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ORIGINAL RESEARCH ARTICLE

Impact of heavy metal migration from surface and groundwater to irrigated soil and wheat plants in some areas of central Iraq

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ABSTRACT

This research investigates the deposition of heavy metals – lead (Pb), cadmium (Cd), copper (Cu) and nickel (Ni) from surface water and groundwater sources to soil and wheat (Triticum aestivum L.) plants in Babylon central Iraq region. To achieve the purpose of determining space and season variability, water, soil and wheat samples were taken in two seasons, autumn and spring Metal. Concentrations were determined by atomic absorption spectro-photometry and X-ray fluorescence, and pollution indices were computed to examine the extent of pollution. The investigation found river water, particularly in autumn, to contain elevated concentrations of Pb (up to 0.82 mg/L) and Cu (up to 3.60 mg/L) above World Health Organization safety levels. Conversely, the concentrations of all the metals were extremely low in well water. River water-irrigated soil showed greater metal concentration than well water-irrigated soil, whereas the concentration of metals in wheat grains was within the permissible limit for human intake. From the research, surface water sources are widely contaminated and can represent an environmental hazard upon exposure to high levels of use for agricultural irrigation. Conversely, groundwater resources seem to offer a cleaner and longer lasting alternative to use in agriculture in this case.

Keywords: heavy metals; soil pollution; groundwater; irrigation; environmental risk; Babylon; Iraq

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1. Introduction

Heavy metal river water and soil pollution has become a major environmental and agronomic problem in vast areas of the globe under drought and declining rainfall regimes. The most poisonous, widespread and tenacious land and river contaminants are the impurities primarily of lead (Pb), cadmium (Cd), copper (Cu) and nickel (Ni). Unlike plant and organic contaminants, heavy elements do not degrade naturally; Rather, they remain in the soil, ground water, and food chain and finally create a long-term health risk for humankind and ecosystems[1-3]. Heavy metals can enter environmental systems from both natural and anthropogenic sources. Natural inputs originate from the weathering of rocks and volcanic activities, whereas human-induced contamination mainly arises from industrial waste discharge, mining, combustion processes, fertilizer and pesticide use, and sewage irrigation[4–6]. Once these elements are released into the environment, they can easily migrate between air, water, and soil, altering the physical and chemical properties of these media and threatening agricultural sustainability. Numerous studies have confirmed that the presence of heavy metals in irrigation water can degrade soil structure, reduce microbial diversity, disturb nutrient balance (N, P, K), and ultimately decrease plant productivity[7,8]. Globally, the contamination of surface and groundwater systems has reached alarming levels, particularly in developing countries where environmental monitoring and wastewater treatment remain inadequate. The United States Environmental Protection Agency (USEPA) estimates that millions of tons of soil and water are affected by heavy-metal contamination annually, contributing to a complex chain of air–water–plant–human exposure[9,10]. The accumulation of these metals not only decreases soil fertility but also leads to bioaccumulation in edible crops, posing serious risks to food safety and public health[11].

In Iraq, these challenges are compounded by the scarcity of water and the degradation of both surface and groundwater resources. The combined impacts of climate change, prolonged droughts, salinity accumulation, and declining inflows from the Tigris and Euphrates Rivers have drastically reduced the availability of freshwater for agricultural use[12–14]. Groundwater resources in Iraq, though more stable, are not free from contamination. Several researches propose that the pollutants in fertilizers, industrial effluent, and municipal wastes from urban centers can potentially percolate into shallow aquifers, particularly in cases of poor waste management and sandy or fractured soil types[15–17]. Furthermore, the lack of uniform groundwater protection policies and monitoring systems has led to the progressive deterioration of water quality in the majority of rural areas. The issue is not only that water is limited, but also how to maintain its chemical stability for agricultural use in a safe manner. To respond to these challenges, many researches have been exploring various technological and natural approaches. Nanocomposites and hydrogel materials have been employed to adsorb heavy-metal ions with seeming success in water purification processes[18,19]. Similarly, soil conditioners such as organic matter, bentonite, and zeolite have been tested to enhance soil resilience and reduce the bioavailability of heavy metals in agricultural soils[19]. Despite these advances, there remains a lack of comprehensive studies in Iraq that simultaneously assess the transfer of heavy metals from both surface and groundwater sources to soil and crops under field conditions.

