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Review

Environmental Quality and Human Health Risk of Urban Groundwater Sources Based on Hydrochemical Analysis: a Case Study of Suzhou, China

Lijuan Wang[1]*, Yuezan Tao[1], Bin Su[2], Lijun Wang[3], Peigui Liu[1]

[1]School of Civil and Hydraulic Engineering, Hefei University of Technology, Hefei 230009, China
[2]Anhui and Huaihe Water Conservancy Science Research Institute, Hefei 230009, China
[3]Anhui Survey and Design Institute of Water Resources and Hydropower Company Limited, Hefei 230008, China

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Abstract

Groundwater is the main water supply in Suzhou City in China. In recent years, heavy metal contamination of urban groundwater sources has become a serious threat to water quality and human health. Groundwater samples from 87 monitoring wells were collected in the study area and analyzed using ICP-MS spectrometry, their major heavy metals concentrations have been analyzed by a series of chemical and statistical indexes for the evaluation of pollution status and dinking suitability. We found that heavy metals are evenly distributed in the groundwater source, 10% of the samples were of excellent quality and 75% were deemed good; however, 70% of the samples exceeded the allowed Mn content. In 62% of the samples, the carcinogenic risk of As exceeded the recommended levels. Based on the non-carcinogenic health risk values, the metals could be ordered as follows: Mn>Fe>Pb>Cu>As>Zn. Mn accounted for 71% of health risk, and the total health risk was mostly due to excess As. Therefore, the levels of As, Mn, and other heavy metal elements in this region warrant urgent regulatory strategies and methods to reduce the Mn concentration should be continuously investigated.

Keywords: groundwater, environmental geochemistry, heavy metal, environmental quality, human health risk

Introduction

Groundwater is the main drinking water source for many cities. The increase in population and rapid economic development are increasing groundwater pollution, which poses risks to the safety of water consumption from this source.

Contamination with heavy metals is among the greatest hazards to human health [1-6]. Mitchell et al. [7] found that the main heavy metal contaminants in groundwater are As and Mn. The risks of groundwater contamination with As are being widely

*e-mail: wanglj201007@163.com

studied in Bangladesh, India, Pakistan, Vietnam, and China [8-10]; many researchers believe that exposure to As causes serious health problems, including skin and bladder cancer [11-13]. Jedrychowski et al. [14-15] found that exposure to Pb can cause neurological disorders, and other researchers found that exposure to Pb can cause kidney diseases, hypertension, liver crisis, and skin irritation [16-17]. Recent studies also revealed the negative environmental effect of contamination with Fe and Mn [18-19]. Groundwater containing high concentrations of Fe, Mn, Cu, and Zn can also pose health risks [20-22].

To assess the environmental health of groundwater, an evaluation method that aims to estimate the impact degree and the probability of damage from contaminants on human health can be used. It can provide scientific support for health risk management, drinking water safety, and water environment protection [23-27]. Focusing on heavy metals in this evaluation can help evaluate the health risks linked to consumption of the contaminated water and provide a basis for the formulation of water safety policies [28-30].

In this study, we focused on Suzhou City (population 5.32 million people), the largest industrial city in the northern Anhui province, and an important base for production of coal and grain in East China. The city's water supply is heavily dependent on groundwater resources, with 80% of the total water supply (780 million m^3) being extracted from the ground. This caused over extraction of groundwater in Suzhou City, prompting the local government to issue a restriction order on groundwater exploitation [31-32]. Considering the declining groundwater level and the resulting decrease in its flow, there is a risk of high concentrations of contaminants in extracted water. Aiming to provide an improved scientific basis for the protection of groundwater resources, we evaluated the quality of groundwater, specifically concentrating on risks posed by heavy metal contamination to human health.

Material and Methods

Research Area

Suzhou City is located in the northeast of Anhui Province, Central Huaibei Plain, China (33°18′-34°38′N; 116°09′-118°10′E). The groundwater aquifer of Suzhou City is of the porous type, formed of loose rock, and the lithology is mainly silty, consisting of silty sand, sub-sand, local fine sand, and silt. The aquifer is vertical and can be divided into three aquifer groups. For this study, samples were collected from the first aquifer.

Sample Collection and Analysis

Samples were collected from 87 monitoring wells, allowing the sampling to cover the entire study area (Fig. 1). The sampling points covered both centralised and decentralised water sources. The measuring instrument used was the inductively coupled plasma mass spectrometer (ICP-MS)(NexlON 300, USA). Laboratory water was prepared for the Millipore ultrapure water preparation device. The groundwater samples included in the current study were collected following the norms and standards prescribed by the Ministry of Environmental Protection of China (MEP) [33] on sampling collection, transportation, storage, preparation, and instrumental analysis. The method detection limit (LD) was 0.12 μg/L for As, 0.11 μg/L for Cr, 0.08 μg/L for Cu, 0.82 μg/L for Fe, 0.12 μg/L for Mn, 0.09 μg/L for Pb, and 0.67 μg/L for Zn. The test results are shown in Table 1.

Hydrogeochemical Analyses

Hydrogeochemical analysis is the analysis of content and spatial distribution. Analysis of heavy metal hydrogeochemical is based on mathematical statistics

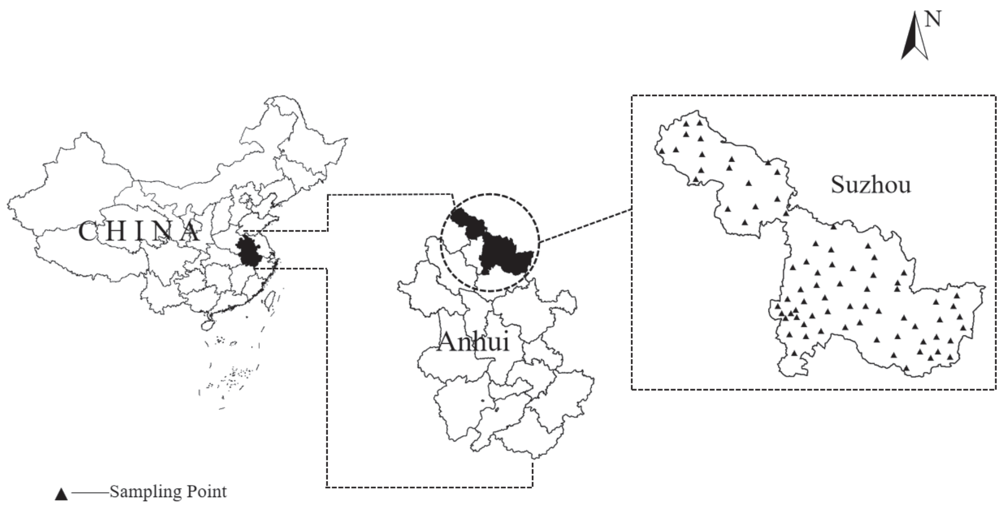

Fig. 1. Sampling locations within of the study area.

