

Evaluation of Groundwater Quality for Drinking Purposes: A Case Study Conducted in the Southwestern Part of Kirkuk City, Iraq

Waleed M. Sh. Alabdraba¹, Aydin Adnan Rashid², Fires Rawan Abdulrahim³, Shahad Ali Abdulhussei⁴

¹Environment Engineering Department, College of Engineering, Tikrit University, Tikrit, Iraq

²Surveying Engineering Department, Technical Engineering College, Northern Technical University, Kirkuk, Iraq

³Ministry of Oil, Iraqi Drilling Company, HSE Department, Kirkuk, Iraq

⁴Ministry of Water Resources, Baghdad, Iraq

Abstract

Background: Groundwater in Iraq, particularly in the Kirkuk Governorate, is under increasing pressure from a range of challenges, including human activities and natural conditions. These factors have led to the presence of contaminants, posing a significant risk to public health and underscoring the urgent need for systematic monitoring and evaluation. Examining the connection between groundwater contamination and its impact on human health is vital for safeguarding public well-being and promoting environmental sustainability.

Methods: This study focused on the southwestern region of Kirkuk Governorate to evaluate the suitability of groundwater for drinking purposes. Twenty groundwater samples were analyzed using water quality indices (Nemerow's Pollution Index and Weighted Arithmetic Index) and Geographic Information System (GIS) techniques. Fourteen physicochemical parameters were assessed. Spatial mapping and statistical data analysis were conducted to provide essential insights into water quality and its management.

Results: The NPI-WQI findings categorized 50% of samples as "seriously polluted" (NPI > 3.5) and 50% as "moderately polluted" (NPI 1–3.5). The WAI-WQI revealed that 80% of samples were deemed "unsuitable for drinking" (WAI > 100), with the highest levels of pollution recorded in wells W14 (WAI = 712.275) and W20 (WAI = 413.676). Critical values surpassed allowable thresholds: TDS (7625 mg/L compared to the WHO limit of 1000 mg/L), EC (10,500 μ S/cm versus 400 μ S/cm), and turbidity (192 NTU against 5 NTU). Spatial maps indicated regional variations, revealing heightened pollution in central and southern areas.

Conclusion: The study contributes valuable data for improving water resource management and protecting public health.

Keywords: Groundwater, Water quality, Water resources, Geographic information system

Citation: Alabdraba WMS, Rashid AA, Abdulrahim FR, Abdulhussein SA. Evaluation of groundwater quality for drinking purposes: a case study conducted in the Southwestern part of Kirkuk city, Iraq. Environmental Health Engineering and Management Journal 2026;13:1492. doi:10.34172/EHEM.1492

Article History:

Received: 6 December 2024

Revised: 27 June 2025

Accepted: 6 July 2025

ePublished: 29 April 2026

*Correspondence to:

Fires Rawan Abdulrahim,
Email: firmas.rawan.en@gmail.com
firmas.rawan.en@gmail.com

Introduction

Groundwater is a vital resource worldwide. Water is a lifeline that supports the environment, people, and the economy (1,2). It is also a source of energy and raw materials for industries. Unfortunately, the quality of this water can be negatively impacted by various human activities. These activities include pollution from residential, commercial, and agricultural sectors, as well as natural processes. A study conducted in Iraq has brought to the fore that the groundwater is highly polluted. The research shows that the concentration of total dissolved solids may reach up to 5000 mg/L, and

nitrate and heavy metals typically exceed the World Health Organization (WHO) limits. The contamination of water in Iraq is a consequence of both farming and industrial pollution (3,4). The problem of water quality in the Kirkuk Governorate due to salinization, as well as human pollutants, has been identified in the studies. This implies the insufficient means of monitoring and the necessity of more efficient methods, such as the Water Quality Index (WQI) and Geographic Information System (GIS) (5). The increase in the population, the development of industries, and climate changes are the factors that lead to deeper troubles in the water quality



of Iraqi groundwater. This source is still indispensable for the life of rural communities (6). The issue becomes even worse due to the presence of contaminants such as pesticides, fertilizers, and domestic wastewater, which inevitably will endanger the health of human beings (7). Therefore, continuous monitoring is very important because it helps in identifying and possibly searching for the sources of pollutants, the reduction of which is definitely necessary since the water quality is among the indicators of the ecosystem's health (8). Nitrate pollution from fertilizers and animal waste is the major source of rural groundwater pollution. Hence, regular monitoring is necessary because of the health risks posed by the nitrates in drinking water (9). Safe drinking water is one of the essential factors for sustainable development. It changes people's lives, health status, and economic stability. Water quality management faces challenges, especially in low-income countries, compounded by population growth and poor water infrastructure (10). The unmet Millennium Development Goals (11) outlined that even though a lot of work has been done worldwide, there are still more than one billion people who do not have access to safe drinking water. The Sustainable Development Goals (SDGs) deal with the problems of water, energy, health, agriculture, and biodiversity, among others (12). Groundwater pollution is a major resource that exhibits different pollution patterns, influenced by land use and geology. The presence of harmful metals, therefore, points to the urgency of responsible management (13). The quality of groundwater is crucial for the safety of the public and the prevention of environmental pollution. This is a significant problem worldwide, as it affects multiple locations simultaneously. Interpretation of big data and water quality indicators is thus essential. It is thus of importance in monitoring the water status (13,14). There are numerous studies in Iraq that emphasize the role of these indicators in evaluating the quality of groundwater in terms of dissolution processes, salinization, and industrial activities (15). In semi-arid areas such as Kirkuk Governorate, the significance of groundwater in the course of which the necessity of thorough investigations using water quality indicators and GIS techniques comes into picture (5). The increasing need for groundwater resources makes it necessary to assess the water quality for the health of the public and the environment. A worldwide concern of groundwater pollution is a vital issue, and it emphasizes the necessity for gathering and analyzing various kinds of information (16). Typical water quality reports in a traditional way mostly concentrate on single parameters, which, consequently, make it confusing for the authorities and the public to understand the situation. Environmental monitoring programs can be more effective if the reporting methods used are simpler. This has thus motivated the emergence of mathematical techniques for combining water quality

parameters (5). Water quality indices such as Nemerow's Pollution Index (NPI) and the Weighted Arithmetic Index (WAI) facilitate the evaluation of water quality as well as the analysis of data. These indices find extensive application in research conducted in Iraq to evaluate the condition of the groundwater (4,17,18). The present research is intended for the identification of the status of groundwater in the Kirkuk Governorate as a source of drinking water, using WQI and GIS methods. The registration of physicochemical measurements from 20 wells will be the source of important data on groundwater that will enable a more efficient way of managing this water resource. Groundwater is commonly regarded as the purest among the water sources. Usually, people in the Kirkuk Governorate are provided with water by means of mechanical drilling or hand-dug wells. The depth of these wells is the main factor that decides the purity of the water (4,19,20). Dependable water management systems are vital to satisfy water needs; at the same time, they should be the least harmful to health and the environment. Proper groundwater quality monitoring and detailed groundwater quality analysis are indispensable for efficient and sustainable water management initiatives. Chemical water contamination of the human health aspect can only be understood if we go through the spectrum of diseases that are caused by the polluted water. Groundwater contaminated with different types of pollutants is the major cause of health issues. Excessive acidity can result in stomach discomfort. High Total Dissolved Solids (TDS) can worsen conditions for those with kidney and heart issues and cause digestive problems (21). Excess chloride can lead to increased urination (14). Infants are particularly at risk for methemoglobinemia from high nitrate levels. High sulfate can cause diarrhea (16). Magnesium deficiency is linked to many health issues (22). Low calcium intake can lead to osteoporosis and high blood pressure. High sodium levels can affect heart health and cause kidney issues (23). High concentrations of aluminum can have severe health consequences (24). Metals like lead, cadmium, chromium, nickel, mercury, and copper can damage kidney and liver function and cause serious illnesses. Long-term exposure to arsenic may result in skin problems and gastrointestinal and heart symptoms. Manganese deficiency can lead to various joint and tissue issues. Excess cobalt can reduce iodine absorption, leading to nausea and other gastrointestinal issues. Selenium deficiency can cause nail loss, while exposure to uranium increases cancer and leukemia risks (25,26). These effects are attributed to a small part of many pollutants and their health impacts. Continued research is necessary to understand the links between groundwater contamination and human health outcomes (27).

