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Zhi Li
East China University of Technology
Xun Li
xli@ecut.edu.cn

East China University of Technology
zhongkui Zhou
Jiangxi University of Water Resources and Electric Power
xiaodong Chu
Geological Environmental Monitoring Institute of Jiangxi geological survey and Exploration Institute
yang Yang
Geological Environmental Monitoring Institute of Jiangxi geological survey and Exploration Institute
yi Zhao
Geological Environmental Monitoring Institute of Jiangxi geological survey and Exploration Institute
Jiye Zhang
East China University of Technology
Huanyin Pei
East China University of Technology

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Pollution Characteristics and Health Risks of Heavy Metals in Groundwater of a Chemical Industrial Park

Zhi Li · Xun Li · Zhongkui Zhou · Xiaodong Chu · Yang Yang · Yi Zhao · Jiye Zhang · Huanyin Pei

Z. Li
School of Water Resources and Environmental Engineering, East China University of Technology, Nanchang 330013, China

X. Li(✉)
School of Water Resources and Environmental Engineering, East China University of Technology, Nanchang 330013, China.Jiangxi Provincial Key Laboratory of Genesis and Remediation of Groundwater Pollution, Nanchang 330013, China
e-mail:xli@ecut.edu.cn

Z. Zhou
Jiangxi University of Water Resources and Electric Power, Nanchang 330099, China.Jiangxi Provincial Key Laboratory of Genesis and Remediation of Groundwater Pollution, Nanchang 330013, China

X. Chu, Y. Yang, Y. Zhao
Geological Environmental Monitoring Institute of Jiangxi geological survey and Exploration Institute, Nanchang 330006, China

J. Zhang, H. Pei
School of Water Resources and Environmental Engineering, East China University of Technology, Nanchang 330013, China

Abstract： This study investigated the heavy-metal pollution characteristics of a chemical industrial park in southern China and conducted a health risk assessment on the groundwater. A total of 127 groundwater samples were collected at the site, and the concentrations of 11 heavy metals were systematically determined. The single-factor pollution index, the Nemero comprehensive pollution index and Pearson correlation analysis were used to explore the pollution characteristics, spatial distribution and source relationships of the heavy metals, and the health risk assessment was conducted by coupling the United States Environmental Protection Agency model with the Monte Carlo simulation method to account for uncertainty. Amongst the heavy metals, Fe had the highest mean concentration followed by Mn, Al, Zn, Co, Ni, Pb, Cu, Cd, As and Tl.All heavy metals exceeded the

Class III values specified in the GB/T 14848-2024 standard for drinking water (i.e. suitable with minimal treatment) except for Cu. According to Nemero comprehensive pollution indices, the Fe, Al, Tl, Pb and Ni concentrations corresponded to severe pollution while the Cd and Co concentrations corresponded to slight pollution. Industrial activities were found to have a notable impact on the concentrations of all heavy metals. In terms of spatial distribution, Al, Mn, Fe and Tl were found throughout the study area while Cd, Co, Ni and Pb had hotspots in the north-central part and lower concentrations in the southern and eastern parts. Pearson correlation analysis identified strongly positive correlations amongst Zn, Al, Cd, Ni and Co. Mn had a significant correlation with most elements while Pb was relatively independent. The health risk assessment indicated that the mean non-carcinogenic hazard index exceeded the safety threshold for both adults and minors. Mn and Co were the core driving factors, and adults faced a higher risk. The mean total carcinogenic risk values for adults and minors were 0.501 and 0.210, respectively, falling within the 'attention-required' range. Depending on the exposure level, the risk to adults exceeded the safety threshold, and Al was the core driving factor. This study provides a scientific basis for targeted prevention, management, and remediation of regional groundwater pollution by heavy metals.

Keywords: Groundwater; Heavy metal pollution; Correlation analysis; Health risk assessment

1. Introduction

Heavy metals used in the production and storage processes of chemical industrial parks can easily leak and contaminate groundwater, which threatens water resources and human health. Thus, many studies have been conducted on the pollution characteristics, source analysis and health risk of heavy metals. Multivariate statistical analyses and isotope tracing techniques are effective at identifying pollution sources. (Chen H, 2023) studied a chemical industrial cluster in Shijiazhuang on the North

China Plain and found that chemical production activities were the primary source of groundwater pollution by heavy metals in the region. (Zhang Z, 2022) investigated a composite pollution area of the Yangtze River Economic Belt and found a similar spatial distribution in the pollution characteristics. (Qian J P, 2018) reported that the leakage of chemical wastewater containing chromium and arsenic was the main cause of excess heavy metals in the area. (Bai L R, 2021) investigated the chemical industrial zone in Taiyuan and found that children have a significantly higher non-carcinogenic risk because of their physiological characteristics. In China, various evaluation methods have been adopted to study the pollution by heavy metals of groundwater or drinking water sources by chemical industrial parks such as the fuzzy comprehensive evaluation method (Mao Y Y, 2024), entropy weight method (Song Y, 2015) and factor analysis method (Liu L P, 2024). The Nemero comprehensive pollution index method considers the weights of influencing factors and the effects of extreme values, which makes its conclusions more accurate.