Therefore, the present study is trying to fill this gap by the systematic evaluation of Pb, Cd, Cu, and Ni levels and migration trends from two of the principal sources of irrigation—surface water (Euphrates and Shatt al-Hillah rivers) and groundwater (agriculture wells)—to the soil and wheat (Triticum aestivum L.) plant grown in the Babylon governorate of central Iraq. Seasonal variation (spring and autumn) in metal concentrations and the measurement of pollution levels using internationally recognized indices such as the Water Pollution Index (PIw) and Soil Pollution Index (PIS) are also taken into account by the study. The integration of hydro chemical, environmental, and agricultural analyses provides an improved perspective on the effects of irrigation practices on soil quality and food safety in arid and semi-arid settings. Finally, the findings of this study are planned to be used to aid in developing sustainable irrigation policies to utilize groundwater resources more safely and environmental protection measures in Iraq and other regions with the same water shortage and pollution issues.

2. Materials and methods

2.1. Study area

The investigation was conducted in the Governorate of Babylon, central Iraq, particularly at latitudes 32°–33° N and longitudes 44°–45° E. The region is part of the Middle Euphrates Basin, one of the important agricultural regions of Iraq. The region has a semi-arid climate with hot dry summers and mild winters with a mean annual temperature of approximately 25 °C and a mean annual rainfall ranging between 100–200 mm. Surface water sources are mainly from distributary river Euphrates and Shatt Al-Hillah, whereas groundwater comes from shallow to intermediate Quaternary alluvial aquifers comprising alternating layers of clay, silt, and sand. The depths of groundwater vary between 5 and 30 meters depending on the topography and proximity to rivers.

Additionally, the clay and clay-loams of this region are moderately alkaline (pH 7–8) with a high calcium carbonate content. The soils support the growth of strategic crops such as wheat (Triticum aestivum L.) and barley but can cause the accumulation of waterborne pollutants in water sources due to continuous irrigation, especially during the dry season. A georeferenced map of the research area (**Figure 1**) shows the spatial distribution of the sampling points in agricultural and industrial sites in Babylon and Al-Musayyib districts. The selected locations cover a range of hydro-environmental conditions and therefore allow one to compare the impacts of surface and groundwater irrigation.