Table 1. Heavy metal concentrations in groundwater (μg/L).

Sampling point	Mn	Cu	Zn	Pb	Fe	As	Sampling point	Mn	Cu	Zn	Pb	Fe	As
1	45	1.48	14.49	0.52	15.92	<LD	46	281	1.84	2.92	0.42	130	<LD
2	104	0.44	12.57	0.25	169.4	0.45	47	43.03	1.08	7.59	0.10	177	2.45
3	92	0.54	85.95	<LD	19.59	0.60	48	561.7	0.79	4.38	<LD	193	12.01
4	4	1.05	17.26	0.23	30.82	1.10	49	98.71	1.31	6.20	0.28	35	5.16
5	544	0.16	392.20	0.48	471.5	<LD	50	176.7	0.47	2.13	<LD	61	0.62
6	223	0.68	33.98	0.60	79.69	0.72	51	143.1	0.80	5.07	0.19	26	<LD
7	50	0.23	11.03	0.44	183.3	<LD	52	463.1	0.41	8.01	0.24	70	0.63
8	2171	0.53	8.83	0.17	182	0.48	53	68.99	0.26	4.62	<LD	70	0.54
9	5163	1.55	3.69	<LD	1229	<LD	54	386	0.67	2.60	0.25	141	0.80
10	291	0.87	12.92	0.19	36.83	<LD	55	614	1.67	7.77	0.19	20	0.88
11	181	1.82	8.98	<LD	222.1	0.93	56	102	0.26	1.53	0.76	61	0.82
12	128	0.13	85.58	0.09	98.44	0.50	57	260	0.12	<LD	<LD	79	0.69
13	181	0.27	264.40	<LD	81.27	1.01	58	8	0.29	14.77	0.50	111	5.56
14	229	<LD	1.34	0.60	412.8	0.69	59	29	<LD	<LD	<LD	6	<LD
15	251.9	0.37	8.33	<LD	32.04	<LD	60	305	0.68	<LD	<LD	65	0.65
16	81.52	3.52	8.84	<LD	1.543	<LD	61	217	3.69	8.32	0.34	116	<LD
17	347.6	0.60	17.17	0.20	70.27	0.60	62	310	0.40	7.16	0.65	5	1.46
18	103.4	0.36	49.38	0.19	12	0.50	63	249	0.26	<LD	<LD	10	0.71
19	424.7	1.22	18.33	0.21	13.36	0.90	64	46.48	0.13	4.84	<LD	3	1.52
20	441.2	0.68	25.45	1.00	128.7	1.90	65	77.94	1.09	279.90	0.20	76	<LD
21	89.68	0.69	20.27	2.07	73.37	<LD	66	1311	0.86	21.33	0.36	15	1.60
22	136.4	0.35	13.13	0.53	49.7	<LD	67	164.3	0.62	14.52	0.60	146	<LD
23	138.8	1.44	20.46	<LD	28.86	0.42	68	261.4	1.11	5.55	0.80	94	1.17
24	37.84	1.14	14.40	<LD	36.82	<LD	69	240.6	0.69	10.05	<LD	315	0.35
25	1012	1.61	10.85	0.50	89.12	1.82	70	133.6	0.21	8.25	0.50	569	<LD
26	226.3	0.43	4.83	<LD	6.706	0.35	71	206.8	2.38	30.62	<LD	68	1.59
27	45.23	1.06	19.85	<LD	43.29	<LD	72	995.5	0.77	14.57	0.30	81	0.46
28	132.3	0.83	20.08	0.12	156	<LD	73	204.2	0.42	4.97	0.52	93	<LD
29	307.2	0.81	<LD	<LD	71.55	0.50	74	71.3	0.10	<LD	0.20	11	0.48
30	781.3	1.01	12.25	0.16	54.07	0.80	75	2.171	0.25	3.79	0.36	<LD	<LD
31	10.77	1.96	138.90	0.26	35.28	0.60	76	895.7	0.36	14.61	0.88	71	2.70
32	228.1	0.59	18.82	0.86	156.1	1.70	77	139.1	0.32	3.12	0.70	186	<LD
33	476.6	0.25	<LD	<LD	294.9	<LD	78	222.1	0.09	61.33	0.82	175	0.62
34	396.7	1.72	16.53	0.17	233.4	<LD	79	204.4	0.08	1.71	0.33	69.92	<LD
35	71.32	0.55	14.36	0.20	224.7	0.40	80	61.34	0.13	1.95	0.20	2.979	0.80
36	243.2	1.35	12.45	0.22	59.33	<LD	81	195.8	<LD	1.30	0.33	99.13	<LD
37	282.9	0.75	3.74	<LD	39	<LD	82	174.7	1.17	6.17	<LD	39.56	<LD
38	404.4	5.23	10.19	2.14	110	0.48	83	60.48	0.42	44.37	<LD	388.1	1.30
39	745.9	0.86	2.43	<LD	81	10.36	84	71.24	0.10	9.93	<LD	467.3	1.50

Table 1. Continued.

40	30.49	0.72	1.51	0.40	6	<LD	85	561.5	0.35	8.89	<LD	<LD	0.90
41	478.1	0.40	3.36	<LD	205	9.86	86	172.8	0.67	184.10	2.18	32.42	<LD
42	188.3	0.67	1.83	<LD	136	0.87	87	58.79	<LD	2.15	<LD	21.96	<LD
43	19.55	1.35	8.20	1.89	7	<LD							
44	77.78	0.64	2.28	<LD	117	2.27							
45	232.5	0.34	2.41	0.30	83	46.90							

of concentration data, and compared the heavy metal concentration in each sample (see Table 2) with the Class III division of the groundwater quality standards [34] that describe the standard required for groundwater to be suitable for use as a centralized domestic and drinking water source.