In a study by Khassaf and Hassan et al. (2017) (28) in Najaf Governorate, researchers assessed groundwater quality by analyzing samples from various wells. The

research results demonstrated that a few wells exceeded the permissible limits for drinking water set by both the Iraqi and the World Health Organization (WHO), particularly for Total Dissolved Solids (TDS), sulfates, and chlorides. The local investigators identified factors of nature and humans as the cause of the deterioration. Geological structures were mentioned as being responsible for the contribution to the high-salinity issue. Intensive farming practices that were associated with fertilizers and pesticides, besides the infiltration of untreated wastewater, were also part of the problem. The paper highlighted the necessity of setting up continuous surveillance programs and formulating strict management policies to ensure that this resource is safeguarded and not ruined.

Another study by Al-Asadi et al. (2020) (29) was conducted in Basra Governorate, whose main theme was the spread of toxic heavy metals in groundwater. Those metals belong to the group of the most hazardous pollutants mainly because of their extremely toxic nature and their ability to bioaccumulate in living entities. They investigated samples of metals such as lead, cadmium, and nickel from groundwater to determine concentrations. The survey found that the levels of some of the metals were dangerously high and exceeded international safety limits. This is the case if among the communities the water serves as a source of drinking and irrigation. The polluters blamed it on unregulated industrial and unregulated waste discharge as the heavy metal sources, together with possible effects of oil-related operations in the area, were environmentally the culprit for the research. The study suggested health risk assessments and cleaning of the environment to be conducted regularly, and strategies to be used as the main pillars in place to protect public health and the environment.

In a broader context, a recent study by Mueller et al. (2021) (30) has dealt with the complex relationship of climate change, water shortage, and their impacts on the groundwater quality in the desert and semi-desert areas of Iraq. The study revealed that the reduced rainfall and increased evaporation due to high temperatures caused the water table to go down, which in turn led to the concentration of pollutants in the water. Furthermore, the authors of the paper examined the implications of dam construction on the Tigris and Euphrates rivers in the neighboring nations of Iraq concerning groundwater replenishment.

Further, the researchers claimed that the above-mentioned factors, in addition to the mismanagement of water, exacerbate the situation of the groundwater quality and become the main reason for the water security problem in Iraq in the future. The authors insist on a great necessity of a proper water resource management plan that should incorporate a variety of activities, such as water harvesting and environmentally sound groundwater

recharge, to be effective in dealing with these issues.

The main aim of this research was to investigate the status of groundwater in the selected localities of Kirkuk City, Iraq. Utilizing NPI-WQI, WAI-WQI, and GIS, they aimed to ascertain the chemical properties of water and subsequently evaluate its suitability for consumption.

Materials and Methods

Description of the Study Area

Kirkuk Governorate is positioned around 283 km north of Baghdad, the capital city of Iraq (Figure 1).

The governorate's geographic coordinates span from 34° 41' 42" to 35° 51' 50" N and from 43° 16' 37" to 44° 43' 60" E. Over the past five decades, the population of Kirkuk Governorate has undergone substantial growth, reaching approximately 996,000 individuals in 2019, signifying an increase of about 50. Due to limited access to surface water in Kirkuk, groundwater has become the primary water source for various essential purposes such as drinking, agriculture, and industrial usage. Kirkuk exhibits a semi-arid climate characterized by chilly, precipitation-laden winters and hot, arid summers. Rainfall-induced floods serve as the primary source of groundwater in the region. The study area for the examined wells is located in the south-west part of Kirkuk Governorate. A total of 20 groundwater samples were obtained from various places within the study region (Figure 1). This study area covers an approximate land area of 1590 km², constituting a portion of Kirkuk's total area, which measures 10188.37 km². The depth of the wells ranged from 57 to 251 meters. Accurate coordinates for each sample were determined using a GPS instrument (Table 1).

Data Collection and Analysis

This study aimed to assess the groundwater quality of 20 wells. The data and information used in the study were obtained from the Kirkuk branch of the Iraqi Ministry of Water Resources/General Groundwater Authority. Throughout the study, a comprehensive set of 14 water quality parameters was measured, including chemical and physical aspects. These parameters included pH, Temperature (C), Turbidity (Tur), Electrical conductivity (EC), Total dissolved solids (TDS), Sulfate (SO₄⁻²), Nitrate (NO₃⁻), Magnesium (Mg⁺²), Calcium (Ca⁺²), Potassium (K⁺), Chloride (Cl⁻), Total Hardness (TH), Bicarbonate (HCO₃⁻), and Sodium (Na⁺¹). All tests for parameters were carried out in the laboratories of the General Authority for Groundwater, Kirkuk branch. The main objective of the study was to evaluate the suitability of groundwater for drinking purposes. The measured values were compared with drinking water standards set by Iraq and the World Health Organization (Table 2) (31–33).