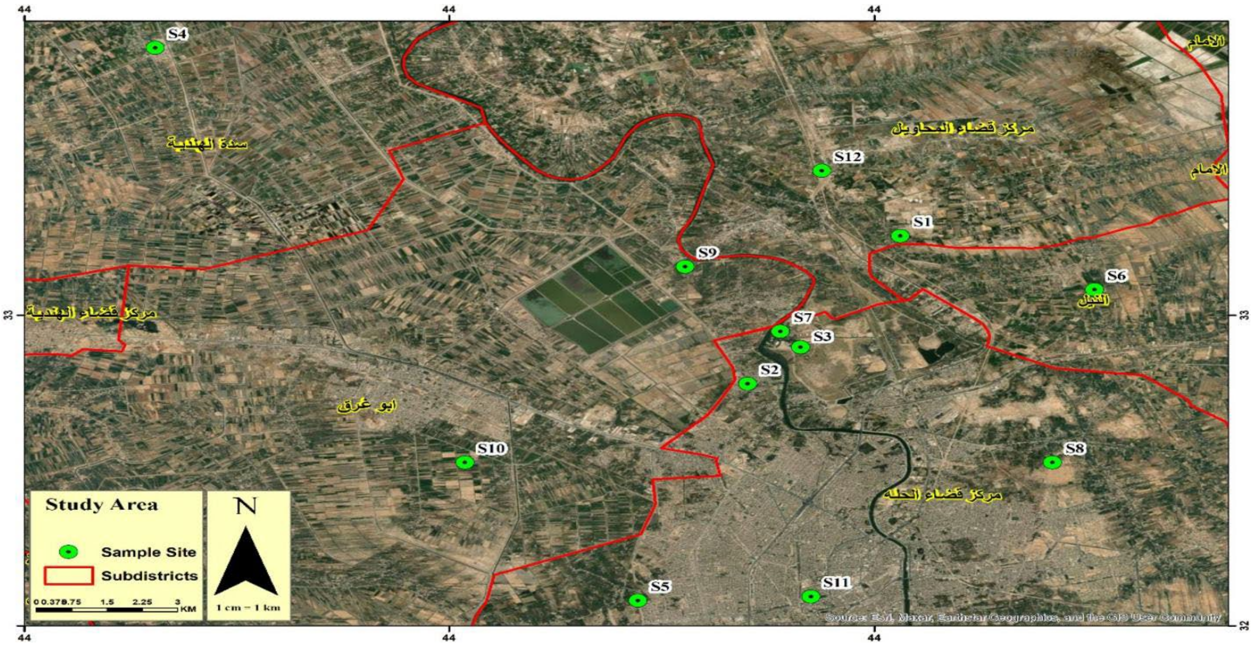

Figure 1. Location map of the study area in central Iraq, Babylon Governorate, with distribution of surface and groundwater sampling sites (S1–S12) and subdistricts.(Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community).

2.2. Water sample collection

A total of twelve (12) water samples were taken over two agricultural seasons:

- Autumn (December 2024) for the low-flow season, and
- April 2024, or the spring (high-flow season).

Six surface-water samples were obtained from the Shatt Al-Hillah and Euphrates River (WS1–WS6) and six groundwater samples from farm wells (WW1–WW6). Wells were purged for 10–15 minutes prior to sampling to remove old water and generate representative samples. Water was siphoned from clean, pre-rinsed polyethylene bottles, acidified to pH < 2 with analytical-grade HNO_3, and refrigerated at 4 °C until analysis. Surface-water samples were collected 20–30 cm below the surface at mid-channel positions to avoid contamination by floating material or bottom sediment **Table 1**.

Table 1. Summary of sampling Sites and water sources in Babylon Governorate.

Site Category	Sample Codes	Number of Sites	Source Type	Remarks
Surface water	WS1–WS6	6	Euphrates River and Shatt Al-Hillah	Represent industrial and agricultural zones
Groundwater	WW1–WW6	6	Agricultural wells (depth ≈ 8–25 m)	Distributed across rural and semi-urban districts

2.3. Soil and plant sampling

Soil and plant samples were also collected from twelve agricultural fields corresponding to the water sampling points (WS1–WS6 for surface water, WW1–WW6 for groundwater) in order to assess the effect of the irrigation source on contamination. Collection of topsoil (0–30 cm) was done using a stainless-steel auger following ISO 11074:2015 recommendatory guidelines for cross-contamination prevention and representativeness. Subsamples of each location were mixed in threes, air-dried, ground, and sieved (2 mm). Wheat (Triticum aestivum L., cv. "Ebaa 99") was cultivated in normal agronomic conditions, sown during November 2024 at a rate of 120 kg ha^{-1}, and irrigated according to the assigned water source. Shoots and grain were separately collected at the stage of full maturity, washed, oven-dried (70 °C, 48 h), powdered, and kept in tightly sealed containers for heavy metal analysis. GPS points, source of water for irrigation, and date of collection were labelled on all the samples, with triplicates maintained for statistical analysis.

2.4. Chemical analysis

• Water: Concentrations of Pb, Cd, Cu, and Ni were measured using Atomic Absorption Spectrophotometry (AAS, Shimadzu AA-7000, Japan), following APHA (2017) methods[20,21].

• Soil and Plant: Samples were digested using a mixture of HNO_3:$HClO_4$ (3:1 mixture of nitric and per chloric acid), and total metal content was determined using X-ray fluorescence spectroscopy (XRF, Thermo Scientific Niton XL2, USA). ICP-AES was not used due to equipment limitations[22].

2.5. Pollution indices

• Water Pollution Index (PIw):

$$PIw = \sum(C_i / S_i)$$

where C_i is the metal concentration and S_i is the permissible WHO limit (**Table 2**)[23].

