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RESEARCH ARTICLE

Groundwater Resources in Muthanna Governorate, South of Iraq

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Abstract: Muthanna Governorate, located in southern Iraq, is the second-largest governorate in the country by area. The unconfined aquifer was studied by identifying the geological formations that form this aquifer. This research aims to use stratigraphic succession to establish geological correlations and identify formations that serve as groundwater aquifers. It also aims to identify and isolate the geological formations comprising the unconfined aquifer, as well as to assess its hydrogeological characteristics and groundwater hydrochemical properties. Geological maps of Muthanna Governorate and data from deep wells as well as fifty-nine drilled wells in the study area were used to prepare a series of geological sections. These sections provide valuable insights into the areas of each geological formation that contribute to the unconfined aquifer. Five main zones were identified, where the unconfined aquifer was sometimes considered an isolated geological formation (e.g., the Umm Er-Radhuma or Dammam formations) and sometimes consisted of a succession of two formations (e.g., the Euphrates and Dammam formations, or the Dammam and Umm Er-Radhuma formations). The results showed that the average hydraulic parameters—namely, thickness, total depth, transmissivity, and water table—were 68.7 meters, 151.5 meters, 133 m^2/day, and 162.6 meters above sea level, respectively. The groundwater salinity distribution map indicated several locations with high salinity values, which are attributed to the different lithologies forming the aquifer as well as the varied environmental depositional conditions of the geological formations that compose it. Additionally, the groundwater moves continuously from recharge areas toward discharge areas in three directions. Two primary salinity types were identified: calcium sulphate and sodium sulphate. The salinity, reflected by cation and anion concentrations, caused groundwater contamination in some areas of Muthanna's unconfined aquifer due to increasing concentrations. Consequently, five groundwater samples were suitable for human consumption, nine were appropriate for agricultural use, and forty-nine were suitable for animal use.

Keywords: groundwater resources, hydrogeology and hydrochemistry, Muthanna Governorate, South of Iraq

1 Introduction

Groundwater is one of the important components in the development of any area. Over two-thirds of the world's population depends on groundwater to meet their water needs. Demand is significantly higher in rural areas [1]. Groundwater quality depends on many. The quality is based upon the physical and chemical soluble parameters due to weathering from source rocks and anthropogenic activities [2, 3].

Located on Iraq's southern border with Saudi Arabia, Muthanna is Iraq's second largest governorate, but also the second least populated. Muthanna governorate has borders with Najaf, Qadissiya, Thi-Qar and Basrah governorates and an international border with Saudi-Arabia. Al-Muthanna Governorate is known for its agricultural areas and palm groves. The governorate is divided into four districts: Al-Samawah, Al-Khidhir, Al-Rumaitha and Al-Salman [4]. (see in Figure 1)

The climate of the area is characterized by arid to semiarid climatic conditions, having an average annual rain fall of 75-100 mm. The mean temperature varies from 12°C in winter season to 34°C in the summer season. The mean seasonal relative humidity is 60% in winter and 20% in summer and the mean annual is 35%. The mean annual amount of evaporation is 4000-4500 mm. The study area is classified as a hot, dry region, particularly in terms of expanding settlement and economic exploitation, based on agriculture and grazing. The water

