

3-23-2026

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How to Cite this Article

Qader, Muzhda Qasim; Jirjees, Shevan Jamel; Hameed, Masoud H.; and Sharif, Chiyai Maroof (2026) "Seasonal Variation and Spatial Distribution of Heavy Metals in Groundwater: Implications for Water Quality and Health Risks," *Baghdad Science Journal*: Vol. 23: Iss. 3, Article 12.
DOI: <https://doi.org/10.21123/2411-7986.5243>

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RESEARCH ARTICLE

Seasonal Variation and Spatial Distribution of Heavy Metals in Groundwater: Implications for Water Quality and Health Risks

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ABSTRACT

Background: This study evaluated the seasonal and spatial distribution of twelve heavy metals in the groundwater samples collected in fifty wells with the aim of assessing the quality of water and health hazards associated with it. The data were analyzed to compare the wet and dry seasons were the analytical data using pollution indices, the Nemerow Pollution Index (NPI), and the Single-Factor Pollution Index (SFPI). The results revealed that the water quality was mainly excellent ($NPI < 0.01$) even though in some areas, lead, vanadium, and copper were contaminated. Arsenic ($0.0008\text{--}0.0145\ \mu\text{g/L}$), chromium ($0.0009\text{--}0.0096\ \mu\text{g/L}$), and nickel ($< 0.0020\text{--}0.234\ \mu\text{g/L}$) concentrations were still within the World Health Organization acceptable limits, but the lead concentrations were high ($0.5387\ \mu\text{g/L}$) and exceeded the guideline values in some places. The seasonal analysis indicated high concentrations of boron, copper, and manganese in the dry season, but vanadium and lithium showed low seasonal changes. The correlation analysis revealed a significant relationship between copper and lead ($r = 0.860$) and a moderate relationship between chromium and nickel ($r = 0.588$). The study also evaluated the heavy metals in groundwater through Hazard Quotient (HQs), and the evaluation showed that the levels of heavy metals had no serious health risks, and all the values were lower than the critical values in both wet and dry seasons. Although most wells were in good water quality, contamination was localized, which highlights the importance of continuous monitoring and the adoption of management strategies to reduce the possibility of health risk.

Keywords: Groundwater contamination, Geospatial analysis, Health risk assessment, Seasonal variability

Introduction

Groundwater (GW) is one of the most precious and indispensable natural resources for human life and sustainable development.¹ According to the distribution of water on Earth, only around 3% of it is fresh, and of that, only 0.8% is reachable or usable, with the remainder frozen in the polar ice caps.² Globally, nearly 80% of the world's population relies on groundwater as a supply of drinking water, making

it the most dependable source of freshwater or/and surface water.³ Groundwater is the major source of water in the city of Erbil and the Bashtapa sub-basin, both as a source of domestic water use and agricultural water to support a rapidly increasing population and various economic activities.^{4,5} Water quality refers to the chemical, physical, and biological quality of water, depending on its intended use.⁶ Physical and chemical characteristics of water play a major role in the distribution and production of aquatic

Received 21 April 2025; revised 12 June 2025; accepted 12 July 2025.
Available online 23 March 2026

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<https://doi.org/10.21123/2411-7986.5243>

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life, as these parameters may directly or indirectly influence the quality of water.⁷ The quality of water is one of the most important issues worldwide, especially in those areas where industrial processes, mining, and urban runoff are observed. Heavy metals and other contaminants are very hazardous to both human health and the environment.^{8–10} The contamination of potentially dangerous substances is split into two categories: anthropogenic (mine, agricultural, and industrial) and natural (bedrock weathering and erosion) actions.¹¹ Heavy metals are considered to be one of the most persistent contaminants in the water, being characterized by their atomic density exceeding $6\text{g}\cdot\text{cm}^{-3}$. They do not break down, unlike other contaminants, and they can accumulate along the food chain, which may pose a threat to human health and disrupt the ecological balance. The heavy metals are of natural origin (weathering of the bedrock, soil erosion) and anthropogenic origin (mining, industrial effluents, farm chemicals, untreated urban wastewater) are sources of heavy metals.^{10,12} The further development of industrial activity and agricultural enhancement of Erbil and Bashtapa pose a threat of metal contamination, and this threat needs to be thoroughly investigated in terms of its occurrence and distribution. Certain metals, such as copper (Cu), manganese (Mn), iron (Fe), and zinc (Zn), are essential micronutrients that are needed by the body, although when they are high, they become toxic. In contrast, other metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg) are widely reported to be harmful to health even at low concentrations. According to the World Health Organization, the impact of exposure to such metals, which most commonly occurs via polluted water, could have hazardous health effects such as neurological disorders, renal damage, and cancer-inducing effects, which is why such metals are also monitored.^{13,14}

The World Health Organization also noted that even the minimum levels of such metals could be detrimental, and thus, the wide scope of assessment of their presence and interaction in the water bodies is required.^{15–17} Conversely, some heavy metals like arsenic, cadmium, chromium, lead, and mercury have the potential to produce biological toxicity. The most common metals in groundwater include lead (Pb), barium (Ba), copper (Cu), and manganese (Mn); each metal poses varying degrees of health risk depending on the degree of exposure and duration of exposure.¹⁸ Lead is a common neurotoxin whose exposure limit is not safe; chronic exposure to contaminated groundwater may cause serious neurological defects, childhood developmental delays, kidney defects, and heart problems in adults.^{19,20}

The World Health Organization (WHO) establishes a strict guideline level of lead in drinking water since it is cumulative in terms of toxicity and it lasts long in the human body. Exposure to barium, which mainly occurs in natural geology or as a result of industrial releases, may cause cardiovascular and gastrointestinal effects at high levels, and the WHO advises that limits be set to avoid hypertension and muscular weakness.²¹ Copper is a crucial micronutrient essential in enzymatic reactions; too much copper in groundwater may lead to gastrointestinal upsets, liver and kidney damage, and, with chronic exposure, may lead to oxidative stress and cellular toxicity. Manganese is also needed in physiological processes like bone formation and metabolism, although excessive amounts of manganese intake have been linked to neurotoxicity, which includes cognitive and motor impairment, especially in the susceptible groups of infants and people with compromised iron metabolism.^{21,22}

The intensities of pollution can be identified in several indices generally determined in groundwater (GW).^{23,24} These indices include the impact of specific HMs on whole water quality; some of them are applicable in finding the combined effect of all the measured metals on total pollution.²⁵ The correlation of these trace metals is critical to quality management and pollution control strategies of water. The research proposes to investigate the relationship between a set of trace metals in water samples in diverse locations, which will give information about their relationship with each other. The exploration of these correlations will help to learn more about the processes of metal contamination and its effects on the safety of water.

Material and methods

Location of study area

The Bashtapa sub-basin is situated in the southern part of the Erbil basin. Geographically, the area is located between the longitudes of ($43^{\circ}50'$ E to $44^{\circ}10'$ E) and the latitudes of ($35^{\circ}50'$ N to $36^{\circ}10'$ N) with an elevation of about 420 m. The total area is approximately 885 km^2 . Also, depending on the climate classification, the area is classified as an arid and semi-arid region.²⁶ According to Hussein *et al.*²⁷ the wells in the region that were investigated were able to enter the Bai Hassan Formation and the Quaternary.^{19,20} Deposits, and some of the wells were also able to penetrate the Muqdadiya Formation. In this area, there are two different kinds of aquifers: confined and unconfined.²⁸ Water samples were collected from different sites within the Bashtapa sub-basin in Erbil City, Kurdistan region of Iraq Fig. 1.

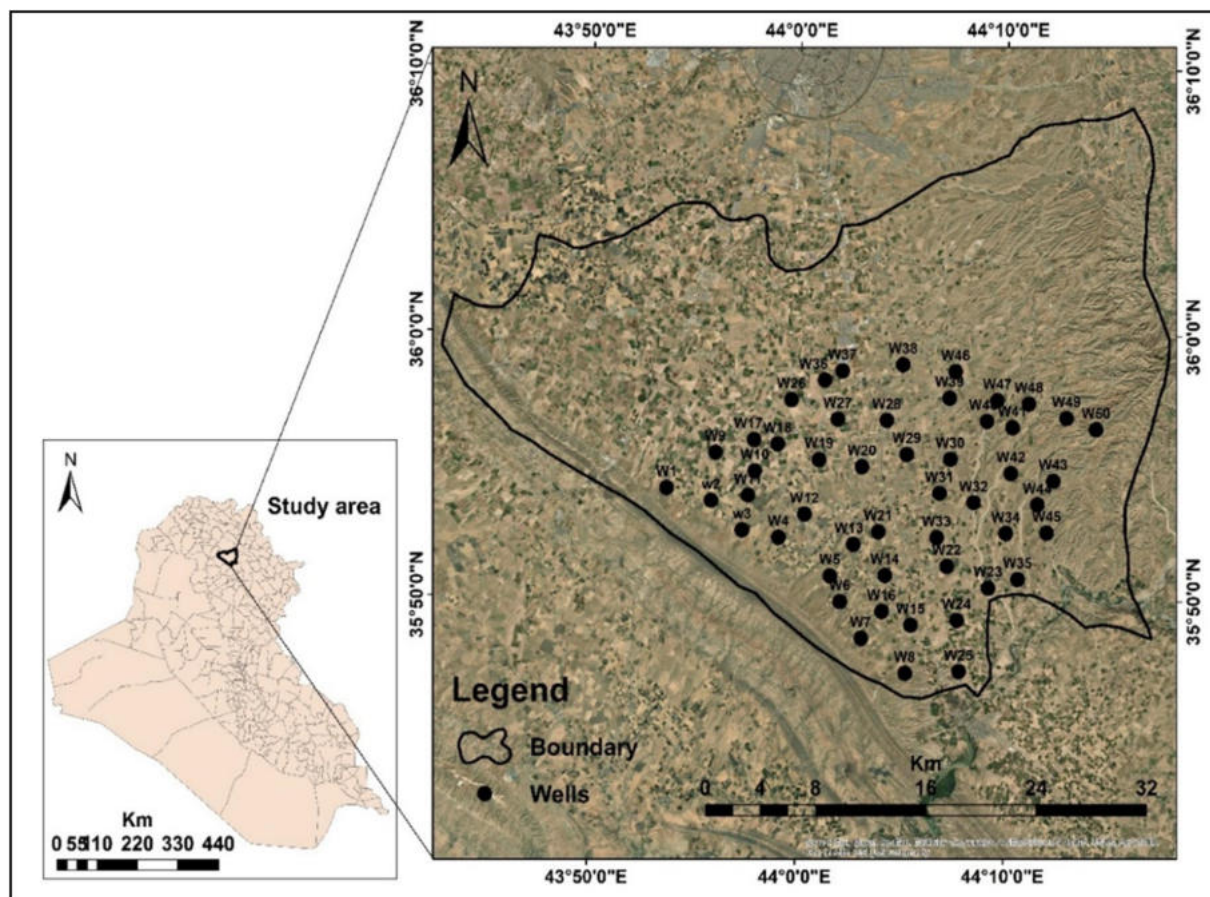


Fig. 1. Location map of different studied wells in the Kurdistan region of Iraq.

Data collection and heavy metal analysis

Fifty water samples were collected from different sites within the Bashtapa sub-basin in Erbil City, Kurdistan region, during both dry and wet seasons. All wells were selected based on their proximity to industrial, agricultural, and other human activities, rather than through random sampling. The selection criteria were primarily determined by the distance between the wells and the surrounding anthropogenic activities. The dry season samples were taken between May 17 and June 4, 2024, while the wet season samples were collected between October 15 and January 5, 2025. Samples were collected in 500 mL high-density polyethylene bottles, which were pre-rinsed with ultrapure deionized water and then with the sampled groundwater. Each sample was filtered through a $0.45\ \mu\text{m}$ membrane filter, acidified with nitric acid to $\text{pH} < 2$ for heavy metal stabilization, and stored at 4°C until analysis. The concentrations of heavy metals were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Agilent 7900, USA).²⁹ Certified reference materials (CRMs) were employed to confirm the accuracy of the found con-

centration. Duplicate samples and procedural blanks were also determined to check for contamination and reproducibility. Calibration was performed with multi-element standard solutions that had been prepared from traceable stock standards, and calibration curves with correlation coefficients (R^2) above 0.999 were ensured. The limit of detection (LOD) of all the metals was established based on three times the standard deviation of the blank analyses. Intergroup interferences on the spectra were minimized using collision/reaction cell technology with the Agilent 7900 ICP-MS and further corrected using the application of correction equations when required. All these precautions were taken to ensure the precision and accuracy of the concentration of the heavy metals.