• Soil Pollution Index (PIS):

PIS = C_sample / C_reference

Reference samples were from non-irrigated soils.The interpretation of PI values is based on the classification provided in (**Table 3**)[24].

2.6. Statistical analysis

Data were processed using the SPSS version 25.0. All analyses were conducted in triplicate ($n = 3$) for every station per season. Means and standard deviations (±SD) were calculated. One-way Analysis of Variance (ANOVA) was used in determining the significant differences between the groups of samples. Post-hoc analysis was performed through Tukey's Honest Significant Difference (HSD) test at $p < 0.05$ level of significance. Superscript letters (a, b, c, etc.) indicate statistically different values within each group of metals[25].

2.7. Analytical standards

All sampling and analysis abided by ISO/IEC 17025 protocols to ensure reliability, repeatability, and accuracy[26].

Table 2. WHO (2011) permissible levels of certain heavy metals in water.

Metal	Limit (mg/L)
Lead (Pb)	0.01
Cadmium (Cd)	0.003
Copper (Cu)	2.0
Nickel (Ni)	0.07

Table 3. Classification of pollution index (PI) values.

PI value range	Pollution level	Grade description
PI < 1	Unpolluted	Grade 1 – Clean
1 ≤ PI < 2	Low pollution	Grade 2 – Slight
2 ≤ PI < 3	Moderate pollution	Grade 3 – Moderate
3 ≤ PI < 5	Strong pollution	Grade 4 – Strong
PI ≥ 5	Very strong pollution	Grade 5 – Severe

3. Results and discussion

3.1. Physical and chemical characteristics of the water

The physical and chemical properties of surface water, well water samples that gathered in various locations autumn and spring season are shown in **Table 4 and 5**[27]. Water samples had pH values ranging from 6.8 to 8.2, signifying that the PH water was relatively suited for carrying out upstream irrigation and farming and also medium alkalinity of these two water sources. The EC (electrical conductivity) values varied widely from 0.119 to 9.212 ds/m; two groundwater samples, i.e., WW5 and WW6, presented the relatively high salinity content. P3: The value of TDS likewise recorded was relatively high for the ground water samples (350 – 680 mg/L).

Other qualities including TH, alkalinity and salinity were more or less within the acceptable limit for irrigation purposes, however those from well were slightly higher. In addition, high presence of nitrate (NO3-) and nitrite (NO2-) in some well samples was observed, notably in WW5 and WW6 which may have been caused by "nitrate leakage" or fertilizer application/leach.

Table 4. Physical and Chemical Properties of Surface Water Samples.

Site	pH	EC (dS/cm)	Salinity (mg/kg)	TH (mg/kg)	$NO3^-$ (mg/kg)	$NO2^-$ (mg/kg)
WS1	6.9 ± 0.2^a	1.469 ± 0.05^a	650 ± 24.78^a	100 ± 1.13^a	0.39 ± 0.01^a	0.03 ± 0.0^a
WS2	7.1 ± 0.32^a	1.313 ± 0.06^a	640 ± 29.92^a	70 ± 1.19^a	0.51 ± 0.02^a	0.07 ± 0.0^a
WS3	6.8 ± 0.19^a	0.642 ± 0.02^a	500 ± 11.29^a	80 ± 2.15^a	0.91 ± 0.02^a	0.08 ± 0.0^a
WS4	7.0 ± 0.08^a	1.239 ± 0.03^a	550 ± 22.42^a	90 ± 3.91^a	1.3 ± 0.03^a	0.07 ± 0.0^a
WS5	6.9 ± 0.12^a	0.642 ± 0.03^a	530 ± 14.72^a	80 ± 2.71^a	0.91 ± 0.02^a	0.08 ± 0.0^a
WS6	6.9 ± 0.08^a	1.239 ± 0.01^a	450 ± 21.35^a	60 ± 1.39^a	1.3 ± 0.06^a	0.06 ± 0.0^a

Note: *Values are presented as mean ± standard deviation (n = 3). Superscript letter "^{a}" indicates no statistically significant differences (p > 0.05) among sample sites based on Tukey's HSD test.*

Table 5. Physical and Chemical Properties of Well Water Samples.