Health risk assessments are often conducted by using the model recommended by the United States Environmental Protection Agency (USEPA), which calculates the daily average exposure dose of pollutants through various pathways (e.g. oral intake) and assesses the potential probability of their harm to human health. However, traditional risk assessment methods do not adequately consider the combined toxic effects of heavy metals and often underestimate the actual harm (Zou C W, 2022). They mostly rely on fixed exposure parameters (e.g. mean of population parameters), which do not fully reflect the differences in actual exposure situations and thus limit the validity of their results. In addition, long-term monitoring data on the dynamic evolution of pollutants are lacking, and problems such as the strong universality of exposure parameters and poor regional adaptability have not been resolved (Qian J P, 2018). One approach to improving health risk assessments has been the

introduction of the Monte Carlo simulation method, which effectively represents uncertainty by constructing a probability distribution of exposure parameters and has been widely applied in related fields (Wang L, 2024).

This study investigated the groundwater of a chemical industrial park and systematically analysed the pollution characteristics and spatial distribution of heavy metals by using the Nemero comprehensive pollution index and Pearson correlation analysis. A health risk assessment was conducted by coupling the USEPA model with the Monte Carlo simulation method to quantify the carcinogenic and non-carcinogenic risks of heavy metals via drinking water exposure, particularly for sensitive populations such as children. The aim was to address current deficiencies in dynamic pollution monitoring and localised exposure parameter calibration and to provide theoretical support and a decision-making basis for controlling and managing the risk of heavy-metal pollution in chemical industrial parks.

2. Materials and Methods

2.1 Overview of the Study Area

The study area contained simple outcrops of the Zhoutian Formation of the Upper Cretaceous (K_2z) and Quaternary strata (Qh^{1-2}). The former comprised purple-red siltstone interbedded with sand-gravel rock, thin siltstone and mudstone. The latter comprised sub-clay, sub-sand and sand-gravel layers distributed in strips that formed terraces and floodplains along the Ban Gang River and its tributaries in the study area. The soil often had a dual-layer structure with an upper layer about 1–5 m thick of cohesive soil and a lower layer about 1–5 m thick of sand-gravel. The floodplain mostly comprised the sand-gravel soil layer. Groundwater flowed from west to east, northeast and southeast to discharge into the Ban Gang River and Xiang River. The groundwater was mainly the HCO_3–Ca type

followed by the Cl–K + Na type. The groundwater was classified into types based on the pore water of loose rocks and clastic rocks.

2.2 Sample collection

Groundwater samples were collected at 127 points within the study area, as shown in Fig.1. Samples were collected at a flow rate of less than 1 L min^{-1}. Samples were only collected when the water was clear and the sand was clean. After collection, the sample container was immediately sealed and labelled with information regarding the sampling date and time, sample number and monitoring items. Samples were stored in a 4°C refrigerated box to avoid direct sunlight and transported immediately to the laboratory for analysis.