Data analysis

Data analysis was conducted using SPSS 26.0. Descriptive statistics were computed to summarize heavy metal concentrations. Data visualization and graph creation were performed using GraphPad Prism software (version 8.0.2). Pearson correlation coefficients were determined to assess relationships among

different metals. Principal Component Analysis (PCA) was performed to identify possible pollution sources. Normality tests (Shapiro-Wilk) and variance homogeneity tests (Levene's test) were conducted prior to ANOVA to compare seasonal variations in contamination levels. The ArcGIS platform was used to create the interpolation map from the inverse distance weighting (IDW) tool to represent the elements distributed in the Central-Erbil sub-basin. Analyzing the spatial distribution of the wells can provide valuable insights into patterns of potential contamination, allowing for the identification of areas that may be at greater risk of environmental impact. Additionally, different environmental indices were used, including the Single Factor Pollution Index (SFPI) and Nemerow Pollution Index (PNPI), to evaluate and quantify the heavy metals pollution in the present study. These indices are commonly used of environment assessment and were selected to evaluate the single pollutions as well as the overall water quality pollution level.

Single-factor pollution index

The single-factor pollution indices are an estimated technique based on the contamination's use of environmental quality criteria. Additionally, it is unable to reverse all pollution levels brought on by a combination of different pollution components.³⁰

$$P_i = \frac{C_i}{S_i} \tag{1}$$

where P_i represents the pollution index of a certain water quality index i ; C_i denotes the observed pollutant concentration (mg l-1); S_i signifies the normal environmental quality level (mg l-1).

Nemerow pollution index

A weighted multi-factor environmental quality indicator called the Nemerow index takes into account extreme values or exceptional maximum values.³¹ Which is the method used to calculate the comprehensive pollution index, as shown in **Tables 1 and 2**, to divide water quality into two different categories:

Table 1. Assessment of water quality levels with the single-factor pollution index.

Water quality level	Pi	Pollution assessment
I	≤ 1	No pollution
II	1.1 – ≤ 2	Slightly pollution
III	2.1 – ≤ 3	Lightly pollution
IV	3.1 – ≤ 5	Moderately polluted
v	> 5	Seriously pollution

Table 2. Assessment of water quality levels with the Nemerow pollution index.

Water quality level	NPI
I	< 0.59
II	0.59 – < 0.74
III	0.74 – < 1.00
IV	1.00 – < 3.50
v	≥ 3.50

$$NPI = \sqrt{\frac{(P_1)^2 + (P_{imax})^2}{2}} \tag{2}$$

Where NPI represents the whole pollution index of the sample location, P_{imax} denotes the highest value of the individual pollution index for the pollutants at the sampling site; $P_1 = \sum P_i$ is signifies the mean value of the single-factor index.

Health risk assessment index

The Hazard Quotient (HQ) is an important parameter of risk assessment in environmental health, as it measures the possible non-carcinogenic health hazards of exposure to chemical substances. It is given as the ratio of estimated exposure dose, usually the Chronic Daily Intake (CDI), to the reference dose (RfD) **Table 3**, which is the highest acceptable dose of the exposure, which is probable to have no significant adverse effects, orally. The HQ can be calculated formally as:

$$HQ = \frac{CDI}{RfD} \quad CDI = \frac{C * IR * EF * ED}{RBW * ATfD} \tag{3}$$

C = metal concentration, IR is the ingestion rate.³² EF is the exposure frequency, and ED is the exposure duration. BW is the average body weight, and AT is the average time to lifespan ($EF \times ED$). RfD = reference dose of metals.^{33,34} An HQ value below unity ($HQ < 1$) implies that the exposure is unlikely to pose appreciable health risks, whereas values exceeding unity ($HQ > 1$) signal potential for adverse effects, necessitating further evaluation or intervention. The calculation of HQ employs standardized exposure parameters, as delineated by the United States Environmental Protection Agency (USEPA) for adult populations via the oral ingestion pathway. These parameters include an ingestion rate (IR) of 2.2 liters per day, an exposure frequency (EF) of 365 days per year, an exposure duration (ED) of 30 years to represent chronic exposure, and a body weight (BW) of 70 kilograms reflecting average adult anthropometry. The averaging time (AT) for non-carcinogenic

risk assessments is set at 10,950 days, corresponding to the exposure duration multiplied by days per year. Collectively, these factors underpin the quantitative assessment of chemical exposure risks and facilitate prioritization in environmental health studies.³⁵

Table 3. Reference Doses (RfD) for Selected Metals (mg/kg/day).

Metal	RfD(mg/kg/day)
Arsenic (As)	0.0003
Barium (Ba)	0.2
Chromium (Cr VI)	0.003
Copper (Cu)	0.04
Lead (Pb)	0.0035
Nickel (Ni)	0.02
Zinc (Zn)	0.3
Manganese (Mn)	0.14
Boron (B)	0.2
Vanadium (V)	0.009
Lithium (Li)	0.002

Results

The concentrations of twelve heavy metals in 50 wells during the wet and dry seasons were assessed as shown in Tables 4 and 5. The analysis of groundwater samples from 50 wells revealed generally low concentrations of heavy metals and trace elements, all measured in micrograms per liter ($\mu\text{g/L}$). Arsenic content ranged between 0.0008 to 0.0145 $\mu\text{g/L}$, which means that there is no significant contamination of arsenic throughout the study area. The concentration of barium and boron had significant variation; the maximum range of 0.1739 $\mu\text{g/L}$ was seen in barium, whereas the highest possible level of 0.6270 $\mu\text{g/L}$ was in boron, which could be attributed to natural geological variations.

The amount of chromium and copper was low, with the highest values of 0.0096 $\mu\text{g/L}$ and 0.6079 $\mu\text{g/L}$, respectively. Another indicator of low concentrations of lead was the high amounts, and the highest levels were 0.5387 $\mu\text{g/L}$, which is far below the normal drinking water standards, and there was no major anthropogenic influence. Lithium, manganese, nickel, vanadium, and zinc were observed to be present in low to moderate concentrations, with the highest maximum concentration of zinc of 4.1301 $\mu\text{g/L}$, suggesting local areas of high zinc concentration. The trace metal levels were in line with the natural levels of background levels across all the wells and did not show a high degree of contamination and pollution. These findings suggest that the groundwater in the sampled area is of good chemical quality with respect to heavy metals, posing minimal risk to human health or the environment based on the analyzed parameters.

Spatial distribution and seasonal variation of heavy metal concentrations

The Earth's crust contains significant amounts of native arsenic, which also appears in small concentrations in rock and soil, air, and water.³⁶ The recorded arsenic levels during the wet season extended between (0.008 to 0.0145 $\mu\text{g/L}$). The ranges in dry season extended from (0.0010 to 0.0146 $\mu\text{g/L}$) as shown in Fig. 2.

Barium (Ba)

The seasonal analysis of Ba element concentration showed values ranging between (0.0004 to 0.0174 $\mu\text{g/L}$) during the wet season. Fig. 3 shows As levels spreading from a minimum of 0.0005 $\mu\text{g/L}$ to a maximum of 0.184 $\mu\text{g/L}$ during the dry season.

Boron (Bo)

Soils containing organic matter at low concentrations contain boron elements because of biological activity.³⁷ According to Lima *et al.*³⁸ As Sb, B, and other trace elements become mobile through natural weathering, biological processes, as well as geochemical reactions, volcanic events, and human-related activities. The Bo element concentration during the wet season ranged from 0.0017 $\mu\text{g/L}$ to 0.627 $\mu\text{g/L}$. Fig. 4.

Chromium (Cr)

The elemental concentration of Cr was determined to range between (0.0009 to 0.0096 $\mu\text{g/L}$) in the wet season, while in the dry season, it varied from (0.0002 to 0.629 $\mu\text{g/L}$). In terms of dry season results, the studied element concentrations stretched from 0.0010 $\mu\text{g/L}$ to 0.0097 $\mu\text{g/L}$ Fig. 5.

Copper (Cu)

Likewise, Cu element measurements spanned from 0.0002 $\mu\text{g/L}$ to 0.608 $\mu\text{g/L}$ and from 0.0009 $\mu\text{g/L}$ to 0.627 $\mu\text{g/L}$ in wet and dry seasons, respectively. The dry season data for the ranges extended from (0.0009 to 0.627 $\mu\text{g/L}$) as shown in Fig. 6.

Lead (Pb)

The range of Pb concentrations found in water samples during the wet season extended from 0.002 to 0.539 $\mu\text{g/L}$. The ranges for this element during the dry season extended from 0.0003 $\mu\text{g/L}$ to 0.541 $\mu\text{g/L}$ Fig. 7.

Table 4. Heavy metal concentrations in the wet season in the study area.

Well No.	Easting	Northing	Arsenic $\mu\text{g/L}$	Barium $\mu\text{g/L}$	Boron $\mu\text{g/L}$	Chromium $\mu\text{g/L}$	Copper $\mu\text{g/L}$	Lead $\mu\text{g/L}$	Lithium $\mu\text{g/L}$	Manganese $\mu\text{g/L}$	Nickel $\mu\text{g/L}$	Vanadium $\mu\text{g/L}$	Zinc $\mu\text{g/L}$
W1	400243	3973708	0.0031	0.0004	0.0081	0.0021	0.0639	0.0007	0.0115	0.0117	0.0020	0.0085	0.0036
w2	403474	3972808	0.0033	0.0316	0.1461	0.0015	0.0859	0.0167	0.0174	0.0177	<0.0020	0.0025	0.3271
w3	405715	3970732	0.0029	0.0928	0.0181	0.0033	0.0029	0.0747	0.0064	0.0180	0.0068	0.0061	0.0039
W4	408355	3970210	0.0036	0.0037	0.1260	0.0025	0.0838	0.0146	0.0176	0.0109	<0.0020	0.0054	0.1031
W5	412073	3967534	0.0011	0.0013	0.0263	0.0018	0.1078	0.0386	0.0073	0.0172	<0.0020	0.0016	0.0021
W6	412803	3965729	0.0024	0.0026	0.0904	0.0033	0.1608	0.0916	0.0099	0.0006	<0.0020	0.0148	0.1021
W7	414328	3963190	0.0066	0.0068	0.1790	0.0043	0.0092	0.0738	0.0188	0.0138	<0.0020	0.0193	0.0032
W8	417507	3960746	0.0023	0.0025	0.1050	0.0018	0.0908	0.0216	0.0119	0.0122	0.0068	0.0176	0.1851
W9	403801	3976169	0.0010	0.0291	0.1401	0.0009	0.1279	0.0587	0.0188	0.0191	<0.0020	0.0021	0.2731
W10	406645	3974873	0.0057	0.0269	0.1041	0.0047	0.0899	0.0207	0.0111	0.0114	<0.0020	0.0041	0.0040
W11	406151	3973171	0.0011	0.0013	0.0227	0.0033	0.0048	0.0598	0.0041	0.0006	<0.0020	0.0033	0.3281
W12	410247	3971818	0.0032	0.0034	0.0915	0.0009	0.0092	0.0738	0.0108	0.0089	0.0028	0.0085	0.3071
W13	413786	3969733	0.0145	0.0056	0.0017	0.0025	0.0063	0.0647	0.0030	0.0194	<0.0020	0.0044	0.1861
W14	416074	3967564	0.0008	0.0010	0.0254	0.0096	0.0081	0.0565	0.0046	0.0186	<0.0020	0.0092	0.3271
W15	417928	3964108	0.0024	0.0026	0.0090	0.0047	0.0145	0.0501	0.0016	0.0149	<0.0020	0.0217	0.3061
W16	415822	3965042	0.0017	0.0019	0.1090	0.0062	0.0722	0.0030	0.0125	0.0128	0.0020	0.0181	0.0011
W17	406594	3977050	0.0022	0.0531	0.0821	0.0030	0.0769	0.0077	0.0100	0.0123	<0.0020	0.0044	0.0021
W18	408297	3976745	0.0033	0.0398	0.1081	0.0022	0.0713	0.0021	0.0117	0.0120	<0.0020	0.0058	0.1031
W19	411307	3975646	0.0033	0.0034	0.0090	0.0009	0.0045	0.0601	0.0016	0.0178	0.0020	0.0029	0.2741
W20	414415	3975157	0.0016	0.0017	0.6270	0.0024	0.0666	0.0020	0.0077	0.0036	<0.0020	0.0066	0.1041
W21	415595	3970596	0.0065	0.0067	0.0848	0.0018	0.0008	0.0638	0.0128	0.0063	<0.0020	0.0090	0.1631
W22	420556	3968189	0.0008	0.0010	0.0081	0.0030	0.0101	0.0747	0.0045	0.0014	<0.0020	0.0026	4.1301
W23	423544	3966669	0.0033	0.0034	0.0081	0.0026	0.0101	0.0747	0.0163	0.0103	<0.0020	0.0016	0.0021
W24	421269	3964430	0.0014	0.0016	0.0081	0.0017	0.0181	0.0827	0.0095	0.0146	<0.0020	0.0025	0.6551
W25	421409	3960859	0.0051	0.0053	0.1470	0.0019	0.0868	0.0176	0.0182	0.0185	<0.0020	0.0092	0.0030
W26	409307	3979825	0.0017	0.0627	0.0978	0.0015	0.0691	0.0034	0.0151	0.0154	<0.0020	0.0036	0.0032
W27	412664	3978470	0.0011	0.0488	0.0895	0.0032	0.1599	0.0907	0.0091	0.0094	<0.0020	0.0082	0.1621
W28	416214	3978380	0.0054	0.1739	0.1781	0.0010	0.0101	0.0747	0.0180	0.0183	0.0028	0.0041	0.0064
W29	417669	3976021	0.0043	0.0045	0.0081	0.0021	0.0036	0.0610	0.0086	0.0098	0.0020	0.0100	0.0021
W30	420814	3975674	0.0024	0.0238	0.0906	0.0087	0.0101	0.0747	0.0100	0.0103	<0.0020	0.0090	0.0608
W31	420036	3973305	0.0035	0.0037	0.0906	0.0037	0.0101	0.0747	0.0112	0.0048	<0.0020	0.0016	0.0021
W32	422502	3972634	0.0027	0.0028	0.0221	0.0018	0.6079	0.5387	0.0003	0.0031	<0.0020	0.0072	0.0299
W33	419820	3970182	0.0026	0.0028	0.0190	0.0015	0.0724	0.0032	0.0113	0.0166	<0.0020	0.0049	0.0074
W34	424832	3970470	0.0048	0.0343	0.0218	0.0016	0.0039	0.0607	0.0033	0.0036	<0.0020	0.0092	4.1291
W35	425693	3967275	0.0037	0.0242	0.0882	0.0031	0.1228	0.0536	0.0136	0.0139	0.2340	0.0166	0.1031
W36	411739	3981189	0.0088	0.0531	0.0966	0.0014	0.0796	0.0104	0.0140	0.0057	<0.0020	0.0046	0.1021
W37	413004	3981828	0.0046	0.0004	0.0221	0.0009	0.0784	0.0092	0.0008	0.0005	0.0020	0.0008	0.0011
W38	417404	3982255	0.0066	0.1059	0.0661	0.0025	0.0029	0.0776	0.0128	0.0172	<0.0020	0.0095	0.0056
W39	420772	3979931	0.0023	0.0285	0.1011	0.0035	0.0724	0.0032	0.0050	0.0053	<0.0020	0.0133	0.0425
W40	423483	3978305	0.0013	0.1689	0.0254	0.0034	0.1069	0.0377	0.0065	0.0068	<0.0020	0.0064	0.0289
W41	425329	3977872	0.0029	0.0030	0.0181	0.0013	0.0101	0.0747	0.0060	0.0118	0.0068	0.0098	0.0618
W42	425211	3974669	0.0048	0.0004	0.0081	0.0009	0.0036	0.0610	0.0008	0.0011	0.0020	0.0008	0.0011
W43	428272	3974134	0.0029	0.0510	0.0987	0.0056	0.0700	0.0008	0.0159	0.0162	<0.0020	0.0142	0.0011
W44	427123	3972470	0.0047	0.0319	0.0221	0.0018	0.6079	0.5387	0.0035	0.0038	<0.0020	0.0130	0.6541
W45	427800	3970498	0.0022	0.0371	0.6261	0.0023	0.0657	0.0011	0.0069	0.0072	0.0069	0.0120	0.0092
W46	421209	3981764	0.0038	0.0291	0.0052	0.0027	0.0002	0.0749	0.0188	0.0152	<0.0020	0.0100	0.0040
W47	424226	3979742	0.0010	0.0967	0.1251	0.0038	0.0829	0.0137	0.0168	0.0171	<0.0020	0.0109	0.2231
W48	426521	3979523	0.0024	0.0316	0.0079	0.0062	0.0036	0.0004	0.0174	0.0302	<0.0020	0.0067	0.1861
W49	429238	3978500	0.0055	0.0209	0.0015	0.0056	0.0051	0.0009	0.0093	0.0262	<0.00020	0.0038	0.0131
W50	431379	3977718	0.0018	0.0344	0.0975	0.0024	0.0805	0.0113	0.0148	0.0151	<0.0020	0.0125	0.0026
	Min.		0.0008	0.0004	0.0017	0.0009	0.0002	0.0020	0.0003	0.0005	0.0020	0.0008	0.0011
	Max.		0.0145	0.1739	0.6270	0.0096	0.6079	0.5387	0.0188	0.0302	0.2340	0.0217	4.1301

