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HUMAN HEALTH RISK ASSESSMENT OF ARSENIC CONTAMINATION IN SOIL AND GROUNDWATER: A CASE STUDY OF CHANGSHU, CHINA

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ABSTRACT: *Arsenic is a highly toxic element that poses significant risks to human health, particularly in steel factory environments where exposure pathways are often overlooked, and studies assessing these risks among workers remain limited. This study evaluates the distribution of arsenic and its associated human health risks within an industrial site, providing both theoretical and practical insights for risk mitigation. A total of 103 soil samples and 10 groundwater samples were collected and analyzed in accordance with the World Health Organization (WHO) and the Chinese technical standards HJ 25.1-2019 and HJ 25.2-2019. Arsenic concentrations in groundwater ranged from 1.3 to 25.5 µg/L, with 99% of samples below the recommended safe limit of 10 µg/L set by WHO, while 10%* exceeded *this limit by 2.5 times; soil concentrations ranged from 6.89 to 26.2 mg/kg. Human health risk assessment across oral, inhalation, and dermal exposure pathways showed non-carcinogenic hazard quotient (HQ) values of 1.10×10^{-3} (oral), 1.45×10^{4} (dermal), and 2.18×10^{-4} (inhalation), with dermal exposure exceeding acceptable limits, while carcinogenic risk (CR) values exceeded the threshold of 1×10^{-4} across all layers, particularly via dermal exposure, with the highest risk in the topsoil layer; overall, dermal contact was identified as the dominant exposure pathway, indicating that mitigation efforts should prioritize reducing dermal exposure to arsenic in steel factory environments.*

KEYWORDS: Arsenic, Carcinogenic and non-carcinogenic risk, Dermal exposure pathway, Human health risk assessment, Industry pollution, Soil and groundwater contamination.

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INTRODUCTION

Environmental pollution remains a critical global challenge, attracting sustained attention from both scientific communities and policymakers due to its implications for ecosystem integrity and human health (Alloway, 2012). Among the various environmental compartments, soil, water, and air are increasingly impacted by anthropogenic activities, with soil often described as a "universal sink" because it accumulates contaminants from multiple sources over time (Kabata-Pendias, 2000). Soil performs indispensable ecological and socio-economic functions, including supporting plant growth, regulating water storage and purification, providing habitat for microorganisms, and serving as a foundation for infrastructure development. Consequently, its degradation through contamination poses significant risks to environmental sustainability and food security.

In recent decades, rapid urbanization and industrialization have intensified the release of pollutants, particularly heavy metals, into the environment, leading to widespread soil contamination (Wuana & Okieimen, 2011). Heavy metals such as arsenic are of particular concern due to their persistence, toxicity, and potential for bioaccumulation. Soil contamination by arsenic not only diminishes soil quality and agricultural productivity but also creates pathways for contaminant migration into groundwater systems, thereby posing serious risks to human health (Smedley & Kinniburgh, 2002). Historically, groundwater was considered a relatively safe source of drinking water due to its natural filtration through soil layers; however, this perception has changed significantly with the increasing detection of toxic elements, especially inorganic arsenic, in aquifers worldwide.

Elevated concentrations of inorganic arsenic in groundwater have been reported across several regions, including Argentina, Bangladesh, Chile, China, India, Mexico, and the United States, where arsenic contamination has been linked to both natural geogenic processes and anthropogenic activities (Ravenscroft et al., 2011; Smedley & Kinniburgh, 2002). The widespread occurrence of arsenic in soil and groundwater underscores the need for site-specific investigations to better understand its distribution, sources, and associated risks. Such studies are essential for developing effective mitigation strategies aimed at protecting soil quality, safeguarding groundwater resources, and minimizing adverse health outcomes.

Despite extensive studies on arsenic contamination in soil and groundwater, most investigations have focused either on environmental concentrations or on human health risks independently. Limited studies have evaluated the coupled behavior of arsenic in soil–groundwater systems within industrial environments while simultaneously assessing site-specific occupational exposure risks. Furthermore, few studies have examined arsenic-related health risks in steel manufacturing facilities in eastern China, where historical industrial activities may contribute to localized contamination.

Therefore, this study investigates arsenic contamination in soil and groundwater at a steel factory site in Changshu, China, by evaluating its concentration levels and spatial distribution, comparing observed concentrations with national and international guideline values, assessing the associated non-carcinogenic and carcinogenic health risks to adult industrial workers through ingestion, inhalation, and dermal exposure pathways, and identifying the dominant exposure routes to support effective risk management and mitigation strategies.

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LITERATURE REVIEW

Arsenic pollution has emerged as a major environmental and public health concern in both developed and developing countries, driven largely by industrialization and intensified mining activities. Increasing awareness of arsenic toxicity has highlighted its association with severe health outcomes, including carcinogenic and systemic effects, particularly through contaminated soil and groundwater pathways (Smedley & Kinniburgh, 2002). Soil, as a fundamental component of terrestrial ecosystems, provides essential functions such as nutrient cycling, plant growth support, and water regulation; however, it also acts as a sink for contaminants, making it highly vulnerable to heavy metal accumulation (Kabata-Pendias, 2000). Consequently, arsenic contamination in soil presents long-term environmental risks due to its persistence, toxicity, and potential for transfer into groundwater systems.

