RESEARCH ARTICLE

Assessment of Groundwater Resources and Hydro-Geochemical Characteristics of Mandali Basin – East Iraq

Hussein Ilaibi Zamil Al-Sudani

Environmental Research Center, University of Technology-Iraq, Baghdad, Iraq

Correspondence to: Hussein Ilaibi Zamil Al-Sudani, Environmental Research Center, University of Technology-Iraq, Baghdad, Iraq;
Email: dr.hussein_alsudani@yahoo.com

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Abstract: Groundwater is an essential natural water resource that supplies the population for various domestic, agricultural, and industrial uses. Mandali Basin, located in Diyala Governorate, in the eastern side of Iraq, was investigated during the fieldwork in 2024. The results showed that the unconfined aquifer consists of interbedded of Bai Hassan formation and Quaternary deposits. The average thickness of this aquifer was 46 meters, while the average water permeability (transmissivity) was 112 square meters/day, with 655 cubic meters/day of maximum yields. The direction of groundwater movement begins from the north-eastern part towards the south-western part in the studied area. The distribution map of salinity of groundwater demonstrates increasing values on the western side of the area. The physical and chemical parameters indicate a continental origin of the groundwater, as it is brackish to saline water. The calcium sulfate was the dominant groundwater type. The groundwater is mainly useful for livestock and irrigation purposes, while some samples indicate its use for human benefits. The area between Mandali and Qazaniya towns reflects a qualified location to increase well drilling, where the aquifer thickness, transmissivity, and maximum yields increase, while salinity decreases.

Keywords: groundwater resources assessment, hydro-geochemical characteristics Mandali, East Iraq

1 Introduction

Hydrogeology is the study of groundwater hydrology. Groundwater is an important component of the hydrological cycle and a significant water source for most of the world's population. Over two-thirds of the world's population depends on groundwater to meet their water needs. Demand is significantly higher in rural areas, where it is even higher [1]. The Mandali Basin, which extends along the Iraqi-Iranian border, situated in Diyala Governorate in the eastern side of Iraq, was investigated to assess the hydrogeological and hydrochemical characteristics, evaluate the hydraulic parameters, as well as determine the groundwater aquifer quality and utilization in the basin. The geographical location of the studied area lies between longitudes 45° 25' 00" – 45° 45' 00" and latitudes 33° 35' 00" – 33° 55' 00", as illustrated in Figure 1, which shows the geological and topographic map and the locations of groundwater wells. The area covers approximately 500 square kilometres. According to the Climate Atlas of Iraq (1951-2022), the climate of the region is characterized by an average annual temperature ranging between 22 and 24°C, an average annual relative humidity of 45%, an aridity index of 20, an average annual evaporation of 3,500 and 4,000 mm, and an average annual rainfall of 200 and 300 mm [2, 3]. This research aims to evaluate the groundwater resources in the study area based on available information and exploitation requirements from theoretical and scientific perspectives, in addition to field studies. The study area is vital, being an agricultural area that depends primarily and directly on groundwater for long periods of the year, and to a lesser extent on rainfall in the winter. In addition, it is a good poultry and grazing area with high and significant investment from an economic point of view.

The work plan in the study area included two main parts during 2023-2024. The first part was the office work, which included collecting all available information and data about the area (maps, water wells, stratigraphic columns), in addition to scientific references and data from the hydrogeological data bank. The second part included field work to inventory drilled and operating water wells in the study area, to determine their geographical locations, stable water levels, and all other hydrogeological information, in addition to collecting water samples from

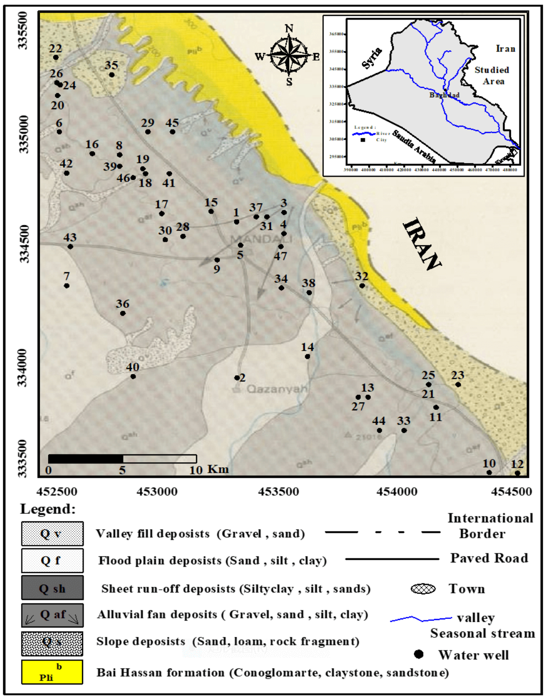

Figure 1 Geological, topographic and water wells locations map in the studied area modified after Barwary [9]

47 wells that can be used in hydrochemical analysis to obtain physicochemical characteristics of groundwater.

