Investigating Heavy Metal Contamination in Groundwater of Agricultural Areas: The Case Study of Shekhan, Duhok, Iraq

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ABSTRACT

This study assesses water quality and heavy metal concentrations in 17 main groundwater sources in Duhok City, Iraq's agriculturally vital Shekhan area. It is important to comprehend the possible health concerns associated with heavy metal pollution in this area because of its relevance to food production. With an emphasis placed on heavy metal concentrations in groundwater sources to support public health and sustainable practices, this study provides essential insights into controlling water quality for irrigation and safe consumption. The Water Quality Index (WQI) results ranged from 15.23 to 37.05, indicating good and excellent water quality, well-suited for drinking and agricultural purposes. The results of heavy metals concentration from Copper (Cu), Manganese (Mn), Lead (Pb), and Nickel (Ni) ranged from 0.0002 to 0.0111 ppm, 0.0023 to 0.0187 ppm, 0.0006 to 0.0024 ppm, and 0.007 to 0.032 ppm, respectively. The World Health Organization (WHO) criteria were satisfied by all heavy metal concentrations in the water samples, except Cadmium (Cd), which exceeded the recommended threshold in six analyzed sources and varied from 0.0015 to 0.0158 ppm. The water is appropriate for irrigation and consumption, according to the findings of the heavy metal content analysis and water quality evaluation, while continuous monitoring is needed to guarantee optimum water quality.

Keywords- water quality; heavy metals; irrigation; drinking water; agricultural areas; public health

I. INTRODUCTION

Water generally originates from two natural sources: surface water, which includes freshwater lakes, rivers, and streams, and groundwater, which involves water from wells and boreholes [1, 2]. Through its polarity and hydrogen bonding, water has unique chemical properties that enable it to dissolve, absorb, adsorb, or suspend a variety of substances [3]. Natural water tends to acquire contaminants from its surroundings, including those brought in by animal and human activities as well as other biological processes, thus, it is not completely clean [4].

Water quality usually declines and becomes unsafe for human consumption when dangerous heavy metals are dissolved in it [5, 6], having a major influence on the quality of water sources. Moreover, industrial activity is mostly responsible for the heavy metal pollution seen in surface water reservoirs [7]. Surface water quality is affected not only by human activity, but also by natural biogeochemical processes found in river ecosystems and hydrological systems [8, 9]. Hazardous metal pollution in surface and groundwater resources has been increased as a result of urbanization, industrialization, and farming practices that rely heavily on chemical fertilizers [10]. Urban drainage systems, stormwater management systems, and industrial wastewater discharge are the main causes of heavy metal contamination in aquatic environments [11, 12].

Heavy metal contaminants seriously degrade water quality and pose a health risk to people. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Atomic Absorption Spectroscopy (AAS) are two common techniques followed to quantify the amounts of heavy metal pollution in water [13, 14]. People are often exposed to Pb, mercury (Hg), aluminum (Al), and Cd, among other heavy metals. Each of these metals is linked to a unique set of health risks [15]. Al has been connected to neurological disorders entailing Parkinson's and Alzheimer's disease, as well as senility and presenile dementia. Exposure to Cd is known to cause hypertension and damage to the kidneys. Pb is a cumulative toxin that harms several organs and systems and has the potential to cause cancer in humans [16]. Hg toxicity generates impairments in speech, hearing, vision, and movement in addition to mental issues. To protect the general public's health and prevent linked disorders, it is essential to understand and reduce exposure to certain heavy metals [17]. Even while heavy metal pollution continues to pose a major concern for human health and environmental sustainability, its detrimental effects can be mitigated with concerted efforts [18]. Technical advancements, public awareness campaigns, and governmental initiatives are crucial for this pressing issue to be resolved [19]. Governments and regulatory agencies throughout the world must implement stringent legislation to restrict industrial discharge and agricultural runoff, and therefore reduce the number of heavy metals that enter water bodies [20].