Site	pH	EC (dS cm^{-1})	Organic Matter (%)	Texture	Salinity (mg/kg)	TH (mg/kg)	Alkalinity (mg/kg)	NO_3^- (mg/kg)
WW1	7.61 ± 0.04^a	3.20 ± 0.10^a	1.25 ± 0.07^a	Clay loam	950 ± 35^a	180 ± 9^a	140 ± 7^a	13.5 ± 0.8^a
WW2	7.57 ± 0.05^a	3.35 ± 0.12^a	1.30 ± 0.05^a	Clay loam	970 ± 38^a	185 ± 8^a	142 ± 6^a	13.8 ± 0.7^a
WW3	7.55 ± 0.03^a	3.42 ± 0.11^a	1.28 ± 0.06^a	Clay loam	980 ± 36^a	182 ± 10^a	145 ± 8^a	14.0 ± 0.6^a
WW4	7.48 ± 0.06^b	2.10 ± 0.08^b	0.98 ± 0.04^b	Clay	730 ± 28^b	150 ± 7^b	115 ± 5^b	10.2 ± 0.6^b
WW5	7.51 ± 0.04^b	2.22 ± 0.07^b	0.95 ± 0.03^b	Clay	745 ± 30^b	152 ± 6^b	118 ± 6^b	10.5 ± 0.5^b

Site	pH	EC (dS cm⁻¹)	Organic Matter (%)	Texture	Salinity (mg/kg)	TH (mg/kg)	Alkalinity (mg/kg)	NO_3^- (mg/kg)
WW6	7.49 ± 0.05^b	2.15 ± 0.09^b	0.96 ± 0.05^b	Clay	720 ± 26^b	148 ± 5^b	113 ± 4^b	10.1 ± 0.6^b

Table 5. (*Continued*)

Note: *Values are presented as mean ± standard deviation (n = 3). Different superscript letters in the same column indicate statistically significant differences at p < 0.05 using Tukey's HSD test.*

3.2. Heavy metal content in water

The mean (± SD) concentrations of Pb, Cd, Cu, and Ni in surface water and well water samples collected during autumn (D) and spring (A) seasons are shown in **Table 6**. Heavy metals Concentration of all heavy metals was significantly higher in the autumn surface water samples (WS1D–WS3D) than those collected in winter, particularly Pb (0.82–0.60 mg/L), followed by Cu (3.60–1.75 mg/L) and Ni (2.41–1.55 mg/L). The concentrations of Cd did not show a significant difference between different seasons 29. These high levels were possibly due to industrial outflow of the neighboring "Al-Mussaib thermal power plant"[28] (as also found in previous study[29]). Meanwhile, concentrations were dramatically lower in spring (WS1A–WS3A) ($p < 0.05$) with Pb ranging from 0.37 to 0.62 mg L-1, Cd from 0.005 to 0.009 mg/L, Cu from 0.07 to 0.09 and Ni from 0.02 to 0.04 mg/L), which is probably ascribed for the increase of river flow in spring leading to metal concentration decrease in water samples. Ground water samples (WW1D–WW3D and WW1A–WW3A) had much lower concentrations of the compounds than surface water. The concentration values of Cu were between 0.02-0.09 mg/L, which could be attributed to earth adsorption by clay minerals, oxides and organic matter[30-32]. The surface water had notably higher Pb than WHO and national permissible levels, while Ni approached the limits. Cd and Cu even in spring were at a safe level. These results have implications for the health risk and agricultural consequences of using surface water for irrigation in the study[33].

Table 6. Mean concentrations (± SD) of heavy metals (mg/L) in surface and well water samples during autumn (D) and spring (A) seasons.