Environmental Water Quality Analyses

The water environment is analyzed by the comprehensive index which was evaluated based on the Nemerow index method [35]. Evaluation criteria of the Nemerow index are shown in Table 3.

Human Health Risk Assessment

The health risk of carcinogens in drinking water was evaluated using the following equation [36]:

$$R_i^c = \frac{1-\exp\left(-(CW_i \cdot IR)/BW \cdot q_i\right)}{L} \quad (3)$$

Where R_i^c is the average annual risk of carcinogenesis for individual person produced by the carcinogen *i* in drinking water, a^{-1}, *qi* is the carcinogenic potency factor of carcinogen *i* in drinking water, mg/(kg.d). A value of 15 for As [37] was used in the present study, and L is the average human lifespan, which was assumed to be 70 years. *CW* is the concentration of the heavy metal in the groundwater (mg/L), *IR* is the daily intake of drinking water (a value of 2.2 L/d was used), *EF* is the exposure frequency (the value used was 365 days/year), *ED* is the exposure duration (70 years for the carcinogen and 30 years for the non-carcinogen), *BW* is the body weight in kg (70 kg was selected for the adults in Suzhou City), and *AT* is the average exposure time (days), which was calculated as 365 × *ED*.

The health risk of non-carcinogens in drinking water was assessed using the following equation:

$$R_j^n = \frac{CW_j \cdot IR \cdot 10^{-6}}{RfD_j \cdot L \cdot BW} \quad (4)$$

Table 2. Classification of groundwater by quality.

Order number	Class	Scope of application
1	I class	Various uses
2	II class	Various uses
3	III class	Centralized domestic and drinking water sources, industrial and agricultural water use
4	IV class	Used for agriculture and in the industry, but can be used for drinking after appropriate treatment
5	V class	Choose according to the purpose of use

Table 3. Groundwater quality classification standard and single-component scoring standard.

Water quality classification	Individual component score values F_i	The Memero Pollution Index, F	Water quality classification
I	0	<0.80	Excellent
II	1	0.80~2.50	Good
III	3	2.50~4.25	Better
IV	6	4.25~7.20	Poor
V	10	>7.20	Extremely Poor

Table 4. Reference values of the risk level (a^{-1}).

Institution name	Maximum acceptable level	Negligible level	Remarks
The Swedish Environmental Protection Agency	1.0×10^{-6}	-	Chemical pollutant
The Dutch Ministry of Construction and the Environment	1.0×10^{-6}	1.0×10^{-8}	Chemical pollutant
Royal Society	1.0×10^{-6}	1.0×10^{-7}	-
International Commission on Radiological Protection	5.0×10^{-5}	-	Radiation
US Environmental Protection Agency	1.0×10^{-4}	-	-

Where R_i^n is the average annual risk to individuals by non-carcinogens i in drinking water (a^{-1}), RfD_i is the reference dose of the non-carcinogen i in drinking water, mg/(kg.d). The value of RfD_i is 0.02 for As, 5×10^{-3} for Cu, 0.3 for Fe, 1.4×10^{-1} for Mn, 1.4×10^{-3} for Pb, and 3.0×10^{-1} for Zn.

The total annual risk of carcinogenesis caused by the carcinogens in groundwater was calculated using Eq. (5). The reference values that we used for each risk level were given by the international standards of various institutions, as given by Table 4.

$$R = \sum_{i=1}^{n} R_i^c + \sum_{i=1}^{n} R_i^n \quad (5)$$

Results and Discussion

Hydrogeochemical Analyses

Content Analysis

Content characteristics analysis of 87 sampling sites in the study area revealed that the content of the six heavy metals in the samples were ranked as Mn>Fe>Zn>As>Cu>Pb (Table 1).

Mn

The average Mn content was 330 μg/L, the maximum Mn concentration was 5163 μg/L, and the coefficient of variation was 185%. 61 sampling points (accounting for 70%) contained excessive amounts of Mn, and the maximum excess multiple was 51.36.

Mn is a common natural groundwater contaminant and is present at concentrations much higher than the recommended drinking water guidelines [38]. Superfluous Mn has been found in groundwater in many countries worldwide, such as western Quebec in Canada [39], the lower Kelantan River Basin on the north-eastern coast of Malaysia [40], the Balat-Teneida area in the El-Dakhla Basin in Egypt [41], and Hidalgo in Mexico [42]. Mn also exceeds the standards in groundwater in some cities in China. Mn and Fe are the main contaminants of the groundwater in Suzhou [43] and excessive amounts of Mn have been found in the southern and northeastern regions of China [44-46].

Fe

The average iron (Fe) content was 121 μg/L, the maximum Fe concentration was 1229 μg/L, and the coefficient of variation was 137 %. The concentration value of each sample was compared with the Class III division of the People's Republic of China Quality Standard for Drinking Water, 7 sampling points (accounting for 8%) contained excessive amounts of Fe, maximum excess multiple was 4.10.

Groundwater contamination occurs owing to the ability of water to dissolve aquifers; any change in water acidity and alkalinity affects this process, and Mn and Fe are very sensitive to water redox conditions [47]. Highly industrialised cities are also at risk of exceeding the accepted Mn and Fe concentration limit in groundwater [48]. This previous study also showed that excessive quantities of Mn and Fe in the groundwater of Suzhou are linked to human activities (such as the excessive exploitation of groundwater and mineral resources).

As

The average Arsenic (As) content was 2.51 μg/L, the maximum As concentration was 46.9 μg/L, and the coefficient of variation was 261 %. The concentration value of each sample was compared with the Class III division of the People's Republic of China Quality Standard for Drinking Water, 3 sampling points (accounting for 3%) contained excessive amounts of As, maximum excess multiple was 4.69. Monitoring of these three Wells should be strengthened.