Table 5. Heavy metal concentrations in dry season in the study area.

Well No.	Easting	Northing	Arsenic $\mu\text{g/L}$	Barium $\mu\text{g/L}$	Boron $\mu\text{g/L}$	Chromium $\mu\text{g/L}$	Copper $\mu\text{g/L}$	Lead $\mu\text{g/L}$	Lithium $\mu\text{g/L}$	Manganese $\mu\text{g/L}$	Nickel $\mu\text{g/L}$	Vanadium $\mu\text{g/L}$	Zinc $\mu\text{g/L}$
W1	400243	3973708	0.0033	0.0005	0.0100	0.0022	0.0829	0.0030	0.0116	0.0126	0.0020	0.0086	0.0045
w2	403474	3972808	0.0035	0.0317	0.1480	0.0016	0.1049	0.0190	0.0176	0.0185	<0.0020	0.0027	0.3280
w3	405715	3970732	0.0031	0.0929	0.0200	0.0034	0.0089	0.0770	0.0065	0.0189	0.0068	0.0062	0.0048
W4	408355	3970210	0.0038	0.0039	0.1279	0.0026	0.1028	0.0169	0.0178	0.0117	<0.0020	0.0056	0.1040
W5	412073	3967534	0.0013	0.0014	0.0282	0.0019	0.1268	0.0409	0.0075	0.0180	<0.0020	0.0018	0.0030
W6	412803	3965729	0.0026	0.0027	0.0923	0.0034	0.1798	0.0939	0.0101	0.0014	<0.0020	0.0150	0.1030
W7	414328	3963190	0.0068	0.0069	0.1809	0.0044	0.0098	0.0761	0.0190	0.0146	<0.0020	0.0195	0.0041
W8	417507	3960746	0.0025	0.0026	0.1069	0.0019	0.1098	0.0239	0.0121	0.0130	0.0068	0.0178	0.1860
W9	403801	3976169	0.0012	0.0292	0.1420	0.0010	0.1469	0.0610	0.0190	0.0199	<0.0020	0.0023	0.2740
W10	406645	3974873	0.0059	0.0270	0.1060	0.0048	0.1089	0.0230	0.0113	0.0122	<0.0020	0.0043	0.0049
W11	406151	3973171	0.0013	0.0014	0.0246	0.0034	0.0238	0.0621	0.0043	0.0014	<0.0020	0.0035	0.3290
W12	410247	3971818	0.0034	0.0035	0.0934	0.0010	0.0098	0.0761	0.0110	0.0097	0.0028	0.0087	0.3080
W13	413786	3969733	0.0146	0.0057	0.0002	0.0026	0.0189	0.0670	0.0031	0.0203	<0.0020	0.0045	0.1870
W14	416074	3967564	0.0010	0.0011	0.0273	0.0097	0.0271	0.0588	0.0048	0.0194	<0.0020	0.0094	0.3280
W15	417928	3964108	0.0026	0.0027	0.0109	0.0048	0.0335	0.0524	0.0018	0.0157	<0.0020	0.0219	0.3070
W16	415822	3965042	0.0019	0.0020	0.1109	0.0063	0.0912	0.0053	0.0127	0.0136	0.0020	0.0183	0.0020
W17	406594	3977050	0.0024	0.0532	0.0840	0.0031	0.0959	0.0100	0.0101	0.0132	<0.0020	0.0045	0.0030
W18	408297	3976745	0.0035	0.0399	0.1100	0.0023	0.0903	0.0044	0.0119	0.0128	<0.0020	0.0060	0.1040
W19	411307	3975646	0.0035	0.0036	0.0109	0.0010	0.0235	0.0624	0.0018	0.0186	0.0020	0.0031	0.2750
W20	414415	3975157	0.0017	0.0018	0.6289	0.0025	0.0856	0.0003	0.0079	0.0044	<0.0020	0.0068	0.1050
W21	415595	3970596	0.0067	0.0068	0.0867	0.0019	0.0198	0.0661	0.0130	0.0071	<0.0020	0.0092	0.1640
W22	420556	3968189	0.0010	0.0011	0.0100	0.0032	0.0089	0.0770	0.0046	0.0023	<0.0020	0.0028	4.1310
W23	423544	3966669	0.0034	0.0035	0.0100	0.0027	0.0089	0.0770	0.0164	0.0111	<0.0020	0.0018	0.0030
W24	421269	3964430	0.0016	0.0017	0.0100	0.0018	0.0009	0.0850	0.0096	0.0155	<0.0020	0.0027	0.6560
W25	421409	3960859	0.0053	0.0054	0.1489	0.0020	0.1058	0.0199	0.0184	0.0193	<0.0020	0.0094	0.0039
W26	409307	3979825	0.0019	0.0628	0.0997	0.0016	0.0881	0.0022	0.0153	0.0162	<0.0020	0.0038	0.0041
W27	412664	3978470	0.0013	0.0489	0.0914	0.0033	0.1789	0.0930	0.0093	0.0102	<0.0020	0.0084	0.1630
W28	416214	3978380	0.0056	0.1740	0.1800	0.0011	0.0089	0.0770	0.0182	0.0191	0.0028	0.0043	0.0073
W29	417669	3976021	0.0045	0.0046	0.0100	0.0022	0.0226	0.0633	0.0087	0.0106	0.0020	0.0102	0.0030
W30	420814	3975674	0.0026	0.0239	0.0925	0.0088	0.0089	0.0770	0.0102	0.0111	<0.0020	0.0092	0.0617
W31	420036	3973305	0.0037	0.0038	0.0925	0.0038	0.0089	0.0770	0.0113	0.0056	<0.0020	0.0018	0.0030
W32	422502	3972634	0.0028	0.0029	0.0240	0.0019	0.6269	0.5410	0.0004	0.0039	<0.0020	0.0074	0.0308
W33	419820	3970182	0.0028	0.0029	0.0209	0.0016	0.0914	0.0055	0.0115	0.0174	<0.0020	0.0051	0.0083
W34	424832	3970470	0.0050	0.0344	0.0237	0.0017	0.0229	0.0630	0.0035	0.0044	<0.0020	0.0094	4.1300
W35	425693	3967275	0.0039	0.0243	0.0901	0.0032	0.1418	0.0559	0.0138	0.0147	0.2340	0.0168	0.1040
W36	411739	3981189	0.0090	0.0532	0.0985	0.0015	0.0986	0.0127	0.0142	0.0151	<0.0020	0.0048	0.1030
W37	413004	3981828	0.0048	0.0005	0.0240	0.0010	0.0974	0.0115	0.0010	0.0019	0.0020	0.0010	0.0020
W38	417404	3982255	0.0068	0.1060	0.0680	0.0026	0.0060	0.0799	0.0130	0.0180	<0.0020	0.0096	0.0065
W39	420772	3979931	0.0025	0.0286	0.1030	0.0036	0.0914	0.0055	0.0052	0.0061	<0.0020	0.0135	0.0434
W40	423483	3978305	0.0015	0.1690	0.0273	0.0035	0.1259	0.0400	0.0067	0.0076	<0.0020	0.0066	0.0298
W41	425329	3977872	0.0030	0.0031	0.0200	0.0014	0.0089	0.0770	0.0061	0.0126	0.0068	0.0100	0.0627
W42	425211	3974669	0.0050	0.0005	0.0100	0.0010	0.0226	0.0633	0.0010	0.0019	0.0020	0.0010	0.0020
W43	428272	3974134	0.0031	0.0511	0.1006	0.0057	0.0890	0.0031	0.0161	0.0170	<0.0020	0.0144	0.0020
W44	427123	3972470	0.0049	0.0320	0.0240	0.0019	0.6269	0.5410	0.0037	0.0046	<0.0020	0.0132	0.6550
W45	427800	3970498	0.0024	0.0372	0.6280	0.0024	0.0847	0.0012	0.0071	0.0080	0.0069	0.0122	0.0101
W46	421209	3981764	0.0040	0.0292	0.0071	0.0028	0.0087	0.0772	0.0190	0.0160	<0.0020	0.0101	0.0049
W47	424226	3979742	0.0012	0.0968	0.1270	0.0039	0.1019	0.0160	0.0170	0.0179	<0.0020	0.0111	0.2240
W48	426521	3979523	0.0026	0.0317	0.0098	0.0063	0.0051	0.0027	0.0176	0.0310	<0.0020	0.0068	0.1870
W49	429238	3978500	0.0057	0.0210	0.0034	0.0057	0.0043	0.0014	0.0094	0.0270	<0.00020	0.0039	0.0140
W50	431379	3977718	0.0052	0.1840	0.0858	0.0025	0.0189	0.0670	0.0122	0.0131	0.0033	0.0163	0.0579
	Min.		0.0010	0.0005	0.0002	0.0010	0.0009	0.0003	0.0004	0.0014	0.0020	0.0010	0.0020
	Max.		0.0146	0.1840	0.6289	0.0097	0.6269	0.5410	0.0190	0.0310	0.2340	0.0219	4.1310

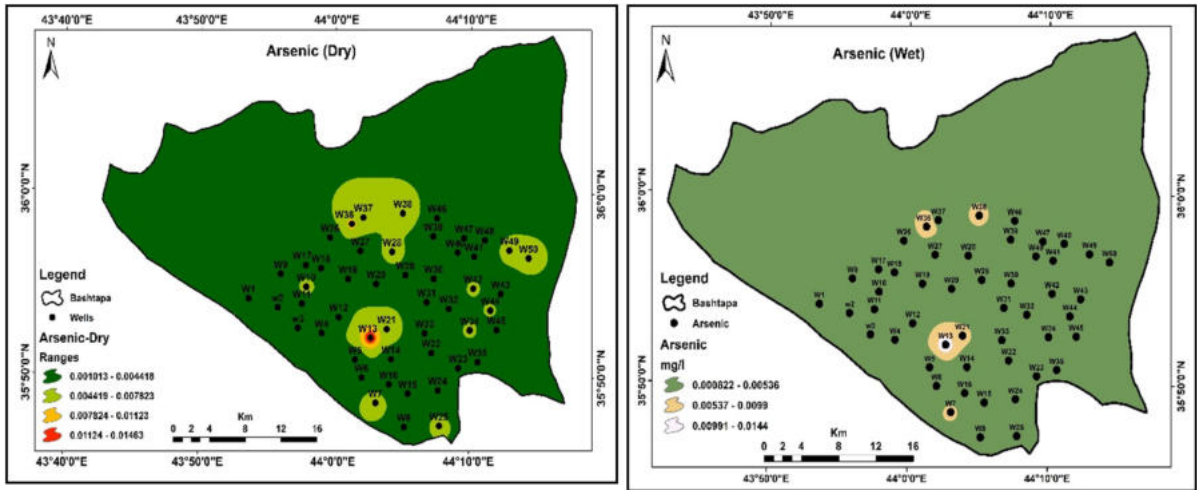


Fig. 2. Spatial distribution and seasonal variation of Arsenic in dry and wet seasons.