Statistical analysis and calculations

For the multivariate statistical data analysis, graphical

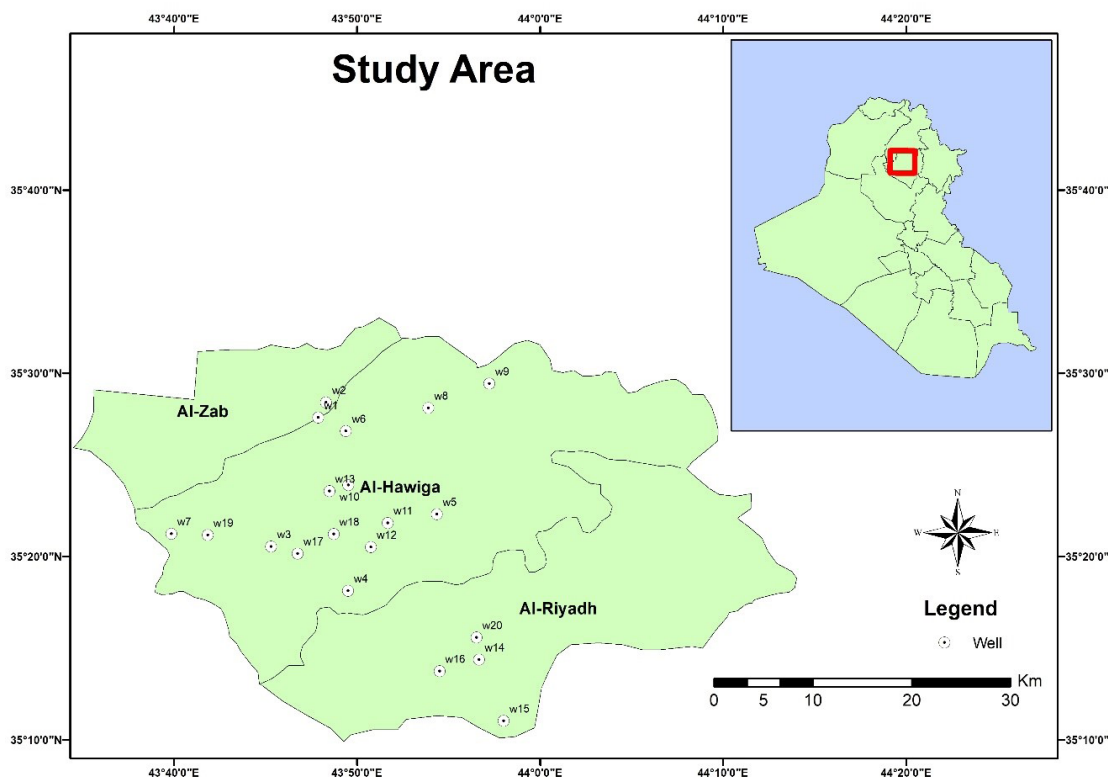


Figure 1. The location of wells studied in Kirkuk Governorate, Iraq

Table 1. The depth (in meters) and coordinates of the study wells

Well No.	Depth (m)	Coordinates	
		Latitude	Longitude
W1	66	35° 27' 35'' N	43° 47' 52'' E
W2	60	35° 28' 23.9'' N	43° 48' 52.6'' E
W3	72	35° 20' 32'' N	43° 45' 18'' E
W4	132	35° 18' 06.9'' N	43° 49' 29.9'' E
W5	156	35° 22' 18'' N	43° 54' 20.9'' E
W6	78	35° 26' 50'' N	43° 49' 23'' E
W7	72	35° 21' 13.8'' N	43° 39' 50.8'' E
W8	120	35° 28' 06'' N	43° 53' 53.3'' E
W9	251	35° 29' 26'' N	43° 57' 13'' E
W10	108	35° 23' 53.9'' N	43° 49' 31'' E
W11	132	35° 21' 49'' N	43° 51' 40'' E
W12	102	35° 20' 30'' N	43° 50' 45'' E
W13	84	35° 23' 34'' N	43° 48' 29'' E
W14	168	35° 14' 22'' N	43° 56' 39'' E
W15	144	35° 11' 01'' N	43° 58' 00'' E
W16	163	34° 53' 20'' N	53° 15' 30'' E
W17	90	35° 20' 09'' N	43° 46' 45'' E
W18	102	35° 21' 13'' N	43° 48' 43'' E
W19	57	35° 21' 10'' N	43° 41' 50'' E
W20	157	35° 15' 34'' N	43° 56' 31'' E

Table 2. Iraqi standards and the World Health Organization criteria for potable water quality

Parameters	Units	IQS, 2009 Standards	WHO 2021 Standards
T	(°C)	-	12 - 25
pH	-	6.5-8.5	6.5 - 8.5
EC	µs/cm	2000	400
Na ⁺	mg/l	200	200
Ca ₂ ⁺	mg/l	150	100
Mg ₂ ⁺	mg/l	100	50
K ⁺	mg/l	12	20
Turbidity	NTU	5	5
Cl ⁻	mg/l	350	250
SO ₄ ⁻	mg/l	400	250
NO ₃ ⁻	mg/l	50	50
TDS	mg/l	1000	500 - 1000
TH	mg/l	500	500
HCO ₃ ⁻	mg/l	200	200

examination of results was conducted using a statistical analysis program, specifically SPSS version 26. The samples were analyzed to discern relationships and variations among variables on a normalized data scale, assisting in simplifying the scope and complexity of data with autonomous behavior (34). In this paper, descriptive statistics techniques such as minimum, maximum, mean, range, and standard deviation are applied to the

physicochemical indicators present in the water collected. Additionally, a Pearson's linear correlation matrix was produced to investigate the relationships between the explored parameters. This combination pattern of the correlation matrix displayed in the form of a matrix made it possible to determine the correlations between different water quality parameters. The analysis was conducted on a dataset with 20 well samples and covering 14 water quality parameters. The assessment of several water quality parameters in a matrix format is essential for demonstrating and analyzing the interrelationships among numerous environmental elements. It involves a crucial function in terms of measuring the impact of water quality on a certain area (35,36). The water quality assessments conducted in this study were performed using Microsoft Excel 2016 for all analytical models.

Water Quality Index (WQI)

Water assessments, being globally recognized, evaluate the quality standards of the water for various kinds of purposes. The Water Quality Index (WQI) is an important tool that integrates various parameters to present an overall idea about water quality. Lower WQI scores indicate poor water quality, while higher scores indicate excellent water quality (37). The Global Environmental Monitoring System (GEMS) in 2007 adopted and endorsed the use of WQI, which has become the widely used method for evaluating water resources for human consumption and other goals as per the instructions of the World Health Organization (WHO) (38). Beginning in 1965, the first numerical Water Quality Index (WQI) was introduced. Since then, several indices have been developed with different structures, principles, application boundaries, and variable selection. Specifically, corrective water quality indices record the level of non-compliance from the existing observed parameter values and local regulatory standards (39). Nevertheless, we should bear in mind that though there is a very strong correlation between WQI and the water quality, it is not absolute proof, and it is important to be very careful when translating this correlation to practical usage. There is a possibility that it possesses a low level of precision and accuracy. However, even efforts that have been directed towards the development of such water quality indices specific to Iraq have received little attention and recognition to take care of the matter effectively (39,40).

Nemerow's Pollution Index (NPI)

The Nemerow Pollution Index (NPI) introduced by Nemerow and Sumitomo is a straightforward measure of pollution (38). By calculating NPI values based on specific water quality parameters, it becomes possible to identify the major pollutants impacting water quality. The status of the water quality can be quickly and easily determined using NPI. There are two approaches to Nemerow's

pollution index method: the single-factor (NPI_i) and the multi-factor (NPI_N). The formula yields the reduced metric known as the single-factor index:

$$NPI_i = \frac{C_i}{L_i} \quad (1)$$

In this case, L_i is the i -th parameter's permitted limit, and C_i is the i -th parameter's observed concentration. The presence of contaminants in the water necessitates treatment before use if the NPI_i value is more than 1.0. Table 3 presents the current state of the water quality based on Nemerow's pollution index.

The multi-factor approach, known as NPI_N , provides a more thorough method of assessing water quality by taking important polluting elements into account. Utilizing the following formula, the comprehensive pollution index (NPIN) is determined:

$$NPI_N = \sqrt{\frac{(NPI_x)^2 + NPI_{imax}^2}{2}} \quad (2)$$

The comprehensive pollution index is denoted by $NPIN$, the average value of the single-factor index is denoted by NPI_x , and the maximum value of the single-item pollution index for pollutants at a particular sample point is indicated by NPI_{imax} . Table 4 provides the water quality level determination based on Nemerow's pollution index approach (41).