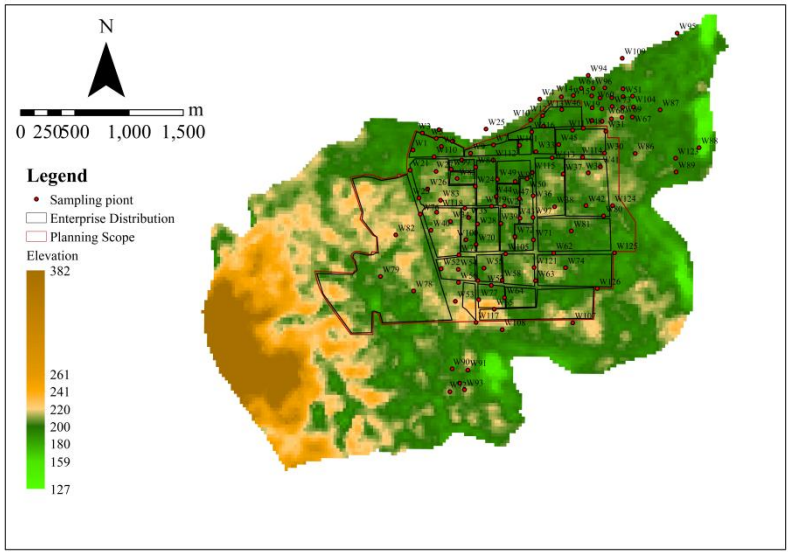


Fig.1 Location of sampling points in the study area

2.3 Evaluation criteria and methods

2.3.1 Pollution assessment

The heavy-metal pollution of the water samples was evaluated by using the single-factor pollution index and Nemero comprehensive pollution index (Chang W J, 2020). The single-factor pollution index represents the pollution degree of individual pollution factors. The Nemero comprehensive pollution index is based on the single-factor pollution index and represents the comprehensive pollution

status of heavy metals in the study area. The single-factor pollution index and Nemero comprehensive pollution index are respectively calculated as follows:

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

$$N_i=\sqrt{\frac{(P_{imax})^2+(P_{iadv})^2}{2}} \quad (2)$$

Where i is a heavy metal, p_i is the pollution index of heavy metal i, C_i is the measured concentration of heavy metal i, S_i is the maximum concentration satisfying the Class III criteria for drinking water in GB/T 14848-2024 (i.e. suitable for drinking with minimal treatment) and N_i is the Nemero comprehensive pollution index. Table 1 presents the pollution levels corresponding to the ranges of the two indices.

Table 1 Pollution indices and the corresponding pollution levels

Pollution assessment		
Single-factor pollution index	Nemero comprehensive pollution index	Pollution level
$p_i \leq 0.7$	$N_i \leq 0.7$	Safety
$0.7 < p_i \leq 1.0$	$0.7 < N_i \leq 1.0$	Cordon line
$1.0 < p_i \leq 2.0$	$1.0 < N_i \leq 2.0$	Mild pollution
$2 < p_i \leq 3.0$	$2 < N_i \leq 3.0$	Moderate pollution
$p_i > 3.0$	$N_i > 3.0$	Severe pollution

The coefficient of variation was used as a quantitative indicator of spatial heterogeneity in heavy-metal concentrations amongst sampling points. A larger coefficient of variation indicated stronger heterogeneity in the spatial or temporal distribution of a heavy metal. The inverse distance weighting interpolation method in ArcGIS 10.8 was used to analyse the spatial distributions of heavy metals in the study area (Zhu H, 2025). Pearson correlation analysis was employed to quantify the internal correlations amongst heavy metals and provide a reference for source identification

2.3.2 Health risk assessment

The health risk assessment comprised calculating the exposure dose of the various heavy metals and the associated sensitivity to evaluate the non-carcinogenic and carcinogenic risks. The three main

pathways through which heavy metals enter the human body are by ingestion, inhalation and skin contact (Huang J L, 2021). Because heavy metals in groundwater are mainly ingested through drinking water, only the health risks related to contact with drinking water were considered. According to the USEPA model, the carcinogenic and non-carcinogenic risks of heavy metals in drinking water can be calculated as follows:

$$ADD=\frac{C\times IR\times EF\times ED}{BW\times AT} \quad (3)$$

$$HI=\sum HQ=\sum\frac{ADD_i}{RfD_i} \quad (4)$$

$$TCR=\sum CR=\sum ADD_i\times SF_i \quad (5)$$

Here, ADD is the average daily intake of heavy metals from drinking water, C is the measured concentration of heavy metals in each sample (mg L^{-1}), IR is the daily intake of drinking water (L d^{-1}), EF is the frequency of exposure to heavy metals per year (d a^{-1}), ED is the exposure duration (d), BW is the bodyweight of the person being exposed and AT is the average exposure time (d). Table 2 presents the values of the parameters used to calculate ADD. HI and HQ are the cumulative and single non-carcinogenic risk indices respectively; RfD_i iis the daily reference dose for exposure via drinking water or skin contact (mg kg^{-1} d^{-1}) TCR and CR are the cumulative and single carcinogenic risk indices respectively; SF_i is the carcinogenic risk slope factor (mg kg^{-1} d^{-1}). Table 3 presents the values of SF and RfD associated with each heavy metal. According to the USEPA model, HI or $HQ > 1$ indicates a potential non-carcinogenic health risk while HI or $HQ \leqslant 1$ indicates that the non-carcinogenic health risk is within an acceptable range. Meanwhile, TCR or $CR > 1 \times 10^{-4}$ indicates a potential carcinogenic risk, TCR or $CR < 1 \times 10^{-6}$ indicates that the carcinogenic health risk can be disregarded and $1 \times 10^{-6} \leqslant TCR$ or $CR \leqslant 1 \times 10^{-4}$ indicates that the carcinogenic health risk is within an acceptable range (Chen B S, 2022). Monte Carlo simulations were conducted to

assess the non-carcinogenic and carcinogenic health risks of the groundwater for adults and minors due to exposure via oral ingestion.

