

DETERMINATION OF GROUNDWATER QUALITY USING GIS: DEWANIYA GOVERNORATE, IRAQ, AS A CASE STUDY

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ABSTRACT: This study was carried out to determine the suitability of groundwater in Dewaniya governorate of Iraq for irrigation and drinking purposes based on Weighted Arithmetic (WAI) and Meireles Water Quality (MWQI) Indices, with analysis of the results using Geographic Information System (GIS). According to the research outcomes, the water types in the study area wells were categorized as good, poor, very poor, and unsuitable for human consumption. The percentages were 2% good, 9% poor, 35% very poor, and 54% unsuitable for drinking purposes, respectively. The type of water in the wells of the study area was Moderate restrictions (MR), High restrictions (HR), and Severe restrictions (SR) for irrigation purposes. MWQI classes with distribution in the study area were 10%, 14%, and 76% for MR, SR, and HR, respectively. The higher values of water quality parameters that exceeded the permissible limit of their standard values led to an effect on WQI values in the region. Groundwater can be used for irrigation of plants in the region with special restrictions.

Keywords: Dewaniya, Groundwater, GIS, Iraq, WQI

1. INTRODUCTION

Water is the main source in nature, which is the most important for maintaining life and is essential in practically all living actions [1]. Groundwater is one of the most important water resources in Iraq, especially in the areas distant from surface water resources. It plays the primary role in the livelihood of people by supplying water for drinking, irrigation, industrial and other purposes. In Iraq, groundwater occurs at depths ranging from the land surface to more than 700 m below the earth's surface within different aquifer systems. These aquifers have been penetrated by more than (150) thousand groundwater wells. The discharge of these wells represents (14%) of the national water resources in Iraq [2].

Ministry of Water Resources Reports indicate that, in recent years, the demand for water in the Republic of Iraq has significantly escalated due to population growth and economic development. This surge coincides with a depletion of surface water resources, primarily attributed to increased exploitation and investment in water resources by neighboring countries (Turkey, Iran, and Syria), as well as the lack of long-term agreements to regulate water allocations with these nations. Given these issues, the utilization of groundwater as an alternative supply is crucial to address the anticipated scarcity of surface water [3]. Due to the increasing population, concerns about access to food are growing, diminishing surface water supply in Iraq. As a result, using groundwater became crucial. Since groundwater originates from deeper regions of

the earth, it is rarely cleaned and is thought to be naturally protected. It is also thought to be free of contaminants that are linked to surface water [4].

Iraq is experiencing impending water shortages. Therefore, it is necessary to evaluate the water quality for usage to ensure drinking and agricultural water shortly [5]. Water can be mean specific area of the Earth's surface, which includes all aspects of the biosphere, both above and below this surface. This encompasses the near-surface climate, soil, terrain features, surface water bodies (lakes, rivers, marshes, and swamps), sedimentary layers close to the surface, and associated groundwater supplies [6, 7]. It includes plant and animal populations, patterns of human settlement, and the physical effects of historical and current human activities. Building dams and controlling the course of the river, especially in upstream countries, is considered one of the human interventions in creating drought, which is a type of socioeconomic drought. Hydrological drought is a decrease in river water flow or groundwater reserves caused by climate change [7, 8].

The Water Quality Index (WQI) is one of the main strategies for identifying and disseminating water quality data to policymakers and citizens. It has become a key indicator for water management and assessment. WQI is a rating system that reflects the composite effect of many water quality parameters [9-11]. The chemical and physical characteristics of a water sample are frequently compared to water quality standards or recommendations in order to evaluate the quality of the water. One of the simplest methods for

evaluating water quality is the use of water quality indicators. For both technical and non-technical researchers interested in water quality outcomes, this tool provides comprehensible summaries of water quality data. Determining water quality metrics is critical for determining the quality, conditions, and contamination level of surface waterways. Water quality indicators are one of the easiest approaches for assessing water quality issues [12]. The WQI concept is to make it easier to comprehend concerns by combining a significant amount of data and giving a score that provides a straightforward definition of water quality conditions like outstanding, fair, bad, and so on [13]. Assessment of groundwater quality is an essential part of sustainable water resource management, especially in areas that are experiencing increasing stress and demand.

Eamrat R et al. [14] conducted a study to determine the quality of groundwater and its suitability for agriculture by studying its chemical and physical properties. Many elements were analyzed, and most of the samples studied by the researchers were suitable for irrigation. The majority of the groundwater samples were classified as having medium salinity with low alkalinity. However, the researchers found that the groundwater samples taken from shallow wells in the Ban Nong I Khem and Ban Tang Mung areas contained high levels of Total Dissolved Solids (TDS) and Electrical Conductivity (EC), which require the cultivation of crops with high tolerance to salinity and the use of special irrigation methods and techniques. Abdullah et al. [15] conducted a comprehensive environmental analysis of the groundwater and surface water of Najaf city to identify pollution sources and their spatial distribution using Geographic Information Systems (GIS) software. This analysis focused on water quality and salinity. They found that electrical conductivity (EC) values ranged from 1500 to 4500 $\mu\text{S}/\text{cm}$, and total solids content in the samples ranged from 850 to 3500 mg/L. Areas with high water quality were found along a narrow strip adjacent to the Euphrates River, and groundwater quality in wells was found to be unsuitable.