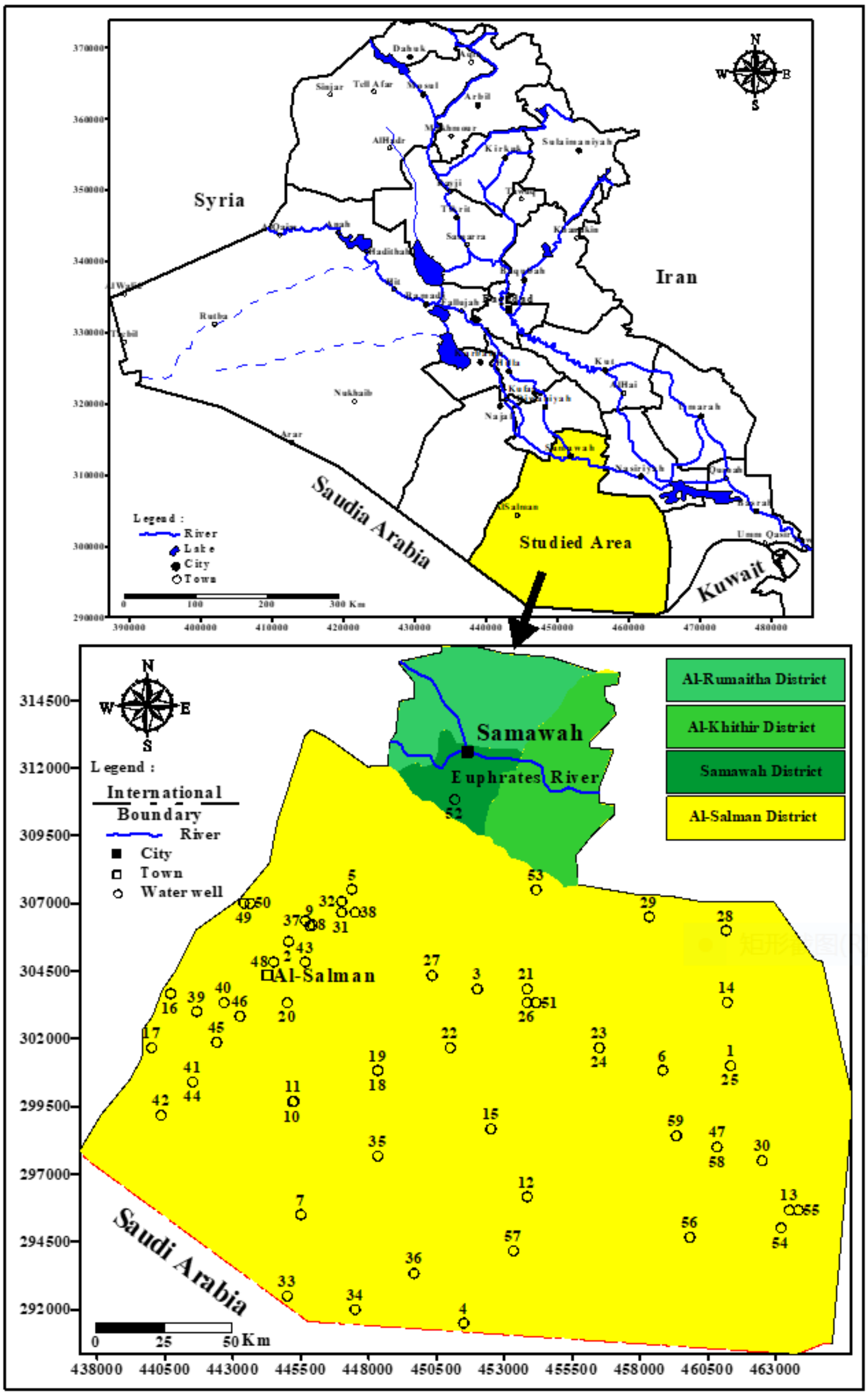

Figure 1 Location and water wells map in the studied area

sources can be divided into two types: surface and groundwater resources. As for groundwater resources, these contain water that is infiltrated from the surface through the fragile soil into the earth's crust formations, later to become a larger groundwater aquifer [5,6].

The Southern Desert represents a rolling and or undulating plain, which may be a flat or slightly rolling in some parts. The drainage system is internal, with most of the surface water percolating to underground through permeable strata, fractures, fissures and karst cavities. All valleys are intermittent draining either into marshes and sebkhas bordering the Euphrates River or are blind valleys [7].

The surface of Al-Muthanna desert is an extension of the surface of the western plateau of Iraq, which is characterized by its varying surface due to the different geological formations and the multiplicity of types of rock structures and their impact on climatic factors (weathering and erosion), as its surface is dominated by gradients from the southwest side towards the northeast [8].

Several geological formations are among the most significant aquifers in the study area due to their wide extent and high water content. They feature cavities, karstified canals, fractures, fissures, and joints, which confer high transmissivity and permeability. This study aims to:

(1) Utilizing stratigraphic succession to establish geological correlations and identify formations that serve as groundwater aquifers.

(2) Predicting the types of aquifers in the study area based on the boundaries of their geological formations.

(3) Isolating and identifying the geological formations that make up the unconfined aquifer.

(4) Creating a map showing the extent of the unconfined aquifer in the area.

(5) Assessing the hydrogeological characteristics and groundwater hydrochemical properties of the unconfined aquifer.

Given the vast area of Muthanna Governorate, it appears that there have been no comprehensive studies on the hydrogeological or hydrochemical evaluation of the groundwater aquifers. At the same time, several studies have been conducted across different parts of Muthanna Governorate. Table 1 shows a simplified overview of those studies and research:

Table 1 Studies across different parts of Muthanna Governorate

No.	Authors	Research title	Year
1	Abed et.al [9]	Study of Hydrology and Geomorphology of the Lake Sawa, Al-Muthanna Province, Iraq.	2022
2	Maaroof et.al. [5]	Geographical Assessment of Natural Resources at Abu-Hadair Drainage Basin in Al-Salman Desert, Southern Iraq.	2021
3	Al-Aajibi and Al-Jiashi [8]	Optimal Use of Natural Resources in Al-Muthanna Desert (Soil as A model).	2021
4	Al-Sheikh & AL-Shamma'a [10]	Hydrochemical of Groundwater for Al Dammam unconfined Aquifer within Al-Salman Basin, Al-Muthana Governorate, South West Iraq.	2019
5	Al-Sudani, H.I.Z. [6]	Groundwater system of Dibdibba sandstone aquifer in south of Iraq	2019
6	Al-Sudani, H.I.Z. [11]	Salinity Pollution of Groundwater in South of Iraq	2019
7	Al-Dabbas et.al. [12]	Groundwater Quality Investigation of the Dammam Unconfined Aquifer, Umaid Area-Muthanna Governorate - Iraq.	2014
8	Al-Sudani et.al [13]	Hydrogeology of aquifers in the western Desert-West and South of Euphrates River.	2001
9	Al-Shamaa, A.M [14]	Hydrogological and tectonic investigation of the southern part of the Western Desert (Qasra-Shbicha area).	1993

2 Description of studied area

The landscape of Muthanna governorate is dominated by desert, with natural water sources confined to the northern areas around the Euphrates River. The capital, Samawah, lies near the site of the ancient city of Uruk, which dates back to the 4^{th} millennium BC. Uruk was one of the world's first major cities, and is the source of the oldest known script. It is located approximately 277 kilometers south of the capital, Baghdad, and covering (51,740) km^2 (11.9% of Iraqi surface area). The current population is close to one million people [4]. The topography of the map area rises gradually from the northeast towards the southwest. The attitude of the Lowest point is about 100 m (above sea level), whereas the highest one reaches up to 485 (m.a.s.l.) near the Iraqi-Saudi Arabian borders. Local topographic elevations and depressions are also common [5, 6].

Geologically, the area is a part of the Southern Desert which is generally, a flat rocky terrain associated with structural ridges and isolated hills and karts depressions. It is structurally lies within the eastern part of the Stable Shelf of Nubio-Arabian Platform. The exposed rocks in the area belong to Paleocene, Miocene, Pliocene-Pleistocene and Quaternary ages [6, 13, 15–18]. (Figure 2)