Table 2 Values of parameters used to measure the average daily intake of heavy metals

Parameters	Meaning	Unit	Adults	Minors
C	Pollutant concentration	$mg \cdot L^{-1}$	C_i	C_i
IR	Water intake	$L \cdot d^{-1}$	(1.23,0.27)	(1.12,0.27)
EF	Exposure frequency	$d \cdot a^{-1}$	(180,350,365)	(180,350,365)
ED	Duration of exposure	a	(0,70)	(0,10)
BW	Weight	kg	(56.4,11.9)	(16.68,1.48)
AT	Average exposure time	d	25550	25550

Table 3 Carcinogenic risk slope factor and daily average reference quantity for each heavy metal

Pollutants	Carcinogenic risk slope factor *SF*（$mg \cdot kg^{-1} \cdot d^{-1}$）	Daily reference measurement *RfD*（$mg \cdot kg^{-1} \cdot d^{-1}$）
Fe	0.1	0.3
Mn	-	0.046
Cu	-	0.04
Zn	-	0.3
Al	10	0.14
As	1.5	0.0003
Cd	6.1	0.0005
Pb	0.0085	0.0014
TI	-	0.000087
Ni	1.7	0.002
Co	-	0.0003

3. Results and Analysis

3.1 Characteristics and pollution assessment of heavy metal pollution

Table 4 presents the descriptive statistical results for heavy-metal concentrations in the groundwater of the study area. Fe had the highest mean concentration followed by Mn, Al, Zn, Co, Ni, Pb, Cu, Cd, As and Tl. The mean concentrations of As and Cu did not exceed the Class III values for drinking water in GB/T 14848-2024 while the mean concentrations of all other heavy metals exceeded the limit. Fe, Mn, Al and Tl exceeded the Class III values the most with excess rates of 72.2%, 92.1%, 48.4% and 55.5%, respectively. This may be attributed to high natural background values or anthropogenic activities causing the concentrations to be much higher at some sampling points. For all heavy-element concentrations, the coefficient of variation was greater than 100% amongst which Pb

had the largest coefficient of variation (722.10%) while Cu had the smallest (157.89%). This indicates that heavy metals were greatly affected by the activities of the chemical industrial park.

The single-factor pollution indices of Fe, Mn, Cu, Zn, Al, As, Cd, Pb, Tl, Ni and Co were 40.55, 58.87, 0.019, 0.22, 25.78, 0.55, 1.11, 4.57, 16.5, 3.68 and 1.5, respectively. The Nemero comprehensive pollution index for the study area was 42.78. These results indicate that the heavy-metal pollution for the study area was severe. Except for Cu, Zn and As, the other heavy metals all showed high levels of pollution. Amongst them, Mn had the highest single-factor pollution index and thus the most serious pollution degree. Fe, Al and Tl also had extremely high single-factor pollution indices. The indices for Pb and Ni also corresponded to heavy pollution while the indices for Cd and Co corresponded to relatively low pollution.

Table 4 Statistical results for heavy-metal concentrations in groundwater

Heavy metal	Maximum ($mg \cdot L^{-1}$)	Minimum ($mg \cdot L^{-1}$)	Average ($mg \cdot L^{-1}$)	Standard deviation ($mg \cdot L^{-1}$)	Coefficient of variation (%)	Class III value ($mg \cdot L^{-1}$)	Exceedance-rate (%)
Pb	3.64	0.00032	0.0457	0.33	722.10	0.01	12.7
Cd	0.361	0.00005	0.0055	0.03	545.45	0.005	8.7
Al	261	0.014	5.16	26.76	518.60	0.2	48.4
Tl	0.0591	0.00002	0.0016	0.0077	481.25	0.0001	55.5
Ni	3.57	0.00006	0.0735	0.3521	479.05	0.02	31
Co	3.13	0.00016	0.0748	0.3241	433.29	0.05	15.1
Zn	9.36	0.00632	0.22	0.91	413.64	1	5.5
Fe	398	0.0223	12.16	47.24	388.49	0.3	72.2
Mn	121	0.0264	5.89	13.46	228.52	0.1	92.1
As	0.0441	0.00023	0.0055	0.01	181.82	0.01	11.9
Cu	0.193	0.00074	0.019	0.03	157.89	1	0