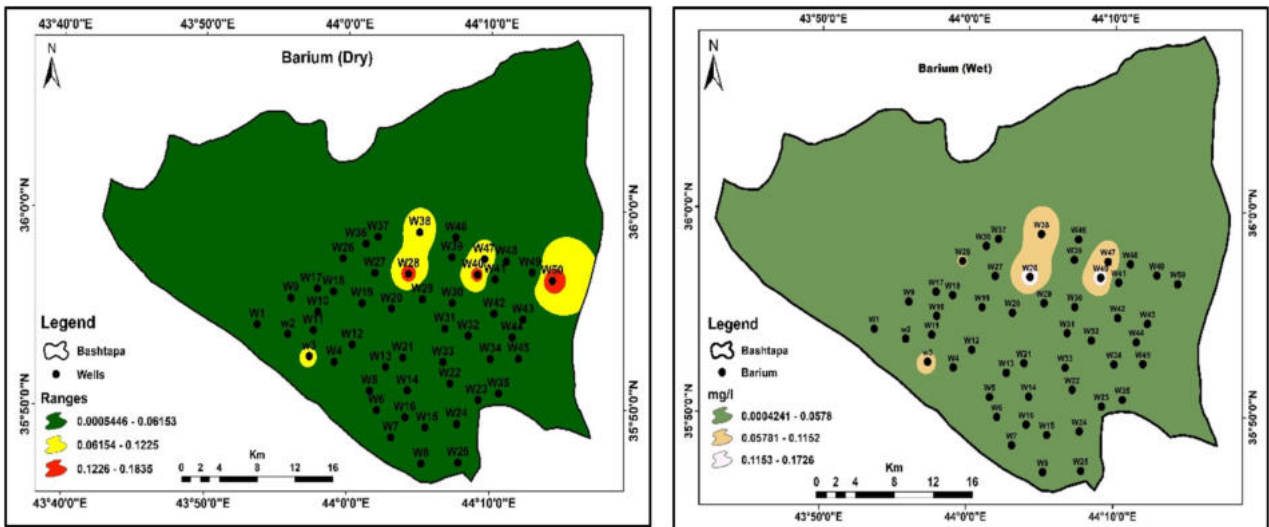


Fig. 3. Spatial distribution and Seasonal variation of Barium in dry and wet seasons.

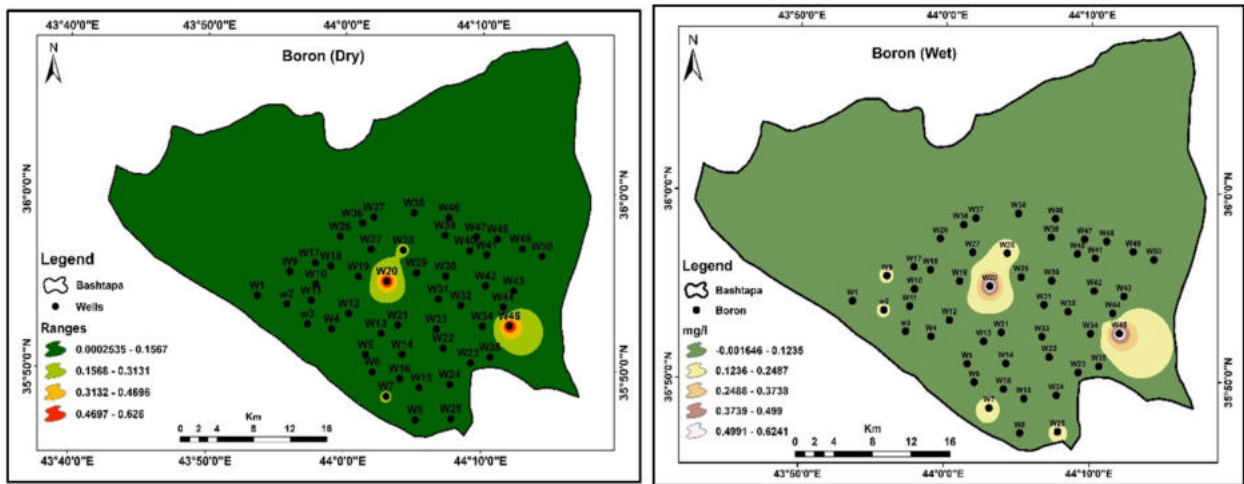


Fig. 4. Spatial distribution and seasonal variation of Boron in dry and wet seasons.

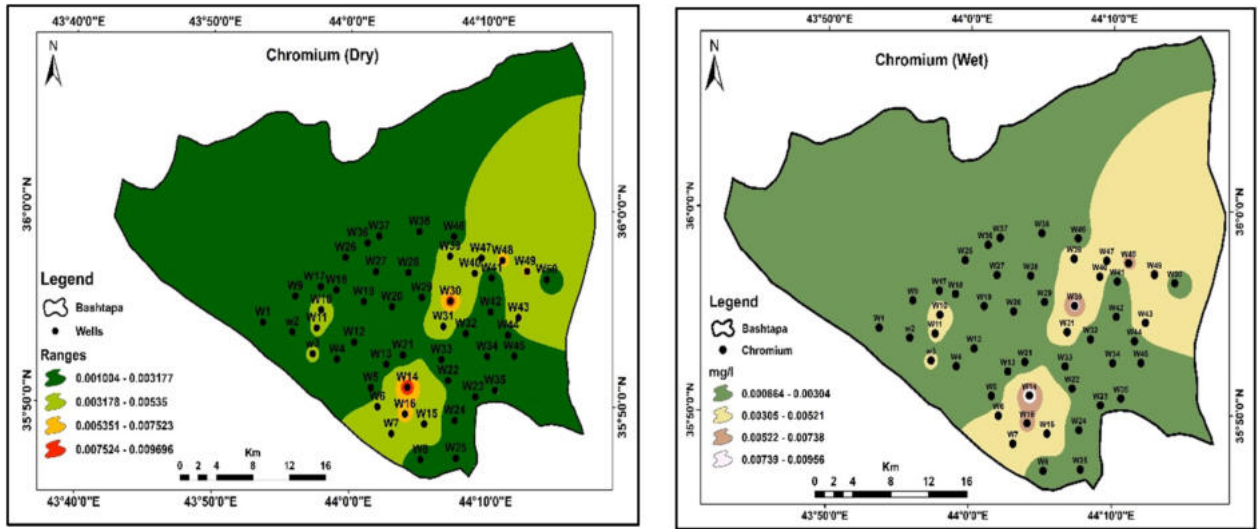


Fig. 5. Spatial distribution and seasonal variation of Chromium in dry and wet seasons.

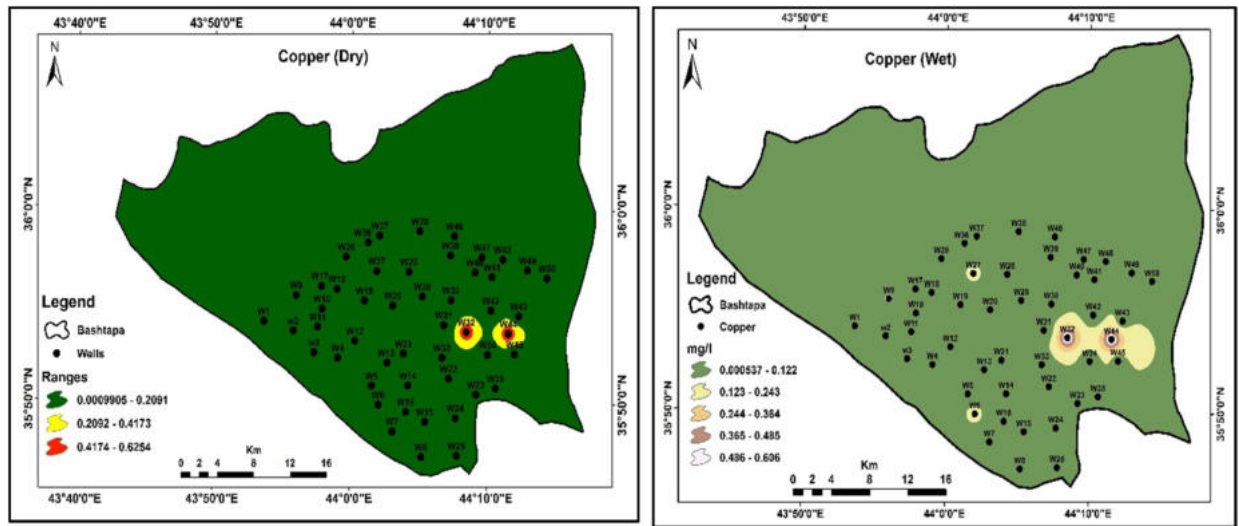


Fig. 6. Spatial distribution and seasonal variation of Copper in dry and wet seasons.

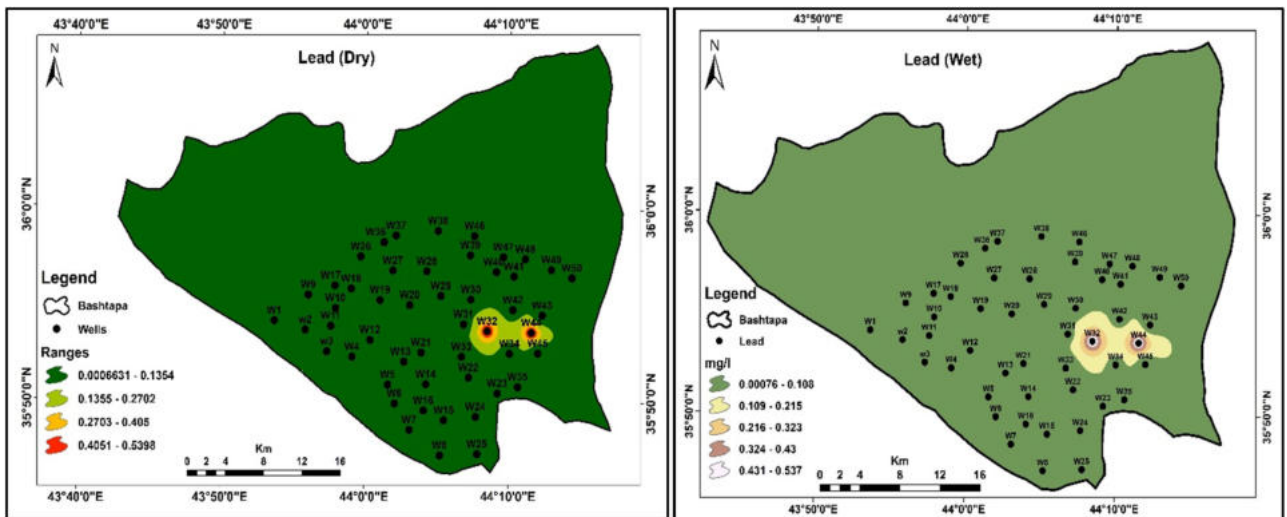


Fig. 7. Spatial distribution and seasonal variation of Lead in dry and wet seasons.