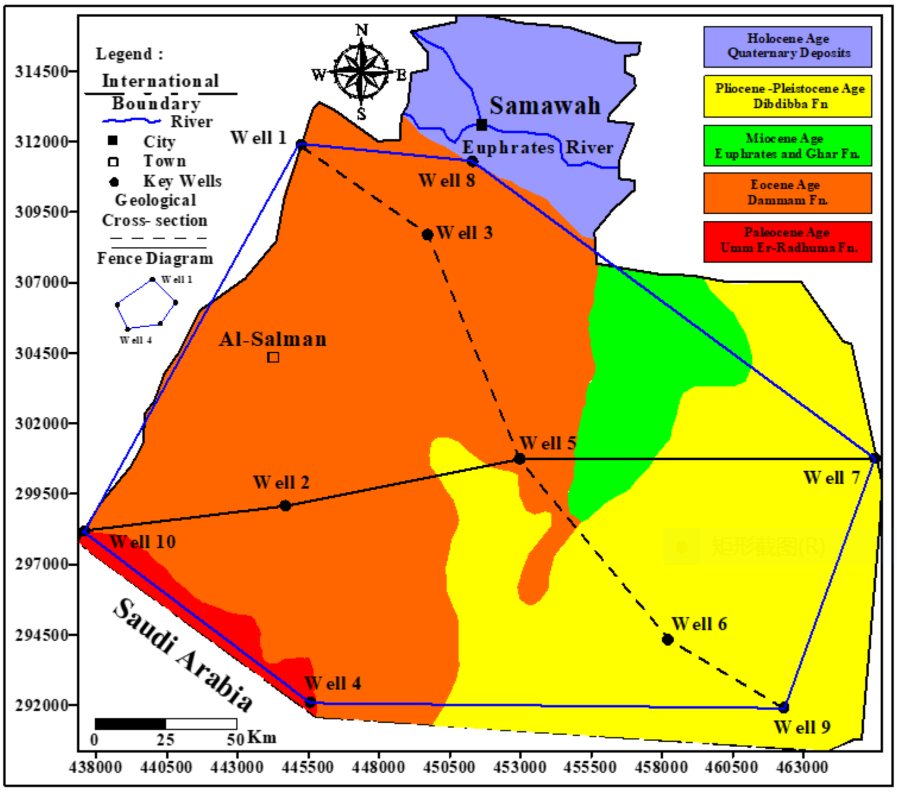

Figure 2 Geology and geological cross sections map of the studied area modified and prepared by Author

2.1 Umm Er-Radhuma Formation (Upper Paleocene)

It composed of recrystallized shelly fine crystalline dolomite limestone, which are locally fractured. The thickness of the formation varies reaching 40 meters. The environment of formation deposition is open marine platform of tropical-subtropical areas ranging from inner shelf zone to central shelf.

2.2 Dammam Formation (Eocene)

It occupies most parts of the area. It is composed of interbedded layers of limestone (100 m.) and breccias or conglomerate (1-3 m.), limestone, marly dolostone and fossiliferous dolostone (30 m.) with yellow limestone (40 m.) and shelly, dolomite burrowed limestone (35 m.) with recrystallized limestone and thin horizons of chalky to marly limestone (10 m.) The Environment of formation deposition is normal marine condition in tropical to subtropical conditions [15, 17].

2.3 Euphrates Formation (Lower Miocene)

The Euphrates formation is characterized either by 2-3 meters thick claystone, with highly fossiliferous limestone and sandy limestone. The thickness of this formation does not exceed 10 meters. The Environment of formation deposition is shallow marine environment of tropical subtropical areas.

2.4 Ghar Formation (Lower Miocene)

The Ghar formation is locally exposed as isolated patches in the northeastern part of the area. It is composed of 2-3 meters basal breccias or red claystone , then followed upwards by alternation of pebbly sandstone, calcareous sandstone and sandy limestone. The thickness of Ghar formation is 10 meters. The Environment of formation deposition indicates transitional environment from marine to continental conditions.

2.5 Zahra Formation (Pliocene -Pleistocene)

The Zahra formation is characterized by one to three cycles. Each cycle is composed of alternation of claystone and limestone or claystone, sandstone and limestone. The thickness of this formation varies from 12-20 meters. The Zahra Formation indicates fresh water fluviatile environment [15, 18].

2.6 Dibdibba Formation (Pliocene-Pleistocene)

The formation composed of sandstones and gravelly sandstone. The gravels are mainly of pebble size. They are of igneous and metamorphic origin with (15 m) thickness. The depositional environment of this formation is fresh water continental sediments [6, 11, 18].

2.7 Quaternary Deposits

(1) Slope deposits (Pleistocene/Holocene): They consist of mixture of fine elastics and rock fragments. The rock fragments decrease in size and amount down the slopes.

(2) Marsh deposits (Holocene): The deposits were developed within the flood plain area of Euphrates river, in the extreme northeastern part of the area. They are composed of clayey silt, silty clay and with occasional sands. The thickness is more than 3.0 m. Marsh deposits was considered as mature stage of lacustrine sediments.

(3) Valley fill deposits (Holocene): They consist of fine elastics or sandy and silty gravels in the main- and deep valleys. Generally the thickness of these deposits does not exceed one meter.

(4) Depression fill deposits (Holocene): The depression fill deposits are generally fine elastics, where calcareous silty clay or loam are more dominant. The thickness of these deposits depends mostly on the size and depth of the depression. The thickness of the depression fill reaches few meters.

(5) Flood plain deposits (Holocene): Lithologically, the deposits are composed of fine clastic deposits i.e. silt, sand and day. These components are mixed together by different proportions.

(6) Aeolian deposits (Holocene): The Aeolian deposits are scattered as small nebkhas or very thin sheet mostly accumulate in the dry wadies or depressions. Two Aeolian accumulations, as sand sheet are recognized in the western part of the map area. They are generally composed of loose fine sand and silt.

(7) Sand dune deposits (Holocene-Recent): They are of irregular shape and size. They consist of yellowish light brown sand.

(8) Sand sheet deposits (Holocene-Recent): The deposits are totally composed of sand, mixed with silt, gypsum content is highly variable. The environment is Aeolian. The environment of quaternary deposition is continental [16].

3 Materials and Methodology

The materials used in this study were:
(1) Topographic and geological maps at a scale of 1:250000.
(2) Using deep well data (Key wells), depending on previous studies conducted in the area of study [13].
(3) Using fifty-nine drilling wells and their stratigraphic sheets, as well as literature reviews, scientific references, and the hydrogeological data bank [19].
(4) Mathematical programs (Surfer, Grapher, and Excel) were used to analyze the data and information obtained and draw all types of maps.