Several factors contribute to the quality of groundwater, such as soil properties, land use, hydrology, and anthropogenic activities such as agriculture and industrialization. GIS offers a powerful tool to incorporate spatial information about these factors, allowing the identification of contamination sources, mapping of sensitive areas, and spatial analysis of water quality changes. GIS-based groundwater analysis provides important information regarding the spatial distribution of water quality parameters and can be useful for decision-making in sustainable groundwater management in Dewaniya Governorate, where

groundwater is a crucial resource for domestic and agricultural purposes [16]. The major chemical and physical parameters are linked with the level of plenty of water. The concentration of the parameters in the water has a great impact on assessing the WQI [17]. In all geographical and spatial aspects of the development and management of water resources, geographic information systems (GIS) are crucial. These methods offer powerful analytical and visual tools for characterizing, evaluating, and modelling the functions and processes of natural systems [18, 19]. This research evaluates the suitability of groundwater in Al-Diwaniyah Governorate for drinking and irrigation purposes using the Weighted Arithmetic Index (WAI) and Meireles Water Quality Index (MWQI). The study includes the description of the study area, groundwater data collection, laboratory analyses, and the methodologies adopted for water quality assessment. The obtained results are interpreted using GIS-based spatial analysis to identify the distribution of groundwater quality classes across the governorate. The findings contribute to understanding the current condition of groundwater resources and provide information that can support sustainable water resource management in the region.

2. RESEARCH SIGNIFICANCE

Al-Diwaniyah Governorate is considered the food basket of Iraq and contains many agricultural crops and is currently suffering from water scarcity as a result of low rainfall, drought, and low water releases reaching the governorate from the Euphrates River. This has led to an increase in the migration of farmers to the city due to the lack of flowing water in the rivers, which requires finding alternative sources to the rivers, such as well water. The purpose of this research is to assess the groundwater suitability in Dewaniya governorate for irrigation and drinking purposes based on Weighted Arithmetic (WAI) and Meireles Water Quality (MWQI) Indices, with analysis of the results using GIS.

3. MATERIALS AND METHODS

3.1 The study area

Dewaniya governorate, with an approximate area of 8258 km², was selected as the study area. It is located between (44° 30' and 45° 30') easting and (31° 30' and 32° 30') northing as shown in Fig. 1.

Hydrogeological investigations in the governorate indicate the presence of three underground reservoirs are the formation of Dammam, Euphrates, and the sediments of the flood plain. The sources of feeding the Dammam reservoir are the rainfall as well as the water seeping in the

valleys close to the depths during the seasons of flow, and the thickness of this reservoir ranges from 80 to 200 meters in the region. As for the Euphrates reservoir, it is believed that it is hydraulically connected to the Dammam reservoir, and the petrometric level for them is about 41 meters.

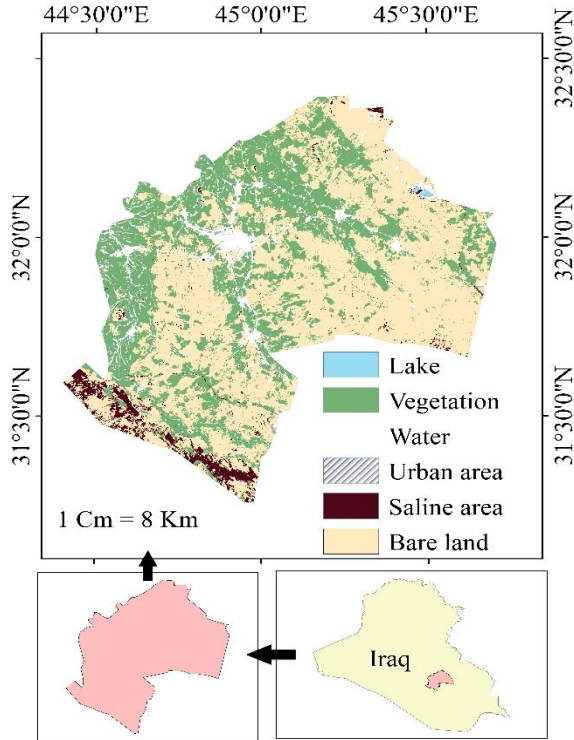


Fig.1 Location map of the study area: Al-Diwaniya Governorate, Iraq, showing governorate boundaries, main cities, and the Euphrates River. The Coordinate system: GCS WGS84 (Geographic Coordinate System, World Geodetic System 1984), units in degrees.