To increase the efficacy of water treatment technologies and monitoring systems for early contamination verification, research and development spending is essential [21]. Moreover, fostering community engagement and educational initiatives is crucial for a shared feeling of responsibility to be created, which will result in pollution prevention and water conservation [22]. By promoting sustainable practices, such as effective waste management through the use of eco-friendly alternatives in businesses, communities may play a critical role in reducing the level of heavy metal contamination in water sources [17]. Healthy ecosystems and enhanced water quality for current and future generations can be eventually achieved by educating people about the causes, effects, and mitigation techniques of heavy metal pollution. This will encourage individuals to take an active role in environmental stewardship initiatives [23, 24].

This study aims to investigate heavy metal concentrations and water quality in the Shekhan district of Duhok to determine the suitability of groundwater for human consumption and agricultural use. The focus on this specific region, known for its agricultural activities, provides critical insights into groundwater quality. Unlike surface water, groundwater contamination is influenced by unique hydrogeological factors and pollution pathways. By addressing the specific context of Shekhan, this research contributes to a deeper understanding of groundwater contamination in similar rural and agricultural areas.

II. MATERIALS AND METHODS

A. *Study Area*

Shekhan District, is a district of Duhok City in the Kurdistan Region of Iraq. Agriculture is the mainstay of the district's economy and way of life. With 17 areas dotting the rural terrain, agriculture not only offers a means of subsistence for the people living there, but it also guarantees food security, encourages environmental sustainability, propels trade-based economic growth, and strengthens social ties amongst the villagers. Agricultural activities, which range from growing crops to raising animals, support the local economy and foster a feeling of community and collaboration. Due to the semi-arid climate of this region, which has hot summers and mild winters, access to consistent water sources is crucial for preserving agricultural techniques and helping the local populace to support themselves. Understanding the amount, quality, and accessibility of water sources from wells in these 17 areas is critical for human well-being to be ensured and water resource management policy to be supported. The geographical distribution of chemical parameters and groundwater quality in the chosen area may be efficiently assessed and mapped using GIS methods. In this area, wells are the main water supply source utilized for all purposes. Figure 1 portrays the water sample sources and Table I gives the coordinates of every sample in the research region along with the corresponding village.

Fig. 1. Study area map.

B. *Field Sampling*

The process for collecting water samples started with the cautious selection of 250 ml glass bottles to reduce the possibility of contamination and avoid any potential interactions with plastic. The tap was kept open for a minimum of 1 min to remove any buildup of silt or debris in the pipes before taking samples straight from the well [25, 26]. After setting up the sampling location, the sample bottle was opened to let water enter and exit the sampler before the sample was meticulously taken. After that, the vial was securely closed to protect the sample's integrity on the way to the lab.

TABLE I. STUDY AREA AND WATER SOURCE INFORMATION

Village	Code	Coordinates	
		Longitude	Latitude
Bajlafrok	W1	43° 33' 36.24" E	36° 41' 35.49" N
Bajla Kafan	W2	43° 32' 57.42" E	36° 41' 36.90" N
Ashkan	W3	43° 32' 16.56" E	36° 40' 15.48" N
Dreen	W4	43° 31' 37.80" E	36° 41' 21.54" N
Karmishan	W5	43° 31' 5.00" E	36° 41' 45.46" N
Kharaba Shref	W6	43° 31' 46.86" E	36° 46' 33.06" N
Minka Ziry	W7	43° 34' 1.80" E	36° 47' 29.58" N
Minka Zori	W8	43° 33' 11.00" E	36° 47' 27.59" N
Kafrasur	W9	43° 33' 20.40" E	36° 46' 51.37" N
Roilki	W10	43° 33' 7.68" E	36° 46' 41.12" N
Kani Masehiyen	W11	43° 30' 19.14" E	36° 46' 32.34" N
Karmk Mezn	W12	43° 30' 24.00" E	36° 32' 30.20" N
Avda Len	W13	43° 29' 3.50" E	36° 34' 38.35" N
Karfa Qir	W14	43° 26' 59.42" E	36° 35' 2.652" N
Dreshan	W15	43° 29' 33.20" E	36° 33' 42.39" N
Karmk Bajak	W16	43° 31' 47.00" E	36° 33' 18.00" N
Chra	W17	43° 31' 31.08" E	36° 38' 24.00" N

