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HEAVY METAL POLLUTION IN GROUNDWATER: ASSESSING ENVIRONMENTAL AND HUMAN HEALTH RISKS NEAR THE MASS IRON AND STEEL PLANT, BAZIAN, SULAYMANIYAH, IRAQ

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Abstract

This study investigates the environmental and public health impacts of heavy metal pollution in groundwater originating from Iraq Mass Steel Smelting facilities and adjacent regions in the Bazian Sub-basin. Twenty groundwater samples were collected and tested for iron (Fe), lead (Pb), chromium (Cr), copper (Cu), aluminum (Al), nickel (Ni), and cadmium (Cd) via Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The results demonstrated that Pb and Al concentrations surpassed the safety limitations set by the World Health Organization (WHO), although the levels of other metals remained below permissible limits. To assess the extent of contamination and associated health risks, several indices were utilized, including the Heavy Metal Pollution Index (HPI), Metal Index (MI), Hazard Quotient (HQ), Hazard Index (HI), and Carcinogenic Risk (CR). The results indicated substantial pollution levels, with HPI varying from 290.31 to 491.58 and MI from 14.69 to 25.57. Lead was the only heavy metal with an HQ and HI over one, whilst all other metals adhered to acceptable limits. This underscores the possible health hazards linked to lead pollution. The Total Carcinogenic Risk (TCR) values exceeded tolerable limits (10^{-4}). Children were identified as being at a higher risk than adults. Multivariate statistical methods, encompassing cluster analysis (CA) and principal component analysis (PCA), reveal that groundwater contamination in the research area is predominantly driven by industrial and agricultural activity. The Iraq Mass Steel Smelting facility is recognized as a significant source of heavy metal contamination. The outputs have shown that immediate action is required to address contamination concerns and restore the water supply for human consumption, agricultural use, and industry.

Keywords: Groundwater pollution; Trace element; Health risk; Environmental risk assessment; Pollution indices.

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1. Introduction

An important freshwater resource that sustains ecological balance as well as human life and development is groundwater (Shi et al., 2024). Groundwater is susceptible to pollution when it traverses aquifers that already contain various contaminants. As a result, pollutants could potentially compromise water quality by penetrating aquifers from both surface and subterranean sources (Talpur et al., 2024; Talpur et al., 2025). Heavy metals are extremely toxic at low quantities, making their poisoning of groundwater a significant environmental concern (Ayejoto et al., 2024; Ugwu et al., 2024). The industrial and anthropogenic activities have increased human exposure to heavy metals, which have had serious detrimental health effects (Niu et al., 2023). Many contamination releases, such as direct air deposition, natural weathering, agricultural pesticide and fertilizer releases, waste from homes, industrial waste, and municipal waste, can all cause metal contamination (Rashid et al., 2023). Due to their environmental longevity and severe toxicity, elevated concentrations of heavy metals in groundwater might jeopardize human health through ingestion and dermal exposure (Shi et al., 2022). A comprehensive evaluation of heavy metal pollution in groundwater is essential for safeguarding drinking water and reducing potential health hazards. Extended exposure to heavy metals can significantly adversely affect human health (Tyczyńska et al., 2024). Cu, Zn, Mn, and Fe are vital micronutrients; however, elevated levels of these metals can present considerable health hazards (Ceramella et al., 2024). Cr, Pb, Ni, and Cd are classified as heavy metals with carcinogenic properties due to their high toxicity, ability to induce genetic mutations, and link to cancer formation (Jiang et al., 2021; Sadeghi et al., 2022). The HPI is a crucial metric for analyzing the cumulative effects of heavy metal contamination, assessing overall water quality, and determining its appropriateness for human consumption (Singh et al., 2023; Zainudin et al., 2023). The MI methodology was utilized alongside the HPI to perform a comprehensive evaluation of heavy metal contamination and its effects on water quality (Liang et al., 2011). A health risk assessment entails evaluating the probability of a hazardous source releasing risk agents into the environment, determining the degree of their interaction with human-environment interfaces, and analyzing the subsequent health effects of exposure (Alidadi et al., 2019; Toi Bissang et al., 2024). These evaluations take into consideration the many toxicological properties of the chemical components involved in order to differentiate between carcinogenic and non-carcinogenic dangers (Sun et al., 2024). The current study assessed groundwater implications on the smelting site and the adjacent area to solve these challenges. Inside the construction site and surrounding neighborhoods, sampling was done. The Direct Reduced Iron (DRI) plant is vital to maximizing local iron ore and waste metal usage. However, poorly managed waste outputs from this facility may threaten groundwater quality. This study examines the occurrence of Al, Cr, Cu, Fe, Pb, Ni, and Cd in groundwater sources. The primary objectives are (1) to assess the concentration levels and spatial distribution of heavy metals using key assessment indices, specifically the HPI and MI, and (2) to evaluate the associated health risks by analyzing both carcinogenic and non-carcinogenic effects across various age groups, including adults and children.

2. Materials and methods

2.1. Study area

This study focuses on the Iraq Mass Iron and Steel Plant, located in the Bazian Sub-basin, approximately 38 kilometers west of Sulaymaniyah City. The facility covers an extensive area of about 10 km² (Figure 1). The sub-basin, which is a crucial part of the larger Basara Basin, is renowned for its lush terrain, which makes it ideal for agriculture, and it acts as the center of several industrial activities and resources. Geographically, the area is bounded between the latitude N 35°38′39″ and N 35°41′09″ and the longitude E 45°03′45″ and E 45°01′15″. The Mass Iraq Iron and Steel Industry was created in 2015 to develop the regional industry. However, its industrial waste management, hazardous material use, and other pollution sources threaten nearby groundwater quality. Industrial operations proximity to groundwater recharge zones and the subsurface's porosity increase the potential of aquifer contamination. The Mediterranean climate has long, hot, and arid summers and cold, rainy winters.

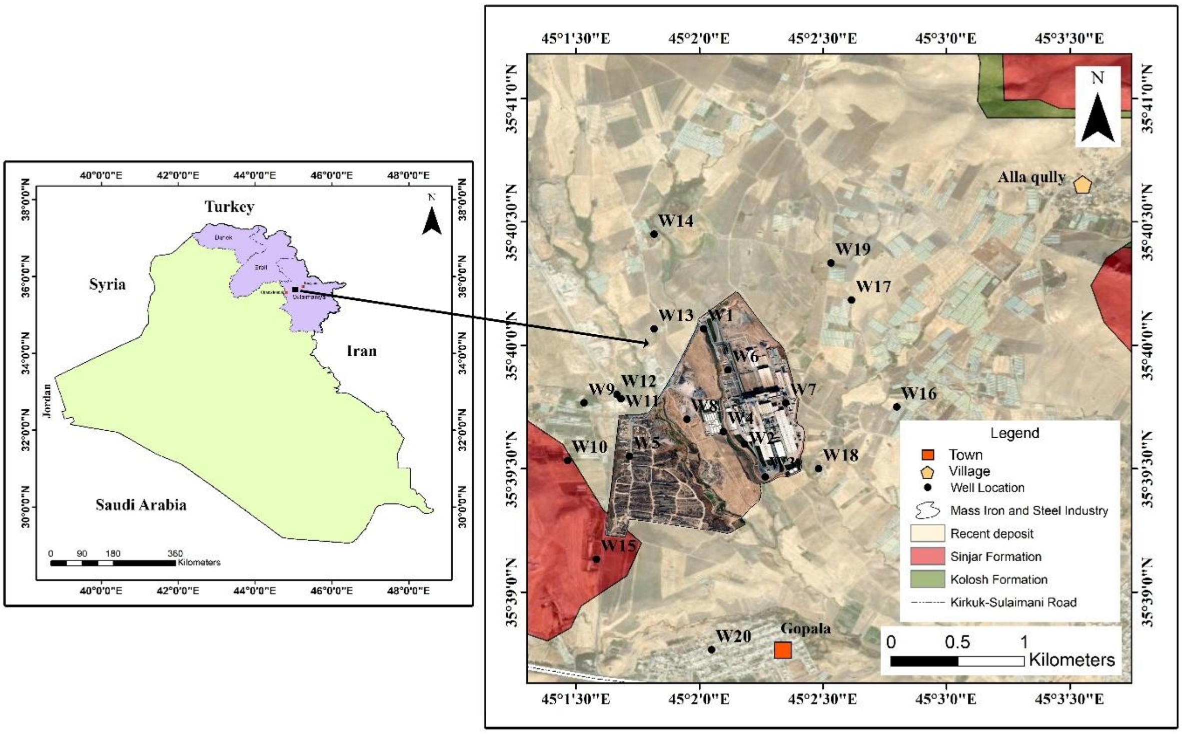

Figure 1. The location and geological map show the groundwater sampling points.

For the past two decades, Bazian Meteorological Station data show a mean annual temperature of 17°C. July averages 33°C, whereas January averages 1°C. The research region averages 671 mm of precipitation and 1865.90 mm of evapotranspiration. The plains land is mostly used for agriculture, and groundwater extraction for irrigation, industry, and domestic usage has grown (Mohammed et al., 2020). Geologically, the Kolosh Formation (Paleocene) is the oldest exposed geological formation in the region. It consists of an alternation of thin-bedded sandstone, siltstone, and calcareous shale. The Sinjar Formation (Paleocene – Lower Eocene) is characterized by thick to massive beds of yellowish-gray reefal limestone. The youngest deposits in the area are the Resent deposits, which cover most of the plain area (Ahmed & Al-Manmi, 2019; Hamamin, 2011; Hamarashid et al., 2022). From a hydrogeological perspective, the Bazian Sub-basin comprises three distinct aquifer systems (Hamamin, 2018; Mohammed et al., 2022). The water-bearing units are characterised by heterogeneous and anisotropic properties: the Eocene Karstic Fissured Aquifer (EKFA), the Alluvium Intergranular Aquifer (AIA), and the Aquiclude (Figure 2). The examined region is situated inside the Alluvium Intergranular Aquifer (AIA), distinguished by fragmented sediments including gravel, sand, silt, and clay. The sediments offer substantial storage and permeability for groundwater flow, establishing the AIA as the principal aquifer supplying wells in the area. The hydraulic gradient and intergranular porosity of the deposits influence groundwater flow in this aquifer (Hamamin & Ali, 2013). Groundwater in the study area flows generally from the north and northwest toward the south and southeast (Figure 2).