To achieve the study's objective, previous studies were utilized to predict, isolate, and determine the type and geological formation that form the unconfined aquifer in the area. These studies provided very valuable information through deep well data (Key wells) and their distribution in the area, covering the entire Muthanna Governorate. The primary purpose of using these key wells was to draw geological sections (fence and two cross-sections) through which the geological layers were compared in each key well with respect to the geological formations' exposures on the surface. The final geological correlation was done, which was used to track the extension and distribution of the unconfined aquifer all over the study area and to evaluate the thickness and depth of the unconfined aquifer. These geological cross-sections identified the zones where different geological formations formed the unconfined aquifer, as will be discussed later. The available stratigraphic columns and groundwater levels of fifty-nine drilled wells were also utilized in this study. These wells were studied carefully after comparing their stable and dynamic groundwater levels with their stratigraphic sections, which provides a suitable distribution of wells map in the area. These wells were used to determine the hydrogeological characteristics of the unconfined aquifer and groundwater hydrochemical properties, depending on groundwater sampling. The groundwater sampling was used for hydrochemical analysis to obtain the physical and chemical properties of groundwater. The analyzed hydrochemical parameters, such as pH, electrical conductivity, total dissolved solids, and cations and anions, are used to describe groundwater quality and suitability for various purposes. The chemical analysis was done in the General Commission of Groundwater Laboratories, Ministry of Water Resources.

4 Rustles and Discussion

4.1 Unconfined Aquifer Determination

The compiled geological maps of Muthanna Governorate and deep (key) wells obtained from available sources, in addition to the fifty-nine drilled wells information distributed in the area of study, were used to prepare a set of geological sections. The paths of these sections are shown in Figure 2. The primary purpose of preparing these geological sections, whether transverse, longitudinal, or fence diagram, is to trace the horizontal and vertical extension of geological formations throughout the study area. These sections will play an important role in identifying unconfined aquifers, whose groundwater is heavily relied upon in the region. The geological sections, along with information from geological maps and drilled wells, will provide a significant opportunity to identify the areas of each geological formation that form the unconfined aquifer, whether it is an isolated formation or multiple or interbedded formations. The hydraulic characteristics and hydrochemical properties of the water-bearing layers will vary depending on the nature of the geological formations forming this aquifer.

Table 2 presents the key wells data used in geological cross-sections that facilitated the preparation of geological sections. These sections are shown in Figure 3-5. The distribution of the zones of the unconfined aquifer in Muthanna Governorate was drawn, as shown in Figure 6. This map reflects the five main zones, where the aquifer is sometimes characterized as being formed by an isolated formation, as is the case with Umm Er-Radhuma or Dammam formation, and sometimes it is formed by a succession of two formations, as is the case with the Euphrates and Dammam formations or the Dammam and Umm Er-Radhuma formations.

Table 2 Key wells data used in drawing Geological cross-sections

Well No.	Longitude Coordinates	Latitude Coordinates	Total Depth (m.)	Top Elevation (m.)	Geological Formation
1	445280	311901	180	130	Dammam + Rus
2	444667	299104	775	322	Dammam + Umm Er-Radhuma + Tayarat
3	449723	308709	530	110	Dammam + Rus + Umm Er-Radhuma + Tayarat
4	445543	292078	630	356.5	Umm Er-Radhuma + Tayarat
5	452942	300700	560	224.3	Dammam + Umm Er-Radhuma
6	458185	294341	200	248.5	Dibdibba + Dammam + Umm Er-Radhuma
7	465504	300727	500	106.7	Dibdibba + Ghar/Euphrates + Dammam + Umm Er-Radhuma
8	451266	311341	700	48.5	Dammam + Rus + Umm Er-Radhuma + Tayarat
9	462311	291945	660	313.5	Dibdibba + Dammam + Rus + Umm Er-Radhuma
10	437588	298170	645	415	Umm Er-Radhuma + Tayarat

The geological maps of the studied area show wide exposure of the Dibdibba and Dammam formations, followed by limited exposure of Umm Er-Radhuma and Euphrates formations in the southwest and northeast, respectively, while the Quaternary deposits are exposed in the north of the study area. The unconfined aquifer is composed either of the Dammam formation only when it is exposed in the northwestern part of the studied area, or in succession with the Umm Er-Radhuma formation in the central and western parts of the area. On the other hand, the Dammam formation formed the unconfined aquifer, either when it is underlying the Dibdibba formation in the southern and southeastern part of the studied area, although the wide exposure of the Dibdibba formation, which is characterized as a dry formation, or when the Euphrates formation is exposed overlying the Dammam formation, where both formations forming the unconfined aquifer in the northeastern part of the study area. The Umm Er-Radhuma formation mainly forms the unconfined aquifer in the area where it is exposed on the surface in the southwestern part of the area.

4.2 Hydrogeological Characteristics of Unconfined Aquifer

The main aim of groundwater studies is to assess the physical and chemical characterizations of water-bearing layers as a goal for assessing their suitability for various purposes. The