In China, rapid industrialization and urbanization have significantly contributed to widespread soil contamination. Estimates indicate that large areas of agricultural land have been impacted by heavy metals, including arsenic, due to multiple anthropogenic sources such as industrial wastewater discharge, atmospheric deposition, sewage irrigation, livestock waste, and sludge application (Wuana & Okieimen, 2011). These inputs have led to substantial exceedances of soil quality standards in cultivated lands, posing serious risks to food safety, ecological integrity, and human health. The characteristics of heavy metal contamination in soils—namely persistence, accumulation, and irreversibility—further complicate remediation efforts and increase the likelihood of long-term environmental exposure.

The linkage between contaminated soils and groundwater systems is particularly critical for arsenic, as mobilization processes can facilitate its transport into aquifers used for drinking water. Elevated arsenic concentrations in groundwater have been widely reported across various regions, where both geogenic and anthropogenic factors contribute to contamination (Ravenscroft et al., 2009; Smedley & Kinniburgh, 2002). This dual pathway of soil accumulation and groundwater contamination underscores the need for integrated environmental assessment approaches that consider both media simultaneously.

In response to the risks posed by contaminated soils, developed regions such as the United States and Europe have implemented comprehensive regulatory frameworks and remediation programs (USEPA, 2012; Van Liedekerke et al., 2014). For instance, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) established mechanisms for identifying and remediating contaminated sites, while complementary legislation such as the Resource Conservation and Recovery Act (RCRA) and the Superfund Amendments and Reauthorization Act (SARA) strengthened regulatory oversight and remediation standards (Mikelonis et al., 2018). Similarly, the Environmental Protection Act 1990 in the United Kingdom emphasized the "polluter pays" principle, reinforcing accountability in environmental management (Fogleman, 2014). Despite these advances, many developing regions still face limitations in technical capacity, funding, and regulatory enforcement, constraining effective remediation of arsenic-contaminated soils (Wuana & Okieimen, 2011).

While significant progress has been made in understanding and managing heavy metal contamination, important gaps remain in site-specific characterization and risk assessment, particularly concerning arsenic dynamics in coupled soil–groundwater systems. Addressing

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these gaps is essential for developing effective mitigation strategies and protecting environmental and human health.

CONCEPTUAL FRAMEWORK

The conceptual framework of this study is based on the source–pathway–receptor model commonly applied in contaminated land risk assessment. Historical industrial activities serve as the primary source of arsenic contamination. Arsenic released into the environment accumulates in soil and may subsequently migrate into groundwater through leaching processes. Human receptors, represented by adult industrial workers, may be exposed through incidental soil ingestion, dermal contact, and inhalation of contaminated particulates. The resulting exposure doses are used to estimate non-carcinogenic and carcinogenic risks. This framework links contamination sources, environmental transport mechanisms, exposure pathways, and health outcomes, thereby providing a basis for risk characterization and management.

METHODOLOGY

Study Area

Changshu City is located in the southeastern part of Jiangsu Province within the Yangtze River Delta region of China, between 120°33′–121°03′E and 31°33′–31°50′N. The area lies within a highly developed economic corridor influenced by nearby major cities such as Shanghai and Suzhou. The city covers approximately 1,264 km² and is characterized by a dense population, rapid industrialization, and intensive land use activities.

The area is predominantly a low-lying alluvial plain with elevations generally between 3 and 7 m, interspersed with minor hills such as Yushan (263 m). The landscape is dominated by an extensive river network associated with the Taihu Lake basin, with higher drainage density in the southeast and relatively lower density in the northwest.

Changshu experiences a humid subtropical monsoon climate with four distinct seasons, an average annual temperature of about 16.9 °C, and high annual rainfall exceeding 1,600 mm. The region is characterized by interconnected rivers and lakes, including Kuncheng Lake and Shanghu Lake, which are integral to regional water circulation. The combination of intensive industrial activity, dense river networks, and agricultural land use makes the area particularly vulnerable to soil and groundwater contamination, necessitating continuous monitoring of heavy metals such as arsenic.

The study area was selected because it is an active steel manufacturing facility. Steel production processes can contribute to the release and accumulation of potentially toxic elements, including arsenic, in surrounding soil and groundwater through emissions, raw material handling, waste generation, and industrial activities. Furthermore, the presence of workers, ongoing industrial operations, and a shallow groundwater system increases the potential for human and environmental exposure. Therefore, the site provides an appropriate setting for

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evaluating arsenic distribution and assessing potential health risks associated with industrial activities, thereby supporting environmental monitoring and risk management efforts.

DATA SAMPLING AND ANALYSIS

Soil Sampling

Soil samples were collected in summer to minimize the error due to heterogeneity of arsenic distribution. The sampling depth of soil monitoring points was defined as 3.0m; the sample cutting depth was set layer by layer according to the soil structure, with a cut-off length of 20cm. Approximately 103 soil samples were collected.

In order to guarantee the quality of the samples, reduce the disturbance to the pollutants in the soil during the sampling process, and ensure the representativeness and accuracy of the samples, the disturbance-free direct push sampling rig (Geoprobe 7822DT) was used as the sampling equipment.