Zn, Cu, Pb

The average Zinc (Zn) content was 28.44 μg/L, the maximum Zn concentration was 392.2 μg/L. The average Copper (Cu) content was 0.85 μg/L, the maximum Cu concentration was 5.23 μg/L.The average lead (Pb) content was 0.51 μg/L, the maximum Pb concentration was 2.18 μg/L.The contents of these three metals are lower than the limit of the Class III division

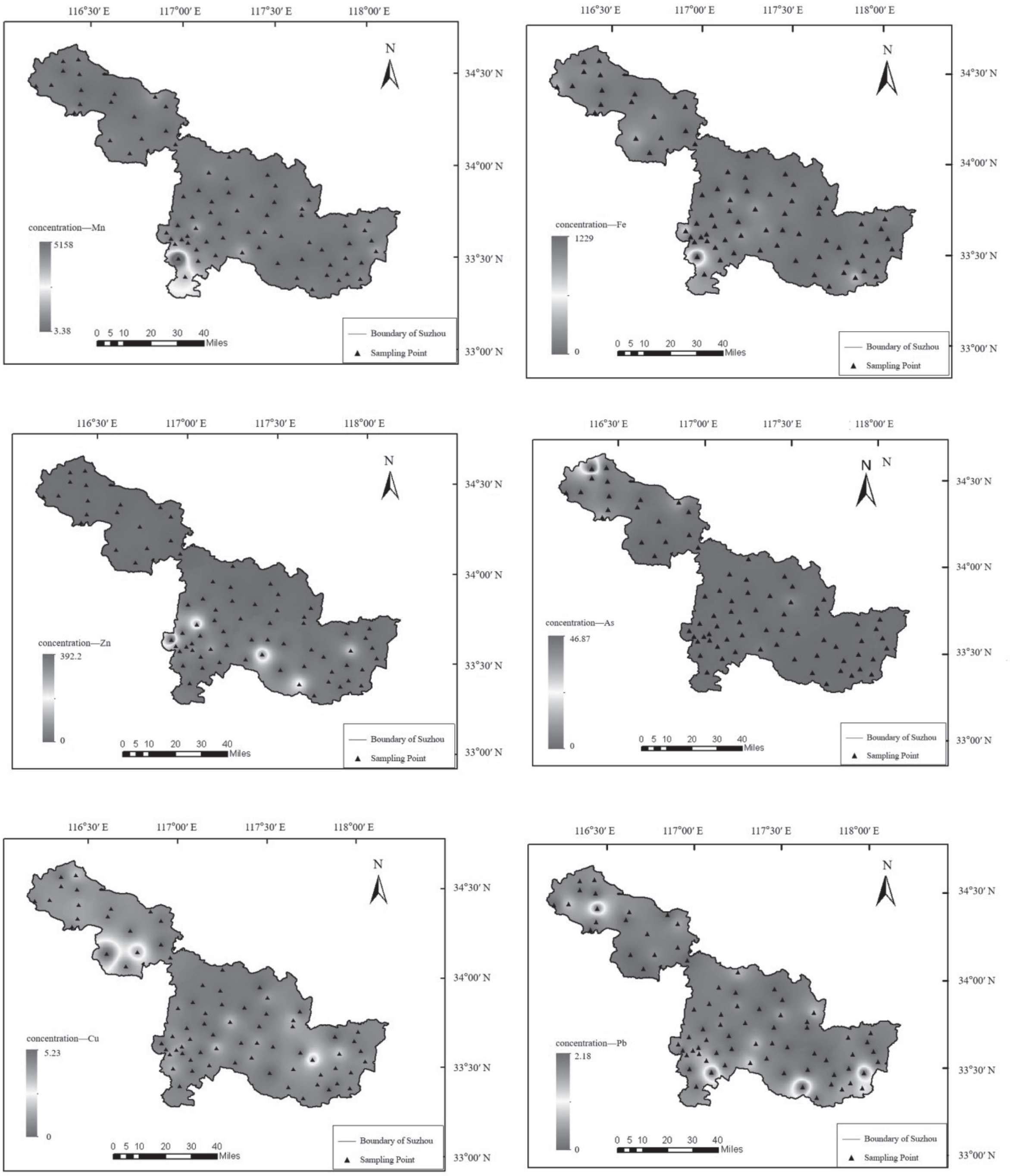

Fig. 2. Concentration spatial distribution of heavy metals.

of the People's Republic of China Quality Standard for Drinking Water.

Spatial Characteristic Analysis

The spatial distribution characteristics can directly reflect the concentration value of heavy metals in a specific area. Mn was generally high in the whole groundwater sources, and there are one point where the Mn was very high,it could be that the well was seriously contaminated (Fig. 2). The sampling point with the highest concentration was found in south part of Suzhou City where located in the Sunan mining area, there is a high possibility that the water quality at this sampling point has been disturbed by human activities. Fe in the same area shows high concentration as Mn. This result may contribute to their common tendency in redox changes and similar geochemical features [49], and it could be its mixed lithologic and anthropogenic origins [50]. The concentration of six heavy metals varies gently in regional distribution, except for a few points. The uniform concentration distribution indicates that the water source is not affected by regional pollution [51].

Comprehensive Quality Evaluation

The quality of water samples evaluated using the Nemerow method is shown in Table 5. Among the evaluated sampling sites, 9 sites (10 %) had an excellent water quality classification, 65 sites (75 %) had a good water quality classification, 11 sites (13 %) had a poor water quality classifications, and 2 sites (2 %) had an extremely poor water quality classification. These results are similar to the data given in the Suzhou Water Resources Bulletin and suggests that the study area generally has good water quality. The groundwater water type in Suzhou city is medium to deep pore water and carbonate karst water, and the system is mainly semi-closed. Because atmospheric precipitation does not seep directly into the sampling wells, and because contaminants from surface water are absorbed by rock and adsorbed by gas, the quality of groundwater is effectively preserved. There are a few water source wells where the water intake layers are closely related to rainfall or surface water. This runoff water may be affected by human activities, causing groundwater pollution.

Table 5. The calculation of F value.