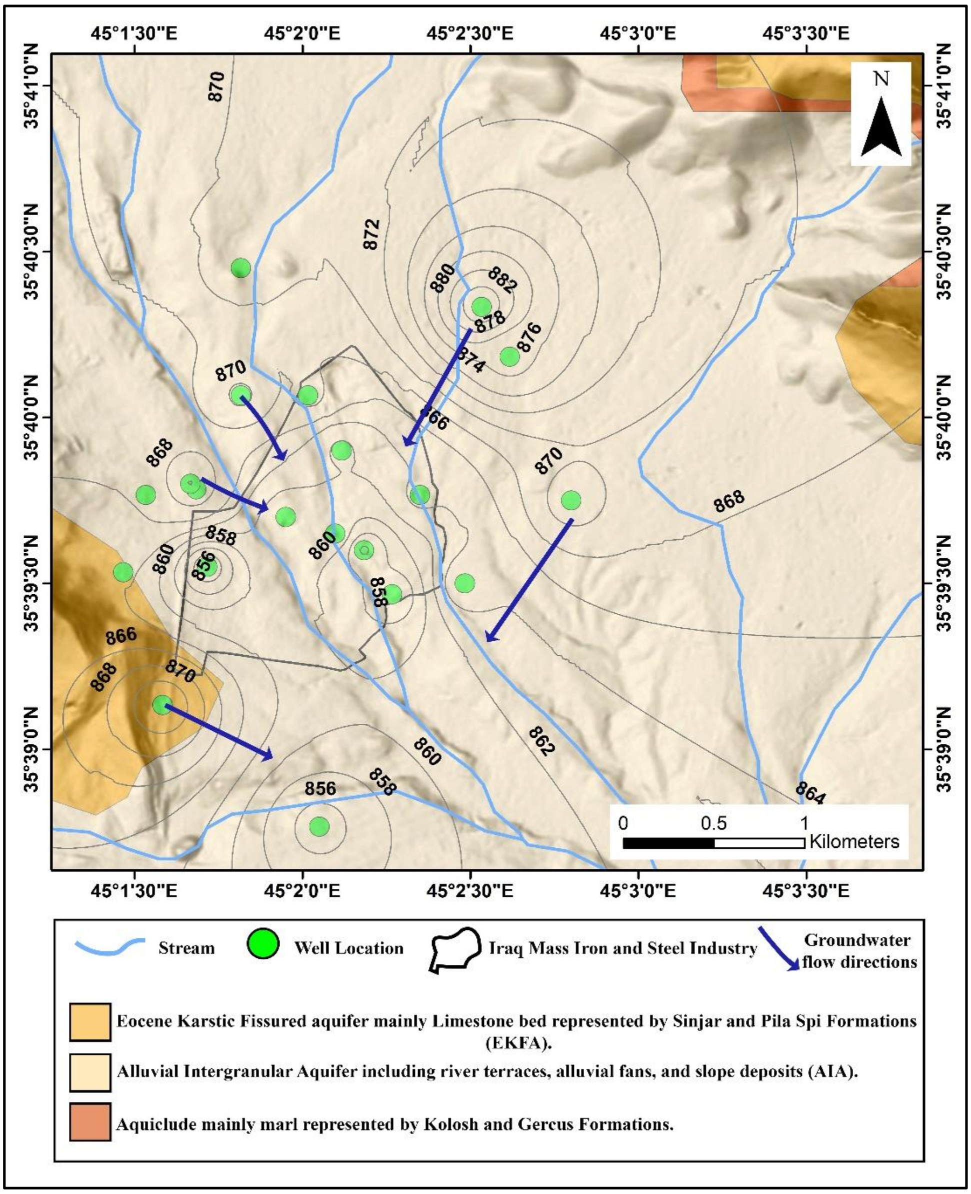

Figure 2. Hydrogeological map of the study area.

2.2. Sampling Collection and Analysis

In September 2024, twenty groundwater samples were obtained from several sites, including the Mass Iraq for Iron and Steel Industry Company, the neighboring scrap yard, and nearby wells (Figure 1). The depths of the selected wells range from 65 to 202 meters. Sampling sites were deliberately chosen to evaluate the influence of industrial operations on the condition of groundwater. Particular focus was directed toward operations at the Mass Iraq Iron and Steel Industry Company, the collection of scrap metal and iron in the yard, and other associated industrial processes. To avert contamination during heavy metal analysis, 500 mL glass bottles, pre-rinsed with distilled water, were employed. Water samples were collected, labeled, and transported in insulated coolers, ensuring a consistent temperature of 4°C. The samples were subsequently filtered with a 0.45-µm membrane to enable trace element analysis. To remove contaminants, 50 mL of the filtrate was discarded, and the remainder was transferred into pre-cleaned polypropylene containers. The sample was subsequently acidified with pure HNO_3, reducing the pH to 2 or lower to assure preservation and inhibit the precipitation of trace elements. Trace elements, including Cu, Pb, Ni, Cr, Cd, Fe, and Al, were examined in water samples following established analytical protocols (Association, 1926; Rice et al., 2012) utilizing ICP-AES (Perkin Elmer Optima 2100DV). The samples were analyzed at the University of Sulaimani, Department of Chemistry. Where necessary, water quality evaluation, sampling, and instrumental precision inaccuracies were resolved. After five samples, a standard solution was examined to verify instrument accuracy. Analytical-grade standard solutions were always used, with deionized water as a blank.

2.3. Pollution Measurement Indicators

2.3.1. Heavy Metal Pollution Index (HPI)

The HPI is known as a key tool to quantify heavy metal contamination in aquatic ecosystems (Al-Hejuje et al., 2017). Groundwater contamination levels were assessed by calculating evaluation scores using a weighted arithmetic mean method (Sheng et al., 2022). According to Mohan et al. (1996), the HPI model was computed using the following approach:

$$HPI = \frac{\sum_{i=1}^{n} WiQi}{\sum_{i=1}^{n} Wi} \quad (1)$$

The parameters Wi and Qi represent unit weights and sub-indices allocated to the chosen trace elements specified in Table 3. This study investigates seven trace heavy metals (n=7). The sub-indices (Wi) and (Qi) are obtained by Equations (2) and (3):

$$Wi = \frac{K}{Si} \quad (2)$$

In this context, k denotes a proportionality constant. For the sake of simplifying calculations, its value is designated as 1 (Wanda et al., 2012).

$$Qi = \sum_{i=1}^{n} \frac{|(Mi - Ii)|}{(Si - Ii)} \times 100 \quad (3)$$

Mi represents the monitored concentration of the ith heavy metal parameter in µg/l, whereas the concentration limits, namely the standard permitted value (Si) and the maximum intended value (Ii), for each parameter were established according to the standards set by the WHO (2017), to determine the HPI with the latest water quality data, consult Table 3. The HPI result under 100 signifies a negligible amount of heavy metal pollution. When this value attains 100, it signifies a crucial barrier beyond which detrimental health impacts are probable. A HPI result beyond 100 indicates that the water is not suitable for consumption (Badeenezhad et al., 2023; Mohan et al., 1996; Prasad & Bose, 2001). The categorization of waters according to HPI comprises two classes, as presented in Table 1.

Table 1. HPI categorization.

HPI Values	Contamination level
<100	Low water contamination
>100	High water contamination

2.3.2. Metal Index (MI)

The MI functions as an indicator for assessing water quality concerning metal pollution. It is based on a comprehensive analysis of trends indicative of the current condition (Edet & Offiong, 2002). The MI is calculated by comparing the ratio of each metal's concentration in water to its specified maximum acceptable concentration (MACi), as seen in Table 3. A preliminary definition of the MI for potable water is as follows (Tamasi & Cini, 2004):

$$MI = \sum_{i=1}^{n} \frac{Ci}{MACi} \quad (4)$$

In this context, 'Ci' denotes the measured concentration of the ith parameter, whereas 'MACi' signifies the upper permissible limit for each metal. The symbol 'i' denotes the corresponding sample. The calculated values were categorized into six unique categories to represent groundwater contamination levels (Ojekunle et al., 2016), as outlined in Table 2.

Table 2. Categorization of the MI.

MI Value	MI Classification
<0.3	Very pure
0.3 – 1.0	pure
1.0 – 2.0	Slightly affected
2.0 – 4.0	Moderately affected
4.0 – 6.0	Strongly affected
>6.0	Seriously affected

Table 3. The WHO (2017) standards for heavy metals and weight scores.

Heavy metals	Mean (μg//L)	Si (μg/L)	Unit weight Wi=(K/Si)	MACi (μg /L)
Fe	52.387	300	0.0033	300
Ni	27.333	70	0.0143	70
Al	351.573	200	0.0050	200
Cu	148.488	2000	0.0005	2000
Cr	23.686	50	0.0200	50
Cd	1.190	3	0.3333	3
Pb	169.080	10	0.1000	10

2.4. Assessment of Human Health Risks

Human health risk assessment evaluates the impact of environmental contaminants on public health. The USEPA stands for the United States Environmental Protection Agency, which conducts assessments that include gathering data, analytical evaluation, exposure assessment, hazard analysis, and risk classification. Carcinogenic (CR) and non-carcinogenic (NCR) risks exist (EPA, 1989). Health risks are assessed using the HQ, HI, and CR. Pb, Cr, Cd, Fe, Al, Cu, and Ni were evaluated for non-carcinogenic risk in children and adults, while Pb, Cr, Cd, and Ni were analyzed for carcinogenic dangers.

2.4.1. Exposure assessment

This assessment evaluates exposure by measuring daily heavy metal (HM) consumption. Trace metals can be inhaled, absorbed, or ingested. Water consumption usually occurs by ingestion or skin contact (De Miguel et al., 2007; EPA, 2004; Mahato et al., 2016; Wu et al., 2009). The exposure assessment was calculated using the following equations:

$$ADDi = \frac{(Ci \times IR \times EF \times ED)}{(BW \times AT)} \quad (5)$$

$$ADDd = \frac{(Ci \times SA \times Kp \times ET \times EF \times ED \times CF)}{(BW \times AT)} \quad (6)$$

The ingestion and dermal absorption average daily doses are ADDi (µg/kg/day) and ADDd (µg/kg/day), respectively. Equations (5) and (6) provide 'Ci' as the concentration of heavy metals (µg/L), whereas 'IR' is the daily intake rate (2 L/day for adults and 0.64 L/day for children). 'EF' denotes the frequency of exposure, established at 350 days annually, while 'ED' represents the duration of exposure, extending over 30 years for adults and 6 years for children. 'BW' denotes body weight, documented as 70 kg for adults and 15 kg for children. 'AT' signifies the mean exposure duration for non-carcinogenic agents. 'SA' quantifies the exposed skin surface area, measuring 18,000 cm^2 for adults and 6,600 cm^2 for children, while 'ET' denotes the exposure duration, recorded at 0.58 hours for adults and 1 hour for children daily. 'CF' serves as a conversion factor (0.001 L/cm^3), while 'Kp' denotes the dermal permeability coefficient (cm/h, Table 5) for heavy metals in water. The reference values for the parameters were derived from the US EPA manual (EPA, 2004) and (Wu et al., 2009) (Kumar et al., 2019; Wang et al., 2017).