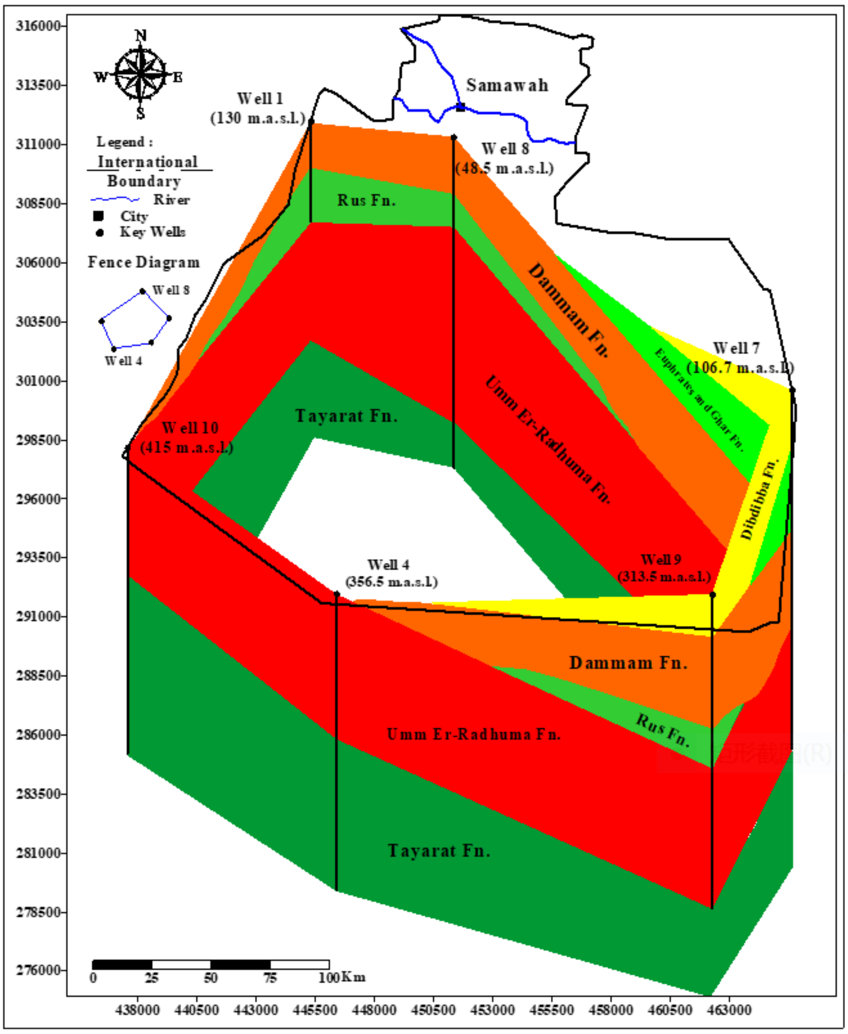

Figure 3 Fence diagram of the geological formations distributed in the area

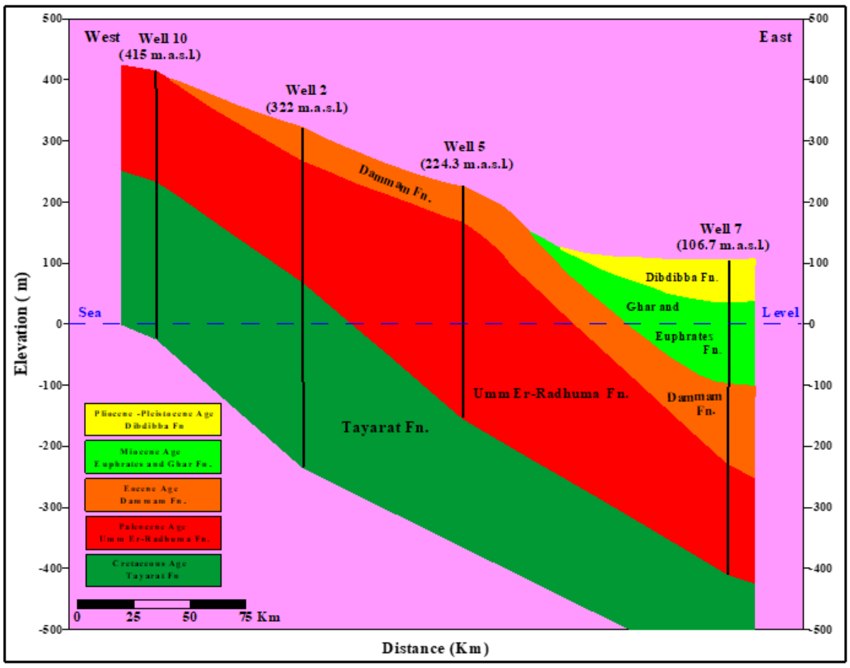

Figure 4 Lateral geological cross-section prepared in the area of study

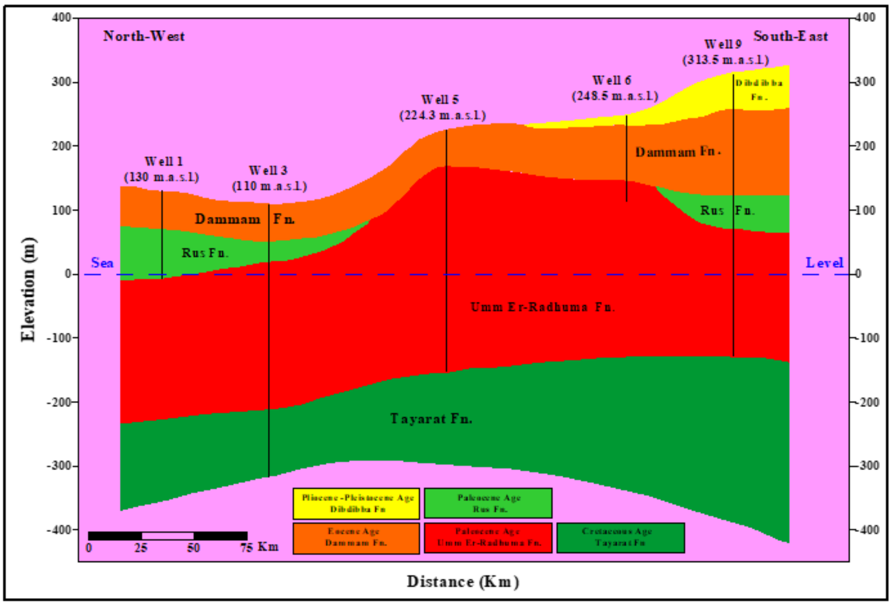

Figure 5 Vertical geological cross-section prepared in the area of study

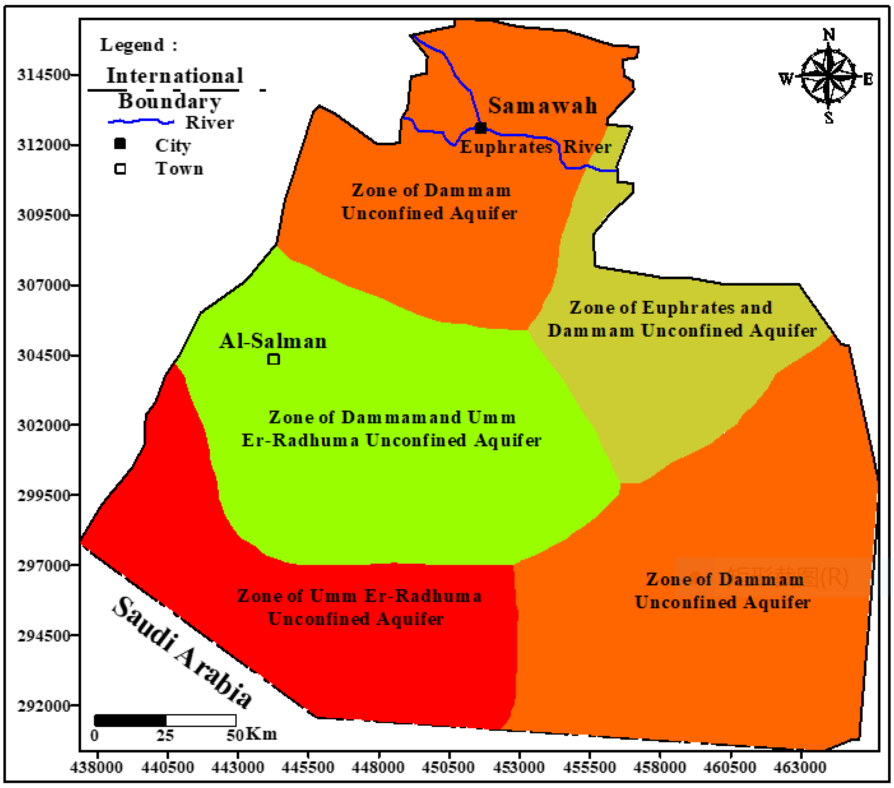

Figure 6 Map of unconfined aquifer zones in the studied area

lithology that forms the unconfined aquifer, as previously described, consists of three main geological formations: Umm Er-Radhuma, Dammam, and Euphrates. These formations consist of crystalline dolomite, fractured limestone, marly dolostone, and sandy limestone. Table 3 shows of the hydrogeological characteristics the unconfined aquifer depend on the fifty-nine drilling wells found in the area of study. The mean of the main parameters of thickness, total depth, transimissivity and water table were (68.7 m), (151.5 m), (133 m^2/day) and (162.6 m.a.s.l), respectively.

Table 3 Hydrogeological characteristics of unconfined aquifer

Parameters	No. of values	Minimum	Maximum	Mean
Elevation (m)	39	30	380	226.9
Static water level (m)	59	3	209.5	71.71
Dynamic water level (m)	59	5	218.1	85.22
Water Table (m.a.s.l.)	38	16.1	300	162.6
Total depth (m)	56	70	326	151.5
Depth to water (m)	59	2	251	77.93
Thickness (m)	59	15	156	68.7