Sample point	F_{max}	$\overline{F}$	F	Sample point	F_{max}	$\overline{F}$	F
1	0	0.0	0.0	46	3	1.0	2.2
2	3	1.0	2.2	47	3	1.0	2.2
3	3	1.0	2.2	48	6	2.3	4.5
4	3	0.9	2.2	49	3	1.3	2.3
5	6	2.3	4.5	50	3	0.9	2.2
6	3	0.9	2.2	51	3	0.9	2.2
7	1	0.3	0.7	52	3	0.9	2.2
8	10	3.0	7.4	53	3	0.9	2.2
9	10	3.7	7.5	54	3	1.0	2.2
10	3	0.9	2.2	55	3	0.9	2.2
11	3	1.3	2.3	56	3	0.9	2.2
12	3	1.0	2.2	57	3	0.9	2.2
13	3	1.4	2.3	58	3	1.0	2.2
14	6	2.1	4.5	59	0	0.0	0.0
15	3	0.9	2.2	60	3	0.9	2.2
16	3	0.9	2.2	61	3	1.0	2.2
17	3	0.9	2.2	62	3	1.3	2.3
18	3	0.9	2.2	63	3	0.9	2.2
19	3	0.9	2.2	64	3	0.9	2.2
20	3	1.4	2.3	65	3	1.0	2.2
21	3	0.9	2.2	66	6	2.1	4.5
22	3	0.9	2.2	67	3	1.0	2.2
23	3	0.9	2.2	68	3	1.3	2.3
24	0	0.0	0.0	69	6	2.1	4.5
25	6	2.1	4.5	70	6	2.1	4.5
26	3	0.9	2.2	71	3	1.3	2.3
27	0	0.0	0.0	72	3	0.9	2.2
28	3	1.0	2.2	73	3	0.9	2.2
29	3	0.9	2.2	74	3	0.9	2.2

Table 5. Continued.

30	3	0.9	2.2	75	0	0.0	0.0
31	1	0.3	0.7	76	3	1.3	2.3
32	3	1.4	2.3	77	3	1.0	2.2
33	3	1.3	2.3	78	3	1.1	2.3
34	3	1.3	2.3	79	3	0.9	2.2
35	3	1.3	2.3	80	3	0.9	2.2
36	3	0.9	2.2	81	3	0.9	2.2
37	3	0.9	2.2	82	3	0.9	2.2
38	3	1.0	2.2	83	6	2.6	4.6
39	6	2.1	4.5	84	6	2.6	4.6
40	0	0.0	0.0	85	3	0.9	2.2
41	3	1.7	2.4	86	3	1.0	2.2
42	3	1.0	2.2	87	3	0.9	2.2
43	0	0.0	0.0				
44	3	1.4	2.3				
45	6	2.1	4.5				

Human Health Risk Assessment

Carcinogenic Health Risks Assessment

Of the total sampling points, 33 sampling points measured at a 0 value for carcinogenic risk. However, our results indicated that the cancer risk from As in the study area was high. Among the evaluated sampling sites, 54 sites (62 %) exceeded the level of maximum acceptable carcinogenic risk recommended by the Swedish Environmental Protection Agency, the Ministry of Construction and Environment in the Netherlands and the Royal British Association, 6 sites (7 %) exceeded the level of maximum acceptable carcinogenic risk recommended by the ICRP, and 4 sites (5 %) exceeded the level of maximum acceptable carcinogenic risk recommended by the US.EPA (see Table 6).

A high concentration of arsenic in groundwater is a worldwide problem, high concentration of arsenic in groundwater has been documented as a major health issue around the globe. Exposure to arsenic poses a serious risk of different types of cancer [52-56], and on several occasions the presence of As has been reported to have caused serious threat to health by causing keratosis and melanosis [57].

Arsenic (As) contamination in different areas of the world has been reported, more than 230 million people worldwide, which include 180 million from Asia, are at risk of arsenic poisoning. Southeast Asian countries, Bangladesh, India, Pakistan, China, Nepal, Vietnam, Burma, Thailand and Cambodia, are the most affected [58]. Arsenic has been found in groundwater in many Chinese cities, Northern China has been identified as high-risk area. Our results are supported by several published studies, where arsenic pollution has been measured in the groundwater around Suzhou [69-62].

High arsenic groundwater is mainly distributed in the areas with reducing environment [63]. Many scholars believe that arsenic aggregation is caused by human activities that use arsenic-containing minerals, and after release in the environment through a redox reaction, arsenic mixes with surface water to contaminate groundwater [64-69].

Considering the carcinogenic health risks caused by As in Suzhou, we recommend that research efforts are directed towards the development of countermeasures that reduce the adverse impact of human activities on the environment.

Non-Carcinogenic Health Risks Assessment

The non-carcinogenic health risks ranged between 3.20×10^{-13} and 1.66×10^{-8} for Mn, Cu, Zn, Pb, Fe, and As (Table 6). Only 1 site measured a health risk value for Mn that exceeded the level set by the Dutch Ministry of Construction and Environment, however this value was still within the acceptable limits of the recommendations set by other institutions. The calculated health risk values can be ranked as Mn>Fe>Pb>Cu>As>Zn, among which Mn presented as the greatest risk, measuring at 71 % of the total risk (Fig. 3). Although Mn is a common element in groundwater, in excessive quantities it poses a hazard to human health. Chronic exposure to excessive Mn levels causes increased infant mortality in mothers with

Table 6. Health risk (a^{-1}).