Table 1: Table showing a summary of soil sampling depth, pH, and arsenic concentration

Spot number	Depth	pH	Longitude	Latitude	As concentration mg/kg
LTS 1	0.3 – 0.5	7.2	120°79′10.85″	31°80′46.37″	14.0
	2.8 – 3.0				14.0
	4.3 – 4.5				14.0
LTS 2	0.3 – 0.5	7.2	120°78′99.02″	31°80′43.21″	14.4
	2.8 – 3.0				14.7
	4.3 – 4.5				14.7
LTS 3	0.3 – 0.5	7.4	120°79′06.95″	31°80′42.54″	13.2
	2.8 – 3.0	7.4			13.4
	4.3 – 4.5	7.3			14.4
LTS 4	0.3 – 0.5	7.4	120°79′05.79″	31°80′53.99″	12.5
	2.8 – 3.0				12.8
	4.3 – 4.5				12.8
LTS 5	0.3 – 0.5	7.4	120°78′98.43″	31°80′61.22″	12.3
	2.8 – 3.0				12.4
	4.3 – 4.5				12.5
LTS 6	0.3 – 0.5	7.4	120°78′97.40″	31°80′50.42″	12
	2.8 – 3.0				12.3
	4.3 – 4.5				12.5
LTS 7	0.3 – 0.5	7.4			11.9
	2.8 – 3.0				12.0

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	4.3 – 4.5		120°78′46.00″	31°80′55.54″	12.0
LTS 8	0.3 – 0.5	7.4			11.5
	2.8 – 3.0				11.5
	4.3 – 4.5		120°78′87.19″	31°80′56.40″	11.9
LTS 9	0.3 – 0.5				11.2
	2.8 – 3.0	7.4			11.2
	4.3 – 4.5		120°78′85.51″	31°80′61.83″	11.3
LTS 10	0.3 – 0.5				10.9
	2.8 – 3.0	7.4			10.9
	4.3 – 4.5		120°78′91.03″	31°80′61.24″	11.0
LTS 11	0.3 – 0.5				10.7
	2.8 – 3.0	7.4			10.8
	4.3 – 4.5		120°78′90.57″	31°80′67.22″	10.9
LTS 12	0.3 – 0.5	7.6			10.4
	2.8 – 3.0	7.6			10.5
	4.3 – 4.5	7.5	120°78′98.25″	31°80′68.11″	10.6
LTS 13	0.3 – 0.5	7.6			10.2
	2.8 – 3.0				10.3
	4.3 – 4.5				10.3
LTS 14	0.3 – 0.5				9.89
	2.8 – 3.0	7.6			9.99
	4.3 – 4.5		120°78′63.82″	31°80′63.39″	10.1
LTS 15	0.3 – 0.5				9.7
	2.8 – 3.0	7.6			9.71
	4.3 – 4.5		120°78′57.66″	31°80′69.58″	9.74
LTS 16	0.3 – 0.5	7.6			9.46
	2.8 – 3.0				9.51
	4.3 – 4.5		120°78′62.94″	31°80′56.26″	9.56
LTS 17	0.3 – 0.5	7.6			9.44
	2.8 – 3.0				9.45
	4.3 – 4.5		120°78′45.32″	31°80′66.80″	9.46
LTS 18	0.3 – 0.5				9.35
	2.8 – 3.0	7.6			9.37
	4.3 – 4.5		120°78′53.19″	31°80′62.00″	9.38
LTS 19	0.3 – 0.5				9.29
	2.8 – 3.0	7.6			9.3
	4.3 – 4.5		120°78′47.97″	31°80′59.16″	9.34
LTS 20	0.3 – 0.5				9.11
	2.8 – 3.0	7.6			9.15
	4.3 – 4.5		120°78′71.47″	31°80′33.24″	9.17
LTS 21	0.3 – 0.5				8.96
	2.8 – 3.0	7.6			9.04
	4.3 – 4.5		120°78′58.60″	31°80′50.92″	9.04
LTS 22	0.3 – 0.5				8.82
	2.8 – 3.0	7.6			8.84

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	4.3 – 4.5		120°78′72.26″	31°80′30.31″	8.84
LTS 23	0.3 – 0.5	7.6	120°79′29.36″	31°80′48.20″	8.8
	2.8 – 3.0				8.8
	4.3 – 4.5				8.8
LTS 24	0.3 – 0.5	7.7	120°79′39.26″	31°80′60.10″	8.74
	2.8 – 3.0	7.7			8.74
	4.3 – 4.5	7.6			8.79
LTS 25	0.3 – 0.5	7.7	120°80′29.50″	31°80′64.88″	8.6
	2.8 – 3.0				8.66
	4.3 – 4.5				8.68
LTS 26	0.3 – 0.5	7.8	120°80′43.36″	31°80′60.20″	8.5
	2.8 – 3.0				8.53
	4.3 – 4.5				8.58
LTS 27	0.3 – 0.5	7.8	120°83′22.01″	31°80′45.99″	8.41
	2.8 – 3.0				8.43
	4.3 – 4.5				8.48
LTS 28	0.3 – 0.5	7.8	120°83′77.86″	31°80′55.22″	8.36
	2.8 – 3.0				8.37
	4.3 – 4.5				8.37
LTS 29	0.3 – 0.5	7.8	120°81′31.09″	31°80′42.88″	8.22
	2.8 – 3.0				8.3
	4.3 – 4.5				8.34
LTS 30	0.3 – 0.5	7.8	120°81′77.12″	31°80′42.20″	8.13
	2.8 – 3.0				8.13
	4.3 – 4.5				8.21
LTS 31	0.3 – 0.5	7.8	120°86′29.64″	31°80′57.53″	8.04
	2.8 – 3.0				8.08
	4.3 – 4.5				8.11
LTS 32	0.3 – 0.5	7.8	120°84′41.07″	31°80′69.20″	7.96
	2.8 – 3.0				7.98
	4.3 – 4.5				8.03
LTS 33	0.3 – 0.5	8	120°84′79.33″	31°80′53.40″	6.89
	2.8 – 3.0				6.9
	4.3 – 4.5				7.03
LTS 34	0 – 0.2	7	120°87′02.45″	31°80′48.20″	15.4
LTS 35	0 – 0.2	7	120°87′29.19″	31°80′55.01″	17.4
LTS 36	0 – 0.2	6.8	120°87′67.84″	31°80′58.22″	23.1
LTS 37	0 – 0.2	6.6	120°88′33.76″	31°80′51.20″	26.2