2.4.2. Estimation of non-carcinogenic risk

The non-carcinogenic risk for oral and dermal exposure pathways is assessed by estimating the ratio of exposure via each pathway in relation to its respective reference dose (RfD) (Tripathee et al., 2016). The HQ was calculated for both oral intake and dermal contact pathways to evaluate possible dangers, utilizing Equations (7) and (8) (Kumar et al., 2019; Saleem et al., 2019).

$$HQi = \frac{AADi}{RfDi} \quad (7)$$

$$HQd = \frac{AADd}{RfDd} \quad (8)$$

If the Hazard Quotient (HQ) is below 1 (HQ < 1), it indicates acceptable risk. However, if HQ > 1, non-carcinogenic health effects become severe (EPA, 2011; Tripathee et al., 2016). RfDi and RfDd denote the reference doses designated for ingestion and oral/dermal exposure, respectively, as specified in Table 5, with units measured in (µg/kg/day).

The Hazard Index (HI) determines the comprehensive health risk by aggregating the cumulative effect of Hazard Quotients (HQs) from all exposure paths, as delineated in equation (9) (Saleem et al., 2019; Toi Bissang et al., 2024).

$$HI = \sum_{i=1}^{n} HQing/derm \quad (9)$$

HI ≤ 1 signifies an acceptable range; however, HI > 1 indicates a potential risk to human health (Zhang et al., 2017).

2.4.3. Determination of carcinogenic risk

Potential carcinogenic risks (CRs) linked to heavy metals were assessed to determine the probability of one developing cancer over their lifetime owing to extended exposure to recognized carcinogens. The carcinogenic risk from ingesting, external exposure, and overall cancer risk associated with various heavy metals was computed using Equations 10 and 11, respectively (EPA, 2011; Jiang et al., 2021; Toi Bissang et al., 2024).

$$CRi = ADDi \times SF \quad (10)$$

$$CRd = ADDd \times SF \quad (11)$$

The slope factor (SF) measures toxicity by comparing dosage and response. Cadmium, chromium, lead, and nickel are designated as carcinogenic heavy metals, with the following SF values (mg/kg/day): Cadmium (Cd) = 15, Chromium (Cr) = 0.5, Lead (Pb) = 1.7, and Nickel (Ni) = 1.7 (Kumar et al., 2019; Sanad, Moussadek, et al., 2024). The CR was estimated by adding the CRs for each hazardous metal, as shown in equation (12).

$$CR = \sum CRi + CRd \ (12) \quad (12)$$

Carcinogenic risks from ingesting and dermal absorption are CRi and CRd, respectively. The USEPA establishes that the acceptable cancer risk threshold for regulatory purposes is between 1×10^{-6} and 1×10^{-4} (EPA, 2004; EPA, 1989). Risks over 1×10^{-4} are regarded as unacceptably elevated.

2.5. Statistical analysis

To analyze groundwater heavy metal (HM) linear relationships, we used Pearson's correlation analysis. We used Kaiser's criterion (eigenvalue > 1) for Principal Component Analysis (PCA) to minimize dimensionality and identify HM distribution components. By using Ward's approach in Hierarchical Cluster Analysis (HCA) to categorize heavy metals by similarity, strong categorization was achieved. The hierarchical dendrogram was created from HM connection linkage distances. Excel was used to statistically assess groundwater metal concentrations. Minimum, maximum, and mean values were analyzed. OriginPro 2025 (version 10.2.0) was used for statistical analysis and data visualization, and ArcGIS 10.8's Kriging was used to represent the pollution index's spatial distribution.

3. Results and Discussion

3.1. Subsection

The distribution of HMs concentrations in different water samples is established in Table 4. The findings indicate that the mean amounts of Al and Pb surpassed the reference thresholds. Conversely, the concentrations of Fe, Ni, Cd, Cr, and Cu remained under the safety thresholds established by the World Health Organization (WHO, 2017).

Table 4. Statistical summaries of Heavy Metals (HMs) Concentrations (µg/L) in Groundwater Samples.

	Fe	**Ni**	**Al**	**Cu**	**Cr**	**Cd**	**Pb**
Minimum	37.90	20.23	62.81	64.54	16.56	0.00	114.48
Maximum	85.83	36.11	474.14	442.90	41.49	3.20	221.33
Mean	52.39	27.33	351.57	148.49	23.69	1.19	169.08
Standard Deviation	15.41	4.83	112.97	109.13	6.46	0.86	32.11
Coefficient of variation	29.42	17.24	32.13	73.50	27.28	71.99	18.99
WHO (2017)	300	70	200	2000	50	3	10

Cadmium concentrations in soils and groundwater, which are essential for food and water, can rise from geogenic and anthropogenic sources. Mining, smelting, agriculture, sewage irrigation, and traffic cause most groundwater cadmium pollution (Hoareau et al., 2022). The analysis indicated that Cd concentrations ranged from 0 to 3.20 µg/L, with an average value of 1.19 µg/L, as shown in Table 4. All samples conformed to the WHO's acceptable threshold of 3 µg/L (WHO, 2017), except for sample W11 at 3.20 µg/L. Cadmium levels were highest in W11 and lowest in W5, W7, and W18 (Figure 3). The remaining samples contain low and safe cadmium levels, but agricultural and industrial activities, especially those of the Mass Steel Company and neighboring companies, may have affected them in the future. The cadmium pollution may arise from agricultural practices, with fertilizer use also elevating groundwater Cd concentrations(Loganathan et al., 2003). The spatial distribution of cadmium (Cd) in groundwater revealed lower concentrations (<1.0 µg/L) within the smelting site, where no agricultural chemicals are used, compared to elevated levels (>1.0 µg/L) in surrounding farmlands. This contrast suggests that external sources, such as fertilizer application in crop production, may contribute to higher Cd levels outside the industrial zone. The minimal contamination within the smelting site implies that current industrial activities are not the primary driver of groundwater Cd pollution in the study area.

Cadmium causes degenerative bone disease, gastrointestinal distress, renal impairment, hepatic, and pulmonary disorders (Fay et al., 2018). Cadmium exposure in children damages the respiratory, renal, skeletal, and cardiovascular systems and causes lung, kidney, prostate, and stomach cancers (Kinuthia et al., 2020).

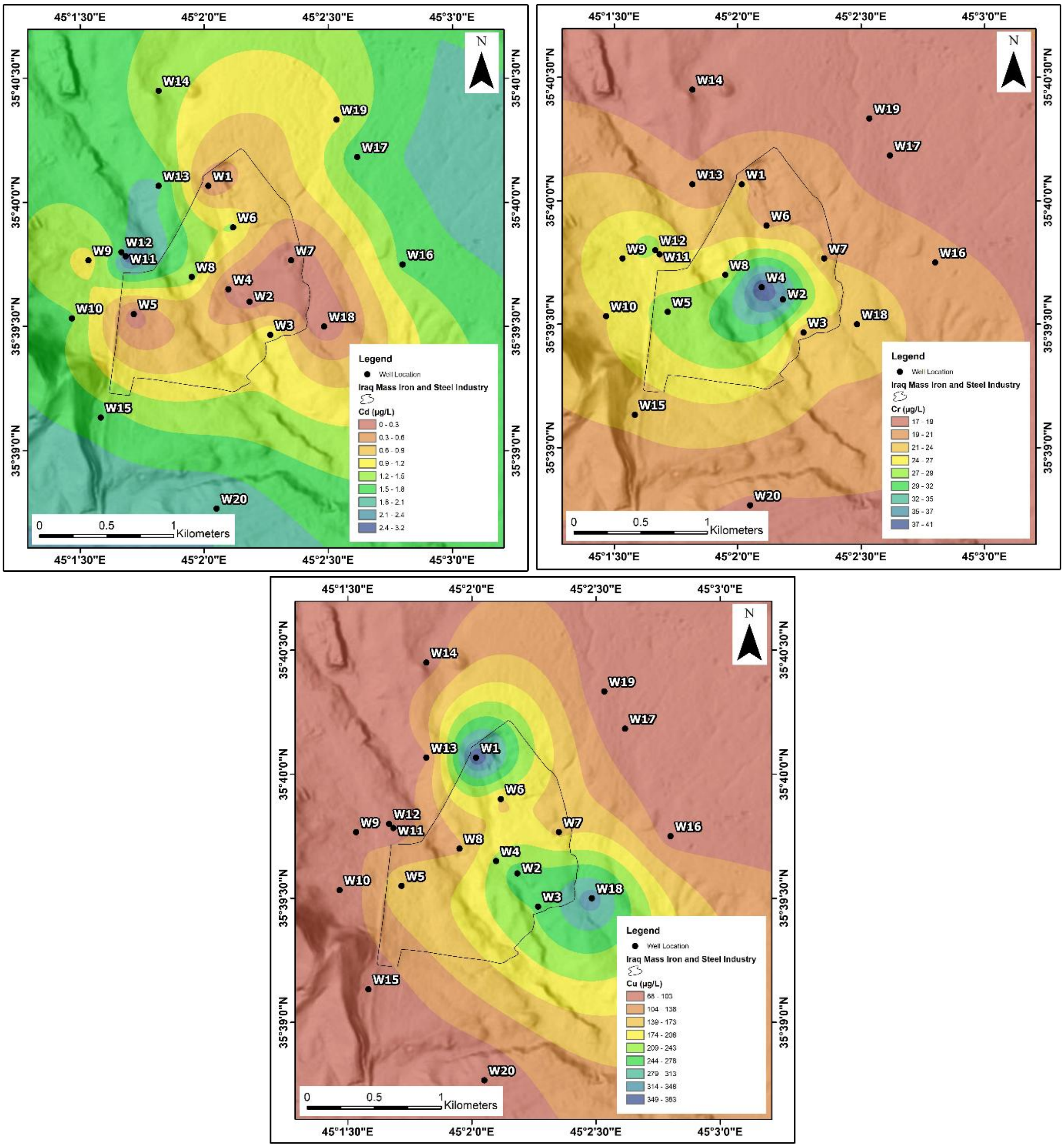

Figure 3. Spatial distribution of cadmium (Cd), chromium (Cr), and copper (Cu) concentrations (µg/L) in groundwater, displayed with groundwater flow directions.