Sample point	Non-carcinogenic risk						Carcinogenic risk	Total health risk
	Mn	Cu	Zn	Pb	Fe	As	As	
2	3.34×10^{-10}	3.95×10^{-11}	1.88×10^{-11}	8.02×10^{-11}	2.54×10^{-10}	1.00×10^{-11}	7.01×10^{-6}	7.01×10^{-6}
3	2.95×10^{-10}	4.85×10^{-11}	1.29×10^{-10}	0	2.93×10^{-11}	1.35×10^{-11}	9.43×10^{-6}	9.43×10^{-6}
4	1.28×10^{-11}	9.43×10^{-11}	2.58×10^{-11}	7.38×10^{-11}	4.61×10^{-11}	2.47×10^{-11}	1.73×10^{-5}	1.73×10^{-5}
5	1.74×10^{-9}	1.44×10^{-11}	5.87×10^{-10}	1.54×10^{-10}	7.06×10^{-10}	0	0	3.21×10^{-9}
6	7.15×10^{-10}	6.11×10^{-11}	5.09×10^{-11}	1.92×10^{-10}	1.19×10^{-10}	1.62×10^{-11}	1.13×10^{-5}	1.13×10^{-5}
7	1.60×10^{-10}	2.07×10^{-11}	1.65×10^{-11}	1.41×10^{-10}	2.74×10^{-10}	0	0	6.13×10^{-10}
8	6.96×10^{-9}	4.76×10^{-11}	1.32×10^{-11}	5.45×10^{-11}	2.72×10^{-10}	1.08×10^{-11}	7.57×10^{-6}	7.58×10^{-6}
9	1.66×10^{-8}	1.39×10^{-10}	5.52×10^{-12}	0	1.84×10^{-9}	0	0	1.85×10^{-8}
10	9.33×10^{-10}	7.81×10^{-11}	1.93×10^{-11}	6.09×10^{-11}	5.51×10^{-11}	0	0	1.15×10^{-9}
11	5.80×10^{-10}	1.63×10^{-10}	1.34×10^{-11}	0	3.32×10^{-10}	2.08×10^{-11}	1.45×10^{-5}	1.45×10^{-5}
12	4.10×10^{-10}	1.17×10^{-11}	1.28×10^{-10}	2.89×10^{-11}	1.47×10^{-10}	1.12×10^{-11}	7.82×10^{-6}	7.82×10^{-6}
13	5.80×10^{-10}	2.42×10^{-11}	3.96×10^{-10}	0	1.22×10^{-10}	2.27×10^{-11}	1.59×10^{-5}	1.59×10^{-5}
14	7.34×10^{-10}	0	2.01×10^{-12}	1.92×10^{-10}	6.18×10^{-10}	1.54×10^{-11}	1.08×10^{-5}	1.08×10^{-5}
15	8.08×10^{-10}	3.35×10^{-11}	1.25×10^{-11}	0	4.80×10^{-11}	0	0	9.02×10^{-10}
16	2.61×10^{-10}	3.16×10^{-10}	1.32×10^{-11}	0	2.31×10^{-12}	0	0	5.93×10^{-10}
17	1.11×10^{-9}	5.40×10^{-11}	2.57×10^{-11}	6.38×10^{-11}	1.05×10^{-10}	1.35×10^{-11}	9.43×10^{-6}	9.43×10^{-6}
18	3.32×10^{-10}	3.20×10^{-11}	7.39×10^{-11}	6.16×10^{-11}	1.80×10^{-11}	1.12×10^{-11}	7.85×10^{-6}	7.86×10^{-6}
19	1.36×10^{-9}	1.09×10^{-10}	2.74×10^{-11}	6.67×10^{-11}	2.00×10^{-11}	2.02×10^{-11}	1.41×10^{-5}	1.41×10^{-5}
20	1.41×10^{-9}	6.12×10^{-11}	3.81×10^{-11}	3.21×10^{-10}	1.93×10^{-10}	4.27×10^{-11}	2.98×10^{-5}	2.98×10^{-5}
21	2.88×10^{-10}	6.20×10^{-11}	3.03×10^{-11}	6.64×10^{-10}	1.10×10^{-10}	0	0	1.15×10^{-9}
22	4.37×10^{-10}	3.17×10^{-11}	1.97×10^{-11}	1.71×10^{-10}	7.44×10^{-11}	0	0	7.34×10^{-10}
23	4.45×10^{-10}	1.29×10^{-10}	3.06×10^{-11}	0	4.32×10^{-11}	9.47×10^{-12}	6.63×10^{-6}	6.63×10^{-6}
24	1.21×10^{-10}	1.03×10^{-10}	2.16×10^{-11}	0	5.51×10^{-11}	0	0	3.01×10^{-10}
25	3.25×10^{-9}	1.45×10^{-10}	1.62×10^{-11}	1.60×10^{-10}	1.33×10^{-10}	4.09×10^{-11}	2.86×10^{-5}	2.86×10^{-5}
26	7.26×10^{-10}	3.85×10^{-11}	7.23×10^{-12}	0	1.00×10^{-11}	7.81×10^{-12}	5.47×10^{-6}	5.47×10^{-6}
27	1.45×10^{-10}	9.48×10^{-11}	2.97×10^{-11}	0	6.48×10^{-11}	0	0	3.34×10^{-10}
28	4.24×10^{-10}	7.41×10^{-11}	3.01×10^{-11}	3.72×10^{-11}	2.33×10^{-10}	0	0	7.99×10^{-10}
29	9.85×10^{-10}	7.30×10^{-11}	3.20×10^{-13}	0	1.07×10^{-10}	1.12×10^{-11}	7.85×10^{-6}	7.86×10^{-6}
30	2.51×10^{-9}	9.10×10^{-11}	1.83×10^{-11}	5.10×10^{-11}	8.09×10^{-11}	1.80×10^{-11}	1.26×10^{-5}	1.26×10^{-5}
31	3.45×10^{-11}	1.76×10^{-10}	2.08×10^{-10}	8.21×10^{-11}	5.28×10^{-11}	1.35×10^{-11}	9.43×10^{-6}	9.43×10^{-6}
32	7.32×10^{-10}	5.28×10^{-11}	2.82×10^{-11}	2.74×10^{-10}	2.34×10^{-10}	3.82×10^{-11}	2.67×10^{-5}	2.67×10^{-5}
33	1.53×10^{-9}	2.22×10^{-11}	6.23×10^{-13}	0	4.41×10^{-10}	0	0	1.99×10^{-9}
34	1.27×10^{-9}	1.55×10^{-10}	2.47×10^{-11}	5.45×10^{-11}	3.49×10^{-10}	0	0	1.86×10^{-9}
35	2.29×10^{-10}	4.97×10^{-11}	2.15×10^{-11}	6.54×10^{-11}	3.36×10^{-10}	9.07×10^{-12}	6.35×10^{-6}	6.35×10^{-6}
36	7.80×10^{-10}	1.21×10^{-10}	1.86×10^{-11}	6.93×10^{-11}	8.88×10^{-11}	0	0	1.08×10^{-9}
37	9.07×10^{-10}	6.73×10^{-11}	5.60×10^{-12}	0	5.84×10^{-11}	0	0	1.04×10^{-9}
38	1.30×10^{-9}	4.70×10^{-10}	1.53×10^{-11}	6.86×10^{-10}	1.65×10^{-10}	1.09×10^{-11}	7.60×10^{-6}	7.61×10^{-6}
39	2.39×10^{-9}	7.70×10^{-11}	3.64×10^{-12}	2.79×10^{-11}	1.21×10^{-10}	2.33×10^{-10}	1.62×10^{-4}	1.62×10^{-4}
40	9.78×10^{-11}	6.44×10^{-11}	2.25×10^{-12}	1.28×10^{-10}	8.98×10^{-12}	0	0	3.02×10^{-10}

Table 6. Continued.