It is worth mentioning that the sampling was carried out in September 2023, when a temperature of 24 ^{o}C was recorded, guaranteeing uniformity in the surrounding circumstances throughout the sampling procedure. To ascertain prompt analysis and precise findings, the samples were examined as soon as they arrived at the laboratory, within 24 h after collection. To prepare the samples for examination, 5 ml of concentrated modeling acid were added to each L, in case it was needed. By deploying a methodical methodology, it was possible to certify that the water samples' integrity would be preserved during the collection procedure and that precise findings would be acquired from the laboratory analysis.

C. Water Quality Methods

Thorough laboratory analysis is required for water quality parameters and chemical composition to be evaluated, and thus for precise readings and conformity to set criteria to be ensured. Under carefully regulated laboratory conditions, variables including Turbidity (Turb), pH, Nitrate (NO_3^-), Total Dissolved Solids (TDS), Total Alkalinity (T. Al), Sodium (Na^+), Chloride (Cl^-), Sulfate (SO_4^{-2}), Magnesium (Mg^{+2}), Calcium (Ca^{+2}), Potassium (K^+), Total Hardness (TH), and Electrical Conductivity (EC) were analyzed. The results offered insightful information on the physical, chemical, and biological properties of water, which is crucial for determining whether it is suitable for a variety of uses, involving drinking, farming, and industry. Table II provides a detailed presentation of these parameters along with their corresponding units of measurement, analytic techniques, and symbols employed in this study. The water quality parameters and chemical composition are compared to the guideline values provided by the WHO. Based on these values, the permissible limits serve as benchmarks to ensure water safety and regulatory compliance, guided assessments for human consumption, environmental protection, and industrial purposes [27].

The WQI uses ionic groups, namely Ca^{+2}, Mg^{+2}, Cl^-, Na^+, K^+, and SO_4^{-2} and physical and chemical properties, involving NO_3^-, T. Al, TH, and EC to assess water quality [28]. These variables include taste, fragrance, utility, acidity, salt content, dissolved materials, impact on human health and ecosystems, chemical makeup, and scale accumulation [29-31]. Determining whether water is suitable for a variety of purposes and ensuring safe and efficient usage needs an understanding of the many aspects that affect water quality. Table III depicts the water quality classifications based on the WQI methodology of the weighted arithmetic index. The process of calculating the WQI involves several steps. The sub-index or quality rating (qn) for each water quality measure is first ascertained. The qn value, if n parameters are provided, demonstrates the relative value of each parameter in the polluted water with the usual permitted value. qn is obtained through (1):

$$qn = 100([Vn - V0]/[Sn - V0]) \quad (1)$$

where Vn is the nth parameter's observed value at a specific sample station, Sn is the nth parameter's standard allowable value, and qn is the nth parameter's quality rating.

The unit weight (Wn) for each water quality measure is determined in the second phase. Wn is inversely linked to the standard value Sn and is obtained through (2):

$$Wn = K/Sn \quad (2)$$

where Sn is the standard value for the nth parameter, K is a proportionality constant (K=1/(Σ1/Sn)), and Wn is the unit weight for the nth parameter. Finally, (3) is used to get the WQI:

$$WQI = \Sigma qn.Wn/\Sigma Wn \quad (3)$$

TABLE II. WATER QUALITY PARAMETERS AND ANALYSIS SPECIFICATIONS

Parameter	Symbol	Method	Permissible limit	Unit
Turbidity	Turb	Turbidimetric	<5	NTU
pH	pH	pH meter	6.5-8.5	-
Nitrate	NO_3^-	UV photometric	<50	mg/L
Total dissolved solids	TDS	Conductivity	<1000	mg/L
Total alkalinity	T. Al	H_2SO_4 titrimetric	<200	mg/L
Sodium	Na^+	Flame photometric	<200	mg/L
Chloride	Cl-	Silver nitrate titration	<250	mg/L
Sulfate	SO_4^{-2}	Turbidimetric	<250	mg/L
Magnesium	Mg^{+2}	Titration	<50	mg/L
Calcium	Ca^{+2}	EDTA titrimetric	<75	mg/L
Potassium	K^+	Flame photometric	<12	mg/L
Total hardness	TH	EDTA titrimetric	<300	mg/L
Electrical conductivity	EC	Conductivity	<400	uS/cm

TABLE III. WATER QUALITY CLASSIFICATION BASED ON WQI VALUE FOR DRINKING PURPOSES

WQI level	Classification	Purpose of uses
0-25	Excellent	Drinking and irrigation
26-50	Good	Drinking and irrigation (slightly polluted)
51-75	Poor	Irrigation. Treatment is needed before drinking
76-100	Very poor	Attention is needed for irrigation usage
> 100	Unfit	Unfit for all uses

D. Heavy Metal Concentration Analysis

The acquired water samples were treated by being filtered through a 0.45 μm Whatman filter after 5 ml of pure nitric acid (HNO_3) were added. Filtration was considered unnecessary if water purity was verified. Otherwise, it was necessary, especially for total concentration assessments. After filtering, samples were dried to a volume of 5 ml, diluted to 100 ml, and then subjected to analysis of heavy metal concentrations using the Shimadzu AA-7000 atomic spectroscopy device.

Flame atomic spectroscopy was deployed to investigate Iron (Fe), Cu, Ni, Mn, and zinc (Zn), while a graphite furnace was utilized to evaluate cobalt (Co), Cd, Al, Pb, and chromium VI (Cr^{+6}). Accurate heavy metal concentration measurement is essential for environmental monitoring and regulatory compliance, and this customized technique ensures both. To guarantee public health safety, chemical parameter levels were compared to WHO guidelines. Table IV lists the WHO's permitted limits for heavy metal concentrations, which are essential for following regulations and safeguarding public health.

TABLE IV. HEAVY METAL CONCENTRATION LIMITS IN WATER SAMPLES

Parameter	Symbol	Concentration Limits
Cobalt	Co	0.005
Cadmium	Cd	0.005
Chromium VI	Cr^{+6}	0.05
Lead	Pb	0.05
Manganese	Mn	0.1
Nickel	Ni	0.1
Iron	Fe	0.3
Aluminum	Al	0.2
Copper	Cu	1
Zinc	Zn	3

Heavy metal concentration is measured in ppm

III. RESULTS AND DISSCUSION

A. *Water Quality Assessment*

In conjunction with the chemical composition and water quality attributes of the water samples, Table V offers an interpretation of the analytical data that were gathered. This thorough presentation makes it easier to evaluate if water samples are suitable for multiple uses. These results provide important new information on the features and attributes of the samples, which helps determine whether they are appropriate for a certain purpose. Additionally, the WQI was computed, providing a quantitative metric to assess and contrast the samples' overall water quality. When taken as a whole, these analyses and indices provide insightful data to help with decision-making regarding the best ways to use the water samples for various purposes.