Chromium (Cr) is essential for the metals and chemical industries. It is a naturally occurring metal in geological formations with varied corrosion resistance (Jacobs & Testa, 2005). Chromium (Cr) concentrations in groundwater ranged from 16.56 to 41.49 µg/L, with the highest levels (W4) near smelting activities and the lowest (W14) upstream, indicating industrial influence Table 4. Despite spatial variability, all samples remained below the (WHO, 2017) limit of 50 µg/L. Concentrations decreased gradually along surface and groundwater flow paths, suggesting dilution and distance-dependent attenuation from the smelting site (Figure 3).

The main health risks of chromium compounds are impatience, small intestine and abdominal ulcers, anemia, and male reproductive system and sperm damage (Li Chen et al., 2009).

Copper (Cu) is an essential nutrient required for various physiological processes in the human body. Nonetheless, excessive water intake may present risks to health (Samantara et al., 2017). Copper (Cu) concentrations in groundwater ranged from 64.5 to 442.9 µg/L (Table 4), with the highest levels (W1, W18) occurring inside or close to the factory premises, implicating industrial activities as the likely source. While all samples remained below the (WHO, 2017) limit of 2000 µg/L, the spatial pattern, higher Cu inside and lower outside, suggests potential future risks of contaminant migration via groundwater flow if mitigation measures are not implemented. Proactive monitoring and containment strategies are recommended to prevent broader environmental impact. A small amount of Cu is needed for metabolism, enzymes, cytochrome, and hemoglobin production. Conversely, excessive copper consumption can cause neurological diseases, hypertension, hepatic issues, and renal malfunction (Mirlohi & Health, 2022).

Iron (Fe) concentrations in groundwater ranged from 37.9 to 85.8 µg/L (mean: 52.39 µg/L; Table 4), well below the (WHO, 2017) guideline of 300 µg/L. The highest Fe levels were detected near industrial areas (W6) and agricultural zones (W19, W17), likely influenced by industrial activity and fertilizer use, respectively. While Fe generally decreased along groundwater flow paths toward the southeast, localized increases in the northern area (W19, W17) correlated with intensive well use for irrigation and potential groundwater head changes (Figure 4). This suggests both anthropogenic and hydrogeological controls on Fe spatial distribution.

Nickel is a ferromagnetic element found in Earth's crust as oxides and sulfides with oxygen and sulfur. Nickel (Ni) concentrations in groundwater ranged from 20.23 to 36.11 µg/L (mean: 27.33 µg/L), all below the (WHO, 2017) limit of 70 µg/L. The highest level (36.11 µg/L at W6) and spatial distribution peaking centrally and decreasing along groundwater flow paths suggest leaching from local geology (Genchi et al., 2020) with transport governed by aquifer dynamics. Localized Ni increases in northern irrigation zones (e.g., W16/W17), mirroring Fe trends, imply additional anthropogenic influence from groundwater extraction and head changes (Figure 4).

Lead is the most prominent heavy metal toxin, with its inorganic forms being absorbed through consumption via food, drink, and inhalation (Jaishankar et al., 2014). The dataset showed very consistent Pb readings, ranging from 114.48 to 221.33 µg/L, with an average concentration of 169.08 µg/L (Table 4). All well readings surpassed the WHO limit of 10 µg/L, with significant variation present in wells near the Mass Steel Company. The spatial distribution of lead (Pb) concentrations indicates elevated levels in the central and downstream regions of the research area, suggesting that groundwater flow affects the transport and spread of lead pollution. This pattern suggests that toxins are likely moving in accordance with the direction of groundwater flow (Figure 4). The lead (Pb) levels in groundwater samples from wells near the Bazian Oil Refinery varied from 200 µg/L to 920 µg/L (Rasheed & Faqesaleh, 2016). This variance suggests that the Mass Iron and Steel factory and nearby industrial and agricultural activity affect pollution levels. Long-term lead exposure can cause psychosis, cognitive decline, kidney damage, and lung issues through inflammatory and oxidative pathways (Engwa et al., 2019). It also disrupts hemoglobin synthesis, leading to anemia and reduced intellectual capacity in children (Kinuthia et al., 2020).

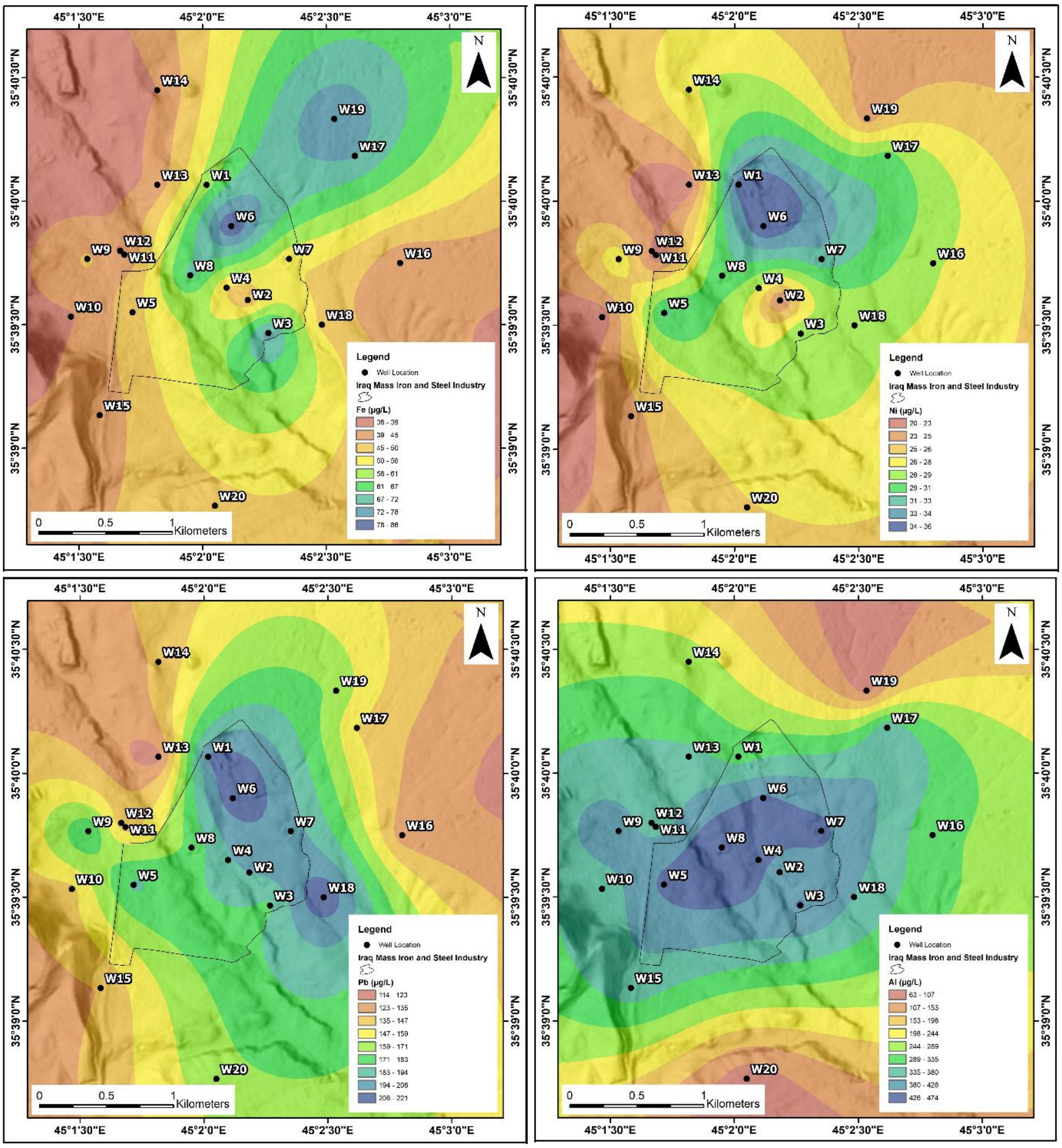

Figure 4. Spatial distribution maps of iron (Fe), nickel (Ni), lead (Pb), and aluminum (Al) concentrations (µg/L) in groundwater, displayed with groundwater flow directions.

Aluminum is among the most prevalent elements in the Earth's crust, and mostly occurs in the environment in its trivalent ($^{+3}$) oxidation form (Jaishankar et al., 2014). Aluminum (Al) concentrations (62.81 – 474.14 µg/L) exceeded the(WHO, 2017) threshold of 200 µg/L in most wells, with only W19 and W20 remaining below this limit. The highest levels formed a diffuse plume centered on industrial zones, suggesting primary contamination from smelting activities (e.g., metal yard leaching, onsite operations) rather than directional groundwater flow.

The Al contamination plume radiates uniformly from industrial zones, unaffected by natural flow paths, a pattern distinct from other metals (Figure 4). While smelting operations (historical and current) are the likely primary source, elevated peripheral levels suggest agricultural activities may be mobilizing Al through irrigation or soil disturbance. This multi-source pollution scenario requires targeted sampling to apportion blame between industrial legacy and farming impacts. This widespread Al pollution warrants urgent remediation, as both the local sand surrounding the industrial operation input appears to be driving chronic groundwater degradation. High aluminum levels in groundwater-drinking areas may cause Alzheimer's disease (Flaten, 2001).

3.2. Evaluation of Pollution with Heavy Metal Indices

HPI values in the Bazian Sub-basin, especially near the Mass Steel Company, varied from 290.31 to 491.58, with a mean of 388.04. As illustrated in Figure 5a, groundwater contamination varies greatly across the region. The HPI regularly classifies the research area's groundwater as High-Water Pollution. All samples (100%) exceed the HPI criterion of 100. The mean MI was 20.17, ranging from 14.69 to 25.57. The MI classification classifies all groundwater samples as "Seriously Affected" because each value exceeds 6.0 (Figure 5b). The Iraq Mass Iron and Steel facility and the surrounding area's groundwater are heavily contaminated with heavy metals, putting the aquatic ecology at risk, according to HPI and MI. Lead (Pb) and aluminum (Al) are the main groundwater contaminants, according to the study. In the studied area, human activities cause high pollution. Industrial operations, agricultural returned water, and chemical fertilizers significantly pollute groundwater. These metals, especially if HPI and MI values exceed critical levels, require immediate treatment. Restoring groundwater quality for human use and other uses requires reducing their concentrations.