Maximum yield (m^3/day)	59	98	1518	457.6
Transmissivity (m^2/day)	59	6	712	133

The distributions of hydraulic parameters of thickness, total depth, transmissivity, and groundwater flow net in the unconfined aquifer are shown in Figure 7 (A, B, C, D), respectively. The distribution of both thickness and total depth has a symmetrical pattern across the unconfined aquifer. The mean thickness and total depth of the aquifer reached 70 and 150 meters, respectively, while these two parameters increased significantly in the southeastern area, reaching 100 and 225 meters.

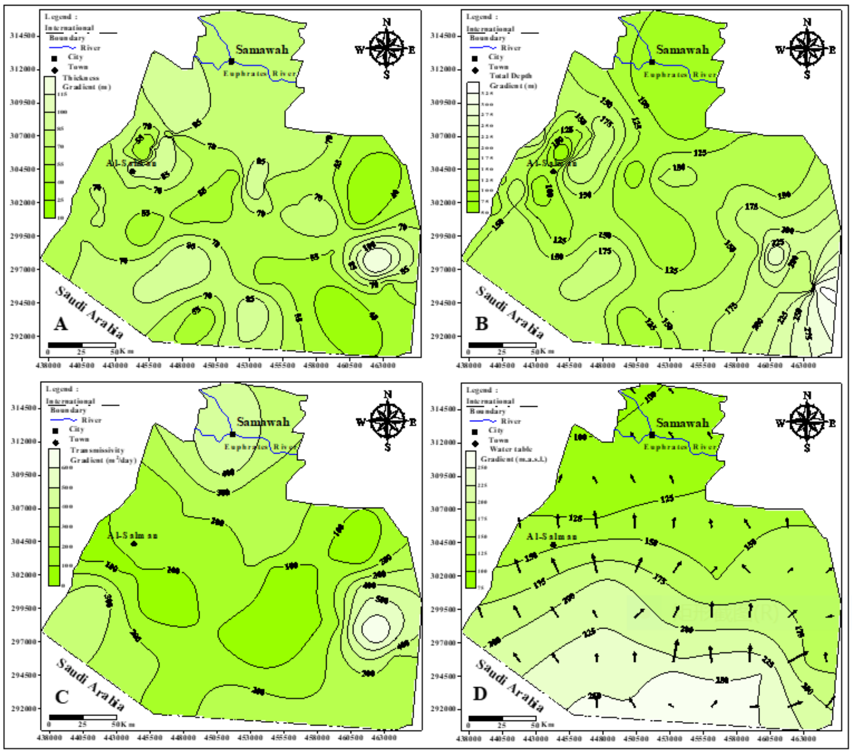

Figure 7 The combined hydraulics parameters (A: Thickness, B: Total depth, C: Transimissivity, D: Groundwater flow net) of unconfined aquifer in the area.

The increased values of these parameters are located where Dammam formation forms the unconfined aquifer beneath the Dibdibba formation. The economic aspect affects well-drilling activities, as the beneficiaries depend on the shallowest depths to access groundwater for various purposes. Therefore, it seems that both penetrated thickness and total depth in the unconfined aquifer have similarly distributed values across the area of study, since the lowest drilling costs are enough to extract groundwater effectively. While these beneficiaries seek a suitable and satisfying depth and thickness of the water-bearing layer to exploit it adequately.