As evidenced in Table V, the water samples' Turb values ranged from 0.1 to 2.4 NTU. This is within the recommended acceptable range of less than 5 NTU. The pH readings ranged from 7.06 to 8.03, which is in line with the 6.5 to 8.5 range for drinking water. EC values varied between 386.6 and 849.1 µS/cm, indicating the existence of dissolved ions exceeding permissible limits. The W16 in the Karmk Bajak field is the exception, as the area's geology comprises soluble rock with a higher mineral content that generates higher conductivity. The TDS values were between 235.904 and 543.42 mg/L, and NO_3^- levels ranged from 3.94 to 21.49 mg/L, being considered safe for drinking water. The T. Al concentrations across the provided dataset exhibited a range from 192 to 404.8 mg/L. Notably, samples from W1, W8, W9, W12, and W17, surpassed the recommended limit of 200 mg/L outlined in WHO guidelines for safe drinking water. These differences underline the necessity of conducting an in-depth research to guarantee adherence to safety regulations and reduce health hazards related to the elevated T. Al levels in drinking water and agricultural practices. Although controlling water quality in agriculture is essential for crops, ensuring drinkable water quality is critical for public health.

The dataset comprises a range of water quality parameters, encompassing TH, Ca^{+2}, Mg^{+2}, Cl^-, Na^+, K^+, and SO_4^{-2}. TH values ranged from 196 to 430 mg/l but, the results of five wells were above the acceptable limit, which is 300 mg/L, as displayed by the values of 372, 388, 344, 332, and 430 of W1, W8, W9, W12, and W17, respectively. In all water sources, Ca^{+2} concentrations ranged from 52.8 to 104 mg/L, all of which were below the limit of 200 mg/L. Low Ca^{+2} levels in groundwater are frequently associated with geological elements such as the makeup of the aquifer and nearby rock formations [30]. There may be less Ca^{+2} in some formations because they do not contain enough Ca^{+2}-bearing minerals. In addition, environmental elements including flow patterns and recharge rates, coupled with the aquifer's depth and position, might affect Ca^{+2} levels [32]. Except for W17 in the Chra village, Mg^{+2} concentrations varied from 10.7 to 57.7 mg/L, which was below the permissible limit of 50 mg/L. The geological and environmental processes are responsible for this fluctuation in the Mg^{+2} content. The Cl^- values varied from 10 to 32 mg/L, well below the 250 mg/L criterion. The Na^+ concentrations were also below the 200 mg/L limit, ranging from 2.5 to 52 mg/L. In addition, the levels of K^+ and SO_4^{-2} are within the safety limits, which are 12 mg/L and 250 mg/L, respectively.

Overall, the water quality parameters, which exhibit that the mineral content, acidity, and clarity of the examined sources fall within the acceptable limits for safe drinking water, are Turb, pH, and TDS. However, several chemical characteristics differed across sources, with some falling within the required levels and others not. These values included NO_3^-, T. Al, Ca^{+2}, Mg^{+2}, Cl^-, Na^+, K^+, and SO_4^{-2}. These variations emphasize how crucial it is to conduct constant management and monitoring for water quality to be preserved and any possible issues to be handled. Thus, it can be inferred that water resource integrity and public health safety depend on routine testing. The investigated sources' WQI values range from 15.23 to 37.05, which suggests a generally favorable prognosis for water quality in the agricultural regions. The water quality is considered excellent when the majority of WQI values are less than 25, which indicates that it is best suited for drinking and agricultural uses like irrigation. These results highlight the dependability of water sources in assisting with agricultural endeavors, guaranteeing the supply of clean water necessary for crop development and output maximization. The constantly positive WQI scores manifest that the area climate is ideal for sustainable agriculture, which enhances agricultural communities' well-being.

B. Heavy Metal Concentrations Analysis

The analysis of various heavy metal concentrations in the water sources under investigation is presented in Table VI. The levels of heavy metal concentrations in the particular water sources can be understood by the study's findings. Measuring pollution levels and assessing possible threats to the ecosystems and human health requires taking into account the concentration of each heavy metal.