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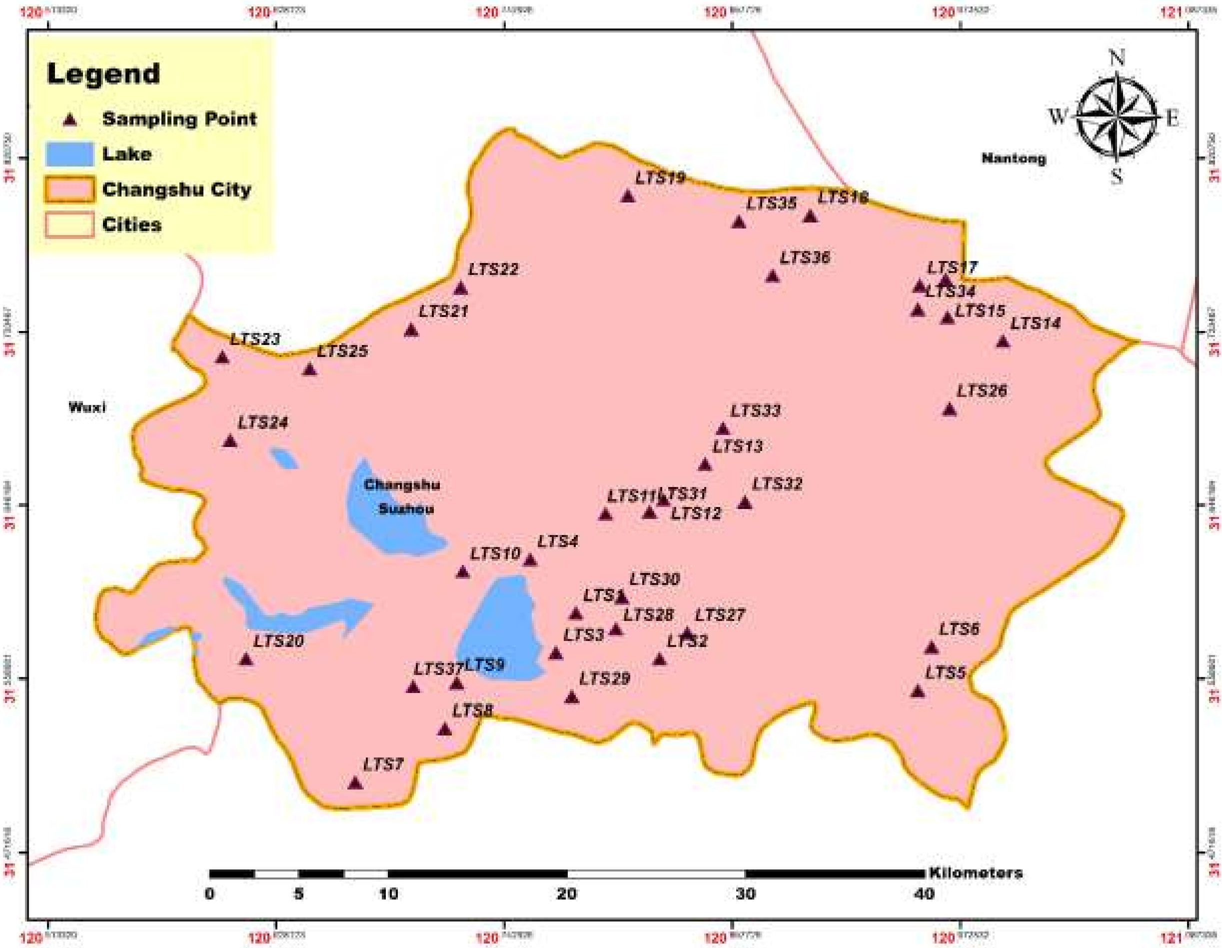
Figure 1: Overview of study area and location of sampling points.



Groundwater Sampling and Collection

Approximately 10 groundwater monitoring wells were constructed to check the level of arsenic contamination in the study area (Table 2). The contour map of shallow groundwater of the site was established (Figure 3). It can be seen from the figure that the groundwater level is higher in the south and lower in the north, and the water approximately flows from south to north. The construction process of groundwater monitoring wells included drilling, installation of filter pipes and well casings, filter material filling, sealing, and fixing procedures. Groundwater monitoring wells were constructed using Geoprobe 7822DT, and groundwater monitoring well casings were installed after drilling. The structure of the monitoring well is shown in Figure 2.