On the other hand, the transmissivity exhibited a variety of values across the study area, with increased values in two locations: the northwestern and the southeastern parts, reaching between 400 and 500 square meters per day, respectively. The aquifer in these two locations consists of Dammam formation only. In the southeastern part, the increasing values of transmissivity have a similar behavior to increased values of thickness and total depth. In the other sites of the studied area, the mean transmissivity reached 150 square meters per day. This hydraulic parameter varied in the area of study due to the strong effect of fractures and cavities in carbonate rocks that form the aquifer lithology. Therefore, the distribution of these fractures and cavities was irregularly distributed within the unconfined aquifer, which affects the values of the results obtained [20, 21]. It seems that when Dammam formation forms the unconfined aquifer in both zones, as shown in Figure 6, the transmissivity was highly valued as mentioned before, which means that the formation has a regular zone of high cavities, karstified canals, and fractures, which qualifies the aquifer in these two locations for a high quantity of groundwater transmitting and storage.

The geological conditions, especially the topographical gradient, are crucial in controlling the movement of groundwater from recharge areas to discharge areas [22]. In groundwater hydraulics, the water pressure surface and the water table elevation are called the hydraulic head. Hydraulic head drives groundwater movement. Groundwater always moves downhill along the hydraulic head gradient. The hydraulic gradient is often, but not always, similar to that of the land surface [1]. Groundwater movement in unconfined aquifers depends on the slope of the land. Typically, groundwater flows from higher elevations in the southern part of the study area toward three directions: north, northwest, and northeast. A key feature of the geological formations and their aquifers in the southern desert region of Iraq is the hydraulic connection among geological formations layers, allowing groundwater to flow from deeper to shallower aquifers through these connections [13, 28]. Some sources also suggest that groundwater may flow from transboundary aquifers in Saudi Arabia into Iraqi territory [13].

4.3 Hydrochemical Properties of Unconfined Aquifer

Several factors influence the variation in groundwater recharge sources and ionic exchange activities that directly affect groundwater salinity. The main factors include recharge, rock type, aquifer depth, and the pathway of groundwater movement [23]. While groundwater quality depends on numerous factors such as geology, source water quality, land use type, and the composition of recharge water, it also involves interactions between water and soil, residence time, and reactions within the aquifer [24–26].

Hydrochemical data of groundwater properties are presented in Table 4. Fifty-nine samples were analyzed to determine the physicochemical parameters. The results for pH, electrical conductivity (EC), and total dissolved solids (TDS) showed variation, indicated by their minimum and maximum values. The pH ranged from 7 to 8.5, EC from 617 to 8808 μmhos/cm, and TDS from 365 to 7536 mg/l. According to references, the groundwater of unconfined aquifers is brackish to saline when TDS exceeds 1000 mg/l [27].

Table 4 Groundwater hydrochemical properties in the unconfined aquifer

Parameters	No. of values	Minimum	Maximum	Mean
PH	25	7	8.5	7.77
EC (mcomh/cm)	59	617	8808	4713
TDS (PPM)	59	365	7536	3696
Ca (PPM)	59	54	760	461
Ca (EPM)	59	2.7	38	23.047
Mg (PPM)	59	25	400	176
Mg (EPM)	59	2.08	33.33	14.64
Na (PPM)	59	37	1390	527.5
Na (EPM)	59	1.60	60.43	22.93
HCO_3 (PPM)	58	12	300	156.3
HCO_3 (EPM)	58	0.38	9.67	5.04
SO_4 (PPM)	59	68	3240	1617.5
SO_4 (EPM)	59	1.41	67.5	33.69
Cl (PPM)	59	31	1899	750.6
Cl (EPM)	59	0.87	53.5	21.14
NO_3 (PPM)	38	1	255	68
NO_3 (EPM)	38	0.016	4.11	1.09
SAR	56	0.49	12.85	5.28
Na %	55	5.36	57.31	34.74

Figure 8 shows the groundwater salinity distribution map of the unconfined aquifer in the study area, where the lowest salinity concentration was recorded in the central and southern parts. The map showed several locations where high values of groundwater salinity were recorded due to the different types of lithology forming the aquifer, as previously discussed, along with varying environmental depositions of geological formations that make up this aquifer, as well as the continuous movement of groundwater away from the recharge area toward the discharge area in three directions. All these reasons contribute to an increase in salinity concentration in some locations due to ongoing ion exchange activities.

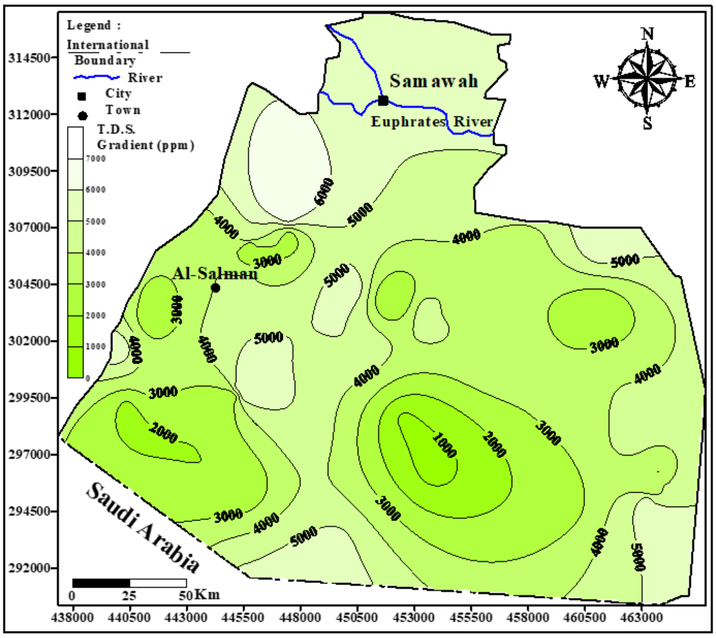

Figure 8 Groundwater salinity (TDS) map of the unconfined aquifer in the area

4.4 Groundwater Origin and Types

According to the Kurlov formula [29–31], which depends on the positive and negative ionic concentrations measured in epm%, the groundwater quality can be determined. The groundwater in the study area was characterized as moderately brackish to saline (TDS>1000 mg/l), as mentioned previously, while the origin of groundwater was marine as a result of its presence in the marine environmental geological formation deposition. Table 5 shows the origin of groundwater in the studied area, while Table 6 shows the percentage of each water type of groundwater in the unconfined aquifer.