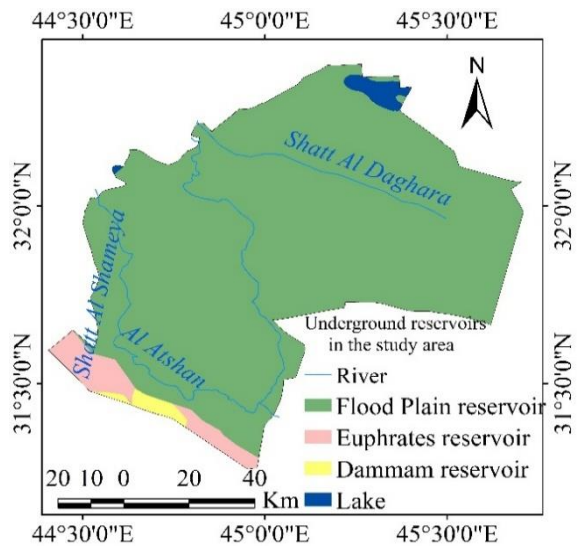


Fig.2 Underground reservoirs in the study area

The thickness of this reservoir is estimated to range between 30 and 50 meters. The amount of water in this reservoir is less than that of the Dammam reservoir and is more concentrated in salts. Therefore, mixing its water with the Dammam reservoir leads to an increase in the salinity of the water rising from the Dammam reservoir. As for the reservoir of the flood plain, which covers most of the province, which consists of clay, silt, sand and gravel, in addition to the salt sediments, the sources of nutrition for this reservoir are primarily the neighboring water bodies such as the Delmaj Marsh, rivers and streams, which are spread throughout the regions of the governorate, as well as the rainwater that seeps into the ground [20] as shown in Fig. 2. The depths of the groundwater in the governorate ranges between (5 – 45) meters as shown in Fig. 3.

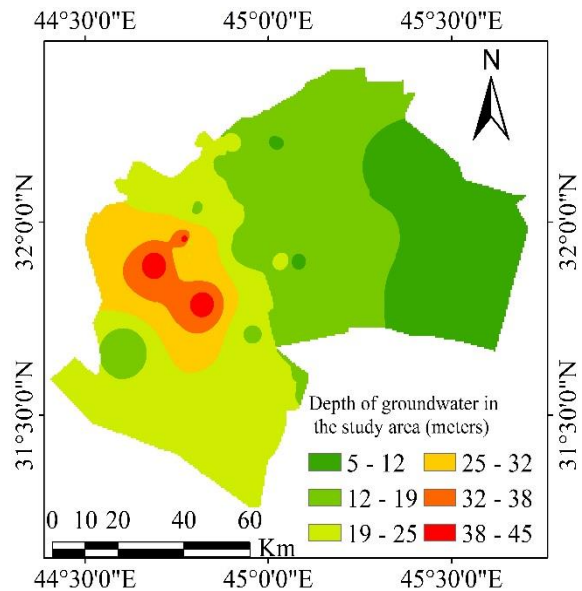


Fig.3 Depth of groundwater in the study area

These wells belong to the Iraqi Ministry of Water Resources / General Commission for Groundwater. The researchers did not choose their locations; rather, they were already present within the ministry's infrastructure in the study area.

3.1.1 Laboratory Analysis and Statistical Summary

Data collected and analyzed by Water Desalination Laboratory at the University of Technology. Table 1 shows the statistical analysis of the parameters of water quality.

The analytical procedures used in the laboratory were based on the Standard Methods for Testing Water and Wastewater issued by the American Public Health Association (APHA) and the American Water Works Association (AWWA).

3.2 Water quality index calculation and equation

In this research, the methods of weighted arithmetic and Meireles Water Quality (MWQI) were employed to determine the water quality index (WQI) for drinking and irrigation purposes, respectively.

Table 1. The statistical analysis of water parameters

Parameters	Min	Max	Average	Measuring method
pH	7.1	7.9	7.3	pH Meter
EC (µS/cm)	1522	31900	6192	Conductivity Meter
TDS (mg/L)	1099	22916	4439	Gravimetric Method
K (mg/L)	4	170	67	Flame Photometer
Na (mg/L)	85	1300	551	Flame Photometer
Mg (mg/L)	22	840	190	Titrimetric method
Ca (mg/L)	51	960	330	Titrimetric method
Cl (mg/L)	163	2414	819	Mohr's method
SO ₄ ²⁻ (mg/L)	389	3600	1331	Turbidimetric method
HCO ₃ ⁻ (mg/L)	60	885	377	Acid-base titration
NO ₃ ⁻ (mg/L)	2	10	4	UV spectrophotometric method
SAR (mg/L)	2	10	6	Calculated

3.3 Data Collection and Water Quality Parameters

Figure 4 shows the Location of wells in the study area.