3.2 Spatial Distribution Characteristics of Heavy Metals

Fig.2 shows the spatial distribution of heavy metals in the study area. The Cu concentration did not exceed the Class III value while the concentrations of all other heavy metals exceeded this standard. The Mn, Fe, Al and Tl concentrations were extremely high over most of the study area. The Ni, Pb, Cd and Co concentrations show localised spikes that were continuously distributed in the east-central part of the study area. The Ni concentration showed a relatively wide distribution while the Pb distribution

showed a relatively scattered distribution. The Cd and Co concentrations had small but significant distributions. The Zn and As concentrations were both low with only a few slightly polluted sites. The overall spatial distribution of heavy metals in the study area comprised the superposition of non-point source background pollution and local point source pollution. The east-central region was affected by the superposition of multiple pollutants, which resulted in the most severe pollution. These characteristics not only reflect differences in the driving mechanisms of different heavy metals but also indicate that the central and northern parts of the study area are key to controlling and managing heavy-metal pollution of the groundwater.

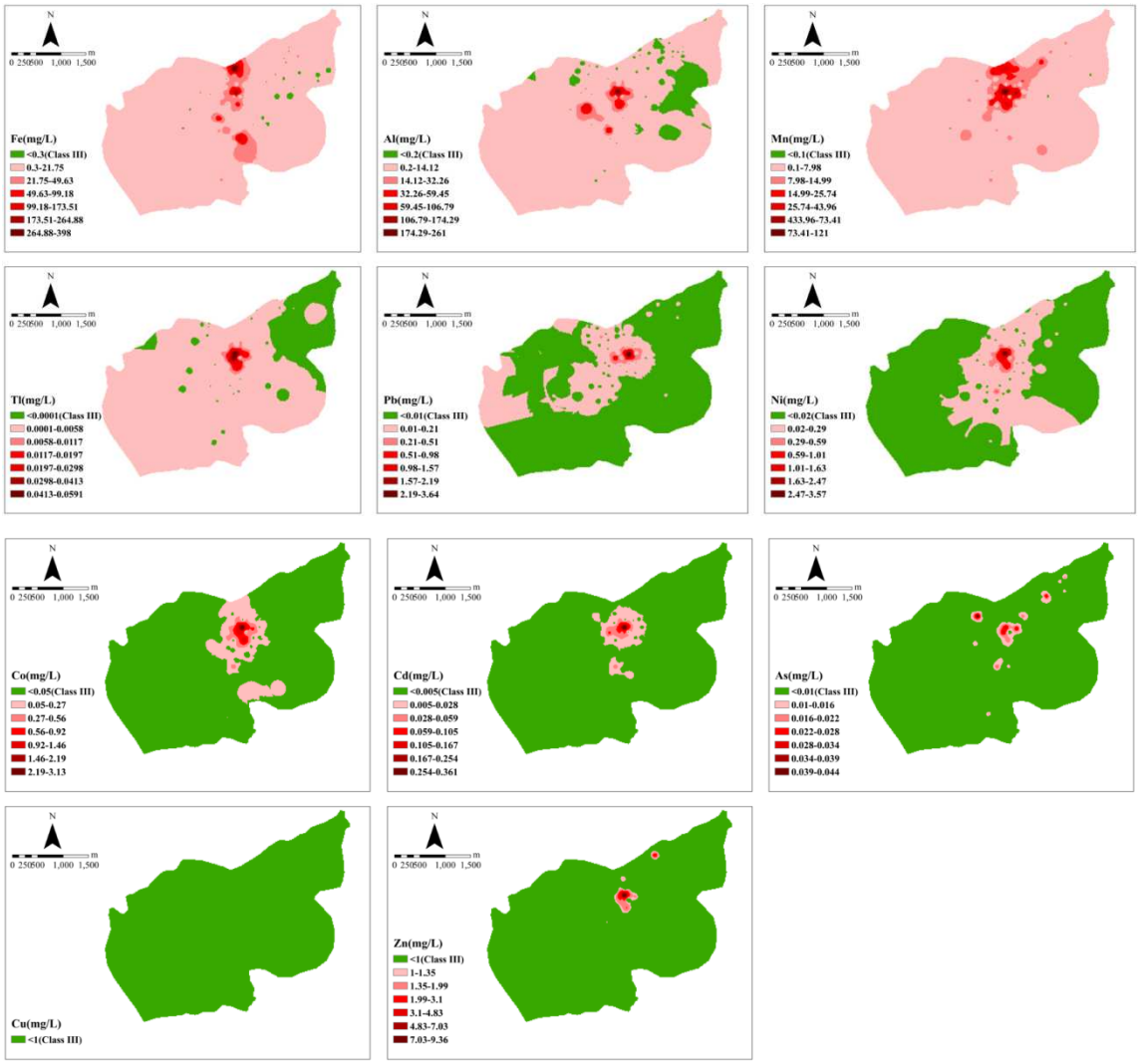