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Figure 2: Real shot of the well (left) and structural sketch of the monitoring well (right)

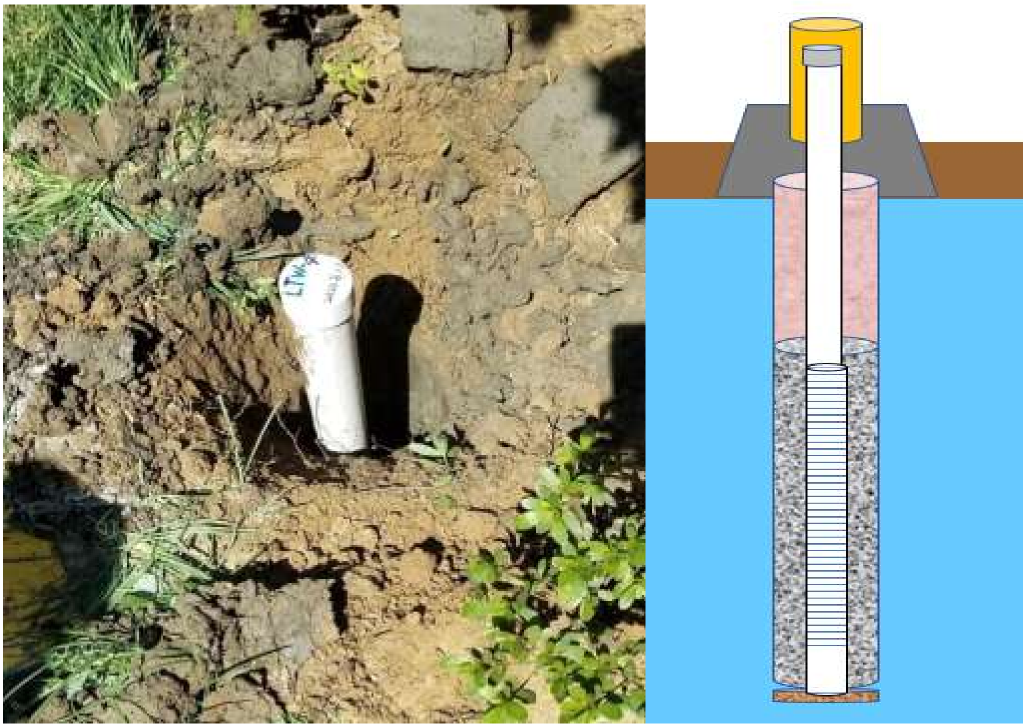

Table 2: Burial Depth at the Stable Water Level of Groundwater in the study area

Monitoring Well No.	Monitoring Well Depth (m)	Floral Tube Position (m)	Stable Water Level (m)	Arsenic concentration (µg/L)
FW-1	6	3-6	1.35	4.5
FW-2	6	3-6	1.46	25.5
FW-3	6	3-6	1.28	7.8
FW-4	6	3-6	1.36	5.3
FW-5	6	3-6	1.86	5.9
FW-6	6	3-6	1.75	1.3
FW-7	6	3-6	1.39	1.6
FW-8	6	3-6	1.28	1.4
FW-9	6	3-6	1.84	5.2
FW-10	6	3-6	1.47	4.6

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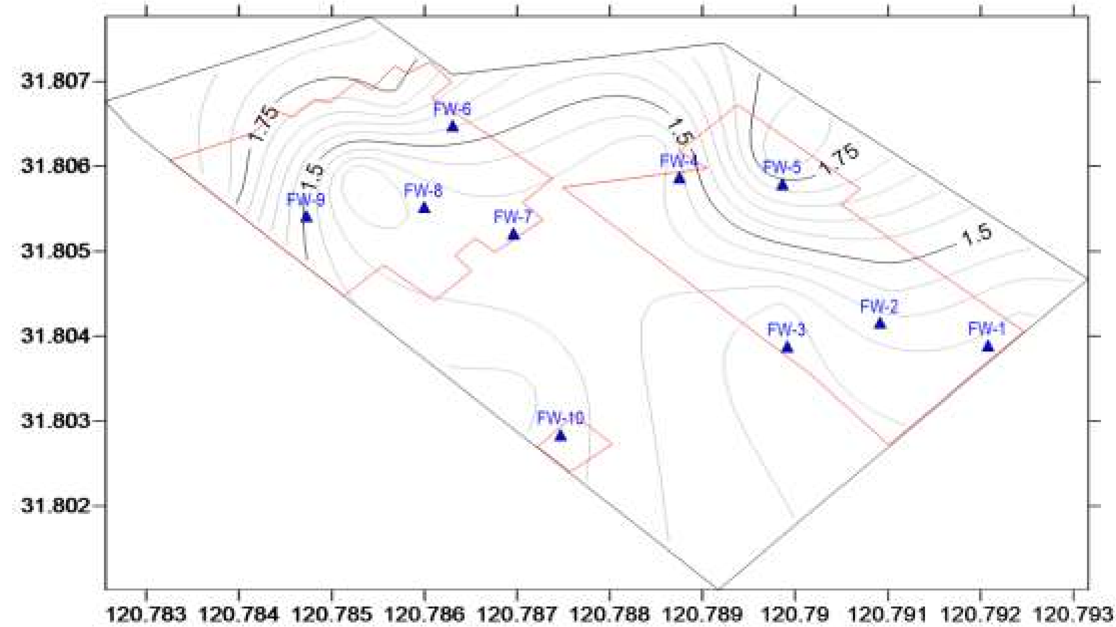
Figure 3: Groundwater level contour map of the study area



Laboratory Analysis

Soil and groundwater samples were submitted to a certified third-party environmental laboratory for arsenic analysis. Sample collection, preservation, transportation, and laboratory analysis were conducted in accordance with the Chinese Technical Guidelines for Environmental Site Investigation (HJ 25.1-2019) and Technical Guidelines for Monitoring During Risk Control and Remediation of Contaminated Sites (HJ 25.2-2019). Laboratory analytical procedures followed the quality assurance and quality control requirements established by the testing laboratory to ensure the reliability and accuracy of analytical results.