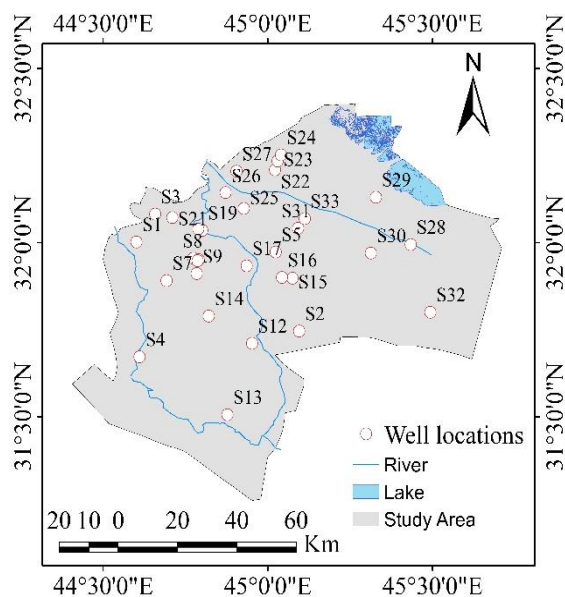


Fig.4 Location of wells in the study area

The parameters in this paper of WQ such as Hydrogen Ion (pH), Total Dissolved Solids (TDS), Potassium (K), Electric Conductivity (EC), Magnesium (Mg²⁺), Sodium (Na⁺), Calcium (Ca²⁺), Sulfate (SO₄²⁻), Chloride (Cl⁻), Bicarbonate (HCO₃⁻), and Nitrates (NO₃⁻) have been collected from 33 wells to evaluate groundwater quality for the purposes of irrigation and drinking in the study area as illustrated in Figure 4.

3.3.1 Weighted Arithmetic method (WAI)

In this method, the WQI for each selected well in the study area were calculated using the following Equations [12]:

$$Q_i = \left(\frac{v_i - D_i}{s_i - D_i} \right) * 100 \tag{1}$$

$$w_i = \frac{1}{s_i} \tag{2}$$

$$WQI = \frac{\sum_i^n w_i * Q_i}{\sum_i^n w_i} \tag{3}$$

Where: Qi shows the ith parameter sub-index, Wi represents the ith parameter for inverse weight of the standard value (Si), the ith parameter standard value is represented by Si, vi represents ith parameter measured concentration value, and Di shows the ideal value for each parameter in water, which equals zero, excluding the pH values which are equal to 7 respectively.

For each well in the study area, the WQ rating was given the deserve classification based on this method as shown in Table 2.

Table 2. Classes of WQI for Drinking Purposes [12]

Class	Value of Index
Excellent	0-25
Good	25-50
Poor	50-75
Very poor	75-100
Unsuitable	More than 100

In this study, the Iraqi standard limits for drinking water 2009 will be used, as shown in Table 3.

3.3.2 Meireles Water Quality (MWQI) method

The data were analyzed using the Irrigation Water Quality Index model developed by Meireles (2010). This model is known for its ability to determine the suitability of water for agriculture, particularly in arid and semi-arid regions. In constructing the proposed WQI, the parameters Na⁺, EC, SAR, Cl⁻, and HCO₃⁻ were considered the most relevant to irrigation. These properties were specifically chosen because they directly affect crop

growth, soil permeability, and the potential for salinization and toxicity over time with irrigation.

Table 3. Iraqi Standards Limits for WQI drinking (Central Organization for Standardization and Quality Control, 2009)

Parameter	Standard limits
pH	6.5-8.5
EC (µS/cm)	1000
TDS (mg/L)	1000
K(mg/L)	20
Na(mg/L)	200
Mg(mg/L)	100
Ca(mg/L)	150
Cl(mg/L)	350
SO ₄ ²⁻ (mg/L)	400
NO ₃ ⁻ (mg/L)	50

In this procedure, the WQI for each selected well in the research region were determined using the following equations:[4]:

$$MWQI = [\sum_{i=1}^n Qi * Wi] \quad (4)$$

$$Qi = qi_{max} - [(x_{ij} - x_{inf}) * qi_{amp} / x_{amp}] \quad (5)$$

Where:

wi represents the the nth parameter normalized weight as shown in Table 4.

qi_{max} represents the the class Maximum value of qi.

x_{ij} represents value of the laboratory analysis of WQ parameter.

x_{inf} represents the value corresponding to the minimum for the category to which the parameter.

qi_{amp} represents the amplitude of the class

x_{amp} represents the amplitude of the class to parameter.

Table 4. Standard weights for the MWQI parameters[21]

HCO ₃ ⁻	EC	Na	Cl	SAR	Parameter
0.202	0.211	0.204	0.194	0.189	Weight

The University of California Advisory Committee's and Ayers and Westcott's (1999) guidelines for irrigation water quality, Table 5, show the values of (qi) estimated based on the value of each parameter.