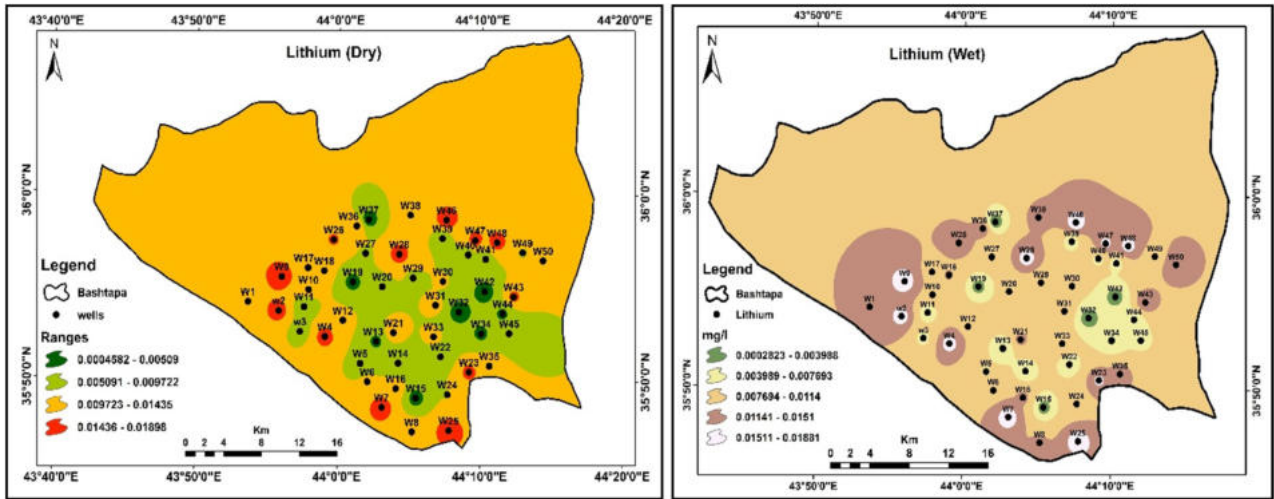


Fig. 8. Spatial distribution and seasonal variation of Lithium in dry and wet seasons.

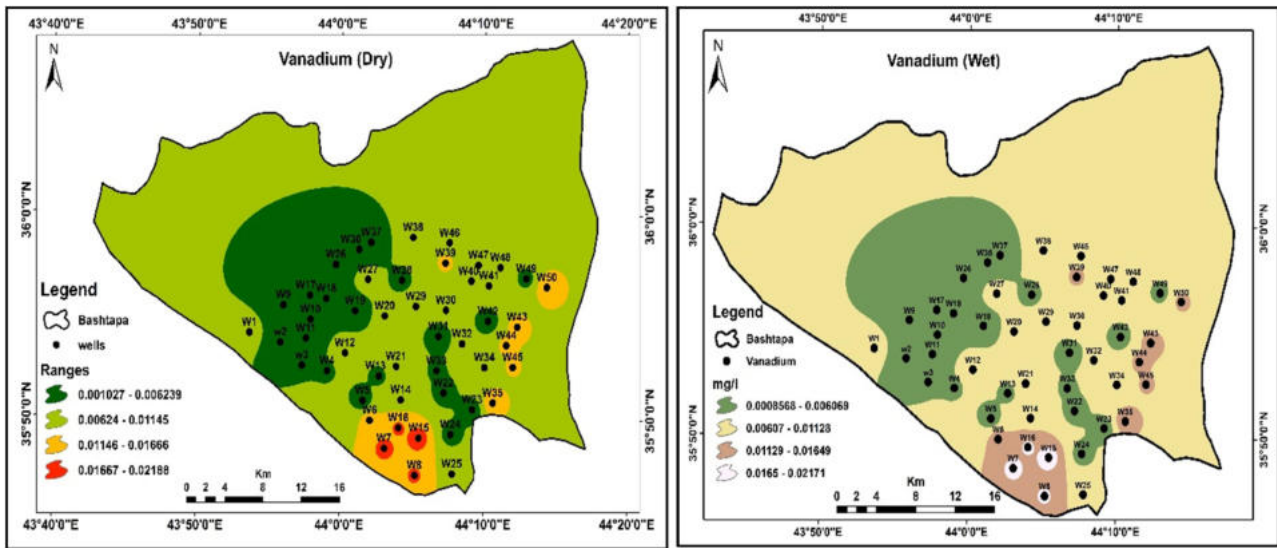


Fig. 9. Spatial distribution and seasonal variation of Manganese in dry and wet seasons.

Lithium (Li)

The analysis of Li concentrations in water during the wet season showed levels between (0.0003 to 0.0188 $\mu\text{g/L}$). The measurement areas in dry season spanned from (0.0004 to 0.0190 $\mu\text{g/L}$) according to Fig. 8.

Manganese (Mn)

Natural bedrock, together with environmental pollutants, serve as two primary sources of manganese found in drinking water.³⁹ Scientific research showed that higher manganese concentrations in water affect neurodevelopment and behaviors in children.⁴⁰ The seasonal evaluation of Mn element concentration dis-

played a range from (0.0005 to 0.0302 $\mu\text{g/L}$) during the wet season Fig. 9.

Vanadium (V)

The Vanadium concentrations measured 0.0008 to 0.0217 $\mu\text{g/L}$ in the wet season and extended to 0.0010 to 0.0146 $\mu\text{g/L}$ during the dry season Fig. 10.

Zinc (Zn)

Zinc concentrations ranged between 0.0011 and 4.130 $\mu\text{g/L}$ during both wet and dry seasons. The mean Zn concentration was 0.275 $\mu\text{g/L}$ throughout the wet season. The ranges measured during the dry season extended from (0.0020 to 4.131 $\mu\text{g/L}$) as shown in Fig. 11.

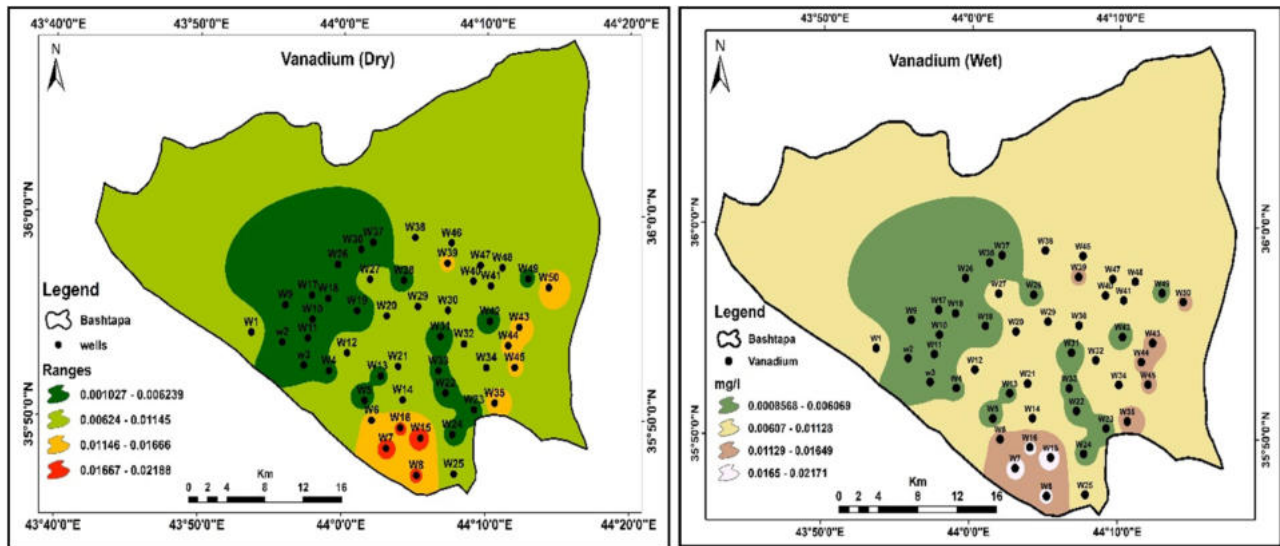


Fig. 10. Spatial distribution and seasonal variation of Vanadium in dry and wet seasons.

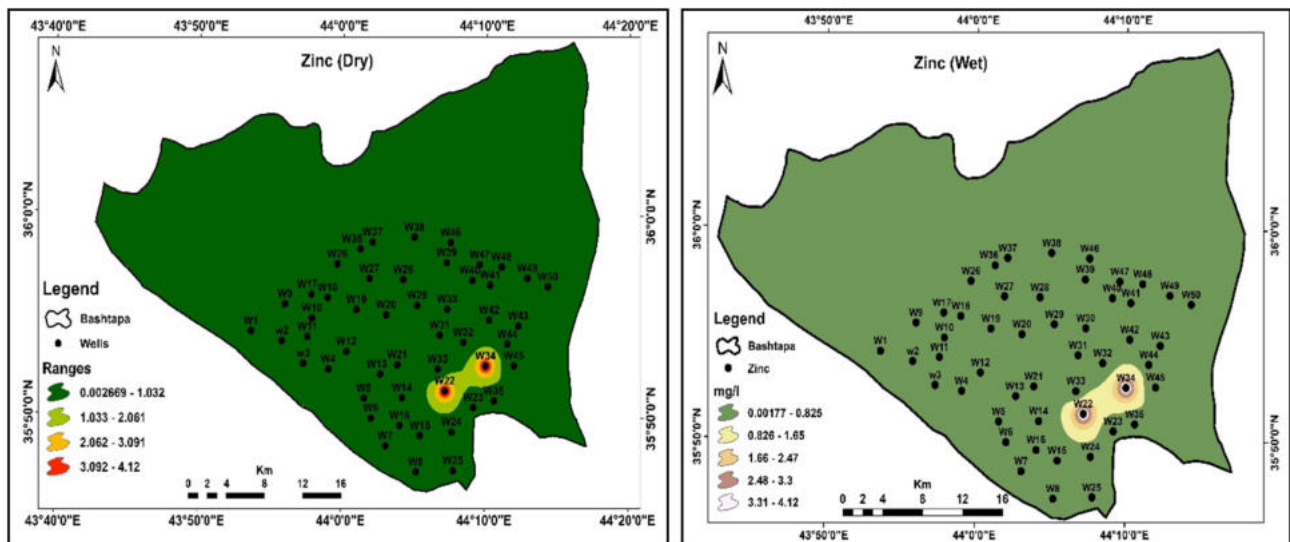


Fig. 11. Spatial distribution and seasonal variation of Zinc in dry and wet seasons.

Correlation analysis of heavy metals in water samples

The results of the correlation matrix, as shown in Fig. 12, indicated that there was a very significant positive correlation between Pb and Cu (0.860). A moderate positive association of (0.588) was detected between Cr and Ni (0.588). Correlation Analysis of (0.636) between Ba and Cr indicated a potential relationship where higher barium levels may coincide with increased chromium levels in the water samples. The results demonstrated that there is a positive correlation between Copper and Arsenic (0.432) observed. In contrast, (−0.319) indicated a moderate negative correlation between Lead and Lithium

(−0.319). Additionally, a weak negative correlation (−0.245) was indicated by Manganese and Lead. In contrast, metals such as zinc, lithium, and vanadium demonstrated weak or negligible correlations with the other trace metals. For instance, zinc exhibited a minimal correlation with other metals, with r values ranging between −0.107 and −0.078.

Environmental assessment

The results of the overall pollution analysis of the Nemerow Pollution Index (NPI) indicated different degrees of pollution in the studied wells in the Fig. 13. Wells 1, 2, 17, 18, 20, 25, 26, 33, 36, 37, 48, and 49 had an NPI value of 0.001, which represented a

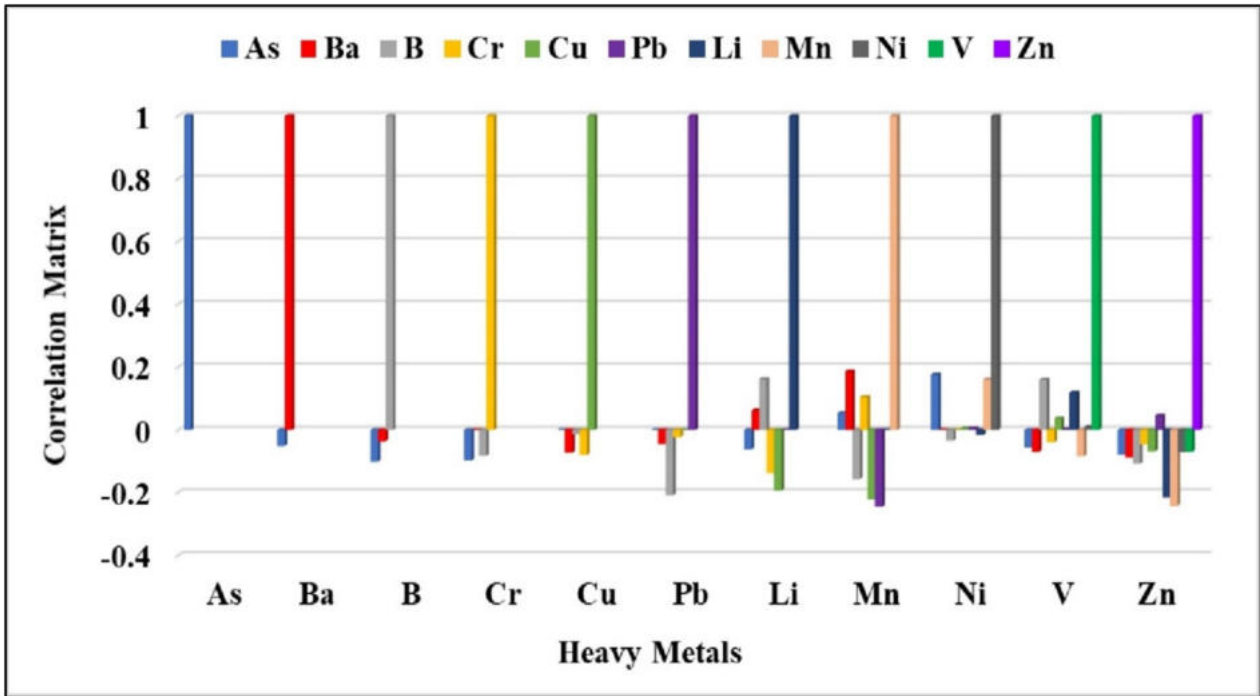


Fig. 12. Correlation matrix of heavy metal concentrations.