Quality Assurance and Quality Control (QA/QC)

To ensure data quality, standardized sampling protocols were followed throughout field investigations. Samples were properly labeled, preserved, and transported under controlled conditions to prevent contamination and degradation. Quality control measures implemented by the accredited laboratory included routine instrument calibration, analysis of blanks and duplicate samples, and verification against applicable analytical standards. Only validated analytical results were used in subsequent risk assessment calculations.

Baseline Human Health Risk Assessment (HHRA)

Exposure Pathways

Human exposure to soil contaminants occurs primarily through ingestion, inhalation, and dermal contact. In many cases, toxicological data are available for only one route of exposure, typically ingestion, which introduces uncertainty when assessing multi-pathway exposure scenarios. Adjustments for relative absorption efficiency across pathways may be applied where toxicological endpoints are consistent; however, such adjustments are often limited by insufficient data for most contaminants (Kasamas et al., 1998).

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Fine-grained soil particles tend to adhere more readily to the skin, potentially resulting in higher contaminant concentrations in adhered particles compared to bulk soil. This enrichment effect may be significant, particularly for metals in sandy soils, and should be considered in exposure assessments involving ingestion (hand-to-mouth transfer), dermal contact, and inhalation pathways. Empirical studies have proposed correction factors based on soil type, with values ranging from 1.5 for clay soils to 10 for sandy soils (Sheppard & Evenden, 1992). Despite these findings, the incorporation of such factors into regulatory frameworks varies across countries.

Site-Specific Exposure Scenario

Baseline HHRA represents the initial phase of risk evaluation for the study site. Given the designated industrial land use, adult outdoor workers were identified as the primary receptors under the exposure scenario. Exposure assessment considered three principal pathways: incidental soil ingestion, dermal contact with contaminated soil, and inhalation of soil particulates.

Average daily intake (ADI) for each pathway was estimated using standard exposure models (Eqs. 1–3), with parameter values and assumptions summarized in Table 3. These estimates form the basis for subsequent risk characterization and evaluation of potential human health impacts associated with arsenic contamination.

$$CI = \frac{CS \times EF \times IRO \times CFI \times RBA}{BW \times AT} \text{ ingestion exposure (1)}$$

$$AD = \frac{CS \times EF \times ED \times SA \times AF \times ABS_d \times CF1}{BW \times AT} \text{ dermal exposure (2)}$$

$$PE = \frac{CS \times EF \times ED \times ET}{PEF \times AT} \text{ inhalation exposure (3)}$$

where CI is contaminant ingestion intake (mg/kg/day), CS is concentration in soil (mg/kg), AD is absorbed dose (mg/kg/day), and PE is pulmonary exposure (mg/m^3). The non-cancer risks and cancer risks were assessed separately. For non-cancer risks, the hazard quotients (HQ) were applied depending on the exposure pathway:

Table 3: Calculation parameters used in human health risk assessment (Li et al., 2019; Wcisło et al., 2016)

Parameter	Symbol	Units	Value
Body weight	BW	Kg	61.5[a] (Adult outdoor workers)
Averaging time	AT	Days	14,600 (Non-carcinogenic), 25,550 (Cancer)
Exposure time	ET	h/h	0.33(Adult outdoor workers)
Exposure duration	ED	Years	40[c] (Adult outdoor workers)

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Exposure frequency	EF	Days/year	240[b]
Relative bioavailability factor	RBA	Unitless	0.6
Ingestion rate	IR_o	mg/day	100 (Adult outdoor workers)
Conversion factor	CF_1	kg/mg	1E – 06
Skin surface area exposed	SA	cm^2	3300 (Adult outdoor workers)
Adherence factor to skin	AF	$mg/cm^2/day$	0.2
Dermal absorption factor	ABS_d	Unitless	0.03
Gastrointestinal absorption factor	ABS_{GI}	Unitless	1
Particle emission factor	PEF	m^3/kg	1.36E + 09
Ingestion reference values	RfD_o	mg/kg/day	3.00E – 04
Dermal reference values	RfD_d	mg/kg/day	3.00E – 04
Inhalation reference values	RfD_c	mg/m^3	1.50E -05
Oral cancer slope factor	CSF_o	$(mg/kg/d)^{-1}$	1.5
Dermal adjusted cancer factor Slope factor	CSF_d/ABS_{GI}	$(mg/kg/d)^{-1}$	1.5
Inhalation unit risk	IUR	$(mg/m^3)^{-1}$	4.3

[a]BW value was obtained from Chinese residents' nutrition and chronic disease status reports (Lu et al., 2015)

[b]240 working days per year was assumed
[c]40 year's work period was assumed due to the lack of relevant local statistical data for this area

$HQ_o = \frac{CI}{RfD_o}$ oral exposure (4)

$HQ_d = \frac{AD}{RfD_d}$ dermal exposure (5)

Where $RfD_d = RfD_o \times ABS_{GI}$ (5a)

$HQ_{inh} = \frac{PE}{RfD_c}$ inhalation exposure (6)

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If the HQs exceeded the non-cancer target risk of one, these values express how many times the sample contamination exceeds the reference doses, which will raise concern for potential non-cancer effects. The hazard index (HI) is then calculated by summing up the HQs calculated for multiple exposure pathways.