Fig. 2 Spatial distributions of heavy-metal concentrations in the study area

3.3 Correlation analysis of heavy metal pollution

Fig.3 shows the results of the Pearson correlation analysis. Zn, Al, Cd, Ni and Co formed a strongly positively correlated group with correlation coefficients generally above 0.8 (p<0.001). The correlation coefficient between Ni and Co was 0.98, which indicates nearly perfect collinearity. High correlations were also observed between Zn and Cd (r=0.90), Zn and Ni (r=0.92) and Cd and Ni (r=0.93). These results indicate that the above heavy metals may have similar geochemical affinity characteristics or share common sources in the study area (e.g. same mineralisation process or pollution sources) based on the synchronous variations in their concentrations (Chang W J, 2020).

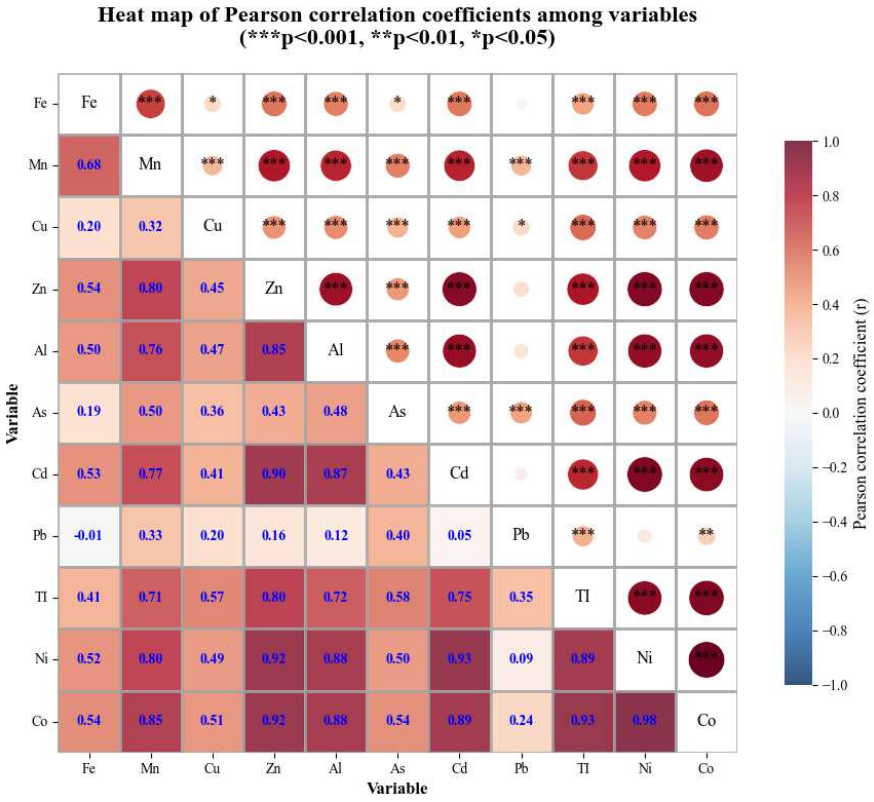


Fig. 3 Correlation coefficients between heavy metals in groundwater

Mn had a significant positive correlation with most elements: its correlation coefficients were within the range of 0.75–0.85 (p<0.001) with Zn (r=0.80), Al (r=0.76), Cd (r=0.77), Ni (r=0.80) and Co (r=0.85) and above 0.50 (p<0.05) with Fe, Cu and As. This means that Mn may play a ‘linking’ role in the

209 migration and enrichment processes of heavy metals and that its geochemical behaviour is affected by
210 multiple heavy metals.