Weighted Arithmetic Water Quality Index Method (WAI)

Using frequently measured variables, the weighted arithmetic water quality index approach classifies water quality according to its degree of purity. This approach has been widely used by many scientists (42,43). Applying the following equation yields the water quality index (WQI) computation (44) using the following equation:

$$WAI = \frac{\sum qnW_n}{\sum W_n} \quad (3)$$

The quality rating scale (qn) for each parameter is calculated using the following equation:

$$q_n = \frac{100(V_n - V_{io})}{(S_n - V_{io})} \quad (4)$$

Where

- V_n is the measured concentration of the n -th parameter.

Table 3. Nemerow's pollution index and criteria of water quality status

Nemerow's pollution index	Water quality status
≤ 1.0	No pollution
1-2	Slightly pollution
2-3	Lightly pollution
3-5	Moderately polluted
> 5	Seriously pollution

Table 4. Assessment of water quality levels utilizing Nemerow's pollution index methodology

Nemerow's pollution index	Water quality status
≤0.59	No pollution
0.59-0.74	Slightly pollution
0.74-1	Lightly pollution
1-3.5	Moderately polluted
>3.5	Seriously pollution

- *vio* is the parameter's optimal value in pure water.
- For most parameters (e.g., contaminants), *vio* = 0.
- Exceptions: pH, *vio* = 7.0 and Dissolved Oxygen, *vio* = 14.6 mg/l.

The suggested standard value for the nth parameter is S_n .

Each water quality parameter's unit weight (W_n) is determined using the following equation:

$$W_n = \frac{K}{S_n} \quad (5)$$

Where K is the proportionality constant that can also be calculated by the following equation:

$$K = \frac{1}{\sum \frac{1}{s_n}} \quad (6)$$

The rating of water quality according to this WQI is given in Table 5.

Results

This study conducted an extensive examination of the chemical and physical properties of groundwater, focusing on 14 criteria. The findings are presented in Table S1, which includes important statistical information for each parameter, such as averages, standard deviations, and minimum and maximum values. To evaluate water quality, these findings were compared to the Iraqi Quality Standards (IQS, 2009) and the World Health Organization (45).

Furthermore, spatial distribution maps were created using ArcGIS 10.5 software to visually represent the regional variations of the examined characteristics. These maps are displayed in Figures 2–4, highlighting the spatial distribution of parameters such as pH, Electrical Conductivity (EC), turbidity, and total dissolved solids (TDS). The correlations between the 14 physicochemical parameters were analyzed using Pearson correlation coefficients, which are presented in Table S2. This correlation matrix provides insights into the relationships and potential interactions among the parameters.

Additionally, the Water Quality Index (WQI) was calculated using the Nemerow Pollution Index (NPI) and Weighted Arithmetic Index (WAI) methods. The results, shown in Table S3, classify the groundwater samples based on their pollution levels. The visual representation of the WQI results is provided in Figure 5.

Table 5. Status of water quality based on the Weighted Arithmetic Index method

Index Value	Notes	Grading
0-25	Excellent water quality	A
26-50	Good water quality	B
51-75	Poor water quality	C
76-100	Very poor water quality	D
> 100	Unsuitable for drinking	E

Discussion

The results in Table S1 demonstrate that multiple parameters surpassed the allowable thresholds for potable water as defined by the IQS (2009) and WHO (2021). Wells W5, W14, and W20 demonstrated markedly elevated levels of Total Dissolved Solids (TDS) and Electrical Conductivity (EC), which are higher than the permitted thresholds. Spatial distribution maps (Figures 2–4) further confirm the regional variability of these parameters. For instance, Figure 2b highlights elevated EC levels in several wells, particularly W14 and W20, reflecting their higher salt content (46).

These findings are consistent with previous studies that have reported similar spatial heterogeneity in groundwater quality, often attributed to both natural and anthropogenic factors (47,48).

The groundwater's pH values, as shown in Table S1 and spatially distributed in Figure 2a, were found to be within the acceptable range (6.9–8.3). This aligns with previous studies conducted in Kirkuk and Mosul, which reported that groundwater in these regions has a high acid-neutralizing capacity (ANC) due to the significant presence of carbonate compounds in the soil and water (49). Similar trends have been observed in other regions, where carbonate-rich geology contributes to stable pH levels (47,50).

The correlation matrix (Table S2) reveals a significant positive relationship between pH and several parameters, including HCO_3^- ($r=0.166$), with p-values indicating statistical significance ($P<0.05$).

The turbidity levels in the study area ranged from 3.76 to 192 NTU, with an average value of 38.46 NTU (Table S1, Figure 3b). Notably, W1 exhibited the highest turbidity, which can be attributed to issues such as low pressure, failure of pipe linings, or improper well development (51).

These observations are in line with findings from other regions, where infrastructure and maintenance issues have been linked to elevated turbidity (47).

The correlation analysis (Table S2) shows a positive relationship between turbidity and parameters such as EC ($r=0.134$) and Ca^{2+} ($r=0.166$), emphasizing the influence of dissolved solids on water clarity.

The TDS values, which ranged from 381 mg/L in well W18 to a staggering 7625 mg/L in well W20, exceeded the permissible limit of 500 mg/L in most wells

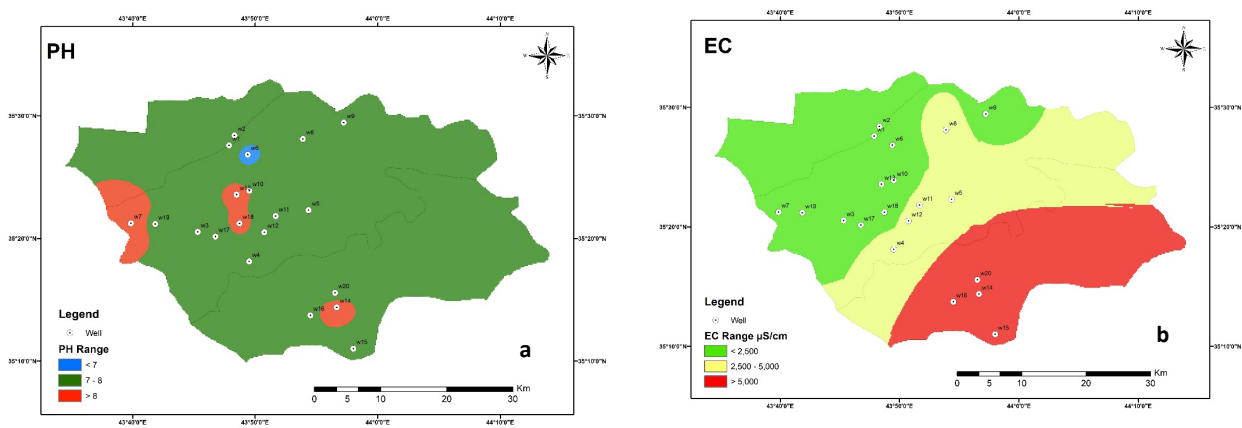


Figure 2. Spatial distribution of parameters of the study area: (a) pH, (b) EC

(Table S1, Figure 3e). TDS demonstrated strong positive correlations with parameters such as Ca^{2+} ($r=0.684$), Mg^{2+} ($r=0.747$), and Na^+ ($r=0.920$), as shown in Table S2, further highlighting the contribution of these ions to the overall dissolved solids in groundwater. Similar patterns of elevated TDS and strong ionic correlations have been documented in other studies, often linked to both gigantic sources and anthropogenic activities such as agriculture and urbanization (48,52).