Cancer risks (CR) were assessed by multiplying the predicted slope factor. The slope factor (SF) is made up of oral slope factors for ingestion, dermal contact, and inhalation unit risk (IUR). The CR values were applied depending on the exposure pathway:

$CR_o = CI \times CSF_o$ oral exposure (7)

$CR_d = AD \times CSF_d$ dermal exposure (8)

where $CSF_d = \frac{CSF_o}{ABS_{GI}}$ (8a)

$CR_{inh} = PE \times IUR$ inhalation exposure (9)

If the CR value is lower than 1E - 06, the cancer risk is acceptable for individual contaminants. If the CR value is between 1E - 06 and 1E - 04, the cancer risk is acceptable for the combination of contaminants (cumulative site risk); if the CR value exceeds 1E - 04, then the clean-up decisions at contaminated sites are recommended.

RESULTS

Soil Samples

Soil arsenic concentrations ranged from 6.89 to 26.2 mg/kg, with all measured values below the Chinese industrial soil screening value of 60 mg/kg. Although regulatory exceedances were not observed, elevated concentrations were predominantly associated with surface soils (0–0.2 m), suggesting potential accumulation from historical industrial activities and atmospheric deposition.

Arsenic concentrations generally decreased with depth, indicating limited vertical migration within the investigated profile. The observed pH range of 6.6–8.0 may also contribute to reduced arsenic mobility under near-neutral conditions.

Figure 4 illustrates the spatial distribution of mean arsenic concentrations across the study area. Elevated arsenic concentrations were observed in localized portions of the site, particularly around the active industrial operation areas, while relatively lower concentrations were observed in peripheral locations.

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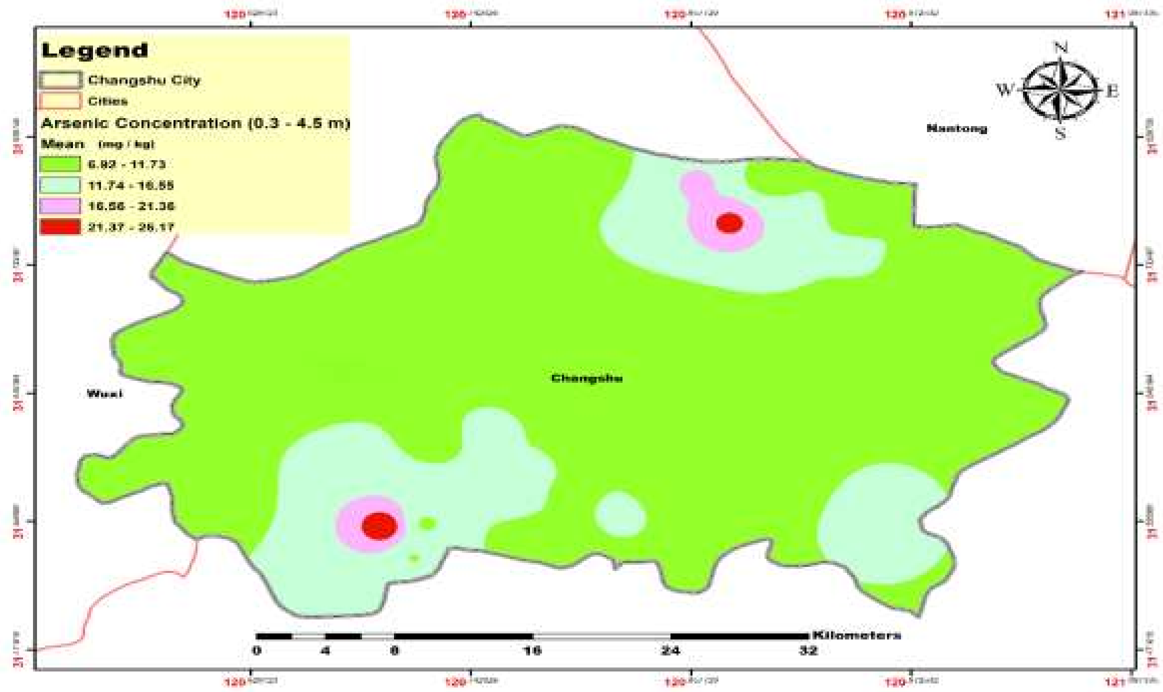
Figure 4: Spatial distribution of mean arsenic concentrations (mg/kg) in soils across the study area showing localized zones of elevated arsenic accumulation.



Groundwater samples

Groundwater arsenic concentrations ranged from 1.3 to 25.5 µg/L. Nine of the ten monitoring wells contained arsenic concentrations below the WHO drinking water guideline of 10 µg/L, while one monitoring well exceeded the guideline value. This localized exceedance suggests the existence of a potential contamination hotspot rather than widespread groundwater contamination across the site.