4. RESULTS AND DISCUSSION

WAI and MWQI Indices were applied to determine the appropriateness of Dewaniya governorate groundwater for irrigation and drinking purposes. The final maps were analysed and drawn using the ArcGIS 10.4 program based on the Inverse Distance Weighting (IDW) method. The research results illustrated that all water quality paraments were incompatible with Iraqi water quality standards

except pH and NO₃⁻ in most of wells in the study area as shown in Figs. 5-14.

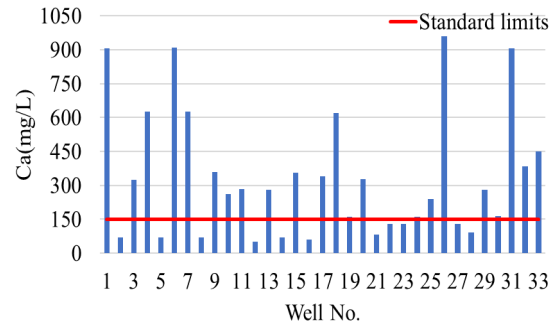


Fig.5 The Ca Concentration in the Wells

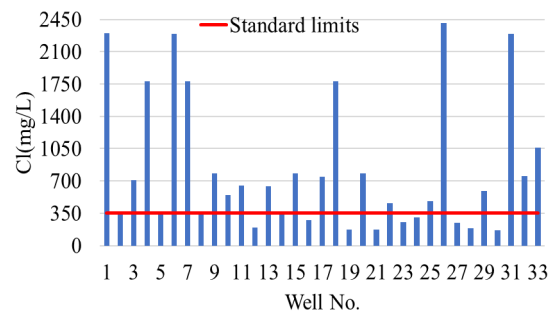


Fig.6 The Cl Concentration in the Wells

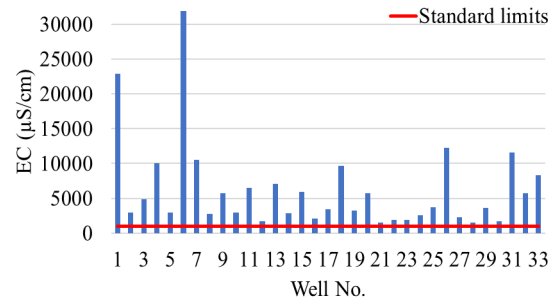


Fig.7 The EC Concentration in Wells

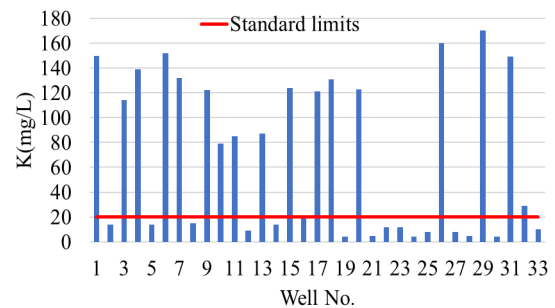


Fig.8 The K Concentration in the Wells

The high concentrations of TDS, EC, Na + , SO₄²⁻ and Cl - in most of the wells can be explained by a number of interrelated environmental and hydro-geological factors:

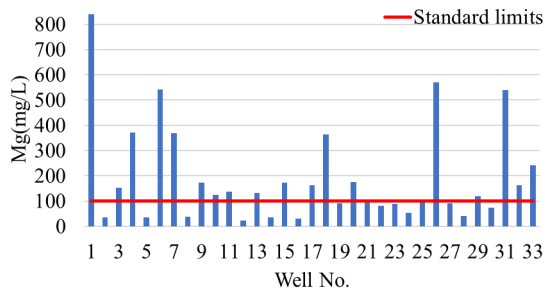


Fig.9 The Mg Concentration in the Wells

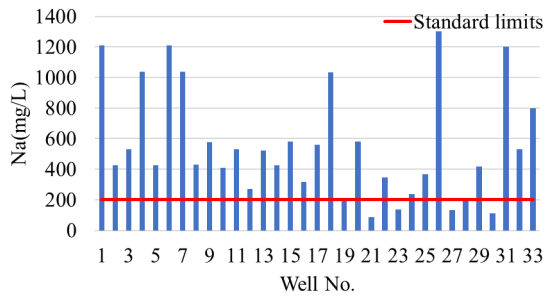


Fig.10 The Na Concentration in the Wells

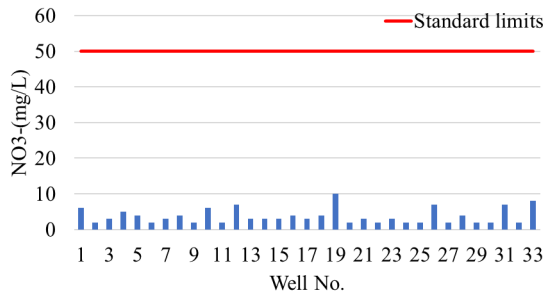


Fig.11 The NO₃⁻ Concentration in the Wells

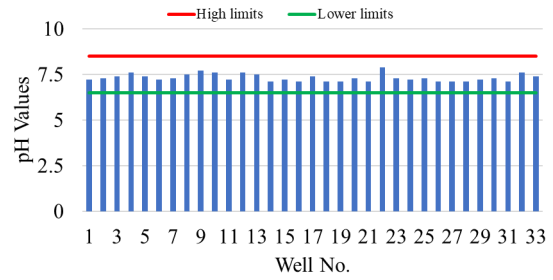


Fig.12 The pH Concentration in the Wells

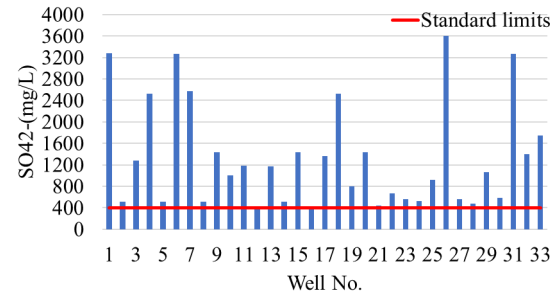


Fig.13 The SO₄²⁻ Concentration in the Wells

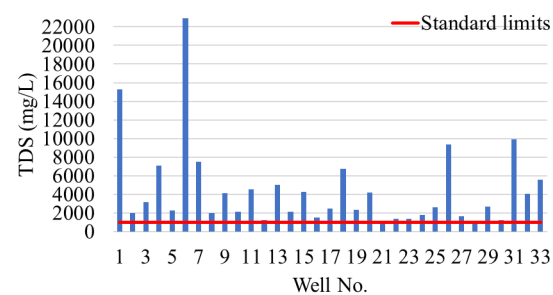


Fig.14 The TDS Concentration in the Wells

Table 5. Parameter criterion values for quality (Qi) [4]

Qi	Class	EC (μS/cm)	SAR (mg/L)	Na (mg/L)	Cl(mg/L)	HCO ₃ ⁻ (mg/L)
85-100	High	200≤EC<750	SAR<3	2≤Na<3	Cl<4	1≤HCO ₃ ⁻ <1.5
60-85	Medium	750≤EC<1500	3≤SAR<6	3≤Na<6	4≤Cl<7	1.5≤HCO ₃ ⁻ <4.5
35-60	Low	1500≤EC<3000	6≤SAR<12	6≤Na<9	7≤Cl<10	4.5≤HCO ₃ ⁻ <8.5
0-35	Very low	EC<200or EC≥ 3000	SAR≥12	Na<2or Na ≥9	Cl≥10	HCO ₃ ⁻ <1or HCO ₃ ⁻ ≥8.5

1. Geology and Aquifer Parameters: The study area has three main aquifers, which are the Dammam formation, Euphrates reservoir and the flood plain sediments as described in Section 3.1. The Euphrates reservoir is hydraulically connected to the Dammam reservoir and exhibits higher concentrations of salts. The mixing between these two reservoirs increases the salinity of the groundwater abstracted from the Dammam formation. In addition, the floodplain reservoir, which constitutes the majority of the governorate, is composed of clay, silt, sand, gravel, and salt

sediments, which in turn increases mineral dissolution.

2. Shallow Groundwater and High Evapotranspiration: The groundwater depth of the region varies from 5 to 45 m (Figure 3). The shallow depth, together with the high temperatures and evaporation rates of summer in arid and semi-arid climates, leads to evaporative enrichment of dissolved salts. This process naturally increases the levels of TDS, EC, Na + and SO₄²⁻.

It was therefore concluded that the poor quality of groundwater in Diwaniyah Governorate is not only caused by natural conditions; it has also been affected and exacerbated by natural and human

factors that contribute to improving these conditions, such as human-caused processes (agricultural practices, intensive extraction of groundwater) and climatic conditions (drought, hot evaporation conditions).

The water in the wells in the research region was graded as excellent, bad, extremely poor, and unsuitable for drinking. One well was classified as excellent, thirteen wells were good, two wells were poor, and one well was very poor, while sixteen were unsuitable for human drinking purposes, as shown in Fig. 15.

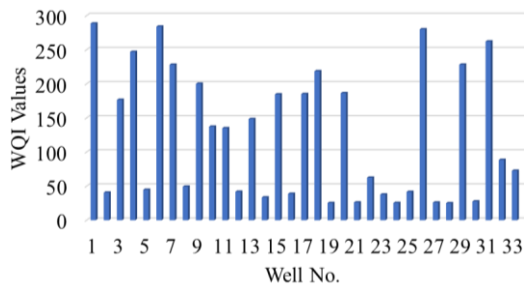


Fig.15 WQI drinking values in the Wells

Also, the classes of water quality in the study area according to the final map were 2% good, 9% poor, 35% very poor, and 54% unsuitable for drinking purposes, as shown in Fig. 16.