Table 5 Groundwater types of groundwater of the unconfined aquifers

Statistics	r(Na) epm	r(Ca) epm	r(Mg) epm	r(SO_4) epm	r(Cl) epm	r(HCO_3) epm	Kurlov Formula	Sum of wells
Minimum	2	6.85	2.08	6.37	0.87	2.35		
Maximum	26	32	20.75	51.29	25.01	8.26	Ca-Sulphate	29
Mean	13.84	23.67	12.75	32.75	12.97	4.97		
Minimum	24	22.2	9.08	32.77	20	0.387		
Maximum	60.43	38	30.41	67.5	52	8.06	Na- Sulphate	14
Mean	38.59	27.46	17	43.97	34.6	4.05		
Minimum	28	22	7.66	14.35	32	3.83		
Maximum	54	36	24.16	42.5	53.49	8.48	Na-Chloride	7
Mean	42.8	26.96	17.96	32.8	40.62	5.24		
Minimum	3.08	6.8	7.33	8.54	3.49	4.71		
Maximum	28	30.4	33.33	57.3	25.5	7.09	Mg- Sulphate	5
Mean	12.52	13.28	21.38	31.56	11.24	5.64		
Minimum	1.60	3	2.08	1.41	1.01	8.87		
Maximum	1.78	6	5.25	5.8	1.80	9.67	Ca-Bicarbonate	2
Mean	1.69	4.5	3.66	3.60	1.40	9.27		
	3.82	2.7	2.41	1.89	1.40	8.16	Na-Bicarbonate	1

Table 6 Percentage of groundwater types in the unconfined aquifers

Groundwater Types	Samples Accounts	Percentage (%)
$CaSO_4$	29	50
Na_2SO_4	14	24.13
$NaCl_2$	7	12.06
Mg_2SO_4	5	8.62
$CaHCO_3$	2	3.44
$NaHCO_3$	1	1.72
Total	58	99.97%

The two major types were obtained, with 50% and 24% of the groundwater types recorded as calcium and sodium sulphate, respectively. The bicarbonate groundwater types were about 1.7% which reflects a very limited ratio of groundwater recharge due to the climate situation in the area and low precipitation recorded in the area.

4.5 Groundwater Utilization

The 59 analyzed groundwater samples, as shown in Table 7, indicated that only five samples of groundwater could be used for human purpose, nine samples are qualified to be used in agriculture, while forty nine samples indicate to be used for animal purposes. Salinity reflected by cations and anions caused groundwater contamination in some areas of the unconfined aquifer in Muthanna governorate due to increasing concentrations.

Table 7 The utilization of groundwater in unconfined aquifer

Parameter	PH	E.C. (μmoh/cm)	TDS (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	SO_4 (mg/l)	NO_3 (mg/l)	SAR	Utilization
Number of samples	25	59	59	59	59	59	59	58	59	38	56	
Minimum	7	617	365	54	25	37	31	12	68	1	0.49	
Maximum	8.5	8808	7536	760	400	1390	1899	300	3240	255	12.85	
WHO (2011) [32]	6.5-8.5	-	1000	75	125	200	250	200	250	50	-	For Human
IQS [33]		-	1000	50	50	200	250	200	250	50	-	
Standard FAO/1989 [34]	-	-	2000	40	5	20	30	10	20	-	15	For Irrigation
Standard FAO/1989 Poultry + Livestock [34]	-	5000	-	-	250	-	-	-	-	100	-	For Animal

5 Conclusions

The geological sections that were prepared using geological maps of Muthanna Governorate and deep wells with fifty-nine drilled wells, reflect the five main zones of unconfined aquifer locations. The unconfined aquifer is sometimes characterized as an isolated formation (Umm Er-Radhuma or Dammam formation), or sometimes formed by a succession of two formations (Euphrates and Dammam formations or the Dammam and Umm Er-Radhuma formations).

The Dammam formation was considered the most geological formation forming the unconfined aquifer in a vast region. This formation, as an isolated formation, forms the aquifer in two different zones, the southeastern and northwestern parts of the studied area. Both Dammam and Umm Er-Radhuma formations, Dammam and Euphrates formations, gathered to form the unconfined aquifer in other two zones, the central and western parts, and the northeastern one, respectively. The Umm Er-Radhuma formation mainly forms the unconfined aquifer in the area where this formation is exposed on the surface in the southwestern part of the area.

The hydrogeological characteristics of the aquifer related to several hydraulic parameters showed that both thickness and total depth have a symmetrical pattern across the unconfined aquifer. The mean thickness and total depth of the aquifer reached 70 and 150 meters, respectively, while these two parameters increased significantly in the southeastern area, reaching 100 and 225 meters. The other important parameter was the transmissivity, which exhibited a variety of values across the study area, with increased values in two locations: the northwestern and the southeastern parts, reaching between 400 and 500 square meters per day, respectively. Groundwater movement in unconfined aquifers depends on the slope of the land. Typically, groundwater flows from higher elevations in the southern part of the study area toward three directions: north, northwest, and northeast.

Hydrochemical data of groundwater properties showed that the pH ranged from 7 to 8.5, EC from 617 to 8808 μmhos/cm, and TDS from 365 to 7536 mg/l. The groundwater of unconfined aquifers is brackish to saline. Groundwater salinity distribution map showed several locations where high values were recorded due to the different types of lithology forming the aquifer and the continuous movement of groundwater away from the recharge area toward the discharge area in three directions. Two major types were obtained, where calcium sulphate and sodium sulphate were recorded. Salinity reflected by cations and anions caused groundwater contamination in some areas of the unconfined aquifer in Muthanna governorate due to increasing concentrations. Thus, five samples of groundwater could be used for human purposes, nine samples are qualified to be used in agriculture, while forty-nine samples are indicated to be used for animal purposes.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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