Sample	Pb (mg/L)	Cd (mg/L)	Cu (mg/L)	Ni (mg/L)
WS1D	0.82 ± 0.03^a	0.010 ± 0.001^a	3.60 ± 0.10^a	2.41 ± 0.08^a
WS2D	0.80 ± 0.02^a	0.010 ± 0.001^a	1.80 ± 0.09^b	1.70 ± 0.07^b
WS3D	0.60 ± 0.02^b	0.010 ± 0.001^a	1.75 ± 0.08^b	1.55 ± 0.06^c
WS1A	0.62 ± 0.02^b	0.005 ± 0.001^b	0.08 ± 0.01^c	0.04 ± 0.01^e
WS2A	0.37 ± 0.02^c	0.008 ± 0.001^b	0.09 ± 0.01^c	0.03 ± 0.01^e
WS3A	0.56 ± 0.02^b	0.009 ± 0.001^b	0.07 ± 0.01^c	0.02 ± 0.01^e
WW1D	0.30 ± 0.01^d	0.009 ± 0.001^b	0.09 ± 0.01^c	0.009 ± 0.001^f
WW1A	0.25 ± 0.01^d	0.008 ± 0.001^b	0.08 ± 0.01^c	0.007 ± 0.001^f
WW2D	0.25 ± 0.01^d	0.002 ± 0.001^c	0.03 ± 0.01^d	0.009 ± 0.001^f
WW2A	0.19 ± 0.01^e	0.001 ± 0.001^c	0.02 ± 0.01^d	0.008 ± 0.001^f
WW3D	0.18 ± 0.01^e	0.008 ± 0.001^b	0.35 ± 0.01^e	0.003 ± 0.001^f
WW3A	0.16 ± 0.01^e	0.006 ± 0.001^b	0.32 ± 0.01^e	0.001 ± 0.001^f

Note: *Different superscript letters within the same column indicate statistically significant differences at p < 0.05 using Tukey's HSD test.*

3.3. Heavy metal material in soil

Table 7 presents offers concentrations of heavy metals in the soil that is watered with surface water from the river and close to Al-Hillah. During the fall season, 23.55–31.25 mg kg⁻¹ for Pb, 0.0019–0.0045 mg/kg for Cd, concentrations for Cu 9.26–13.47 mg/kg, and 7.22–12.02 mg/kg for Cu. In the spring season, these values increased to 28.16-38.25 mg/kg (Pb), 0.0028-0.0050 mg/kg (CD), 8.89-15.45 mg/kg (Cu), and 11.83-13.03 mg/kg (Ni). This growth can be attributed to the accumulation of heavy metals due to effective industrial waste treatment and the increase in the population, as well as increase in emissions from vehicles. The highest lead level was seen in areas near larger roads, suggesting atmospheric statements as an important source of PB pollution. It is noteworthy that although most heavy metal concentrations were under the allowable area determined by the Iraqi standard (2001), lead levels were higher than the limit in some places. Studies have shown that atmospheric statements contribute more to soil pollution than irrigation water. In contrast, well-cured soil with water showed lower heavy metal concentrations during both seasons. In the autumn, the value is 8.01–9.35 mg/kg (Pb), 0.0011–0.0014 mg/kg (CD), 4.21–6.42 mg/kg (Cu), and 5.61–9.10 mg/kg (NI), while from 15.03 mg/ kg (Cu) and 8.16–9.56 mg/kg (Ni). These findings suggest that well water is more suitable for irrigation purposes than surface water due to the low pollution level[34-36].

Table 7. Total concentration of heavy metals (Pb, Cd, Cu, Ni) in soils irrigated with river water and well water during the autumn (December) and spring (April) seasons (mg/kg).

					Soil Sample				
SS1 SS2	**December - fall semester**				**Soil samples**	**April - spring semester**			
	Pb	**Cd**	**Cu**	**Ni**		**Pb**	**Cd**	**Cu**	**Ni**
SS3	23.55	0.0031	8.66	12.02	SS$_4$	29.13	0.0036	8.89	13.03
SSd	27.40	0.0045	13.47	10.36	SS$_5$	28.16	0.005	15.45	11.83
SS4	31.25	0.0019	9.26	7.22	SS$_6$	38.25	0.0028	10.35	12.01
SS5	13.05	0.002	5.34	10.01	SS$_a$	20.10	0.0021	6.17	11.57
					SS6				
SSsa	8.01	0.0011	4.21	8.06	SW$_4$	15.03	0.0013	7.25	9.19
SW1	8.12	0.0012	5.13	9.10	SW$_5$	18.75	0.0013	8.33	9.56
SW2	9.35	0.0014	6.42	5.61	SW$_6$	16.34	0.0012	6.88	8.16
SW3	4.14	0.001	2.18	7.05	SW$_a$	13.13	0.001	0.20	0.001