3.3. Assessment of Human Health Risk

The HQ and HI values for trace element intake and external routes for adults and children are represented in Table 5. The data demonstrate the cumulative health risks of groundwater heavy metal exposure. The evaluation was based on the arithmetic Average concentrations of potentially toxic elements (Al, Cd, Cr, Cu, Fe, Ni, and Pb) in groundwater samples. Both adults and children had health quotient intake values below 1 for Cu, Ni, Cr, Fe, Al, and Cd, indicating no health risks. However, the HQ_ingestion value for Pb is above 1, suggesting potential health risks and non-carcinogenic concerns from everyday oral consumption. For all components, the Hazard Quotient for dermal exposure (HQ_dermal) consistently remained below 1 for both adults and children. These components pose little external absorption risk. Children have higher HQ_ingestion and HQ_dermal values than adults, indicating greater vulnerability to waterborne trace element exposure. Both adults and children had Pb HIs greater than 1. We conclude that Pb contributes the most to chronic risks in the research area. Although abundant in water, aluminum caused no health concern. Its high reference dose (RfD) indicates the body's ability to tolerate higher exposure levels without harm. At all sampling locations, children had higher hazard index (HI) values than adults, indicating they are more vulnerable (Figure 6).

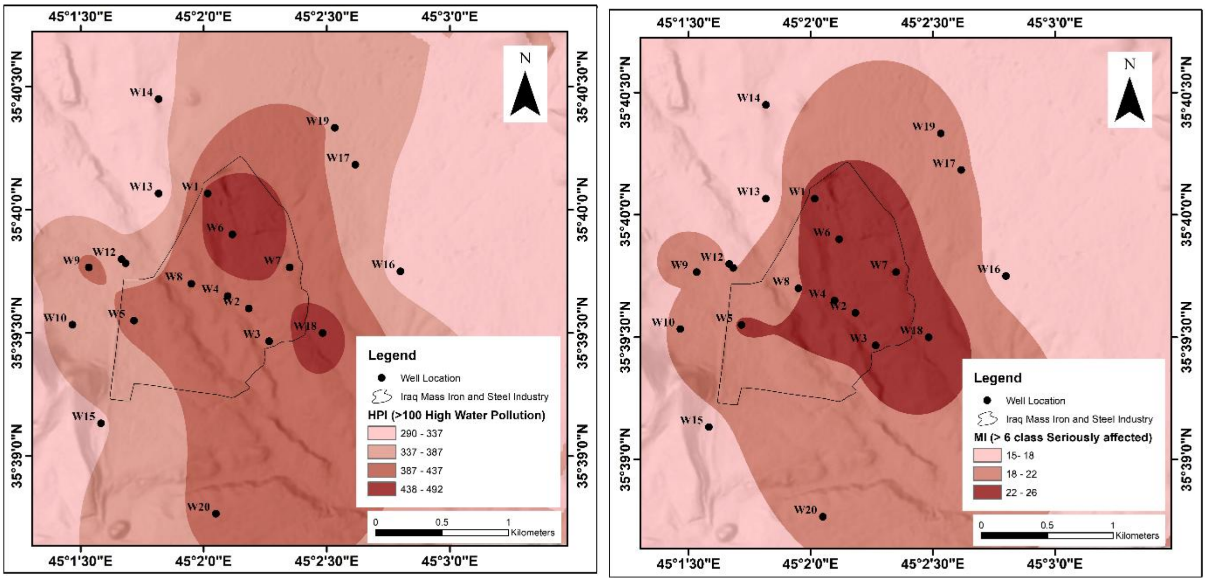

Figure 5. Spatial distribution of (a) HPI, (b) MI values in the study area.

Table 5. Health Risk Assessment of Heavy Metals: Dermal Permeability, Reference Dose, Hazard Quotient, and Hazard Index.

Metals	Kp cm/h	RfD (μg//kg-day) oral	RfD (μg//kg-day) dermal	Adult HQi	Child HQi	Adult HQd	Child HQd	Adult HI	Child HI
Fe	1.00E-03	7.00E+02	1.40E+02	2.05E-03	3.06E-03	5.35E-05	1.58E-04	2.10E-03	3.22E-03
Ni	2.00E-04	2.00E+01	8.00E-01	3.74E-02	5.59E-02	9.77E-04	2.88E-03	3.84E-02	5.88E-02
Al	1.00E-03	1.00E+03	2.00E+02	9.63E-03	1.44E-02	2.51E-04	7.42E-04	9.88E-03	1.51E-02
Cu	1.00E-03	4.00E+01	8.00E+00	1.02E-01	1.52E-01	2.65E-03	7.83E-03	1.04E-01	1.60E-01
Cr	2.00E-03	3.00E+00	7.50E-02	2.16E-01	3.23E-01	9.03E-02	2.66E-01	3.07E-01	5.90E-01
Cd	1.00E-03	5.00E-01	2.50E-02	6.52E-02	9.74E-02	6.81E-03	2.01E-02	7.20E-02	1.17E-01
Pb	1.00E-04	1.40E+00	4.20E-01	3.31E+00	4.94E+00	5.76E-03	1.70E-02	3.31E+00	4.96E+00

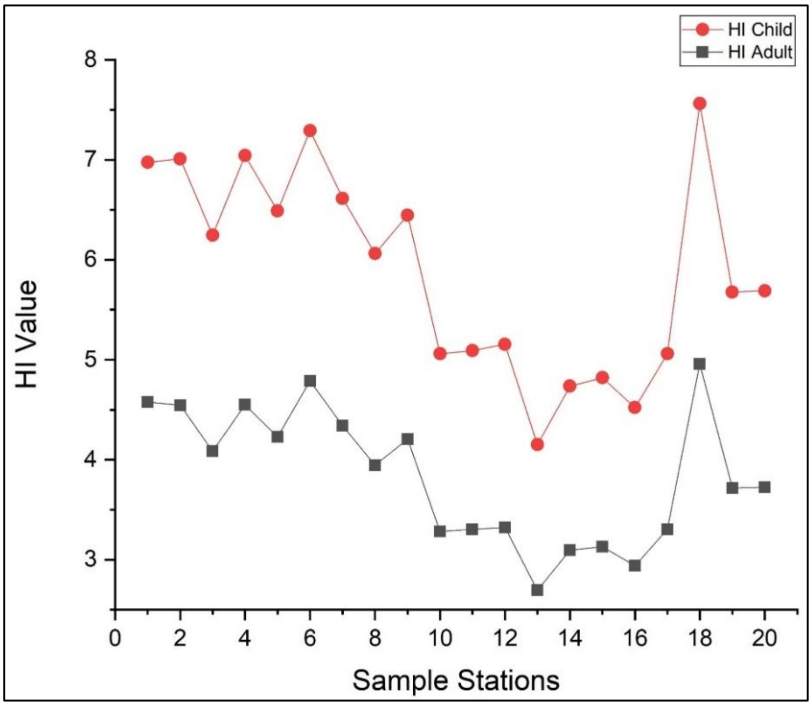

Figure 6. Hazard Index of Heavy Metals in Groundwater for Adults and Children in the study area.

The TCR assesses groundwater carcinogenic heavy metal health hazards. Adults and children were tested for carcinogenic risks by ingestion and skin exposure. Children and adults are at risk for cancer regardless of oral or cutaneous exposure Table 6. EPA (1989, 2004) specified a TCR range of (10^{-6} to 10^{-4}) as acceptable. The cumulative carcinogenic risk from heavy metals is greater in children compared to adults (Figure 7). The recorded TCR levels exceeded regulatory acceptable risk criteria (10^{-6} to 10^{-4}). Public health requires regular risk assessment and mitigation. Children absorb more heavy metals per weight than adults; therefore, avoid contaminated water. The risk of heavy metal ingestion was much higher than external exposure. The risk assessments show that water heavy metal concentrations are carcinogenic and non-carcinogenic. Enforcement of heavy metal pollution restrictions is essential. Top metal levels were in the research area, exceeding limits. Lead causes most adult and child non-carcinogenic and carcinogenic concerns.

Table 6. Carcinogenic risk of various HMs in groundwater.

Metals	Adult CRi	Child CRi	Adult CRd	Child CRd	Adult TCR	Child TCR
Ni	1.27E-03	1.90E-03	1.33E-06	3.92E-06	1.27E-03	1.91E-03
Cr	3.24E-04	4.85E-04	3.39E-06	9.99E-06	3.28E-04	4.95E-04
Cd	4.89E-04	7.30E-04	2.55E-06	7.53E-06	4.92E-04	7.38E-04
Pb	7.87E-03	1.18E-02	4.11E-06	1.21E-05	7.88E-03	1.18E-02

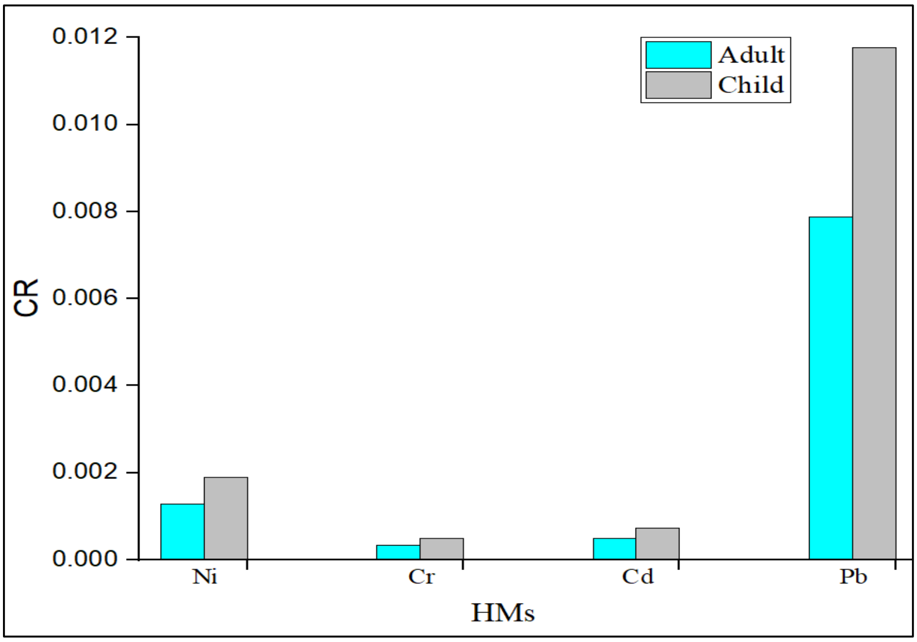

Figure 7. Carcinogenic risk (CR) of various heavy metals in the study area.