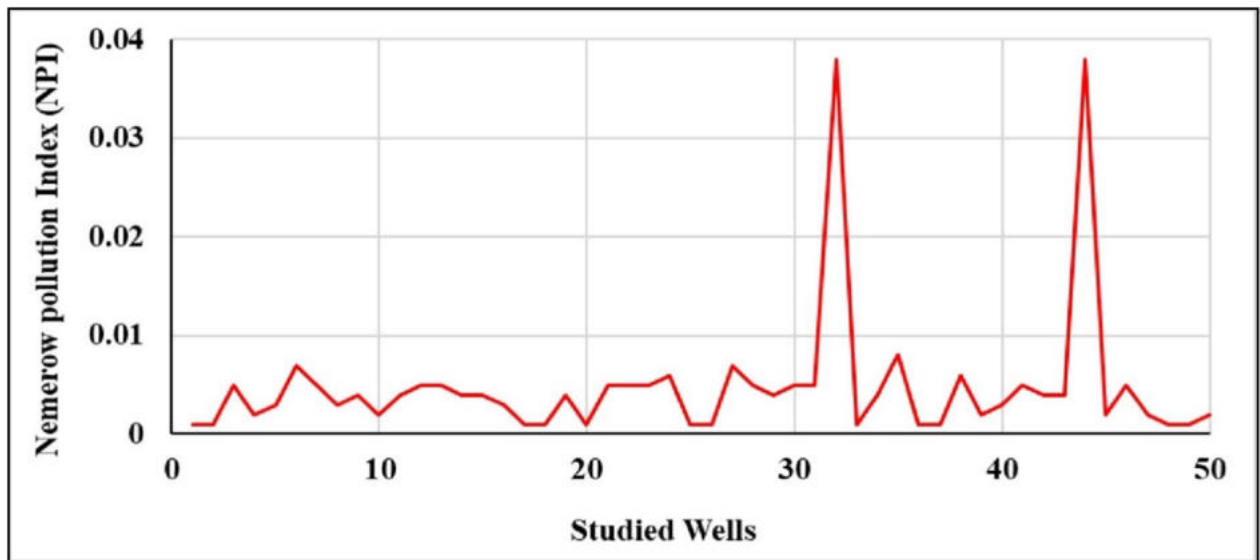


Fig. 13. Nemerow pollution index values for monitoring indicators in the studied wells.

level of water quality of I (excellent). Wells 4, 10, 39, 45, 47, and 50 also had slightly higher NPI values of 0.002, which were also in the category of excellent water quality. Wells 5, 8, 16, and 40 had an NPI value of 0.003, whereas 9, 11, 14, 15, 19, 29, 34, 42, and 43 had a value of 0.004, thus still having a high level of water quality. Wells 3, 7, 12, 13, 21, 22, 23, 28, 30, 31, 41, and 46 recorded a NPI value of 0.005, which was slightly higher but still excellent. Wells (24 and 38) recorded higher NPI values of 0.006 and

0.007 (6 and 27), respectively. Well 35 showed the lowest NPI value, 0.008, and the largest NPI value was recorded in wells (32 and 44) that nonetheless fell into the category of excellent quality levels.

Single factor pollution index

The index of single factor index (Pi) of the indicators observed in the wells under study indicated a significant variation in heavy metals concentration,

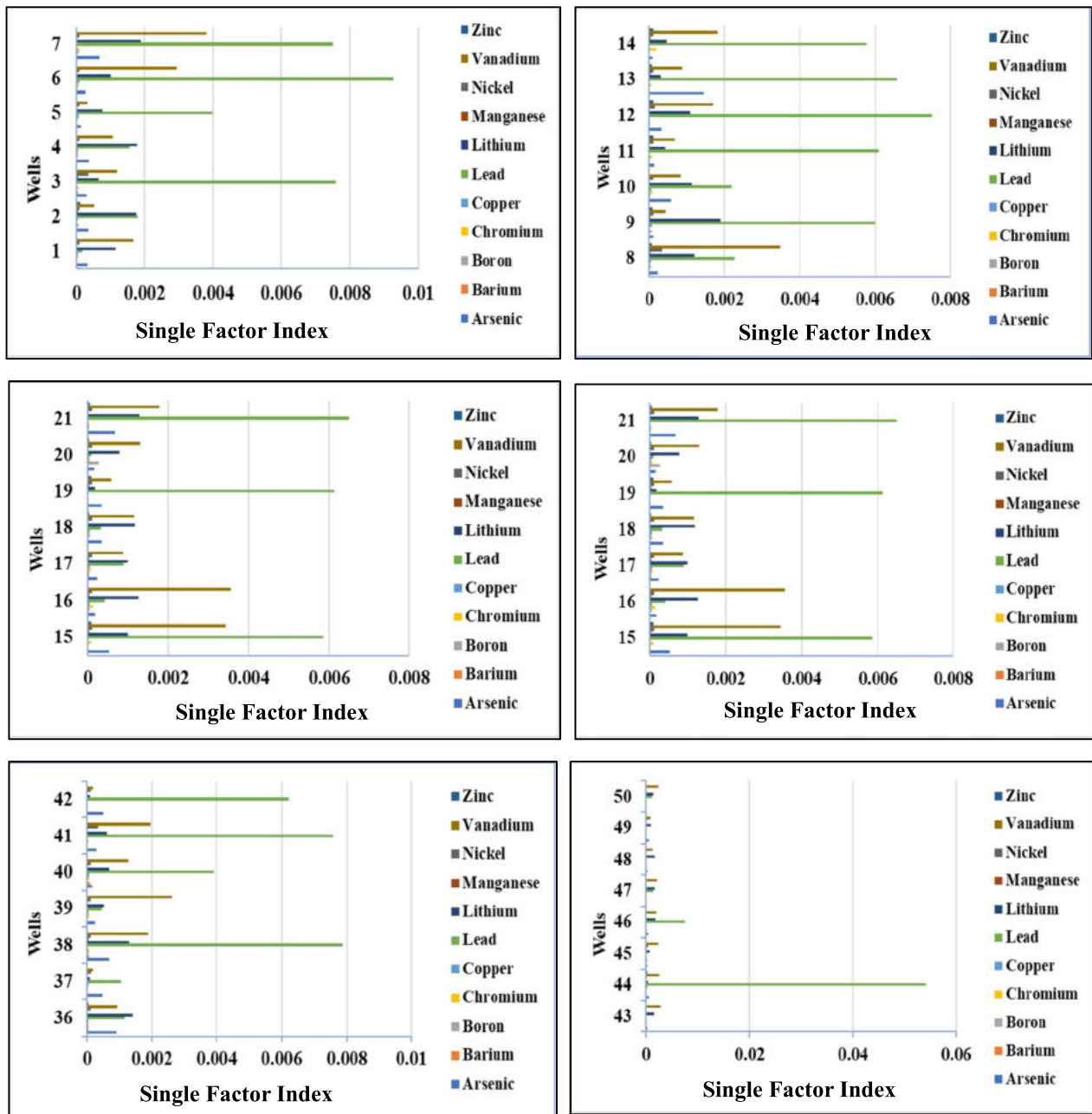


Fig. 14. Single factor index values for monitoring indicators in the studied wells.

as the levels of contamination varied, as demonstrated in Fig. 14. Arsenic had similar values of Pi when compared to different wells, with the highest value observed in Well 7 (0.000671), which showed slight contamination. The contamination of Barium was also low, with Pi often near or below detection limits, but in only a few instances, like Well 5 (0.000031). Localized increases were demonstrated in the higher levels of boron that were observed in Well 7 (0.000075) and Well 26 (0.000075) in the highest Pi levels. Chromium revealed moder-

ate variability, ensuring the maximum Pi in Well 32 (0.001428) and slightly high values in Well 7 (0.000087) and Well 3 (0.000067). There were also low copper levels with low contamination of wells, except that the Pi value of Well 27 was at its peak (0.00919). There was a high spatial variability of lead with high Pi values in various wells, especially Well 32 (0.053985), Well 7 (0.007498), and Well 24 (0.008385). There was a moderate decrease and increase in lithium levels, with the greatest Pi value of Well 7 (0.001893) and Well 27 (0.001833),

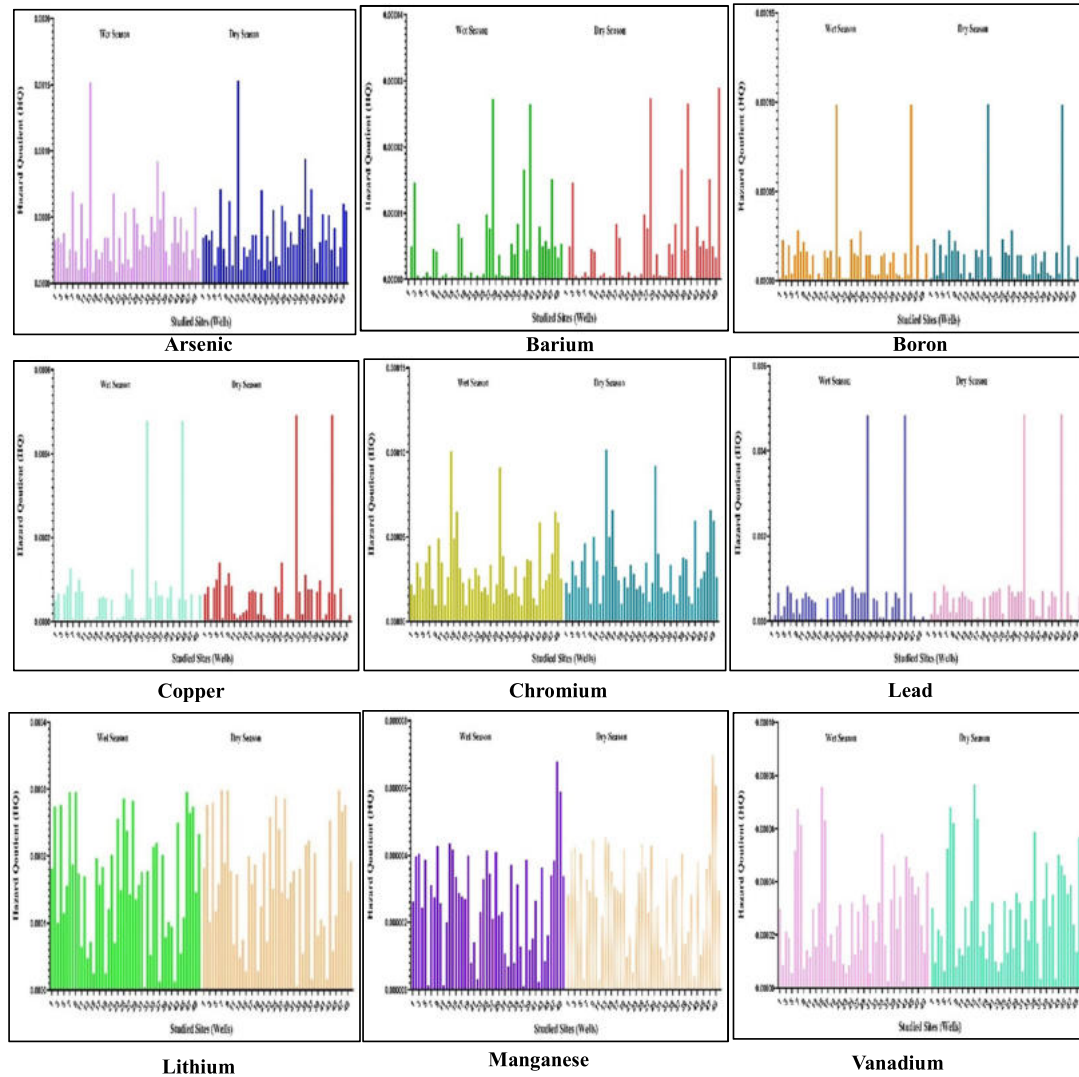


Fig. 15. Seasonal variation of hazard quotient (HQ) values for heavy metals in groundwater across sampled wells.

and the rest of the wells having relatively lower concentrations. Manganese had low levels of contamination in general, with Pi value considered the highest in Well 7 (0.000037). Nickel concentrations remained consistent across wells, with a Pi value of 0.0001 dominating most locations, except for a slight increase in Well 35 (0.0117). Vanadium concentrations showed notable spatial variability, with the highest Pi values in Well 42 (0.004735), Well 7 (0.003807), and Well 32 (0.001428), indicating localized contamination. Zinc concentrations were generally low, with isolated peaks observed in Well 34 (0.00138) and Well 7 (0.000034), Fig. 14.