Wells like W14, W15, and W20 exhibited alarmingly high TDS levels due to anthropogenic activities and natural salt dissolution, making the water unsuitable for drinking (5,53).

Electrical Conductivity (EC), a critical indicator of dissolved salts, showed a range from 630 $\mu\text{S}/\text{cm}$ (well W18) to 10,500 $\mu\text{S}/\text{cm}$ (well W20) (Table S1, Figure 2b). These elevated levels are consistent with the high TDS values observed in the same wells. Correlation data (Table S2) reveal significant relationships between EC and parameters such as Ca^{2+} ($r=0.725$), Mg^{2+} ($r=0.874$), and Na^+ ($r=0.924$), reinforcing the relationship between ionic concentration and conductivity (3,54).

These findings are corroborated by similar studies employing water quality indices and regression analysis to evaluate the influence of major ions on EC and TDS (50,52).

The Water Quality Index (WQI) data, displayed in Table S3 and illustrated in Figure 5, categorize the water quality of the wells. According to the NPI-WQI method, 50% of the samples were categorized as “seriously polluted,” while the remaining 50% were classified as moderately polluted. On the other hand, the WAI-WQI model found that majority of the water samples (80%) were from the category of “unsuitable for drinking,” while 10% were from “very poor water quality” class. The experimental data obtained from wells W14 and W20 are in line with the notion depicted in Figure 5 and Table S1 that these wells’ WQI scores are caused by TDS, EC, and other parameters’ high concentration; thus, the results of these parameters are set by Table S1 and Figure 5. Similar results from the

studies relying on advanced WQI modeling and spatial analysis are presented by Adimalla and Qian (2020) and Kumar et al. (2018) (47,52), who have reported that there are many groundwater contamination cases existing in those regions that are affected by natural as well as human-caused factors.

The research findings strongly indicate the poor groundwater quality in the investigated area and the high necessity for the implementation of suitable water management strategies. It is evident that the high presence of TDS, EC, and turbidity, as well as the strong correlation among these factors presented in Table S2, reveals the joint influence of natural and anthropogenic sources on water quality. The study’s results stipulate that it is necessary to treat the water for the greatest number of wells before it can be considered safe for human consumption; the same applies to the research reported in similar studies in like hydrogeological settings (48,50).

Conclusion

According to the present study conducted in the southwestern region of Kirkuk Governorate, Iraq, the groundwater in the area is unsuitable for direct usage. Groundwater quality assessment using water quality indices and GIS techniques showed that the water is beyond permissible levels for a number of important parameters such as turbidity, electrical conductivity, total dissolved solids, sulfate, magnesium, calcium, potassium, chloride, bicarbonate, and sodium. The research underlines the need for the implementation of proper management actions for the protection and safe use of groundwater resources not only in Kirkuk Governorate, but also in the neighboring regions. Water quality indices, such as Nemerow’s Pollution Index (NPI) and the Weighted Arithmetic Index (WAI), were employed to assess groundwater quality. Nevertheless, the findings indicated that the groundwater levels were higher than those permitted for drinking water, requiring additional treatment or the use of alternate water sources. Significant information on pollutant distribution and

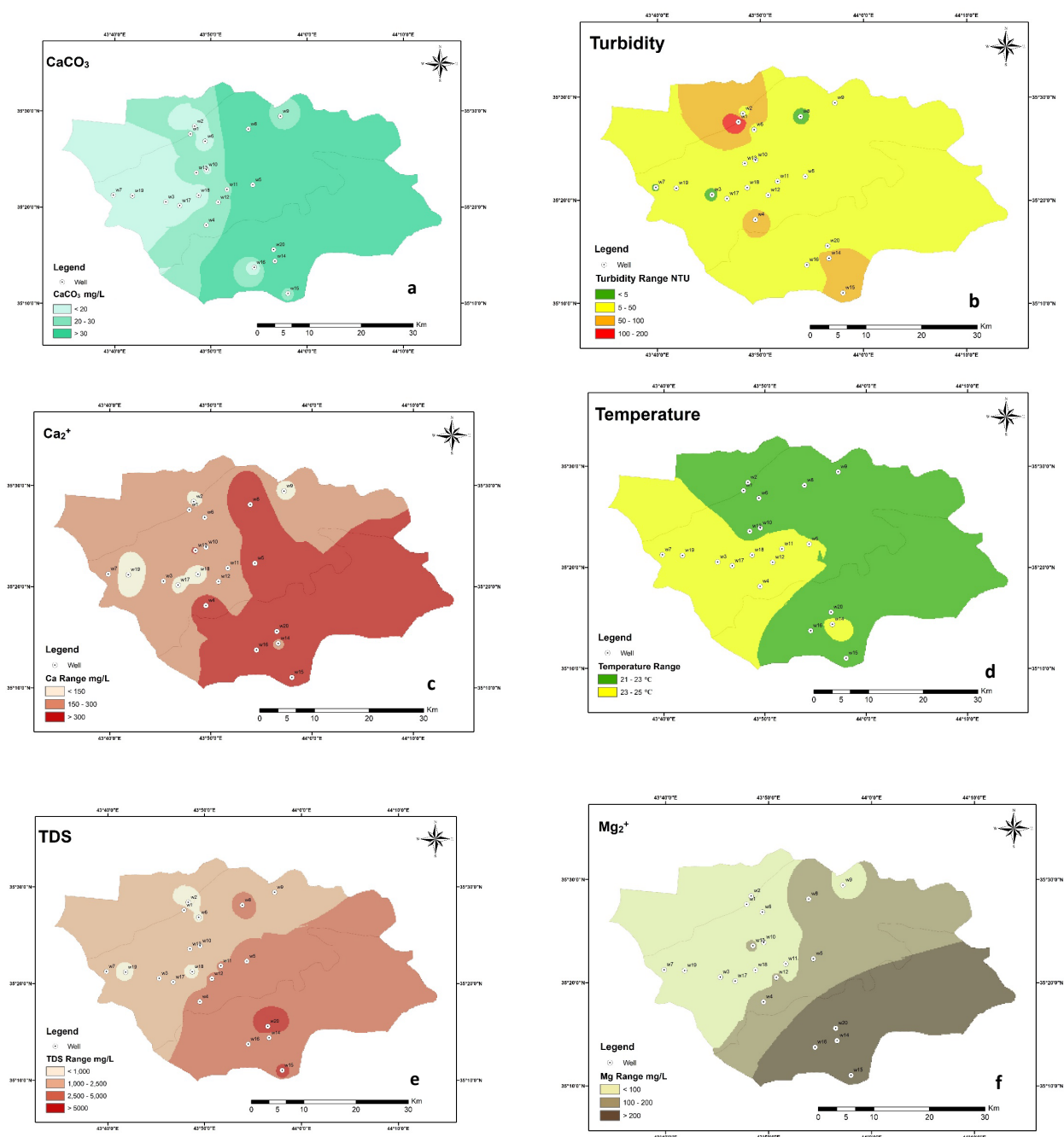


Figure 3. Spatial distribution of parameters of the study area: (a) CaCO_3 , (b) Turbidity, (c) Ca^{+2} , (d) Temperature, (e) TDS, (f) Mg_2^{+}

its effects on groundwater quality was uncovered by the spatial mapping of physicochemical data from 20 wells. Making informed decisions and creating plans to address groundwater contamination in Kirkuk Governorate will be made easier using this information. The results of this study emphasize how vital it is to make all-out efforts to protect and maintain the region's clean, healthy groundwater resources. It highlights how important it is to continuously monitor, analyze, and regulate groundwater quality in a way that preserves public health and advances sustainable development.