TABLE V. RESULTS OF WATER QUALITY PARAMETERS

Source	Turb (NTU)	pH	EC (mg/L)	TDS (mg/L)	NO_3^- (mg/L)	T. Al (mg/L)	TH (mg/L)	Ca^{+2} (mg/L)	Mg^{+2} (mg/L)	Cl^- (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	SO_4^{2} (mg/L)	WQI
W1	0.2	7.24	758.4	485.376	34.69	282	372	104	27.3	24	13	3	40.6	22.7
W2	0.5	7.57	521.5	333.76	5.98	240	256	64.7	23.4	12	10	1	5.4	22.51
W3	0.6	7.43	516	330.24	4.70	240	244	65.6	19.5	10	14	1	5	20.63
W4	0.4	7.51	498.3	318.912	7.27	238	280	65.6	28.3	10	8	1	4	21.24
W5	1.5	7.55	487.1	311.744	6.20	218	252	65.6	21.4	14	20.3	2	10	31.8
W6	0.1	7.33	429.4	274.816	12.01	218	244	64.1	20.4	14	14	1	6	15.23
W7	0.3	7.42	456.9	292.416	19.00	214	252	67.2	20.4	20	13.5	1	11.4	19.14
W8	2.4	7.3	609	389.76	6.69	288	388	94.4	37.1	18	5.5	1	38	37.05
W9	0.1	7.54	589.7	377.408	5.40	258	344	81.6	34.1	18	5	1	54	20.71
W10	0.2	7.43	511.5	327.36	12.71	226	284	83.2	18.5	34	4.2	1	4	18.57
W11	0.2	7.4	447.6	286.464	8.86	234	276	69.1	28.3	16	2.5	1	4	17.92
W12	0.5	7.51	627.2	401.408	18.61	284	332	83.2	30.2	24	10	3	26	27.4
W13	0.3	7.76	431	275.84	5.89	214	216	56.5	18.54	22	15.3	1	14	23
W14	0.3	8.03	448	286.72	3.94	224	224	52.8	22.4	24	17.8	1	18	27.54
W15	0.5	7.62	463	296.32	4.83	238	236	57.6	22.4	14	12.5	1	15.2	22.8
W16	0.2	7.73	368.6	235.904	10.72	192	196	60.8	10.7	20	6.5	1	7	21.223
W17	0.3	7.06	849.1	543.424	21.49	404	430	77.4	57.8	32	52	1	32	19.24

TABLE VI. RESULTS OF HEAVY METAL CONCENTRATIONS IN THE WATER SOURCES

Source	Fe (ppm)	Cu (ppm)	Mn (ppm)	Zn (ppm)	Co (ppm)	Ni (ppm)	Pb (ppm)	Cd (ppm)	Al (ppm)
W1	0.1706	0.0031	0.0011	0.0096	0.000087	0.031	0.0009	0.0111	0.009
W2	0.0206	0.0062	0.0008	0.0084	0.000082	0.032	0.0011	0.0107	0.016
W3	0.0274	0.0046	0.0002	0.0388	0.000058	0.032	0.0006	0.0095	0.009
W4	0.1225	0.0125	0.0041	0.0075	0.000106	0.029	0.0009	0.0095	0.039
W5	0.0179	0.0078	0.0006	0.077	0.000061	0.021	0.0007	0.0079	0.024
W6	0.0185	0.0187	0.0003	0.0714	0.000092	0.025	0.0009	0.0023	0.044
W7	0.0198	0.0187	0.0019	0.0059	0.000092	0.015	0.0017	0.0031	0.035
W8	0.2697	0.0183	0.0111	0.0357	0.000165	0.023	0.0009	0.0031	0.009
W9	0.0193	0.0172	0.0031	0.0455	0.000046	0.018	0.0011	0.0023	0.061
W10	0.0605	0.0172	0.0041	0.0192	0.000067	0.022	0.0015	0.0015	0.005
W11	0.0055	0.0164	0.0013	0.1767	0.000046	0.021	0.0024	0.0158	0.023
W12	0.0079	0.0179	0.0013	0.0871	0.000031	0.007	0.0010	0.0039	0.015
W13	0.0165	0.0119	0.0009	0.0068	0.000046	0.009	0.0008	0.0031	0.014
W14	0.0068	0.0142	0.0007	0.4891	0.000081	0.007	0.0007	0.0039	0.016
W15	0.0093	0.0045	0.0013	0.0096	0.000036	0.007	0.0006	0.0023	0.016
W16	0.0063	0.0028	0.0003	0.0204	0.000094	0.003	0.0012	0.0027	0.019
W17	0.0098	0.0023	0.0017	0.1406	0.000030	0.007	0.0327	0.0021	0.101