Health risk assessment

The calculated Hazard Quotient (HQ) values for the metals across sampled wells during wet and dry seasons are shown in Fig. 15. Arsenic HQs ranged from

about 0.0001 to 0.0015, indicating non-carcinogenic risk well below the concern threshold ($HQ < 1$) at all sites. Barium and Boron HQs were consistently negligible, with maximum values around 10^{-5} and 10^{-4} , respectively. Chromium HQs reached up to 0.00003, while Copper values ranged between 10^{-5} and 10^{-4} . Lead showed slightly higher HQs but remained below 0.001, revealing a low ingestion risk. Lithium and Manganese also exhibited low HQs, typically from 10^{-6} to 10^{-4} . Seasonal comparisons revealed minor variability, with dry-season HQs generally slightly higher than those in the wet season.

Discussion

Traces and heavy metal concentrations showed significant seasonal variations, which were the result of environmental and anthropogenic factors. Mean concentrations of boron, copper, and manganese were

higher in the dry seasons, which is probably caused by the influence of evaporation and the decrease in dilution capacity of water bodies. Furthermore, the high concentrations of boron in the dry season, especially due to evaporation and runoff in agriculture, were consistent with the previous research.^{41,42} The findings are in line with the findings of earlier studies, like those by Oyewo *et al.*,⁴³ who established the influence of weather conditions on the metal levels. These trends showed that there is a complex interaction between the natural and human processes that affects the distribution of the metal in the aquatic environments,^{44–46} and that Pb can be of commercial origin in agricultural fertilizers and household effluents.⁴⁷ Littered gasoline use in cars, generators, and water pumps, which may lead to abnormal levels of lead ions.⁴⁸

Conversely, the elements like vanadium and lithium revealed small seasonal changes, representing high adaptability to the changes in hydrology, just like the results reported by Hassan *et al.*⁴⁹ and Allouhi *et al.*^{50,51} During both seasons, the concentration of arsenic did not exceed the permissible levels, which is explained by geogenic factors and the dilution effect of aquifers, according to Fakhreddine *et al.*⁵² and also this may be due to human and industrial activities and filtering processes, which contributed to the increase in the element Arsenic.^{38,53,54}

Similarly, higher manganese concentrations, averaging 0.0127 $\mu\text{g/L}$ in the dry season, corroborate studies like those by other researchers,^{52,54–56} which reported natural leaching from geological formations and anthropogenic inputs as contributing factors.

Correlation analyses showed that lead and copper had good positive relations ($r = 0.860$) and chromium and nickel had good positive relations ($r = 0.588$), meaning that they were all affected by a common source or route of contamination, similar to results reported by Ougrad *et al.*⁵⁷

Climatic conditions (precipitation, evaporation, and temperature variations) are the main factors that cause seasonal changes in metal concentrations. The decreased groundwater recharge and increased evaporation are found to increase the metals such as boron, copper, and manganese in the dry season. Metals are also mobilized through agricultural irrigation during these periods through runoff, and this increases their levels further. These dynamics are consistent with the results of the research on climate variability and its effects on water quality.^{58,59}

The anthropogenic processes associated with mining, industrial emissions, and agricultural activities in the region are associated with groundwater contamination in Erbil and the Bashtapa sub-basin. The metals included through the mining and industrial processes include lead, chromium, and the agri-

cultural runoff brings in copper, manganese, and vanadium. The emissions of urban wastewaters only contribute to the contamination further, especially around populated regions. The quality of groundwater is evaluated in the urban environment and spatial pollution, this is align with previous researches.^{60,61}

According to health risk assessments as per USEPA, the majority of the heavy metals in groundwater were found to have low risks of non-carcinogenicity ($HQ < 1$). Nevertheless, lead levels in some wells are beyond the limits of safety, which brings up the issue of neurological and renal consequences, with particular attention to vulnerable groups. There is also a potential for neurotoxicity with manganese at high concentrations. This is consistent with the research that has examined the toxicity of heavy metals and the health hazards that are observed in groundwater.⁶²

Correlation analyses provided further insights, revealed strong positive relationships between lead and copper ($r = 0.860$) and chromium and nickel ($r = 0.588$), and indicated shared sources or pathways of contamination, similar to the results of Ougrad *et al.*⁵⁷

Climatic factors like precipitation, evaporation, and change of temperature are the main factors that cause seasonal variations in metal concentrations. During the dry seasons, when groundwater is low and water is lost to the atmosphere, the levels of metals such as boron, copper, and manganese increase. Metals are also mobilized through agricultural irrigation in these periods, through run-offs, which raises the levels even more. These dynamics are consistent with those of a study on climate variability and its effect on the water quality.^{58,59}

The anthropogenic activities in the region, such as mining, industrial emissions, and agriculture, are associated with groundwater contamination in Erbil and the Bashtapa sub-basin. Mining and the industrial processes bring in metals like lead and chromium, and agricultural runoffs bring in copper, manganese, and vanadium. The release of urban wastewater contributes further to the pollution, especially around the densely populated regions. Groundwater quality analysis in the city environment and the space pollution analysis support this local context.^{60,61}

According to the health risk assessment of groundwater using guidelines provided by the USEPA, the majority of heavy metals are low-non-carcinogenic risks ($HQ < 1$) in groundwater. Nevertheless, some wells contain higher amounts of lead than are safe, and lead causes neurological and renal effects, particularly in vulnerable groups. There is also potential neurotoxicity of manganese at high concentrations. These assessments align with studies evaluating heavy metal toxicity and associated health risks in groundwater.⁶²

Conclusion and recommendations

This study revealed that the seasonal variation and spatial heterogeneity have a great impact on the quality of groundwater in the study area. The high boron, copper, and manganese levels in the dry season indicate the impact of reduced rainfall and enhanced evaporation, and the seasonal fluctuation in vanadium and lithium indicates reduced sensitivity of the elements to hydrologic changes. Close relationships between lead and copper, chromium and nickel show that they could have common sources or interact in a geochemical way. The results of the pollution indexes proved that most of the groundwater wells had an excellent water quality (NPI = 0.01 or less), and Hazard Quotient tests showed that there was a low level of non-carcinogenic risks during both seasons.

However, despite these overall positive results, the localized contamination, especially in the wells with the higher NPI values of lead, vanadium, and copper, signaled the need to remediate them specifically and perform the monitoring. More stringent groundwater quality monitoring of the sensitive sites is thus suggested to be conducted so that contamination can be detected early.

In addition, policymakers ought to contemplate the creation of groundwater protection zones in order to limit the release of pollutants in the areas around the sensitive recharge areas. Pollution control precautions on industrial and agricultural processes should also be introduced and implemented in an attempt to reduce the inputs of contaminants. Communities that rely on affected water sources should be provided with proper water treatment solutions, such as filtration and chemical treatment.

All these will help to preserve the health of the population, protect the values of the vital body of water, and foster sustainable management of water in the region.

Authors' declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images that are not ours have been included with the necessary permission for republication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of Hawler Medical.

Authors' contribution statement

M.Q.Q. conceptualized the study, conducted the investigation, managed resources, performed data analysis, drafted the manuscript, and revised the manuscript. M.H.H. was responsible for data collection, as well as manuscript review and editing. S.H.J. oversaw the methodology and mapping. C.M.S. performed data analysis and visualization. All authors made significant contributions to the manuscript and approved the final version.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

References

1. van der Gun J. Groundwater resources sustainability. Global groundwater: Elsevier; 2021. p. 331–45.
2. Owusu-Boateng G, Ampofo-Yeboah A, Agyemang TK, Sarpong K. Assessment of the limnological characteristics of Lake Bosomtwe in the Ashanti Region of Ghana. *Pollution*. 2022;8(3): 792–803. <https://doi.org/10.22059/poll.2022.333036.1231>.
3. Hanrahan G. Surface and Groundwater monitoring. Key concepts in Environmental Chemistry, Academic Press, Elsevier, Amsterdam. 2012:109–52.
4. Mustafa JS, Mawlood DK. Assessment of the Groundwater in Erbil Basin with Support of Visual MODFLOW. *Journal of Ecological Engineering*. 2024;25(4). <http://dx.doi.org/10.12911/22998993/184184>.
5. Qader MQ, Anwer SS, Ismael HM. Integrated biological treatment of heavy metals using microalgae, yeast, and molds: a mixed culture approach. *Bioremediation Journal*. 2025;29(1): 1–13. <http://dx.doi.org/0.1080/10889868.2025.2496988>.
6. Abdul Hameed M Jawad A, Haider S A, Bahram K M. Application of water quality index for assessment of Dokan lake ecosystem, Kurdistan region, Iraq. *J Water Resour Prot*. 2010;2010. <https://doi.org/10.4236/jwarp.2010.29093>.
7. Moses B. Introduction to tropical fisheries: Ibadan University Press; 1992.
8. Zhang P, Yang M, Lan J, Huang Y, Zhang J, Huang S, *et al*. Water quality degradation due to heavy metal contamination: Health impacts and eco-friendly approaches for heavy metal remediation. *Toxics*. 2023;11(10):828.
9. Aljanabi ZZ, Al-Obaidy A-HMJ, Hassan FM. A novel water quality index for Iraqi Surface Water. *Baghdad Sci J*. 2023;20 (6 (Suppl.)):2395. <https://doi.org/10.21123/bsj.2023.9348>.
10. Qader MQ, Ismael HM, Abdulkarim LA, Shekha YA, Sidiq KH. Comparative Analysis and Risk Assessment of Heavy Metal Detoxification by Using Bacterial Strains. *Basrah Journal of Sciences*. 2025;43(1):141–54. <https://doi.org/10.29072/basjs.20250109>.
11. Ali MM, Hossain D, Al-Imran A, Khan M, Begum M, Osman M. Environmental pollution with heavy metals: A public health concern. Heavy metals-their environmental impacts and mitigation. 2021:771–83.