4. Multivariate Statistical Analysis

4.1. Correlation Analysis

This statistical technique is applied in water quality studies to examine the relationships between elements and assess their influence on the chemical composition of water (Oueld Lhaj et al., 2024). The correlation matrix was

used to evaluate the interactions among seven heavy metals. Significant positive relationships were identified between Lead and copper (0.76), nickel and lead (0.62), nickel and iron (0.57), chromium and aluminum (0.43), and copper and nickel (0.45) exhibited strong positive relationships, indicating shared anthropogenic origins such as industrial effluents or smelting operations. These metals may exhibit similar geochemical activity and mobilization mechanisms within the aquifer. The strong relationships between Pb–Cu and Ni–Fe indicate potential co-contamination from the steel sector. Conversely, Cd exhibited significant negative correlations with Pb (-0.72), Cu (-0.69), and Cr (-0.52), signifying divergent geochemical behavior. This phenomenon may result from cadmium's enhanced mobility in reducing settings, whereas chromium and copper often precipitate or adsorb in oxidizing environments (Alloway, 2012; Bradl, 2005). These contrasting behaviors likely explain the inverse relationships observed in Figure 8.

4.2. Principal Component Analysis

This statistical method efficiently reduces intricate datasets with several variables, where principal components with substantial eigenvalues represent the primary differences in heavy metal characteristics (Sanad, Mouhir, et al., 2024). Table 7 shows PCA eigenvalues, variance, and cumulative values. PC1 and PC2 account for almost 70.98% of the dataset's variability (Figure 9), demonstrating that groundwater heavy metals variation is mostly incorporated in these two components. Absolute loading levels exceeding 0.75, ranging from 0.75 to 0.50, and from 0.50 to 0.30 were designated as 'strong,' 'moderate,' and 'weak' factor loadings, respectively (Gao et al., 2016). Pb's moderately positive loading of 0.50 and Cu, Ni, Cr, Al, and Fe's weakly positive loadings of 0.45, 0.39, 0.25, and 0.28 contributed to the first factor's 47.80% variance. These metals' positive loadings are strongly connected, indicating human origin. Fertilizers, pesticides, and industrial activity, especially the Mass Iraq Iron and Steel Plant in the research region, may be sources. Heavy metal-contaminated groundwater is common due to intensive agriculture and industrialization. PC2, which accounts for 23.18% of variance, has positive Cd, Fe, and Ni loadings. Human and natural factors may affect PC2 Table 7.

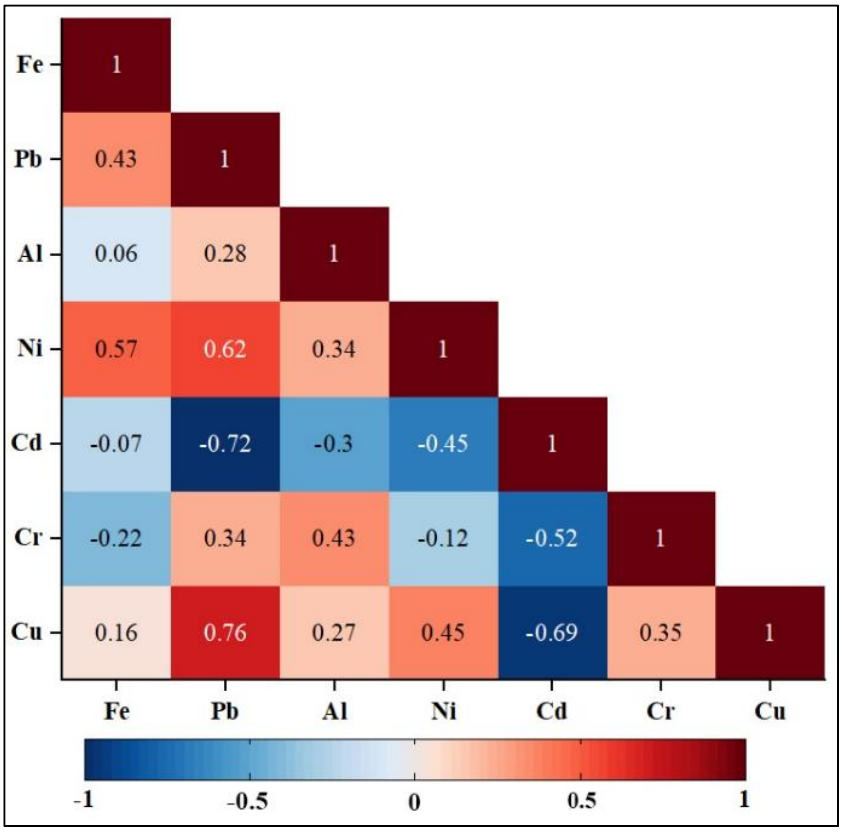

Figure 8. Pearson correlation matrix between heavy metal concentrations.

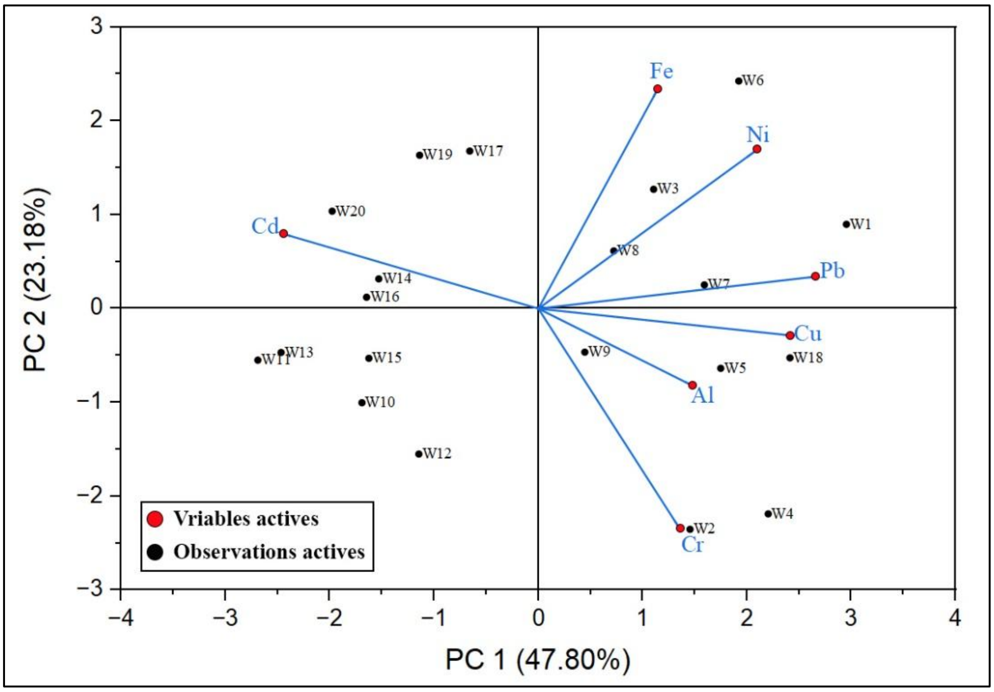

Figure 9. Principal Component Analysis Applied to Groundwater Assessment.

Table 7. Principal component analysis of various heavy metals in groundwater.

Parameters	**Components**	
	PC1	**PC2**
Fe	0.21	0.60
Pb	0.50	0.09
Al	0.28	-0.21
Ni	0.39	0.43
Cd	-0.46	0.20
Cr	0.25	-0.60
Cu	0.45	-0.07
Eigenvalue	3.35	1.62
Variability (%)	47.80	23.18
Cumulative (%)	47.80	70.98

4.3. Hierarchical Cluster Analysis

Hierarchical Cluster Analysis (CA) facilitates the categorization of water samples based on common spatial and chemical properties (Vega et al., 1998). CA exhibited three distinct clustering patterns of heavy metals (Figure 10). Cadmium in Cluster I is predominantly affected by agricultural practices, supplemented by surrounding industrial activities. Several industrial operations contributed aluminum and chromium to Cluster II. Cluster III comprises two sub-clusters: Fe, Cu, and Ni, and Pb, all of which are contaminated by the Mass Iraq for Iron and Steel Industry Company. Elevated Cd concentrations in Cluster I could belong to agricultural and industrial pollution, whereas heavy metals in Clusters II and III demonstrate the influence of industrial discharges, particularly from Iron and Steel smelting.

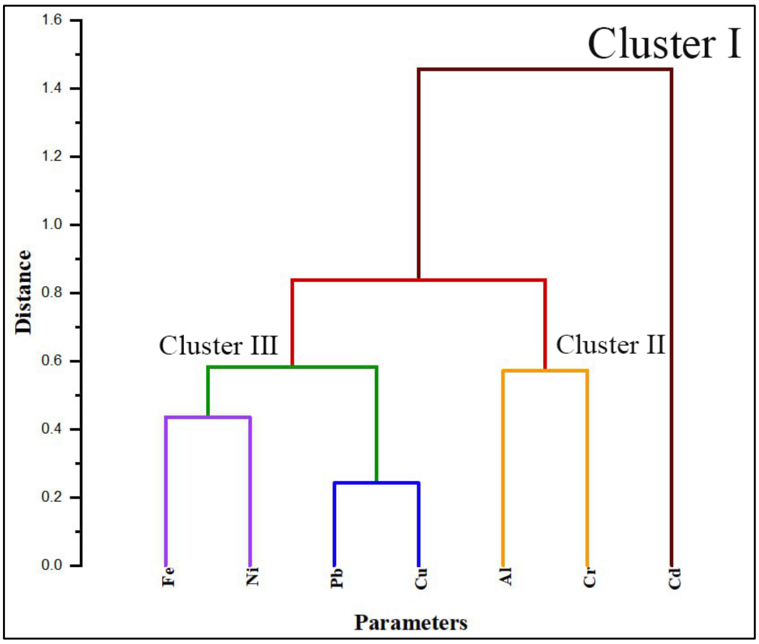

Figure 10. Dendrogram of heavy metals for groundwater in the study area.

5. Conclusions

This study evaluates the pollution of groundwater by trace elements (Fe, Al, Cu, Ni, Cr, Pb, and Cd) in the area near the Iraq Iron Mass Steel Plant and its surroundings in northeast Iraq's Bazian Sub-basin. Most of the trace element concentrations meet WHO (2017) guidelines; however, lead (Pb) and aluminum (Al) exceed limits, indicating local contamination. Environmental and human health risks were assessed utilizing HPI, MI, HQ, HI, and CR, considering both oral and dermal exposure pathways. The groundwater was contaminated regarding Pb and Al, where all the samples had HPI values between 290.31 and 491.58, indicating "High Water Pollution." All samples were "Seriously affected," indicating substantial water quality issues with MI values of 14.69 to 25.57. Every sample had a higher ingestion HQ (HQi) than dermal (HQd).