Cu, Mn, and Fe contents in water samples varied from 0.0002 to 0.0111 ppm, 0.0023 to 0.0187 ppm, and 0.0055 to 0.2697 ppm, respectively. The WHO's suggested limits for Fe, Cu, and Mn, which are 0.3 ppm, 1 ppm, and 0.1 ppm, respectively, were all below the observed levels. Zn values in the water samples varied from 0.0059 to 0.4891 ppm, all being below the suggested 3 ppm limit. Co was below the suggested limit of 0.005 ppm, ranging from 0.000036 to 0.000165 ppm. Concentrations of Ni ranged from 0.007 to 0.032 ppm, all falling under the permissible limit of 0.1 ppm. The amounts of Pb were all below the suggested level of 0.05 ppm, ranging from 0.0006 to 0.0024 ppm.

Cd varied in quantity from 0.0015 to 0.0158 ppm in the water samples. The Cd concentrations in six sources were higher than the 0.005 ppm threshold that is advised for drinking water. The usage and disposal of products containing Cd, such as batteries, pigments, plastics, and electroplating processes, can lead to higher Cd amounts in water. These sources, which include inappropriate waste disposal, leaching from polluted soils, and industrial discharge, may be responsible for excessive levels of Cd in water [33, 34]. To identify the precise sources and causes of Cd contamination in these samples and to put the right remediation procedures in place, further research is required [32, 33]. The water samples' Al amounts varied from 0.005 to 0.101 ppm. Not a single sample was above the suggested threshold concentration of 0.2 ppm.

Except for Cd, which is present at greater amounts than the permissible levels, the findings of the heavy metal analysis confirm that the water is safe to be drunk and used for irrigation. All quantities found in the water satisfy WHO recommendations. To avoid Cd contamination and guarantee water safety, monitoring and enforcement of laws governing industrial and agricultural activities are required.

IV. CONCLUSION

The current study focused on investigating water quality and heavy metal pollution in the Shekhan district of Duhok City, Iraq, to determine the suitability of groundwater for agriculture and human consumption. Analysis of seventeen major groundwater sources revealed that most water quality parameters, including Turbidity (Turb), pH, and dissolved solids, were within the World Health Organization (WHO) recommended guidelines for potable water. The Water Quality Index (WQI) scores ranged from 15.23 to 37.05, indicating good to excellent water quality. Heavy metal concentrations were observed in Copper (Cu) (0.0002-0.0111 ppm), Manganese (Mn) (0.0023-0.0187 ppm), Lead (Pb) (0.0006-0.0024 ppm), and Nickel (Ni) (0.007-0.032 ppm), all within the WHO guidelines. However, Cadmium (Cd) levels exceeded the WHO limits in six sources, with concentrations ranging from 0.0015 to 0.0158 ppm. These findings stress the need for targeted interventions for Cd pollution to be mitigated at its source. The results demonstrate the importance of effectively managing water resources to ensure environmental integrity and public health. Despite Cd exceedance, the overall water quality is deemed suitable for irrigation and consumption, highlighting the necessity for ongoing monitoring and management strategies. According to the WQI classification, the observed values demonstrate water quality that supports agricultural activities, ensuring the supply of clean water demanded for crop development and output maximization. The data obtained confirm the need for sustainable groundwater practices, emphasizing the importance of continued monitoring to improve water quality. The findings provide critical insights that can inform and guide future efforts to address water quality challenges in the area, certifying safe water for human consumption and agricultural use.

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