Notes. *Values are mean ± SD. Different superscript letters within the same column indicate significant differences ($p < 0.05$) according to Tukey's HSD test.*

3.4. Simple Pollution Index of Water and Soil (PIw and PIS)

Data presented in **Table 8** show that the Simple Pollution Index (PIw) for surface water samples from the Euphrates and Shatt al-Hillah Rivers during the autumn season (December) indicated severe contamination with lead (Pb: 15.00–20.50) and nickel (Ni: 5.54–8.16), both exceeding the critical pollution threshold (PIw > 5). Copper and cadmium levels remained low (Cu: 0.22–0.45; Cd: 0.63). The total PIw for all metals combined (∑PIw) ranged between 21.39 and 30.19, confirming very high pollution levels in all river sites during this season. In spring, seasonal dilution led to decreased PIw values for Pb (9.25–15.50), Cd (0.42–0.75), Cu (0.009–0.01), and Ni (0.07–0.14). While Cu and Ni remained at acceptable levels, Pb still showed strong contamination. The total PIw in spring (10.04–16.07) also exceeded the standard limit, indicating ongoing contamination. In contrast, groundwater (well) samples had much lower PIw values in both seasons. In autumn, PIw ranged between 4.50–7.75 (Pb), 0.17–0.75 (Cd), 0.0004–0.04 (Cu), and 0.01–0.13 (Ni). In spring, values were 4.00–6.25 (Pb), 0.08–0.67 (Cd), 0.003–0.04 (Cu), and 0.03–3.57 (Ni). These values were mostly below or near the acceptable limits, suggesting that well water poses a lower environmental risk. Regarding the soil pollution index (PIS)[37-39].

Table 9 indicates that soils irrigated with surface water had low to moderate contamination levels in autumn: Pb (1.80–2.39), Cd (0.50–2.25), Cu (0.62–2.52), and Ni (0.72–1.03). In spring, similar patterns were observed with slightly higher values for most metals: Pb (1.40–1.90), Cd (1.33–2.38), Cu (1.44–2.50), and Ni

(1.02–1.13). Soils irrigated with well water showed generally low PIS values, except for samples SW2 and SW3, which exhibited moderate contamination levels for Pb and Cu (Pb: 2.26; Cu: 2.35–2.54). These findings support the suitability of well water for agricultural irrigation in terms of heavy metal accumulation in soil[40].

Table 8. Simple pollution index of surface water and wells (PIw) compared to limits permitted by WHO (2011).

Water Samples	Pb	Cd	Cu	Ni	∑PI	Water Samples	Pb	Cd	Cu / Ni / ∑PI
WS1	20.50	0.63	0.45	8.61	30.19	WS4	15.50	0.42	0.01 / 0.14 / 16.07
WS2	20.00	0.63	0.23	6.07	26.93	WS5	9.25	0.67	0.01 / 0.11 / 10.04
WS3	15.00	0.63	0.22	5.54	21.39	WS6	14.00	0.75	0.009 / 0.07 / 14.83
WW1	7.75	0.75	0.01	0.13	8.39	WW4	6.25	0.67	0.01 / 0.03 / 6.96
WW2	6.25	0.17	0.0004	0.03	6.45	WW5	4.75	0.08	0.003 / 0.03 / 4.86
WW3	4.50	0.67	0.04	0.01	5.22	WW6	4.00	0.50	0.04 / 3.57 / 8.11

Note. *Values are mean ± SD. Different superscript letters within the same column indicate significant differences ($p < 0.05$) according to Tukey's HSD test.*

Table 9. Pollution Index (PIS) of Heavy Metals in Soil Irrigated with Surface and Well Water During Fall and Spring Seasons.