Acknowledgements

The authors would like to show their gratitude and respect to Mr. Ghassan Fadel, the head of the general groundwater authority branch in Kirkuk, for the technical support, which was very helpful to us in achieving the success of our study. In addition, we really appreciated the University of Tikrit for its support and assistance in preparing this manuscript. Besides these, we are privileged to the Editor-in-Chief and the anonymous reviewer for their smart and useful comments, which contribute greatly to the quality of the whole writing. Their feedback was instrumental in enhancing the content and presentation of our research.

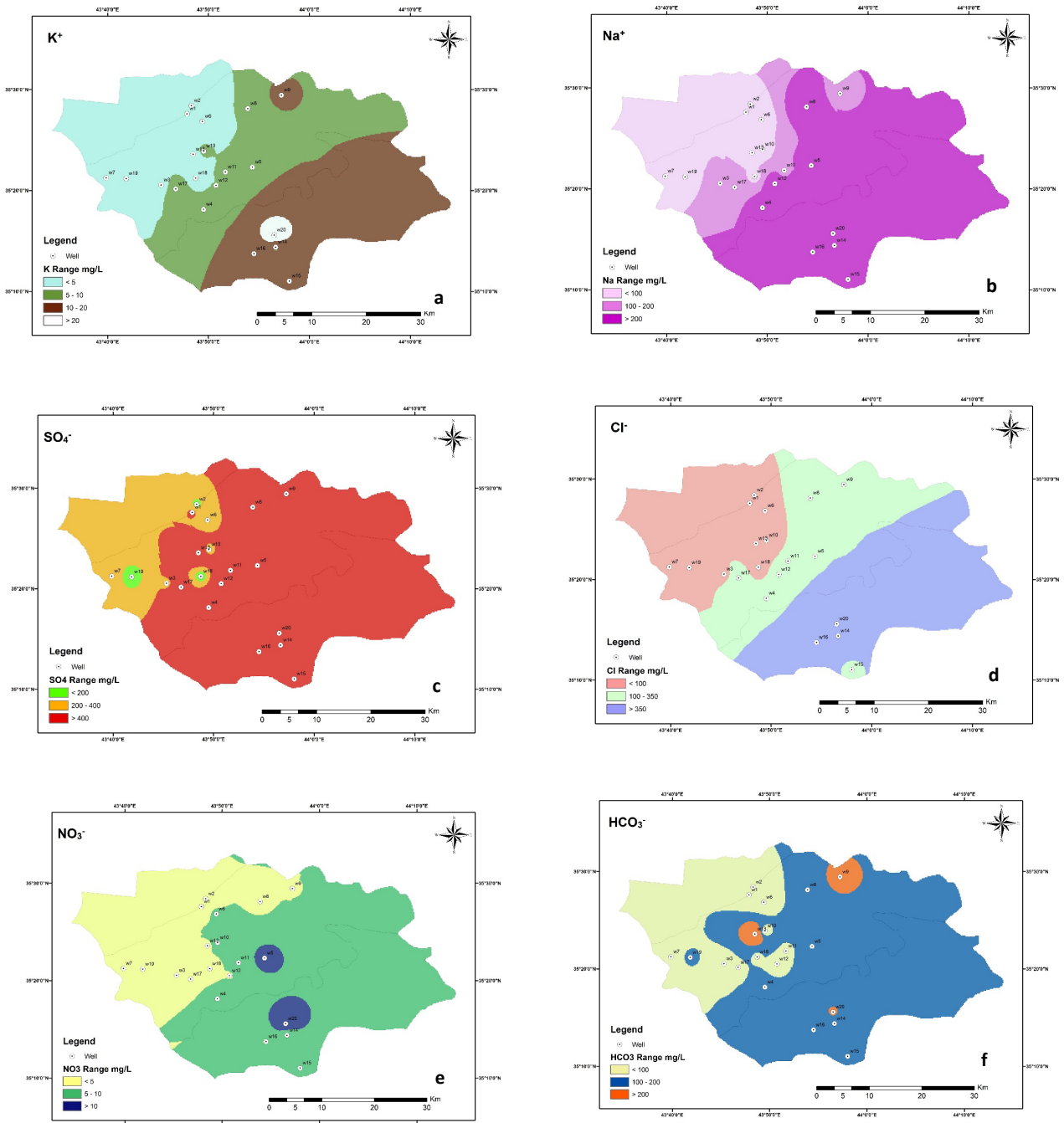


Figure 4. Spatial distribution of parameters of the study area; (a) K^+ , (b) Na^+ , (c) SO_4^- , (d) Cl^- , (e) NO_3^- , (f) HCO_3^-

Author's contributions

Conceptualization: Waleed M. Sh. Alabdraba, Firas R. Abdulrahim

Data curation: Firas R. Abdulrahim, Aydin Adnan Rashid
Formal Analysis: Firas R. Abdulrahim, Aydin Adnan Rashid

Funding acquisition: Waleed M. Sh. Alabdraba

Investigation: Waleed M. Sh. Alabdraba, Firas R. Abdulrahim

Methodology: Aydin Adnan Rashid, Firas R. Abdulrahim

Project administration: Waleed M. Sh. Alabdraba

Resources: Shahad Ali Abdulhussein, Firas R. Abdulrahim

Software: Aydin Adnan Rashid

Supervision: Waleed M. Sh. Alabdraba

Validation: Shahad Ali Abdulhussein

Visualization: Aydin Adnan Rashid

Writing – original draft: Firas R. Abdulrahim

Writing – review & editing: Firas R. Abdulrahim, Aydin Adnan Rashid

Competing interests

The authors declare that they have no competing interests.

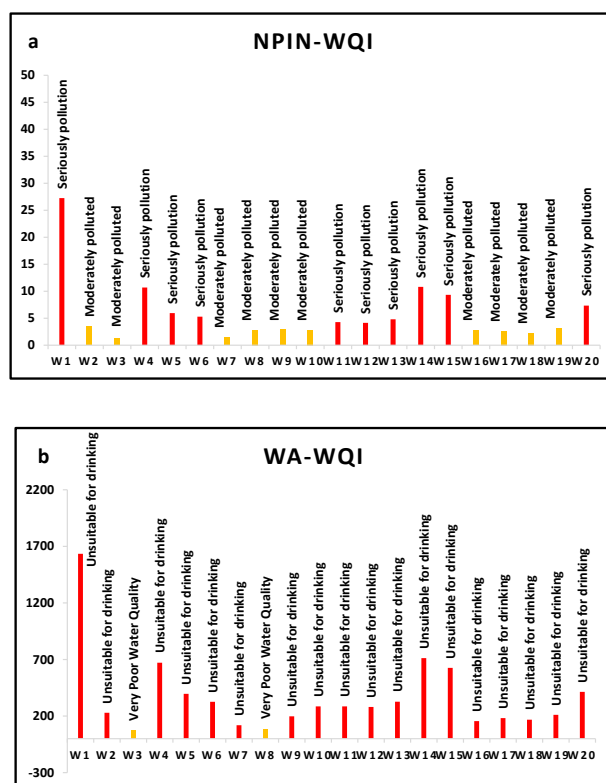


Figure 5. Results of the wells, both methods (a) NPI-WQI, (b) WAI-WQI

Ethical issues

The authors hereby certify that all data collected during the study are as stated in the manuscript, and no data from the study has been or will be published separately elsewhere.