12. Qader M, Shekha Y. Application of two fungal strains *Aspergillus niger* and *Candida albicans* in wastewater quality improvement. *Journal of Education and Science*. 2022;31(4):33–41. <http://dx.doi.org/10.33899/edusj.2022.134802.1261>
13. OB A, Muchie M. Remediation of heavy metals in drinking water and wastewater treatment systems: processes and applications. *Int J Phys Sci*. 2010;5:1807–17.
14. Muter SA, Al-Jiboori MH, Al-Timimi YK. Assessment of spatial and temporal monthly rainfall trend over Iraq. *Baghdad Sci J*. 2025;22(3):910–22. <https://doi.org/10.21123/bsj.2024.10367>.
15. Organization WH. Guidelines for safe recreational water environments: Coastal and fresh waters: World Health Organization; 2003.
16. Papafilippaki A, Kotti M, Stavroulakis G. Seasonal variations in dissolved heavy metals in the Keritis River, Chania, Greece. *Glob Nest J*. 2008;10(3):320–5. <https://doi.org/10.30955/gnj.000528>.
17. Debels P, Figueroa R, Urrutia R, Barra R, Niell X. Evaluation of water quality in the Chillán River (Central Chile) using physicochemical parameters and a modified water quality index. *Environmental monitoring and assessment*. 2005;110:301–22. <https://doi.org/10.1007/s10661-005-8064-1>.
18. Kurnaz A, Mutlu E, Uncumusaoğlu AA. Determination of water quality parameters and heavy metal content in surface water of Çiğdem Pond (Kastamonu/Turkey). *Turk J Agric Food Sci Technol*. 2016;4(10):907–13. <https://doi.org/10.24925/turjaf.v4i10.907-913.825>.
19. Edo GI, Samuel PO, Oloni GO, Ezekiel GO, Ikpekoru VO, Obasohan P, *et al*. Environmental persistence, bioaccumulation, and ecotoxicology of heavy metals. *Chemistry and Ecology*. 2024;40(3):322–49.
20. Akter T, Khan S, Rahman M. Toxic elements in Bangladesh's drinking water. *Environmental Contaminants: Ecological Implications and Management*: Springer; 2019. p. 273–96.
21. Alhagiri IA, Al-Hakimi AN, Al-Hazmy SM, Albadri AE. Determination of trace and heavy metals in bottled drinking water in Yemen by ICP-MS. *Results in Chemistry*. 2024;8:101558.
22. Briffa J, Sinagra E, Blundell R. Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon*. 2020;6(9). <https://doi.org/10.1016/j.heliyon.2020.e04691>.
23. Rao NS, Dinakar A, Sun L. Estimation of groundwater pollution levels and specific ionic sources in the groundwater, using a comprehensive approach of geochemical ratios, pollution index of groundwater, unmix model and land use/land cover—A case study. *Journal of Contaminant Hydrology*. 2022;248:103990.
24. Verma A, Singh N. Evaluation of groundwater quality using pollution index of groundwater (PIG) and non-carcinogenic health risk assessment in part of the Gangetic Basin. *Acta Geochimica*. 2021;40:419–40.
25. Yan T, Shen S-L, Zhou A. Indices and models of surface water quality assessment: Review and perspectives. *Environmental Pollution*. 2022;308:119611.
26. Dara R, Hamed M, Kareem S. Assessment of Groundwater in Erbil Central Basin, N Iraq. *Iraqi Bull Geol Min*. 2024;20(1):53–73.
27. Hussein MH, Azad U. Water Balance Calculation and Climate Type for Proposed Dam in Bastora Basin Erbil, North Iraq. *Iraqi Geol J*. 2023:258–77.
28. Mustafa JS, Mawlood DK. Mathematical modelling for groundwater management for multilayers aquifers (Erbil basin). *Ain Shams Eng J*. 2024;15(7):102781. <https://doi.org/10.1016/j.asej.2023>.
29. EPA U. Method 200.8: Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma-Mass Spectrometry, Revision. United States Environmental Protection Agency Cincinnati, OH, USA; 1994.
30. Liu X, Li G, Liu Z, Guo W, Gao N. Water pollution characteristics and assessment of lower reaches in Haihe River Basin. *Procedia Environ Sci*. 2010;2:199–206. <https://doi.org/10.1016/j.proenv.2010.10.024>.
31. Bin X, Canyao L, Xinwei M. Applicability analysis in water quality assessment for Taihu Nemerow index method. *Water Resour Prot*. 2014;30(2):38–40. <https://doi.org/10.3880/j.issn.1004-6933.2014.02.008>.
32. Oguri T, Suzuki G, Matsukami H, Uchida N, Tue NM, Viet PH, *et al*. Exposure assessment of heavy metals in an e-waste processing area in northern Vietnam. *Science of the Total Environment*. 2018;621:1115–23. <https://doi.org/10.016/j.scitotenv.2017.10.115>.
33. Shen F, Mao L, Sun R, Du J, Tan Z, Ding M. Contamination evaluation and source identification of heavy metals in the sediments from the Lishui River Watershed, Southern China. *International Journal of Environmental Research and Public Health*. 2019;16(3):336. <https://doi.org/10.3390/ijerph16030336>.
34. Agency UEP. Guidelines for the health risk assessment of chemical mixtures. *Fed Reg*. 1986;51(185):34014–25.
35. Means B. Risk-assessment guidance for superfund. Volume 1. Human health evaluation manual. Part A. Interim report (Final). Environmental Protection Agency, Washington, DC (USA). Office of Solid Waste ...; 1989.
36. Dwivedi N, Dwivedi S, Adetunji CO. Efficacy of microorganisms in the removal of toxic materials from industrial effluents. *Microbial Rejuvenation of Polluted Environment: Volume 3*. 2021:325–58. https://doi.org/10.1007/978-3-030-71569-3_14.
37. Nellesen MA, Gasda P, Crossey L, Peterson E, Ali A, Zhang J, *et al*. Boron adsorption in clay minerals: Implications for martian groundwater chemistry and boron on Mars. *Icarus*. 2023;401:115599. <https://doi.org/10.1016/j.icarus.2023>.
38. Lima IQ, Ramos OR, Munoz MO, Aguirre JQ, Duwig C, Maity JP, *et al*. Spatial dependency of arsenic, antimony, boron and other trace elements in the shallow groundwater systems of the Lower Katari Basin, Bolivian Altiplano. *Science of the Total Environment*. 2020;719:137505.
39. Frisbie SH, Mitchell EJ, Dustin H, Maynard DM, Sarkar B. World Health Organization discontinues its drinking-water guideline for manganese. *Environ Health Perspect*. 2012;120(6):775–8. <https://doi.org/10.1289/ehp.1104693>.
40. Khan K, Factor-Litvak P, Wasserman GA, Liu X, Ahmed E, Parvez F, *et al*. Manganese exposure from drinking water and children's classroom behavior in Bangladesh. *Environ Health Perspect*. 2011;119(10):1501–6. <https://doi.org/10.289/ehp.1003397>.
41. Goswami M, Goswami K, Chalapathy C, Shivasharanappa K, Kalva P, Patil S. Physicochemical properties and heavy metal analysis of Avalahalli lake, Bengaluru, Karnataka, India. *Indian J Ecol*. 2020;42(4):917–23.
42. Otieno FAO, Olumuyiwa IO, Ochieng GM. Groundwater: Characteristics, qualities, pollutions and treatments: An overview. *Afr J Agric Res* 2012. <https://doi.org/10.5897/AJARX11.054>.
43. Oyewo OA, Adeniyi A, Bopape MF, Onyango MS. Heavy metal mobility in surface water and soil, climate change, and soil interactions. *Climate Change and Soil Interactions: Elsevier*; 2020. p. 51–88. <https://doi.org/10.1016/B978-0-12-818032-7.00003-0>.

44. Jaiswal D, Pandey J. Human-driven changes in sediment-water interactions may increase the degradation of ecosystem functioning in the Ganga River. *J Hydrol.* 2021;598:126261. <https://doi.org/10.1016/j.jhydrol.2021.126261>.
45. Cui M, Guo Q, Wei R, Tian L. Human-driven spatiotemporal distribution of phosphorus flux in the environment of a mega river basin. *Sci Total Environ.* 2021;752:141781. <https://doi.org/10.1016/j.scitotenv.2020.141781>.
46. Wu S, Yuan B, Liu S, Wang Q, Liu J, Yan C, *et al.* Urbanization-driven anthropogenic and environmental factors shape soil dissolved organic matter in mangrove ecosystems. *Ecosyst Health Sustain.* 2024;10:0154. <https://doi.org/10.1002/ehs2.10154>.
47. Graedel TE, Bertram M, Fuse K, Gordon RB, Lifset R, Recheberger H, *et al.* The contemporary European copper cycle: The characterization of technological copper cycles. *Ecol Econ.* 2002;42(1–2):9–26. [https://doi.org/10.1016/S0921-8009\(02\)00101-5](https://doi.org/10.1016/S0921-8009(02)00101-5).
48. Shareef CM, Aziz FH. Assessment of Some Physico-Chemical Parameters and Heavy Metals in The Greater Zab River Path from Bekhma to Al Guwayr District in Erbil Province-KRI. *Zanco J Pure Appl Sci.* 2023;35(2):94–110. <http://dx.doi.org/10.21271/zjpas>.
49. Hassan N, Mohammed S. Assessment of ground water pollution by heavy metals in some residential areas in Kurdistan Region of Iraq. *Environ Sci Arch.* 2023;2:35–44. <https://doi.org/10.5281/zenodo.7625078>.
50. Allouhi A. A hybrid PV/wind/battery energy system to assist a run-of-river micro-hydropower for clean electrification and fuelling hydrogen mobility for young population in a rural Moroccan site. *J Clean Prod.* 2024;140852. <https://doi.org/10.1016/j.jclepro.2024.140852>.
51. Abebe Y, Alemayehu T, Birhanu B, Alamirew T, Alemayehu E. Demystifying Heavy Metals and Physicochemical Characteristics of Groundwater in a Volcano-Tectonic Region of Middle Awash, Ethiopia, for Multipurpose Use. *Sustainability.* 2024;16(12):5257. <https://doi.org/10.3390/su16125257>.
52. Fakhreddine S, Prommer H, Scanlon BR, Ying SC, Nicot J-P. Mobilization of arsenic and other naturally occurring contaminants during managed aquifer recharge: a critical review. *Environ Sci Technol.* 2021;55(4):2208–23. <https://doi.org/10.1021/acs.est.0c07492>.
53. Etyang FE. Concentrations of Selected Trace Elements in Borehole Water and Their Implications for Human Health in Eldoret municipality: University of Eldoret; 2015.
54. Al-Teay SY, Al-Jumaily HA. Environmental Impact Assessment of Heavy Metals Pollution in the Surface Soil Surrounding the Shwan Private Oil Refinery, Northeastern Kirkuk. *Iraqi Geol J* 2023;67–80. <https://doi.org/10.46717/igj.56.1D.6ms-2023-4-15>.
55. Kamau JN, Gachanja A, Ngila C, Kazungu JM, Gatagwu J. The seasonal and spatial variations of labile copper, iron, manganese, lead and zinc sediment fractions in Lake Naivasha, Kenya. *Lakes Reserv Res Manag.* 2007;12(4):303–13. <https://doi.org/10.1111/j.440-770.2007.00342.x>.
56. Kang J-H, Lee YS, Ki SJ, Lee YG, Cha SM, Cho KH, *et al.* Characteristics of wet and dry weather heavy metal discharges in the Yeongsan Watershed, Korea. *Sci Total Environ* 2009;407(11):3482–93. <https://doi.org/10.1016/j.scitotenv.2009.02.021>.
57. Ougrad I, Ellassassi Z, Mrabet A, Mssillou I, Lim A, Shahaat AA, *et al.* Health Risk Assessment of Trace Elements in Surface Water from Dayat Roumi Lake, Morocco. *Water.* 2024;16(22):3231. <https://doi.org/10.390/w16223231>.
58. Ayejoto DA, Agbasi JC, Egbueri JC, Echefu KI. Assessment of oral and dermal health risk exposures associated with contaminated water resources: an update in Ojoto area, southeast Nigeria. *International journal of environmental analytical chemistry.* 2024;104(3):641–61. <https://doi.org/10.1080/03067319.2021.2023515>.
59. Egbueri JC, Enyigwe MT, Ayejoto DA. Modeling the impact of potentially harmful elements on the groundwater quality of a mining area (Nigeria) by integrating NSFQI, HERisk code, and HCs. *Environmental monitoring and assessment.* 2022;194(3):150.
60. Ezugwu C, Onwuka O, Egbueri J, Unigwe C, Ayejoto D. Multi-criteria approach to water quality and health risk assessments in a rural agricultural province, southeast Nigeria. *HydroResearch* 2: 40–48. 2019. p. <https://doi.org/10.1016/j.hydres.2019.11.005>.
61. Alao J, Abdo H, Ayejoto D, Mohammed M, Danladi E, Saqr A. Evaluation of groundwater contamination and the health risk due to landfills using integrated geophysical methods and physiochemical water analysis. *Case Stud Chem Environ Eng* 8: 100523. 2023. p. <https://doi.org/10.1016/j.cscee.2023.100523>.
62. Egbueri JC, Ezugwu CK, Ameh PD, Unigwe CO, Ayejoto DA. Appraising drinking water quality in Ikem rural area (Nigeria) based on chemometrics and multiple indexical methods. *Environmental monitoring and assessment.* 2020;192(5):308.

التغيرات الموسمية والتوزيع المكاني للمعادن الثقيلة في المياه الجوفية: الآثار على جودة المياه والمخاطر الصحية

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الخلاصة

هدفت هذه الدراسة إلى تقييم التوزيع الموسمي والمكاني لاثني عشر معدناً ثقيلًا في عينات المياه الجوفية المجمعّة من خمسين بئرًا، وذلك بغرض تقييم جودة المياه والمخاطر الصحية المرتبطة بها. تم تحليل البيانات لمقارنة موسمي الأمطار والجفاف باستخدام البيانات التحليلية عبر مؤشرات التلوث، وهي مؤشر نيميرو للتلوث (NPI) ومؤشر التلوث أحادي العامل (SFPI). أظهرت النتائج أن جودة المياه كانت في معظمها ممتازة ($NPI < 0.01$)، رغم وجود تلوث في بعض المناطق بعناصر الرصاص والفيثيوم والنحاس. وكانت تراكيز الزرنيخ ($0.0145-0.0008$ ميكروغرام/لتر)، والكروم ($0.0096-0.0009$ ميكروغرام/لتر)، والنيكل ($>0.00200.234$ ميكروغرام/لتر) ضمن الحدود المقبولة لمنظمة الصحة العالمية، إلا أن تراكيز الرصاص كانت مرتفعة (0.5387 ميكروغرام/لتر) وتجاوزت القيم الإرشادية في بعض المواقع. وأشار التحليل الموسمي إلى ارتفاع تراكيز البورون والنحاس والمنغنيز في موسم الجفاف، في حين أظهر كل من الفيثيوم والليثيوم تغيرات موسمية طفيفة. كما كشف تحليل الارتباط عن وجود علاقة قوية بين النحاس والرصاص ($r = 0.860$)، وعلاقة متوسطة بين الكروم والنيكل ($r = 0.588$). كذلك قيّمت الدراسة المعادن الثقيلة في المياه الجوفية باستخدام معامل الخطورة (HQs)، وأظهرت النتائج عدم وجود مخاطر صحية جسيمة، إذ كانت جميع القيم أقل من الحدود الحرجة في موسمي الأمطار والجفاف. على الرغم من أن معظم الآبار أظهرت جودة مياه جيدة، فإن التلوث كان موضعياً في بعض المناطق، مما يؤكد أهمية الرصد المستمر واعتماد استراتيجيات إدارية للحد من احتمالية المخاطر الصحية.

الكلمات المفتاحية: تلوث المياه الجوفية، التحليل المكاني، تقييم المخاطر الصحية، التغير الموسمي.