211 Pb generally had a weak correlation with the other heavy metals: the correlation coefficient with
212 Fe was close to 0 (r=−0.01), the correlation coefficients with heavy metals in the strongly correlated
213 group (e.g. Zn and Al) were only 0.12–0.13and it had only a moderate positive correlation with As
214 (r=0.40 and p<0.05). This suggests that the enrichment mechanism or source of Pb may significantly
215 differ from that of the other heavy metals and that changes in its concentration are relatively
216 independent.

217 **3.4 Health Risk Assessment Results**

218 Table 5 presents the health risk assessment results. HI was used as the core indicator of the
219 non-carcinogenic health risk and had mean values of 5.39 for adults and 2.25 for minors.
220 This exceeds the acceptable threshold of HI=1 for both groups. Adults were at a substantially higher
221 risk than minors as the mean HI value was approximately 2.4 times higher while the maximum HI
222 value was 2.44 times higher. This indicates that adults are the priority population for preventing and
223 controlling the non-carcinogenic health risk in the study area. HQ was used to assess the contributions
224 of individual heavy metals to the non-carcinogenic health risk, and Mn and Co were found to be the
225 dominant factors driving the non-carcinogenic health risk. Their mean HQ values for adults reached
226 1.20 and 2.35, respectively, which exceeded the threshold of HQ=1. Moreover, the standard
227 deviations of Mn and Co were 2.10 and 4.05, respectively, which indicates a high degree of dispersion
228 and reflects significant differences in exposure levels within the study area. The mean HQ values of
229 Fe, Al, Pb and Ni were 0.3–0.4 which indicates that they are secondary contributors to the

non-carcinogenic health risk. In contrast, the mean *HQ* values of Cu and Zn were less than 10^{-2}, which indicates that their contribution to the overall non-carcinogenic health risk was negligible.

Table 5 Statistical analysis on non-carcinogenic and carcinogenic health risks of heavy-metal exposure in the study area based on Monte Carlo simulations

Risk Type	Heavy Metal	Average		Standard Deviation		Minimum~Maximum	
		Adults	Minors	Adults	Minors	Adults	Minors
HQ	Fe	3.83×10^{-1}	1.60×10^{-1}	6.63×10^{-1}	2.70×10^{-1}	1.66×10^{-2}~1.04	6.61×10^{-3}~4.13×10^{-1}
	Mn	1.20	5.05×10^{-1}	2.10	8.54×10^{-1}	5.24×10^{-2}~3.31	2.14×10^{-2}~1.29
	Cu	4.44×10^{-3}	1.90×10^{-3}	7.66×10^{-3}	3.18×10^{-3}	2.2×10^{-4}~1.19×10^{-2}	9×10^{-5}~4.8×10^{-3}
	Zn	6.87×10^{-3}	2.91×10^{-3}	1.19×10^{-2}	4.88×10^{-3}	3×10^{-4}~1.85×10^{-2}	1.4×10^{-4}~7.4×10^{-3}
	Al	3.48×10^{-1}	1.46×10^{-1}	6.01×10^{-1}	2.46×10^{-1}	1.61×10^{-2}~9.39×10^{-1}	6.8×10^{-3}~3.74×10^{-1}
	As	1.72×10^{-1}	7.21×10^{-2}	2.96×10^{-1}	1.21×10^{-1}	7.52×10^{-3}~4.57×10^{-1}	3.31×10^{-3}~1.83×10^{-1}
	Cd	1.03×10^{-1}	4.35×10^{-2}	1.78×10^{-1}	7.35×10^{-2}	4.45×10^{-3}~2.81×10^{-1}	1.81×10^{-3}~1.11×10^{-1}
	Pb	3.11×10^{-1}	1.29×10^{-1}	8.70×10^{-1}	2.18×10^{-1}	1.43×10^{-2}~8.38×10^{-1}	5.6×10^{-3}~3.34×10^{-1}
	Tl	1.78×10^{-1}	7.56×10^{-2}	3.08×10^{-1}	1.27×10^{-1}	8.14×10^{-3}~4.85×10^{-1}	3.64×10^{-3}~1.94×10^{-1}
	Ni	3.43×10^{-1}	1.44×10^{-1}	5.95×10^{-1}	2.42×10^{-1}	1.53×10^{-2}~9.41×10^{-1}	6.72×10^{-3}~3.67×10^{-1}
	Co	2.35	9.75×10^{-1}	4.05	1.64	1.01×10^{-1}~6.17	4.53×10^{-2}~2.50
HI	总*HQ*	5.39	2.25	7.46	3.04	2.25~9.8	9.66×10^{-1}~4.01
CR	Fe	1.15×10^{-2}	4.80×10^{-3}	1.99×10^{-2}	8.10×10^{-3}	5×10^{-4}~3.12×10^{-2}	2×10^{-4}~1.24×10^{-2}
	Al	4.88×10^{-1}	2.04×10^{-1}	8.42×10^{-1}	3.44×10^{-1}	2.26×10^{-2}~1.32	9.53×10^{-3}~5.23×10^{-1}
	As	8.00×10^{-5}	3.20×10^{-5}	1.30×10^{-4}	5.50×10^{-5}	3×10^{-6}~2.1×10^{-4}	1×10^{-6}~8.3×10^{-5}
	Cd	3.20×10^{-4}	1.30×10^{-4}	5.40×10^{-4}	2.20×10^{-4}	1×10^{-5}~8.6×10^{-4}	1×10^{-6}~3.4×10^{-5}
	Pb	3.70×10^{-6}	1.50×10^{-6}	1.04×10^{-5}	2.60×10^{-6}	1.7×10^{-7}~9.97×10^{-6}	1×10^{-7}~4×10^{-6}
	Ni	1.16×10^{-3}	4.90×10^{-4}	2.02×10^{-3}	8.20×10^{-4}	5×10^{-5}~3.2×10^{-3}	2×10^{-5}~1.25×10^{-3}
TCR	总*CR*	5.01×10^{-1}	2.10×10^{-1}	8.55×10^{-1}	3.50×10^{-1}	3.36×10^{-2}~1.33	1.47×10^{-2}~5.29×10^{-1}