According to MWQI, the type of well water in the study area was classified into Moderate restrictions (MR), High restrictions (HR), and Severe restrictions (SR) for irrigation purposes. Six wells were classified as MR, twelve wells were SR, and fifteen wells were HR for the purposes of irrigation as shown in Fig. 17.

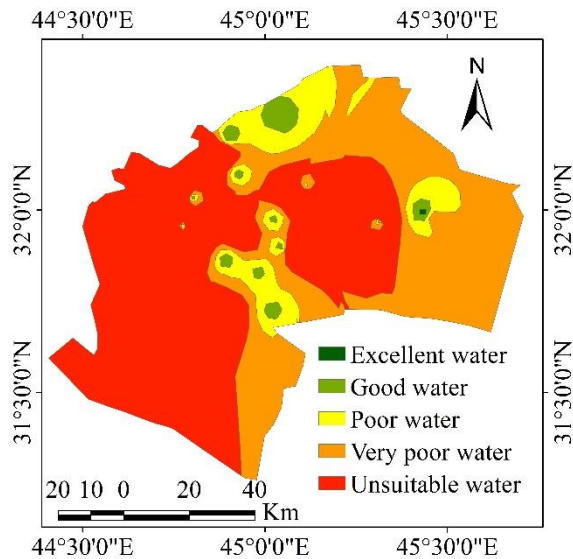


Fig.16 WQI drinking map of the Study Area

The final map showed that the distribution of the above classes in the study area was 10%, 14%, and

76% for MR, SR, and HR, respectively, as shown in Fig. 18.

The variation in these percentages can be observed in Fig. 16 and Fig. 18 when comparing the number of wells, due to the use of the Inverse Distance Weight (IDW) method, where a high value for a single well can affect the overall classification on the map.

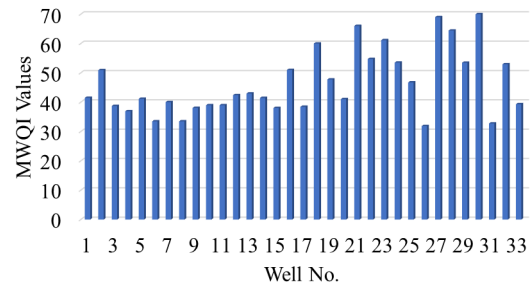


Fig.17 MWQI irrigation values in Wells of Al-Dewaniya

The MWQI states that, with the exception of water with very low HCO_3^- , Cl, and Na levels, the SR class can be used to irrigate the vegetation with high salinity tolerance, whereas the MR class can be used for vegetation with moderate salt tolerance. The HR class is utilized to irrigate plants with moderate to medium tolerance to salt using particular salinity treatment techniques. There was a small percentage of suitable water for human drinking purposes in the region.

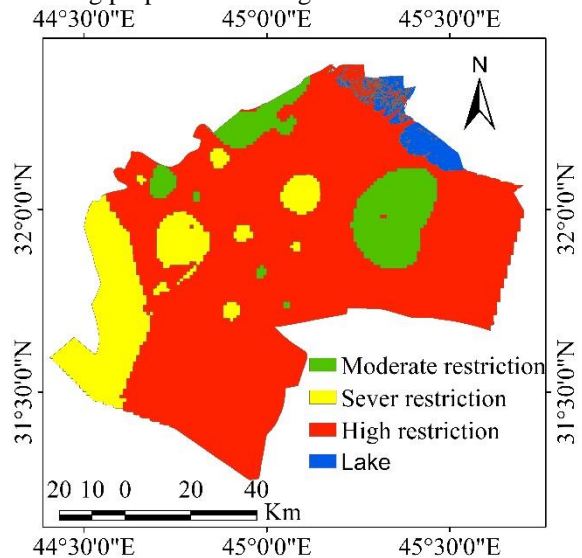


Fig.18 MWQI irrigation map of Al-Dewaniya

The high values of WQ parameters and exceeding the permissible limit of its standard values led to an effect on WQI values in the study area. Groundwater can be used to irrigation of plants in the region with special restrictions as mentioned

above and taking into account the following precautions and measures:

- Crop selection:

Moderate salt-tolerant crops can be grown in MR-class wells, including alfalfa, barley, and sorghum. In SR-class areas, salt-tolerant crops and trees such as date palms, cotton, and sugar beets can be grown. In HR-class areas, Salicornia can be grown as fodder for grazing animals, as this plant is known for its high salt tolerance and can be irrigated with highly saline well water.

- Leaching requirement:

To prevent salt accumulation, it is recommended to irrigate the land during rainy seasons to leach salts from the soil. It is also recommended to increase the water application rate by 10% to 25% during hot seasons to counteract evaporation.

- Drainage improvement:

Drainage channels should be added in highly saline areas, and subsurface drainage systems are preferable to prevent waterlogging and increased salt accumulation.