Groundwater flow patterns indicate south-to-north movement, which may influence future contaminant transport and should be considered in long-term monitoring programs.

Baseline Human Health Risk Assessment

Table 4 presents the mean of non-cancer and cancer risk values in soil for the study area. The total distribution of arsenic in the study area is presented in Figure 4.

Table 4: Summary of non-cancer and cancer risk values in different layers

Layer	Non-cancer risk (unitless)				Cancer risk (unitless)			
	HQ^{a}_{oral}	HQ^{a}_{dermal}	$HQ^{a}_{inhalation}$	Total HI^{a}	CR^{b}_{oral}	CR^{b}_{dermal}	$CR^{b}_{inhalation}$	Total CR^{b}
1	1.10E -03	1.45E + 04	2.18E – 04	1.45E + 04	2.82E - 07	3.72E + 00	8.05E - 09	3.72E + 00

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2	5.34E – 04	7.05E + 03	1.06E – 04	7.05E + 03	1.37E - 07	1.81E + 00	3.91E - 09	1.81E + 00
3	5.38E – 04	7.10E + 03	1.07E – 04	7.10E + 03	1.38E - 07	1.83E + 00	3.95E - 09	1.83E + 00
4	5.22E – 04	6.89E + 03	1.04E – 04	6.89E + 03	1.34E - 07	1.77E + 00	3.83E - 09	1.77E + 00

[a]If HQs>1, these values express how many times the sample contamination exceeds the reference doses
[b]If the CR <1E -06, the cancer risk is acceptable for individual contaminants; if 1E -06<CR <1E -04, the cancer risk is acceptable for a combination of contaminants; if CR>1E-04, the cancer risk is not acceptable.

Layers 1, 2, 3, and 4 represent the four different depths of soil sampling (0.3 – 0.5, 2.8 – 3.0, 4.3 – 4.5, 0 – 0.2) as shown in Table 1.

DISCUSSION

The highest HI was observed in the surface layer (Layer 1), indicating decreasing non-carcinogenic risk with depth. Among the exposure pathways, dermal contact contributed the most to arsenic exposure, followed by oral ingestion and inhalation. The HQ values for oral, dermal, and inhalation exposure pathways were 1.10×10^{-3}, 1.45×10^{4}, and 2.18×10^{-4}, respectively. All HQ values were below the threshold value of 1, suggesting no significant non-carcinogenic risk for oral and inhalation exposure; however, dermal exposure contributed the dominant share of total HI and represented the most important exposure route.

The CR values exceeded the acceptable risk threshold (1×10^{-4}) in all soil layers, indicating potential carcinogenic concern in the study area. For the oral and inhalation pathways, CR values remained within acceptable limits for each exposure route ($CR < 1 \times 10^{-6}$). In contrast, dermal exposure consistently exceeded the acceptable cancer risk level across all layers, with the highest value recorded in Layer 1. This indicates that dermal contact represents the principal pathway contributing to carcinogenic risk for arsenic in the study area.

Although measured arsenic concentrations were below the industrial soil screening value of 60 mg/kg, elevated carcinogenic risk estimates were obtained through the risk assessment model. This apparent inconsistency arises because risk calculations incorporate not only contaminant concentrations but also toxicity factors, exposure duration, exposure frequency, dermal absorption factors, and cancer slope factors. Consequently, contaminants present at concentrations below regulatory screening levels may still generate elevated risk estimates when exposure is assumed to occur over long periods.

The predominance of dermal exposure in the calculated risks is attributable to the exposure assumptions adopted from the Chinese contaminated site risk assessment guidelines. These assumptions include prolonged occupational exposure and conservative dermal absorption parameters, which substantially increase cumulative lifetime risk estimates. Therefore, the elevated risk values should be interpreted as precautionary estimates rather than direct indicators of actual health outcomes.

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Similar findings have been reported by Li et al. (2019), who observed elevated health risk estimates despite relatively moderate arsenic concentrations due to the high toxicity of arsenic and conservative exposure assumptions incorporated into risk assessment models. The present study further demonstrates that risk-based assessment may identify potential health concerns even where concentration-based regulatory thresholds are not exceeded.

Overall, the results suggest that while oral and inhalation exposures are of limited concern under current conditions, dermal exposure to arsenic-contaminated soils may pose both non-carcinogenic and carcinogenic risks, particularly in surface soils. These findings highlight the need for targeted risk management and exposure mitigation strategies for occupational and surrounding populations.

CONCLUSION

This study investigated arsenic contamination in soil and groundwater at an industrial site in Changshu, China, and evaluated associated human health risks. Although all soil concentrations were below the Chinese industrial screening value and most groundwater samples complied with WHO drinking water guidelines, risk assessment identified potential carcinogenic concerns, particularly through dermal exposure pathways.

The findings demonstrate that compliance with concentration-based standards does not necessarily eliminate potential health risks when long-term exposure is considered. Surface soils represented the greatest contributor to estimated risk, highlighting the importance of controlling direct human contact with contaminated soils in industrial environments.

The study contributes site-specific evidence on arsenic behavior in coupled soil–groundwater systems. It provides a scientific basis for risk management, monitoring, and remediation planning in industrial areas affected by historical contamination.

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