Lead's Hazard Index (HI) readings of 3.31 for adults and 4.96 for children are above the safety level of 1. HI and HQ values of less than 1 for additional heavy metals made them less dangerous via external and intestinal pathways. Nickel, chromium, cadmium, and lead have TCR values above 10^{-4}, with lead being the main cause. Children were more sensitive to carcinogenic and non-carcinogenic risks. The study reveals significant groundwater contamination by Pb, Al, Ni, Fe, and Cu near the smelting site, with Al exceeding WHO limits in most wells, while other metals remain below thresholds but show concerning spatial trends linked to industrial and agricultural activities. Industrial operations (especially smelting) emerge as the primary pollution source, though agricultural practices contribute to secondary metal mobilization, evidenced by plumes extending beyond factory boundaries.

Multivariate statistical analysis, encompassing cluster analysis and principal component analysis, assesses the Iraq Mass Steel Smelting plant, agricultural activities, and diverse industrial operations as the principal sources of polluted groundwater by heavy metals in the studied area. This detailed Bazian sub-basin heavy metal contamination study illustrates industrial operations' adverse environmental and health effects. The study stresses proactive monitoring and management by giving site-specific statistics and important risk indicators. Policies and remedies require knowledge of groundwater quality and public health. Proactive measures, including source containment, groundwater monitoring, and farming practice revisions, are urgently needed to mitigate long-term environmental and health risks in the region.

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References

Ahmed, T. H., & Al-Manmi, D. A. M. (2019). Delineation of groundwater productivity zones with the integration of GIS and remote sensing methods, Bazian Basin, Sulaymaniyah, Kurdistan Region, Iraq. *Journal of Basrah Researches (Sciences), 2*(2).

Al-Hejuje, M. M., Hussain, N. A., & Al-Saad, H. T. J. I. J. o. M. S. (2017). Applied heavy metals pollution index (HPI) as a water pollution indicator of Shatt Al-Arab River, Basrah, Iraq. *7*.

Alidadi, H., Tavakoly Sany, S. B., Zarif Garaati Oftadeh, B., Mohamad, T., Shamszade, H., Fakhari, M. J. E. h., & Medicine, p. (2019). Health risk assessments of arsenic and toxic heavy metal exposure in drinking water in northeast Iran. *24*, 1-17. https://doi.org/https://doi.org/10.1186/s12199-019-0812-x

Alloway, B. J. (2012). *Heavy metals in soils: trace metals and metalloids in soils and their bioavailability* (Vol. 22). Springer Science & Business Media.

Ayejoto, D. A., Agbasi, J. C., Egbueri, J. C., & Echefu, K. I. J. I. J. o. E. A. C. (2024). Assessment of oral and dermal health risk exposures associated with contaminated water resources: an update in Ojoto area, southeast Nigeria. *104*(3), 641-661. https://doi.org/https://ui.adsabs.harvard.edu/link_gateway/2024IJEAC.104..641A/doi:10.1080/03067319.2021.2023515

Badeenezhad, A., Soleimani, H., Shahsavani, S., Parseh, I., Mohammadpour, A., Azadbakht, O., Javanmardi, P., Faraji, H., & Babakrpur Nalosi, K. J. S. R. (2023). Comprehensive health risk analysis of heavy metal pollution using water quality indices and Monte Carlo simulation in R software. *13*(1), 15817. https://doi.org/https://doi.org/10.1038/s41598-023-43161-3

Bradl, H. (2005). *Heavy metals in the environment: origin, interaction and remediation* (Vol. 6). Elsevier.

Ceramella, J., De Maio, A. C., Basile, G., Facente, A., Scali, E., Andreu, I., Sinicropi, M. S., Iacopetta, D., & Catalano, A. J. F. (2024). Phytochemicals involved in mitigating silent toxicity induced by heavy metals. *13*(7), 978. https://doi.org/https://doi.org/10.3390/foods13070978

De Miguel, E., Iribarren, I., Chacon, E., Ordonez, A., & Charlesworth, S. J. C. (2007). Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain). *66*(3), 505-513. https://doi.org/https://doi.org/10.1016/j.chemosphere.2006.05.065

Edet, A., & Offiong, O. J. G. (2002). Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria). *57*, 295-304. https://doi.org/https://doi.org/10.1023/B:GEJO.0000007250.92458.de

Engwa, G. A., Ferdinand, P. U., Nwalo, F. N., & Unachukwu, M. N. J. P. i. t. m. w.-n. t. f. a. o. d. (2019). Mechanism and health effects of heavy metal toxicity in humans. *10*, 70-90. https://doi.org/10.5772/intechopen.82511

EPA, A. (2004). *Risk assessment guidance for superfund. Volume I: human health evaluation manual (Part E, supplemental guidance for dermal risk assessment)*.

EPA, U. (1989). *Risk assessment guidance for superfund*. Office of Emergency and Remedial Response, US Environmental Protection Agency.

EPA, U. (2011). Exposure factors handbook. *20460*, 2-6.

Fay, M. J., Alt, L. A., Ryba, D., Salamah, R., Peach, R., Papaeliou, A., Zawadzka, S., Weiss, A., Patel, N., & Rahman, A. J. T. (2018). Cadmium nephrotoxicity is associated with altered microRNA expression in the rat renal cortex. *6*(1), 16. https://doi.org/https://doi.org/10.3390/toxics6010016

Flaten, T. P. J. B. r. b. (2001). Aluminium as a risk factor in Alzheimer's disease, with emphasis on drinking water. *55*(2), 187-196. https://doi.org/https://doi.org/10.1016/S0361-9230(01)00459-2

Gao, L., Wang, Z., Shan, J., Chen, J., Tang, C., Yi, M., Zhao, X. J. E., & Safety, E. (2016). Distribution characteristics and sources of trace metals in sediment cores from a trans-boundary watercourse: an example from the Shima River, Pearl River Delta. *134*, 186-195. https://doi.org/https://doi.org/10.1016/j.ecoenv.2016.08.020

Hamamin, D. F. (2011). *Hydrogeological Assessment and Groundwater Vulnerability Map of Basara Basin, Sulaimani Governorate. Kurdistan Region, Iraq*. Region, Iraq. Unpublished PhD thesis, College of Science, University of Sulaimani, 174 pages.

Hamamin, D. F., & Ali, S. S. J. A. J. o. G. (2013). Hydrodynamic study of karstic and intergranular aquifers using isotope geochemistry in Basara basin, Sulaimani, North-Eastern Iraq. *6*, 2933-2940. https://doi.org/https://doi.org/10.1007/s12517-012-0572-z

Hamamin, D. F. J. S. o. t. t. E. (2018). Passive soil gas technique for investigating soil and groundwater plume emanating from volatile organic hydrocarbon at Bazian oil refinery site. *622*, 1485-1498. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.11.328

Hamarashid, R. A., Fiket, Ž., & Mohialdeen, I. M. (2022). Environmental impact of Sulaimani steel plant (Kurdistan Region, Iraq) on soil geochemistry. *Soil systems*, *6*(4), 86.

Hoareau, C. E., Hadibarata, T., & Yılmaz, M. J. A. J. o. G. (2022). Occurrence of cadmium in groundwater in China: A review. *15*(17), 1455. https://doi.org/https://doi.org/10.1007/s12517-022-10734-x

Jacobs, J. A., & Testa, S. M. J. C. h. (2005). Overview of chromium (VI) in the environment: background and history. 1-21.

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. J. I. T. (2014). Toxicity, mechanism and health effects of some heavy metals. *7*(2), 60. https://doi.org/https://doi.org/10.2478/intox-2014-0009

Jiang, C., Zhao, Q., Zheng, L., Chen, X., Li, C., Ren, M. J. E., & Safety, E. (2021). Distribution, source and health risk assessment based on the Monte Carlo method of heavy metals in shallow groundwater in an area affected by mining activities, China. *224*, 112679. https://doi.org/https://doi.org/10.1016/j.ecoenv.2021.112679

Kinuthia, G. K., Ngure, V., Beti, D., Lugalia, R., Wangila, A., & Kamau, L. J. S. R. (2020). Levels of heavy metals in wastewater and soil samples from open drainage channels in Nairobi, Kenya: community health implication. *10*(1), 8434. https://doi.org/https://doi.org/10.1038/s41598-020-65359-5

Kumar, V., Parihar, R. D., Sharma, A., Bakshi, P., Sidhu, G. P. S., Bali, A. S., Karaouzas, I., Bhardwaj, R., Thukral, A. K., & Gyasi-Agyei, Y. J. C. (2019). Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *236*, 124364. https://doi.org/https://doi.org/10.1016/j.chemosphere.2019.124364

Li Chen, T., Wise, S. S., Kraus, S., Shaffiey, F., Levine, K. M., Thompson, W. D., Romano, T., O'Hara, T., Pierce Wise Sr, J. J. E., & mutagenesis, m. (2009). Particulate hexavalent chromium is cytotoxic and genotoxic to the North Atlantic right whale (Eubalaena glacialis) lung and skin fibroblasts. *50*(5), 387-393. https://doi.org/ https://doi.org/10.1002/em.20471

Liang, F., Yang, S., Sun, C. J. B. o. e. c., & toxicology. (2011). Primary health risk analysis of metals in surface water of Taihu Lake, China. *87*, 404-408. https://doi.org/https://doi.org/10.1007/s00128-011-0379-8

Loganathan, P., Hedley, M., Grace, N., Lee, J., Cronin, S., Bolan, N., & Zanders, J. (2003). Fertiliser contaminants in New Zealand grazed pasture with special reference to cadmium and fluorine—a review. *Soil Research*, *41*(3), 501-532.

Mahato, M. K., Singh, P. K., Tiwari, A. K., Singh, A. K. J. E., & Health. (2016). Risk assessment due to intake of metals in groundwater of East Bokaro Coalfield, Jharkhand, India. *8*, 265-275. https://doi.org/https://doi.org/10.1007/s12403-016-0201-2

Mirlohi, S. J. I. J. o. E. R., & Health, P. (2022). Characterization of metallic off-flavors in drinking water: health, consumption, and sensory perception. *19*(24), 16829. https://doi.org/https://doi.org/10.3390/ijerph192416829

Mohammed, S. A., Attarnejad, R., & Hamamin, D. F. (2022). Aquifer feature estimation in Basara basin using a groundwater modeling system for smart agriculture. *Computers and Electrical Engineering*, *103*, 108354. https://doi.org/https://doi.org/10.1016/j.compeleceng.2022.108354

Mohammed, S. A., Nejad, R. A., & Hamamin, D. F. J. E. J. o. B. (2020). Vulnerability pesticide DRASTIC and risk intensity map for multi aquifer units: a case study from Basara basin, Iraqi Kurdistan Region. *14*(2).