TCR was used to evaluate the total carcinogenic health risk. The mean *TCR* was 0.501 for adults and 0.201 for minors. These are both less than the safety threshold (*TCR*=1) but are still in the range requiring attention. Notably, the maximum *TCR* reached 1.33 for adults, which exceeds the safety threshold. This indicates that targeted and strict control is needed to eliminate the carcinogenic health risk of exposure to heavy metals in the study area. *CR* was used to evaluate the contribution of individual heavy metals to the carcinogenic health risk. As and Cd had mean *CR* values of 8.00×10^{-5} and 3.20×10^{-4}, respectively, which are both far below the threshold of 10^{-4}.Only Al had a mean *CR* value of 4.88×10^{-1}, so it represented the dominant contributor to the carcinogenic health risk.

4. Conclusion

Within the study area, Fe had the highest concentration in the groundwater followed by Mn, Al, Zn, Co, Ni, Pb, Cu, Cd, As and Tl. Except for Cu, the heavy metals all exceeded the Class III values for drinking water. The Nemero comprehensive pollution index reached a value of 42.78, which indicates

that the overall pollution level was severe. Amongst the heavy metals, pollution by Fe, Al, Tl, Pb and Ni was severe while pollution by Cd and Co was slight. The coefficient of variation of all heavy-metal concentrations was over 100%, which indicates that the groundwater is severely affected by the production activities of the chemical industrial park. The core factors driving heavy-metal pollution in the groundwater of the study area were identified, which lays a foundation for targeted pollution control in the future.

The correlation analysis indicated strong correlations amongst Zn, Al, Cd, Ni and Co indicating a common origin. Mn had a significant positive correlation with most heavy metals, which indicates that it may play a linking role in migration and enrichment processes. Pb had a relatively weak correlation with the other heavy metals, which indicates it may have a different source or enrichment mechanism. These results clarify the source characteristics of heavy metals in the study area and provide precise scientific support for source tracing and governance.

The health risk assessment showed that the non-carcinogenic risk caused through drinking water is high for both adults and minors with Mn and Co as the key contributors. The risk is higher for adults than for minors. The carcinogenic health risk is within the range that requires attention and exceeds the safety threshold for some adults with high exposure to heavy metals. Al is the key contributor.

Author contributions Zhi Li: methodology,investigation, manuscript drafting . Xun Li: supervision, manuscript review and editing. Zhongkui Zhou: funding acquisition, manuscript review and editing. Xiaodong Chu：manuscript review and editing. Yang Yang,Yi Zhao,Jiye Zhang,Huanyin Pei: investigation.

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Data Availability The datasets generated and/or analysed during this study are available from the corresponding author

upon reasonable request.

Declarations All authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Consent to Publish declaration: not applicable.

Ethics and Consent to Participate declarations: not applicable.

Conflict of interest The authors declare no competing interests.

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