Funding

This research was supported by the Kirkuk Branch of the Iraqi Ministry of Water Resources, General Groundwater Authority, which provided laboratory facilities and water quality data access. Additional support was provided by Tikrit University, Environment Engineering Department, and Northern Technical University, Surveying Engineering Department.

Supplementary file

Supplementary file contains Table S1 - S3.

References

1. Foster S, Hirata R, Gomes D, D'Elia M, Paris M. Groundwater quality protection: A guide for water utilities, municipal authorities, and environment agencies. Washington, DC: Pan American Health Organization; 2003.
2. Nair IS, Rajaveni SP, Schneider M, Elango L. Geochemical and isotopic signatures for the identification of seawater intrusion in an alluvial aquifer. *Journal of Earth System Science*. 2015;124(6):1281–91. doi:10.1007/s12040-015-0600-y
3. Al-Hashimi O, Hashim K, Loffill E, Marolt Čebašek T, Nakouti I, Faisal AAH, et al. A Comprehensive Review for Groundwater Contamination and Remediation: Occurrence, Migration and Adsorption Modelling. *Molecules*. 2021;26(19). doi:10.3390/molecules26195913
4. Dawood AS. Using of Nemerow's Pollution Index (NPI) for water quality assessment of some Basrah Marshes, South of Iraq. *J Babylon Univ Pure Sci*. 2017;25(5):1708–1720.
5. Al-Tameemi IM, Hasan MB, Al-Mussawy HA, Al-Madhhachi AT. Groundwater Quality Assessment Using Water Quality Index Technique: A Case Study of Kirkuk Governorate, Iraq. In: *IOP Conference Series: Materials Science and Engineering*. Vol 928. IOP Publishing; 2020. p. 072185. doi:10.1088/1757-899X/928/7/072185
6. Tanaka Y. Estimation of Irrigated Agricultural Area and Water Consumption in Iraq. In: *Tigris Euphrates Rivers Their Environment from Headwaters to Mouth*. Cham: Springer; 2021. p. 205–228.
7. Bashir I, Lone FA, Bhat RA, Mir SA, Dar ZA, Dar SA. Concerns and threats of contamination on aquatic ecosystems. In: *Bioremediation Biotechnology Sustainable Approaches to Pollution Degradation*. Berlin: Springer; 2020. p. 1–26.
8. Adamopoulos I, Frantzana A, Adamopoulou J, Syrou N. Climate Change and Adverse Public Health Impacts on Human Health and Water Resources. *Environmental Sciences Proceedings*. 2023; 26(1):178. doi:10.3390/envirosciproc2023026178
9. Shrestha RK, Ladha JK. Nitrate pollution in groundwater and strategies to reduce pollution. *Water Sci Technol*. 2002;45(9):29–35.
10. Dos Santos S, Adams EA, Neville G, Wada Y, de Sherbinin A, Mullin Bernhardt E, et al. Urban growth and water access in sub-Saharan Africa: Progress, challenges, and

- emerging research directions. *Sci Total Environ.* 2017;607-608:497–508. doi:10.1016/j.scitotenv.2017.06.157
11. Weststrate J, Dijkstra G, Eshuis J, Gianoli A, Rusca M. The Sustainable Development Goal on Water and Sanitation: Learning from the Millennium Development Goals. *Social Indicators Research.* 2019;143(2):795–810. doi:10.1007/s11205-018-1965-5
 12. Beisheim M. Country-level politics around the SDGs: Analysing political will as a critical element of the Mid-Term Review of the 2030 Agenda and the SDGs. *Stiftung Wissenschaft und Politik Research Paper*; 2023. Available from: https://www.swp-berlin.org/publications/products/research_papers/2023RP07_UN_Mid-termReview.pdf
 13. Al-Ansari N, Adamo N, Hachem AH, Sissakian V, Laue J, Abed SA. Causes of Water Resources Scarcity in Iraq and Possible Solutions. *Engineering.* 2023;15(9):467–496. doi:10.4236/eng.2023.159036
 14. Jayanthi MK, Aswathi K, Krishna KL, Ramu R. Evaluation of antioxidant and diuretic activities of *Clitoria ternatea* leaf extracts in Wistar albino rats. *J Appl Pharm Sci.* 2021;11(1):152–157. doi:10.7324/JAPS.2021.110118
 15. Saod WM, Yosif YM, Abdulrahman MF, Mohammed AH. Water quality index along the Euphrates between the cities of Al-Qaim and Falluja: A comparative study. In: *IOP Conference Series: Earth and Environmental Science.* Vol 851. IOP Publishing; 2021. p. 012058. doi:10.1088/1755-1315/851/1/012058
 16. Backer LC. Assessing the acute gastrointestinal effects of ingesting naturally occurring, high levels of sulfate in drinking water. *Crit Rev Clin Lab Sci.* 2000;37(4):389–400. doi:10.1080/10408360091174259
 17. Misstear B, Vargas CR, Lapworth D, Ouedraogo I, Podgorski J. A global perspective on assessing groundwater quality. *Hydrogeology Journal.* 2023;31(1):11–4. doi:10.1007/s10040-022-02461-0
 18. Delaire C, Poulin C, Lapworth D, Smedley P, Klingbeil R, Wagner F, et al. Assessing groundwater quality: a global perspective: importance, methods and potential data sources. Paris: UNESCO; 2021.
 19. Al-Mohammed FM, Al-Saadi RJM, Al-Fawzy AM, Mohammed-Ali SH, Mutasher AA, Hommadi AH. The analysis of water quality using Canadian water quality index: Green belt project/Kerbala-Iraq. *Int J Des Nat Ecodynam.* 2021;16(1):91–98. doi:10.18280/ij dne.160112
 20. Habbeeb MG, Sulyman MH, Jumaah HJ. Modeling water quality index using geographic information systems and weighted arithmetic index in Kirkuk, Iraq. *Pollut Res.* 2022;41(1):323–327. doi:10.53550/PR.2022.v41i01.047
 21. Wimalawansa SJ. Effect of water hardness on non-communicable diseases. In: *Chronic Kidney Disease: Multifactorial Origin.* Berlin: Springer; 2016. p. 1–11.
 22. Rude RK. Magnesium deficiency: a cause of heterogeneous disease in humans. *J Bone Miner Res.* 1998;13(4):749–58. doi:10.1359/jbmr.1998.13.4.749
 23. He FJ, Tan M, Ma Y, MacGregor GA. Salt Reduction to Prevent Hypertension and Cardiovascular Disease: JACC State-of-the-Art Review. *J Am Coll Cardiol.* 2020;75(6):632–47. doi:10.1016/j.jacc.2019.11.055
 24. Klotz K, Weistenhöfer W, Neff F, Hartwig A, van Thriel C, Drexler H. The Health Effects of Aluminum Exposure. *Dtsch Arztebl Int.* 2017;114(39):653–9. doi:10.3238/arztebl.2017.0653
 25. Dórea FC, Sanchez J, Revie CW. Veterinary syndromic surveillance: Current initiatives and potential for development. *Prev Vet Med.* 2011;101(1-2):1–17. doi:10.1016/j.prevetmed.2011.05.004
 26. Momodu MA, Anyakora CA. Heavy metal contamination of ground water: The Surulere case study. *Res J Environ Earth Sci.* 2010;2(1):39-43.
 27. Werner AK, Vink S, Watt K, Jagals P. Environmental health impacts of unconventional natural gas development: a review of the current strength of evidence. *Sci Total Environ.* 2015;505:1127–41. doi:10.1016/j.scitotenv.2014.10.084
 28. Kazar FM, Hassan EFF, Khassaf SI. Evaluation of Groundwater Quality in Selected Areas of Najaf Governorate for Different Purposes. *al-Qadisiyah Journal for Engineering Sciences* 2017;10(1):36–53.
 29. Al-Asadi SAR, Al-Qurnawi WS, Al Hawash AB, Ghalib HB, Alkhlifa N-HA. Water quality and impacting factors on heavy metals levels in Shatt Al-Arab River, Basra, Iraq. *Applied Water Science.* 2020;10(5):103. doi:10.1007/s13201-020-01196-1
 30. Mueller A, Detges A, Pohl B, Reuter MH, Rochowski L, Volkholz J, et al. Climate change, water and future cooperation and development in the Euphrates-Tigris basin. In: *Geoscience Research Report.* Bonn: German Development Institute; 2021. p. 38–53.
 31. Mahdi BA, Moyel MA, Jaafar RS. Adopting the Water Quality Index to assess the validity of groundwater in Al-Zubair city southern Iraq for drinking and human consumption. *Eco. Env. & Cons.* 2021;27(1):73–79.
 32. Al-Khashman OA, Alnawafleh HM, Jrai AMA, Ala'a H. Monitoring and assessing of spring water quality in southwestern basin of Jordan. *Open J Mod Hydrol.* 2017;7(4):331–349.
 33. Alanbari MA, Alquzweeni SS, Aldaheer RA. Spatial distribution mapping for various pollutants of al-kufa river using geographical information system (gis). *Int J Civ Eng Technol.* 2015;6(10):1–14.
 34. Johnson RA, Wichern DW. Applied multivariate statistical analysis. 5th ed. Upper Saddle River, NJ: Prentice Hall; 2002.
 35. Singh Y, Jain MK. Pearson's Correlation and Trend Analysis for Physico-Chemical Parameters of Mansagar Lake, Jaipur. Preprints: Preprints; 2021.
 36. Nagaraju A, Sreedhar Y, Thejaswi A, Sayadi MH. Water quality analysis of the Rapur area, Andhra Pradesh, South India using multivariate techniques. *Applied Water Science.* 2017;7(6):2767–77. doi:10.1007/s13201-016-0504-2
 37. Uddin MG, Nash S, Olbert AI. A review of water quality index models and their use for assessing surface water quality. *Ecological Indicators.* 2021;122:107218. doi:10.1016/j.ecolind.2020.107218
 38. Al Yousif MA, Chabuk A. Assessment Water Quality Indices of Surface Water for Drinking and Irrigation Applications – A Comparison Review. *Journal of Ecological Engineering.* 2023;24(5):40–55. doi:10.12911/22998993/161194
 39. Ewaid SH, Abed SA, Al-Ansari N, Salih RM. Development and Evaluation of a Water Quality Index for the Iraqi Rivers. *Hydrology [Internet].* 2020; 7(3):[67 p.].
 40. Prabakaran A, Poorna B. Study on Associative Relationship Impact on Water Quality Index Attributes. *Int J Comput Appl.* 2012;59(9):33–38.
 41. Su K, Wang Q, Li L, Cao R, Xi Y, Li G. Water quality assessment based on Nemerow pollution index method:

- A case study of Heilongtan reservoir in central Sichuan province, China. *PLoS One*. 2022;17(8):e0273305. doi:10.1371/journal.pone.0273305
42. Patel DD, Mehta DJ, Azamathulla HM, Shaikh MM, Jha S, Rathnayake U. Application of the Weighted Arithmetic Water Quality Index in Assessing Groundwater Quality: A Case Study of the South Gujarat Region. *Water*. 2023; 15(19):3512.
 43. Chandra DS, Asadi SS, Raju MVS. Estimation of water quality index by weighted arithmetic water quality index method: A model study. *Int J Civ Eng Technol*. 2017;8(4):1215–22.
 44. Hyarat T, Al Kuisi M. Comparison between weighted arithmetic and Canadian council of ministers of the environment water quality indices performance in Amman-Zarqa Area, Jordan. *Jordan J Earth Environ Sci*. 2021;12(4):295–305.
 45. Aragaw TT, Gnanachandrasamy G. Evaluation of groundwater quality for drinking and irrigation purposes using GIS-based water quality index in urban area of Abaya-Chemo sub-basin of Great Rift Valley, Ethiopia. *Applied Water Science*. 2021;11(9):148. doi:10.1007/s13201-021-01482-6
 46. World Health Organization. Guidelines for drinking-water quality: Incorporating the first and second addenda. 4th ed. Geneva: WHO; 2022.
 47. Acharya S, Sharma SK, Khandegar V. Assessment of groundwater quality by water quality indices for irrigation and drinking in South West Delhi, India. *Data Brief*. 2018;18:2019–28. doi:10.1016/j.dib.2018.04.120
 48. Gu X, Xiao Y, Yin S, Pan X, Niu Y, Shao J, et al. Natural and anthropogenic factors affecting the shallow groundwater quality in a typical irrigation area with reclaimed water, North China Plain. *Environ Monit Assess*. 2017;189(10):514. doi:10.1007/s10661-017-6229-3
 49. Al-Soyffe MAA, Al-Shaker YMS, Saffawi AYTA. Assessment of water quality for irrigation using the sub-index model: A case study of Tigris River water in Mosul City, Iraq. *Journal of Pharmaceutical Negative Results* 2022;13(Special Issue 6):1019–1028. doi:10.47750/pnr.2022.13.S06.136
 50. Saikrishna K, Purushotham D, Sunitha V, Reddy YS, Linga D, Kumar BK. Data for the evaluation of groundwater quality using water quality index and regression analysis in parts of Nalgonda district, Telangana, Southern India. *Data Brief*. 2020;32:106235. doi:10.1016/j.dib.2020.106235
 51. Kistemann T, Classen T, Koch C, Dangendorf F, Fischeder R, Gebel J, et al. Microbial load of drinking water reservoir tributaries during extreme rainfall and runoff. *Appl Environ Microbiol*. 2002;68(5):2188–97. doi:10.1128/aem.68.5.2188-2197.2002
 52. Jha MK, Shekhar A, Jenifer MA. Assessing groundwater quality for drinking water supply using hybrid fuzzy-GIS-based water quality index. *Water Res*. 2020;179:115867. doi:10.1016/j.watres.2020.115867
 53. Ahmad T, Muhammad S, Umar M, Azhar MU, Ahmed A, Ahmad A, et al. Spatial distribution of physicochemical parameters and drinking and irrigation water quality indices in the Jhelum River, Pakistan. *Environ Geochem Health*. 2024;46(8):263. doi:10.1007/s10653-024-02026-y
 54. Rahman A, Mondal NC, Tiwari KK. Anthropogenic nitrate in groundwater and its health risks in the view of background concentration in a semi arid area of Rajasthan, India. *Sci Rep*. 2021;11(1):9279. doi:10.1038/s41598-021-88600-1