Mohan, S. V., Nithila, P., Reddy, S. J. J. J. o. E. S., & A, H. P. (1996). Estimation of heavy metals in drinking water and development of heavy metal pollution index. *31*(2), 283-289. https://doi.org/https://doi.org/10.1080/10934529609376357

Niu, S., Xia, Y., Yang, C., & Liu, C. J. E. P. (2023). Impacts of the steel industry on sediment pollution by heavy metals in urban water system. *335*, 122364. https://doi.org/https://doi.org/10.1016/j.envpol.2023.122364

Oueld Lhaj, M., Moussadek, R., Mouhir, L., Mdarhri Alaoui, M., Sanad, H., Iben Halima, O., & Zouahri, A. J. A. (2024). Assessing the evolution of stability and maturity in co-composting sheep manure with green waste using physico-chemical and biological properties and statistical analyses: a case study of Botanique Garden in Rabat, Morocco. *14*(7), 1573. https://doi.org/ https://doi.org/10.3390/agronomy14071573

Prasad, B., & Bose, J. J. E. g. (2001). Evaluation of the heavy metal pollution index for surface and spring water near a limestone mining area of the lower Himalayas. *41*(1), 183-188. https://doi.org/https://doi.org/10.1007/s002540100380

Rasheed, R. O., & Faqesaleh, L. J. M. B. (2016). Evaluation of some heavy metals from water and soil of Bazian Oil Refinery within Sulaimani Governorate, IKR. *11*, 123.

Rashid, A., Schutte, B. J., Ulery, A., Deyholos, M. K., Sanogo, S., Lehnhoff, E. A., & Beck, L. J. A. (2023). Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health. *13*(6), 1521. https://doi.org/https://doi.org/10.3390/agronomy13061521

Sadeghi, H., Fazlzadeh, M., Zarei, A., Mahvi, A. H., & Nazmara, S. J. I. J. o. E. A. C. (2022). Spatial distribution and contamination of heavy metals in surface water, groundwater and topsoil surrounding Moghan's tannery site in Ardabil, Iran. *102*(5), 1049-1059. https://doi.org/https://doi.org/10.1080/03067319.2020.1730342

Saleem, M., Iqbal, J., & Shah, M. H. J. C. (2019). Seasonal variations, risk assessment and multivariate analysis of trace metals in the freshwater reservoirs of Pakistan. *216*, 715-724. https://doi.org/https://doi.org/10.1016/j.chemosphere.2018.10.173

Samantara, M., Padhi, R., Sowmya, M., Kumaran, P., & Satpathy, K. J. G. f. s. d. (2017). Heavy metal contamination, major ion chemistry and appraisal of the groundwater status in coastal aquifer, Kalpakkam, Tamil Nadu, India. *5*, 49-58. https://doi.org/https://doi.org/10.1016/j.gsd.2017.04.001

Sanad, H., Mouhir, L., Zouahri, A., Moussadek, R., El Azhari, H., Yachou, H., Ghanimi, A., Oueld Lhaj, M., & Dakak, H. J. W. (2024). Assessment of Groundwater Quality Using the Pollution Index of Groundwater (PIG), Nitrate Pollution Index (NPI), Water Quality Index (WQI), Multivariate Statistical Analysis (MSA), and GIS Approaches: A Case Study of the Mnasra Region, Gharb Plain, Morocco. *16*(9), 1263. https://doi.org/https://doi.org/10.3390/w16091263

Sanad, H., Moussadek, R., Dakak, H., Zouahri, A., Oueld Lhaj, M., & Mouhir, L. J. W. (2024). Ecological and health risk assessment of heavy metals in groundwater within an agricultural ecosystem using GIS and multivariate statistical analysis (MSA): A case study of the Mnasra region, Gharb Plain, Morocco. *16*(17), 2417. https://doi.org/https://doi.org/10.3390/w16172417

Sheng, D., Meng, X., Wen, X., Wu, J., Yu, H., & Wu, M. J. S. o. t. T. E. (2022). Contamination characteristics, source identification, and source-specific health risks of heavy metal (loid) s in groundwater of an arid oasis region in Northwest China. *841*, 156733.

Shi, H., Du, Y., Li, Y., Deng, Y., Tao, Y., & Ma, T. J. J. o. E. M. (2024). Determination of high-risk factors and related spatially influencing variables of heavy metals in groundwater. *358*, 120853. https://doi.org/https://doi.org/10.1016/j.jenvman.2024.120853

Shi, J., Dong, Y., Shi, Y., Yin, T., He, W., An, T., Tang, Y., Hou, X., Chong, S., & Chen, D. J. E. R. (2022). Groundwater antibiotics and microplastics in a drinking-water source area, northern China: Occurrence, spatial distribution, risk assessment, and correlation. *210*, 112855. https://doi.org/https://doi.org/10.1016/j.envres.2022.112855

Singh, K. K., Tewari, G., Kumar, S., Busa, R., Chaturvedi, A., Rathore, S. S., Singh, R. K., & Gangwar, A. J. G. f. S. D. (2023). Understanding urban groundwater pollution in the Upper Gangetic Alluvial Plains of northern India with multiple industries and their impact on drinking water quality and associated health risks. *21*, 100902. https://doi.org/https://doi.org/10.1016/j.gsd.2023.100902

Sun, L., Liu, T., Duan, L., Tong, X., Zhang, W., Cui, H., Wang, Z., Zheng, G. J. E. G., & Health. (2024). Spatial and temporal distribution characteristics and risk assessment of heavy metals in groundwater of Pingshuo mining area. *46*(4), 141. https://doi.org/https://doi.org/10.1007/s10653-024-01906-7

Talpur, S. A., Baloch, M. Y. J., Su, C., Iqbal, J., Ahmed, A., & Talpur, H. A. J. J. o. E. S. (2024). Application of synthetic Iron Oxyhydroxide with influencing factors for removal of as (V) and as (III) from groundwater. *35*(3), 998-1009. https://doi.org/https://doi.org/10.1007/s12583-023-1862-y

Talpur, S. A., Rashad, M., Ahmed, A., Rosatelli, G., Baloch, M. Y. J., Khan, A. H. A., Talpur, H. A., & Iqbal, J. J. H. (2025). Pollution indicators and human health risk assessment of fluoride contaminated drinking groundwater in southern Pakistan. *8*, 167-177. https://doi.org/https://doi.org/10.1016/j.hydres.2024.10.005

Tamasi, G., & Cini, R. J. S. o. t. t. e. (2004). Heavy metals in drinking waters from Mount Amiata (Tuscany, Italy). Possible risks from arsenic for public health in the Province of Siena. *327*(1-3), 41-51. https://doi.org/https://doi.org/10.1016/j.scitotenv.2003.10.011

Toi Bissang, B., Aragón-Barroso, A. J., Baba, G., González-López, J., & Osorio, F. J. W. (2024). Integrated Assessment of Heavy Metal Pollution and Human Health Risks in Waters from a Former Iron Mining Site: A Case Study of the Canton of Bangeli, Togo. *16*(3), 471. https://doi.org/https://doi.org/10.3390/w16030471

Tripathee, L., Kang, S., Sharma, C. M., Rupakheti, D., Paudyal, R., Huang, J., Sillanpää, M. J. B. o. e. c., & toxicology. (2016). Preliminary health risk assessment of potentially toxic metals in surface water of the Himalayan Rivers, Nepal. *97*, 855-862. https://doi.org/https://doi.org/10.1007/s00128-016-1945-x

Tyczyńska, M., Gędek, M., Brachet, A., Stręk, W., Flieger, J., Teresiński, G., & Baj, J. J. J. o. C. M. (2024). Trace Elements in Alzheimer's Disease and Dementia: The Current State of Knowledge. *13*(8), 2381. https://doi.org/https://doi.org/10.3390/jcm13082381

Ugwu, C. E., Igbokwe, A. M., Suru, S. M., Dike, C. C., Mbachu, A. N., & Maduka, H. C. C. J. T. R. (2024). Evaluating the human health risks of heavy metal contamination in copper and steel factory effluents in Nnewi, Anambra State, Nigeria. *12*, 614-621. https://doi.org/https://doi.org/10.1016/j.toxrep.2024.05.009

Vega, M., Pardo, R., Barrado, E., & Debán, L. J. W. r. (1998). Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. *32*(12), 3581-3592. https://doi.org/https://doi.org/10.1016/S0043-1354(98)00138-9

Wanda, E. M., Gulula, L. C., Phiri, G. J. P., & Chemistry of the Earth, P. A. b. c. (2012). Determination of characteristics and drinking water quality index in Mzuzu City, Northern Malawi. *50*, 92-97. https://doi.org/https://doi.org/10.1016/j.pce.2012.09.004

Wang, J., Liu, G., Liu, H., & Lam, P. K. J. S. o. t. t. e. (2017). Multivariate statistical evaluation of dissolved trace elements and a water quality assessment in the middle reaches of Huaihe River, Anhui, China. *583*, 421-431. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.01.088

WHO. (2017). Guidelines for drinking-water quality: first addendum to the fourth edition. https://iris.who.int/bitstream/handle/10665/254637/9789241549950-eng.pdf?sequence=1

Wu, B., Zhao, D., Jia, H., Zhang, Y., Zhang, X., Cheng, S. J. B. o. e. c., & toxicology. (2009). Preliminary risk assessment of trace metal pollution in surface water from Yangtze River in Nanjing Section, China. *82*, 405-409. https://doi.org/https://doi.org/10.1007/s00128-008-9497-3

Zainudin, A. M. I., Zulkefli, S. N., Looi, L. J., Aris, A. Z., Sefie, A., & Isa, N. M. J. A. G. (2023). Spatial and temporal evaluation of groundwater hydrochemistry in an active phreatic zone of developed basin in Selangor, Malaysia. *154*, 105656. https://doi.org/https://doi.org/10.1016/j.apgeochem.2023.105656

Zhang, Y., Chu, C., Li, T., Xu, S., Liu, L., & Ju, M. J. S. o. t. T. E. (2017). A water quality management strategy for regionally protected water through health risk assessment and spatial distribution of heavy metal pollution in 3 marine reserves. *599*, 721-731. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.04.232

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