Soil Sample	Pb (Fall)	Cd (Fall)	Cu (Fall)	Ni (Fall)	Soil Sample	Pb (Spring)	Cd (Spring)	Cu (Spring)
SS1	1.80	1.55	0.62	0.83	SS4	1.45	1.71	1.44
SS2	2.10	1.50	2.25	2.52	SS5	1.40	2.38	2.50
SS3	2.39	0.50	1.75	0.72	SS6	1.90	1.33	1.68
SW1	1.53	1.10	1.93	1.14	SW4	1.14	1.30	1.19
SW2	1.96	1.10	2.35	1.29	SW5	1.43	1.30	1.37
SW3	2.26	1.20	2.54	0.80	SW6	1.24	1.20	1.13

Notes. *Values are mean ± SD. Different superscript letters within the same column indicate significant differences ($p < 0.05$) according to Tukey's HSD test.*

**PIS: Pollution Index of Soil. A value < 1 indicates unpolluted soil, 1–2 low pollution, 2–3 moderate pollution.*

3.5. Discussion

The findings of this study revealed the statistically important seasonal and spatial variations in heavy metal concentrations in water, soil and wheat plants. Analysis of physical and chemical properties (**Tables 4 and 5**) showed that groundwater tests (especially WW5 and WW6) were particularly likely due to high electrical conductivity (EC), total dissolved solids (TDS), nitrate levels, long -term percolation and agricultural inputs. These physical chemical differences can affect metal solubility and mobility in irrigation systems. The use of Anova after Tukey's HSD test (**Table 6**) confirmed that surface water tests demonstrated much higher concentrations of PB and nine during the autumn compared to spring and well and well water sources. These high concentrations are attributed to the industrial discharge from al-Musaiyib Thermal Station, Road Runoff and Seasonal Stagnation[41-46]. The weaker effect observed in the spring suggests the role of hydrological dynamics in metal concentration variability. The earthly samples watered with surface water (**Table 7**) showed high levels of PB and Q, especially in the vicinity of industrial areas and roads. These results suggest the cumulative effects of atmospheric statements and frequent watering with contaminated water. Conversely, well-irrigated soil with water showed much smaller concentrations, which supports the natural filtration effect of subcutaneous geological layers. Pollution indices further strengthened these findings. The simple contamination index for PIW in **Table 8** indicated severe pollution with PB and nine in surface water during the fall (Piw> 5), while Brønnvann maintained values within the acceptable threshold. Similarly, in **Table 9**, the soil pollution index man (PI) showed moderate pollution in surface-directed areas and low values in well-irrigated soil, and matched the basic concentrations reported in **Table 7**. When it comes to translation, **Table 9** showed that wheat plants watered with surface water accumulated high levels of PB and Q compared to people watered with water. Although all values remained under international safety standards, the difference was statistically important ($p < 0.05$), indicating potential long-lasting risks with continuous risk. These findings are consistent with studies that postpone heavy metals[47-51]. In summary, the results confirm that the groundwater study is still a safe irrigation alternative. Statistically supported evidence in all tables highlights strict monitoring and treatment of surface water before agricultural use, especially close to areas with industrial and densely populated areas in central Iraq[52,53].

4. Conclusion

The findings of the current study indicate that surface water sources, particularly during fall season, contained significantly higher concentrations of heavy metals (particularly Pb and Ni) compared to groundwater. Surface water irrigation resulted in moderate concentrations of Pb and Cu accumulation in soils, whereas irrigation with well water resulted in low concentrations of contamination staying largely within acceptable levels. Wheat (Triticum aestivum L.) irrigated according to these regimes showed concomitant variation in metal accumulation, thus proving that the source of irrigation is an important determinant of crop contamination risk. Overall, the results highlight environmental and agricultural risks from the continued utilisation of raw surface water for irrigation. Alternatively, controlled groundwater is a safer option for sustainable agriculture production in the Al-Hillah region. These observations highlight the need for constant checking of irrigation water quality, implementation of proper wastewater management practices, and promotion of integrated water resource management (IWRM) practices to restrict heavy metal accumulation in agricultural land and for ensuring food safety.

Conflict of interest

The authors declare no conflict of interest.

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