41	1.53×10^{-9}	3.56×10^{-11}	5.03×10^{-12}	0	3.07×10^{-10}	2.21×10^{-10}	1.54×10^{-4}	1.54×10^{-4}
42	6.04×10^{-10}	6.01×10^{-11}	2.74×10^{-12}	0	2.04×10^{-10}	1.96×10^{-11}	1.37×10^{-5}	1.37×10^{-5}
43	6.27×10^{-11}	1.21×10^{-10}	1.23×10^{-11}	6.05×10^{-10}	1.05×10^{-11}	0	0	8.11×10^{-10}
44	2.49×10^{-10}	5.72×10^{-11}	3.41×10^{-12}	0	1.75×10^{-10}	5.10×10^{-11}	3.57×10^{-5}	3.57×10^{-5}
45	7.46×10^{-10}	3.09×10^{-11}	3.61×10^{-12}	9.62×10^{-11}	1.24×10^{-10}	1.05×10^{-9}	7.18×10^{-4}	7.18×10^{-4}
46	9.01×10^{-10}	1.65×10^{-10}	4.37×10^{-12}	1.35×10^{-10}	1.95×10^{-10}	0	0	1.40×10^{-9}
47	1.38×10^{-10}	9.66×10^{-11}	1.14×10^{-11}	3.21×10^{-11}	2.65×10^{-10}	5.50×10^{-11}	3.85×10^{-5}	3.85×10^{-5}
48	1.80×10^{-9}	7.07×10^{-11}	6.55×10^{-12}	0	2.89×10^{-10}	2.70×10^{-10}	1.87×10^{-4}	1.87×10^{-4}
49	3.17×10^{-10}	1.18×10^{-10}	9.28×10^{-12}	8.82×10^{-11}	5.24×10^{-11}	1.16×10^{-10}	8.08×10^{-5}	8.08×10^{-5}
50	5.67×10^{-10}	4.18×10^{-11}	3.18×10^{-12}	0	9.13×10^{-11}	1.39×10^{-11}	9.74×10^{-6}	9.74×10^{-6}
51	4.59×10^{-10}	7.19×10^{-11}	7.59×10^{-12}	6.16×10^{-11}	3.89×10^{-11}	0	0	6.39×10^{-10}
52	1.49×10^{-9}	3.65×10^{-11}	1.20×10^{-11}	7.63×10^{-11}	1.05×10^{-10}	1.42×10^{-11}	9.96×10^{-6}	9.96×10^{-6}
53	2.21×10^{-10}	2.33×10^{-11}	6.91×10^{-12}	0	1.05×10^{-10}	1.22×10^{-11}	8.55×10^{-6}	8.55×10^{-6}
54	1.24×10^{-9}	6.03×10^{-11}	3.89×10^{-12}	7.86×10^{-11}	2.11×10^{-10}	1.79×10^{-11}	1.25×10^{-5}	1.25×10^{-5}
55	1.97×10^{-9}	1.50×10^{-10}	1.16×10^{-11}	5.97×10^{-11}	2.99×10^{-11}	1.98×10^{-11}	1.39×10^{-5}	1.39×10^{-5}
56	3.27×10^{-10}	2.31×10^{-11}	2.29×10^{-12}	2.44×10^{-10}	9.13×10^{-11}	1.85×10^{-11}	1.29×10^{-5}	1.29×10^{-5}
57	8.34×10^{-10}	1.03×10^{-11}	0	0	1.18×10^{-10}	1.55×10^{-11}	1.09×10^{-5}	1.09×10^{-5}
58	2.57×10^{-11}	2.60×10^{-11}	2.21×10^{-11}	1.61×10^{-10}	1.66×10^{-10}	1.25×10^{-10}	8.72×10^{-5}	8.72×10^{-5}
59	9.30×10^{-11}	0	0	0	8.98×10^{-12}	0	0	1.02×10^{-10}
60	9.78×10^{-10}	6.06×10^{-11}	0	0	9.73×10^{-11}	1.45×10^{-11}	1.02×10^{-5}	1.02×10^{-5}
61	6.96×10^{-10}	3.31×10^{-10}	1.24×10^{-11}	1.10×10^{-10}	1.74×10^{-10}	0	0	1.32×10^{-9}
62	9.94×10^{-10}	3.58×10^{-11}	1.07×10^{-11}	2.08×10^{-10}	7.48×10^{-12}	3.27×10^{-11}	2.29×10^{-5}	2.29×10^{-5}
63	7.99×10^{-10}	2.31×10^{-11}	0	0	1.50×10^{-11}	1.59×10^{-11}	1.11×10^{-5}	1.11×10^{-5}
64	1.49×10^{-10}	1.16×10^{-11}	7.25×10^{-12}	0	4.49×10^{-12}	3.42×10^{-11}	2.39×10^{-5}	2.39×10^{-5}
65	2.50×10^{-10}	9.77×10^{-11}	4.19×10^{-10}	6.54×10^{-11}	1.14×10^{-10}	0	0	9.46×10^{-10}
66	4.20×10^{-9}	7.70×10^{-11}	3.19×10^{-11}	1.14×10^{-10}	2.24×10^{-11}	3.60×10^{-11}	2.52×10^{-5}	2.52×10^{-5}
67	5.27×10^{-10}	5.55×10^{-11}	2.17×10^{-11}	1.93×10^{-10}	2.19×10^{-10}	0	0	1.02×10^{-9}
68	8.38×10^{-10}	9.92×10^{-11}	8.30×10^{-12}	2.55×10^{-10}	1.41×10^{-10}	2.62×10^{-11}	1.83×10^{-5}	1.83×10^{-5}
69	7.72×10^{-10}	6.21×10^{-11}	1.50×10^{-11}	0	4.71×10^{-10}	7.81×10^{-12}	5.47×10^{-6}	5.47×10^{-6}
70	4.28×10^{-10}	1.91×10^{-11}	1.23×10^{-11}	1.61×10^{-10}	8.52×10^{-10}	0	0	1.47×10^{-9}
71	6.63×10^{-10}	2.13×10^{-10}	4.58×10^{-11}	0	1.02×10^{-10}	3.56×10^{-11}	2.49×10^{-5}	2.49×10^{-5}
72	3.19×10^{-9}	6.95×10^{-11}	2.18×10^{-11}	9.62×10^{-11}	1.21×10^{-10}	1.03×10^{-11}	7.23×10^{-6}	7.23×10^{-6}
73	6.55×10^{-10}	3.74×10^{-11}	7.44×10^{-12}	1.67×10^{-10}	1.39×10^{-10}	0	0	1.01×10^{-9}
74	2.29×10^{-10}	8.53×10^{-12}	0	6.41×10^{-11}	1.65×10^{-11}	1.07×10^{-11}	7.48×10^{-6}	7.48×10^{-6}
75	6.96×10^{-12}	2.26×10^{-11}	5.67×10^{-12}	1.15×10^{-10}	0	0	0	1.51×10^{-10}
76	2.87×10^{-9}	3.27×10^{-11}	2.19×10^{-11}	2.82×10^{-10}	1.06×10^{-10}	6.05×10^{-11}	4.23×10^{-5}	4.23×10^{-5}
77	4.46×10^{-10}	2.88×10^{-11}	4.67×10^{-12}	2.24×10^{-10}	2.78×10^{-10}	0	0	9.82×10^{-10}
78	7.12×10^{-10}	8.08×10^{-12}	9.18×10^{-11}	2.63×10^{-10}	2.62×10^{-10}	1.40×10^{-11}	9.77×10^{-6}	9.77×10^{-6}
79	6.56×10^{-10}	7.45×10^{-12}	2.57×10^{-12}	1.06×10^{-10}	1.05×10^{-10}	0	0	8.76×10^{-10}
80	1.97×10^{-10}	1.19×10^{-11}	2.92×10^{-12}	6.41×10^{-11}	4.46×10^{-12}	1.80×10^{-11}	1.26×10^{-5}	1.26×10^{-5}

