, R.; Stang, S.; Wahyu, A.; Astuti, R.D.P. Health risk assessment of potentially toxic elements in Maros karst groundwater: A Monte Carlo simulation approach. *Geomat. Nat. Hazards Risk* **2022**, *13*, 338–363. [CrossRef]
23. Hasan, A.B.; Reza, A.H.M.S.; Siddique, M.A.B.; Akbor, M.A.; Nahar, A.; Hasan, M.; Zaman, M.N.; Hasan, M.I.; Moniruzzaman, M. Spatial distribution, water quality, human health risk assessment, and origin of heavy metals in groundwater and seawater around the ship-breaking area of Bangladesh. *Environ. Sci. Pollut. Res.* **2023**, *30*, 16210–16235. [CrossRef]
24. Sheng, D.; Meng, X.; Wen, X.; Wu, J.; Yu, H.; Wu, M. Contamination characteristics, source identification, and source-specific health risks of heavy metal(loid)s in groundwater of an arid oasis region in Northwest China. *Sci. Total Environ.* **2022**, *841*, 156733. [CrossRef]
25. Edet, A.; Offiong, O. Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria). *GeoJournal* **2002**, *57*, 295–304. [CrossRef]
26. Verma, C.; Hussain, A.; Madan, S.; Kumar, V. Assessment of heavy metal pollution in groundwater with respect to distance from ash pond by using heavy metal evaluation index. *Appl. Water Sci.* **2021**, *11*, 58. [CrossRef]
27. Piyathilake, I.D.U.H.; Ranaweera, L.V.; Udayakumara, E.P.N.; Gunatilake, S.K.; Dissanayake, C.B. Assessing groundwater quality using the Water Quality Index (WQI) and GIS in the Uva Province, Sri Lanka. *Appl. Water Sci.* **2022**, *12*, 72. [CrossRef]
28. Sadat-Noori, S.; Ebrahimi, K.; Liaghat, A. Groundwater quality assessment using the Water Quality Index and GIS in Saveh-Nobaran aquifer, Iran. *Environ. Earth Sci.* **2014**, *71*, 3827–3843. [CrossRef]
29. Adimalla, N.; Li, P.; Venkatayogi, S. Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies. *Environ. Process.* **2018**, *5*, 363–383. [CrossRef]
30. Udeshani, W.; Dissanayake, H.; Gunatilake, S.; Chandrajith, R. Assessment of groundwater quality using water quality index (WQI): A case study of a hard rock terrain in Sri Lanka. *Groundw. Sustain. Dev.* **2020**, *11*, 100421. [CrossRef]
31. Mukherjee, A.; Verma, S.; Gupta, S.; Henke, K.R.; Bhattacharya, P. Influence of tectonics, sedimentation and aqueous flow cycles on the origin of global groundwater arsenic: Paradigms from three continents. *J. Hydrol.* **2014**, *518*, 284–299. [CrossRef]
32. Abbaspour, N.; Hurrell, R.; Kelishadi, R. Review on iron and its importance for human health. *J. Res. Med. Sci. Off. J. Isfahan Univ. Med. Sci.* **2014**, *19*, 164.
33. Bjørklund, G.; Chartrand, M.S.; Aaseth, J. Manganese exposure and neurotoxic effects in children. *Environ. Res.* **2017**, *155*, 380–384. [CrossRef]
34. Feng, S.; Yu, H. Source apportionment and health risk assessment of heavy metals in groundwater of rural area: A case study in Huaibei plain, China. *Hum. Ecol. Risk Assess. Int. J.* **2024**, *30*, 220–236. [CrossRef]
35. Adamiec, E.; Jarosz-Krzemińska, E.; Wieszała, R. Heavy metals from non-exhaust vehicle emissions in urban and motorway road dusts. *Environ. Monit. Assess.* **2016**, *188*, 369. [CrossRef]
36. Xie, Q.; Ren, B.; Deng, X.; Yin, W.; Lu, Y. Quantitative source identification, risk assessment and pollution of heavy metals in soils around a typical Sb smelter in central and southern China. *Stoch. Environ. Res. Risk Assess.* **2023**, *37*, 2495–2511. [CrossRef]
37. Singh, S.K.; Ghosh, A.K. Health risk assessment due to groundwater arsenic contamination: Children are at high risk. *Hum. Ecol. Risk Assess. Int. J.* **2012**, *18*, 751–766. [CrossRef]
38. Zhu, T.; Wu, Q.; Gao, S.; Zeng, J.; Linghu, K.; Zhang, X. Comparative assessment of health risks and water quality of groundwater in urban and rural Guiyang, Southwest China: Insights from PMF and Monte Carlo Simulation. *Ecotoxicol. Environ. Saf.* **2025**, *299*, 118359. [CrossRef]
39. Ma, Z.; Li, J.; Zhang, M.; You, D.; Zhou, Y.; Gong, Z. Groundwater health risk assessment based on Monte Carlo model Sensitivity analysis of Cr and as—A case study of Yinchuan city. *Water* **2022**, *14*, 2419. [CrossRef]
40. Duan, X. *Highlights of the Chinese Exposure Factors Handbook*; Academic Press: Cambridge, MA, USA, 2015.
41. Lei, M.; Li, K.; Guo, G.; Ju, T. Source-specific health risks apportionment of soil potential toxicity elements combining multiple receptor models with Monte Carlo simulation. *Sci. Total. Environ.* **2022**, *817*, 152899. [CrossRef]

42. Chen, H.; Teng, Y.; Lu, S.; Wang, Y.; Wu, J.; Wang, J. Source apportionment and health risk assessment of trace metals in surface soils of Beijing metropolitan, China. *Chemosphere* **2016**, *144*, 1002–1011. [CrossRef] [PubMed]
43. Neshat, A.; Pradhan, B.; Javadi, S. Risk assessment of groundwater pollution using Monte Carlo approach in an agricultural region: An example from Kerman Plain, Iran. *Comput. Environ. Urban Syst.* **2015**, *50*, 66–73. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.