- Irrigation Method:

The common method of irrigation in Iraq is flood irrigation, which increases water consumption and waste. It is recommended to replace it with more modern methods such as sprinkler or drip irrigation, especially in areas with high and low salinity.

The results of this research showed that groundwater quality has deteriorated significantly, both for drinking water and irrigation. Some wells exhibited high TDS levels exceeding standard limits. These wells are located in the southern and central parts of the governorate and are affected by several factors, including geological factors such as the Dammam aquifer, which contains high concentrations of total dissolved solids (TDS), electrical conductivity (EC), sodium (Na^+), and chloride (Cl^-) ions. Another geological factor is the shallow groundwater level and evaporation enrichment. Well depths range from 5 to 45 meters, and they are subject to intense evaporation because temperatures in Diwaniyah Governorate exceed 45°C in the summer. A third geological factor is the low flow of the Euphrates River, which helps to mitigate the aforementioned high levels. The second factor is human activities that exacerbate the problem, including excessive reliance on well water due to the scarcity of surface water, which causes the rise of saltwater from deep layers, as well as the increase in agricultural drainage water and the use of fertilizers, which later seep into groundwater sources.

Generally, wells in the southern and western parts are in worse condition than those in the northern or eastern parts. This is due to the direction of flow in the area, where salts accumulate along the course, causing minerals to concentrate in the southern and western parts of the study area. Furthermore, the northern wells are located near the

Euphrates River and are sometimes subject to water reduction during certain water release and rainfall seasons.

This research was conducted using groundwater samples collected from 33 wells and focused on the major physicochemical parameters commonly applied in WAI and MWQI assessments. Although these parameters provide a reliable evaluation of groundwater suitability, the inclusion of additional indicators such as heavy metals, trace elements, microbiological parameters, and seasonal monitoring would provide a more comprehensive understanding of groundwater quality. In addition, the spatial distribution maps were developed using the IDW interpolation method, and the accuracy of the results is influenced by the number and distribution of available wells. Future research should investigate temporal variations in groundwater quality through long-term monitoring programs and evaluate the impacts of climate change, groundwater abstraction, and land-use changes on aquifer sustainability. The application of advanced geostatistical and machine-learning techniques may further improve groundwater quality prediction and spatial assessment in the region.

5. CONCLUSION

This study assessed the quality of groundwater for drinking and irrigation purposes in the Al-Diwaniyah Governorate of Iraq, considered the country's breadbasket. Samples were taken from 33 locations across the study area. The Arithmetic Weight Index (WAI) was used to measure drinking water quality, and the Merrill Lynch Water Quality Index (MWQI) was used to assess the quality of water suitable for agriculture. Geographic Information Systems (GIS) and IDW interpolation techniques were employed to determine the spatial distribution and calculate the areas of different zones and water types. The results of the study led to the following conclusions:

1- Drinking Water Quality:

The study revealed, using the IDW method, that only 2% of the water in the area was considered to have good drinking quality, while 54% was deemed unfit for drinking. All measured elements gave results that exceeded the limits of the standards, with the exception of pH and nitrate (NO_3^-), which were within the limits of the Iraqi standards. As for the highest deviations, they were recorded for total dissolved solids (TDS), electrical conductivity (EC), sodium ions (Na^+), and sulfates (SO_4^{2-}).

2- Irrigation Water Quality:

The results showed that the majority of the area falls within the High Restrictions (HR) category (76%) for irrigation water quality. This means that no type of crop can be grown; only crops with high salinity tolerance can be cultivated, provided that

specific management practices are followed. The results also showed that only (10%) of the area falls within the Medium Restrictions category, where crops with moderate salinity tolerance can be grown.

3- Causes of Poor Water Quality

There are many factors that have led to the decline in water quality, including natural factors such as the low depth of groundwater in wells, which ranges between 5 and 45 meters, as well as high evaporation rates due to the arid climate and high temperatures. Human factors have also contributed, including the decrease in the flow of the Euphrates River due to the construction of dams and reservoirs upstream, excessive groundwater extraction for various uses, and inadequate drainage infrastructure.

4- Limitation and Future Research

This research was conducted using groundwater samples collected from 33 wells and focused on the major physicochemical parameters commonly applied in WAI and MWQI assessments. Although these parameters provide a reliable evaluation of groundwater suitability, the inclusion of additional indicators such as heavy metals, trace elements, microbiological parameters, and seasonal monitoring would provide a more comprehensive understanding of groundwater quality. In addition, the spatial distribution maps were developed using the IDW interpolation method, and the accuracy of the results is influenced by the number and distribution of available wells. Future research should investigate temporal variations in groundwater quality through long-term monitoring programs and evaluate the impacts of climate change, groundwater abstraction, and land-use changes on aquifer sustainability. The application of advanced geostatistical and machine-learning techniques may further improve groundwater quality prediction and spatial assessment in the region.

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