Table 6. Continued.

81	6.28×10^{-10}	0	1.95×10^{-12}	1.06×10^{-10}	1.48×10^{-10}	0	0	8.84×10^{-10}
82	5.60×10^{-10}	1.05×10^{-10}	9.24×10^{-12}	0	5.92×10^{-11}	0	0	7.34×10^{-10}
83	1.94×10^{-10}	3.79×10^{-11}	6.64×10^{-11}	0	5.81×10^{-10}	2.92×10^{-11}	2.04×10^{-5}	2.04×10^{-5}
84	2.28×10^{-10}	8.53×10^{-12}	1.49×10^{-11}	0	6.99×10^{-10}	3.37×10^{-11}	2.36×10^{-5}	2.36×10^{-5}
85	1.80×10^{-9}	3.10×10^{-11}	1.33×10^{-11}	0	0	2.02×10^{-11}	1.41×10^{-5}	1.41×10^{-5}
86	5.54×10^{-10}	6.02×10^{-11}	2.76×10^{-10}	7.00×10^{-10}	4.85×10^{-11}	0	0	1.64×10^{-9}
87	1.89×10^{-10}	0	3.22×10^{-12}	0	3.29×10^{-11}	0	0	2.25×10^{-10}
Mean	1.06×10^{-9}	7.28×10^{-11}	3.91×10^{-11}	1.04×10^{-10}	1.77×10^{-10}	3.50×10^{-11}	2.42×10^{-5}	2.42×10^{-5}

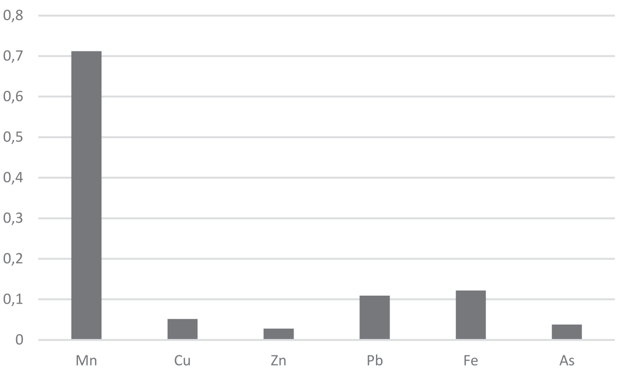

Fig. 3. Non-carcinogenic health risk ratios.

pregnancy-induced iron deficiency anemia [70], and deterioration of child health [71].

Total Health Risk Assessment

The total health risk values at 54 of the sites between 5.47×10^{-6} and 7.18×10^{-4}, whereas the remaining 33 sites had negligible values in relation to total health risk (Table 6). We found that As was the primary pollutant of concern, measuring as 99.99 % of the total health risk.

Water Protection Countermeasures

In total, 70% of the sample points in the study area exceeded the Mn standards for centralized domestic and drinking water sources and industrial and agricultural water use. Mn removal equipment or chemicals must be used in groundwater. Additionally, 8% and 3% of the sample points exceed the standards for Fe and As, respectively. Water treatment facilities could be added to wells or the use of wells could be suspended. Where As content meets the national standards of groundwater to be suitable for use as a centralized domestic and drinking water source; thus, the number of As treatment facilities does not need to be increased. However, at 62% of the sample points, where the health risk was high, monitoring needs to be strengthened and the passage of As into groundwater needs to be obstructed.

Conclusions

The results of groundwater quality study showed that 70% of the sampling points exceeded the minimum safe levels of Mn and, in 8% and 7% of the sampling points, respectively, Fe and As contents exceeded the limits. Heavy metals are evenly distributed in the groundwater source, there was no regional contamination. There is a significant correlation between Mn and Fe, and a significant correlation between Cu and Pb, however, the correlation of the other two heavy metals is not obvious. Groundwater quality was good when using the comprehensive evaluation method. The human health risk study showed that 62% of the sampling sites had carcinogenic risk values exceeding the maximum acceptable level recommended by various institutions, with As being the major carcinogenic factor in the study area. Non-carcinogenic health risk values were below the negligible standard level, and elements were ranked according to their health risk value as Mn>Fe >Pb>Cu>As>Zn, of which Mn accounted for 71%. The carcinogenic health risk is almost entirely caused by the presence of As (99.99%). The focus of future research efforts should be directed towards reducing the content of Mn and monitoring the concentration of As in the groundwater source of Suzhou. The results of this study will assist environmental researchers to increase awareness, business owners and homeowners to receive safe water at a low cost; however, appropriate water safety strategies at the household level need to be created to enhancing water Supply safety. Further research is needed to acquire a better understanding of the individual health risks associated with heavy metals in drinking water sources.

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Conflict of Interest

The authors declare no conflicts of interest.

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