The Diyala governorate is served by several studies regarding the hydrogeological, water balance, morphometric, and groundwater quality investigations and studies. All these studies emphasize evaluating or estimating the hydrological and geochemical properties or the suitability of the groundwater for any purposes in the area of study. Some of this research is dated as follows:

(1) Al-Neamy (2012) studied the hydromorfomatric of Mandli Basin East of Iraq [4];

(2) Al-Sudani (2017) studied the hydraulic parameters of groundwater aquifers in the Khanaqin Basin [5];

(3) Al-Sudani (2018) studied the hydrochemical evaluation and utilization of groundwater in Khanaqin area, Diyala governorate, east of Iraq [6];

(4) Rahi et al. (2019) studied the assessment of surface water resources of Eastern Iraq [7];

(5) Alkilab et al. (2021) studied the water quality evaluation of selected springs in Qazania area, Diala governorate [8];

(6) Al-Sudani et al. (2018) studied the groundwater system of Khanaqin Basin in Diyala governorate - East of Iraq [2];

(7) Al-Sudani (2018) studied the morphometric properties and water balance using Thornthwaite method in Khanaqin Basin, East of Iraq [3].

2 Geology of the Area

The geological map indicates that the Quaternary sediments are widely distributed, reaching 90%, while the older rocks of Bai Hassan formation belong to the Miocene and Pliocene periods. The tectonic and structural setting of the study area is divided into two main parts: the eastern central part of the Mesopotamian zone and the south-western part of the Foothill zone (Makhul Sub Zone). These two parts represent the outer and central units of the unstable shelf of the Arabian Nubia region. It has been observed that the region was generally affected by the intense late regional tectonic movements, which caused the uplifting of the Hemrin structure in the Foothill zone while an asymmetric syncline developed in the Mesopotamian region [9].

2.1 Bai Hassan Formation (Pliocene)

The formation is exposed in the northeast part of the map area. It is composed of conglomerate, claystone, and some sandstone. The thickness is 300-1900m. The upper contact is erosional with different types of Quaternary deposits. The environment of deposition is continental and fluvial.

2.2 Quaternary Deposits

2.2.1 Alluvial Fan Deposits (Pleistocene–Holocene)

Alluvial fans form a continuous belt in the southwestern limb of the Hemrin structure. These poorly sorted deposits consist of gravels, cobbles, and boulders with minor losses of sand, silt, and clay deposits. Stratigraphically, the fan deposits lie uncomfortably over the pre-quaternary formations.

2.2.2 Slope deposits (Pleistocene-Holocene)

These deposits are usually developed on the foothill slopes, often covering the pre-quaternary rocks, by the combined action of sheet wash and gravity. They are developed in the northern part of the map area, mantling the pre-quaternary strata, or sometimes mixed with alluvial fan deposits. Slope deposits are generally composed of gypsiferous sand or loam with rock fragments and gravels. These deposits are massive. Thickness is variable, depending on topographic relief.

2.2.3 Sheet run-off deposits (Pleistocene-Holocene)

They occupy wide areas between the alluvial fans' floodplain and shallow depression fill units within the map area. Lithologically, the unit is made up of silty clays, silts, and sands. The most prevailing deposits are silty clay and clayey silt with some sand admixture. Generally, the grain size increases vertically downwards and laterally eastwards. The nature and distribution of the lithologic constituents are rather complicated, reflecting the variation in sedimentary conditions of local and regional extent.

2.2.4 Floodplain deposits (Holocene)

These deposits are composed of fine sand with thin silt and clay characterized by well-bedded fine- to medium-grain, then gradually pass to clay and silt in the flood basins.

2.2.5 Valley fill deposits (Holocene)

These deposits are characterized to be badly sorted, composed of gravels, sands, and silt; their size decreases downstream. The total thickness of the valley fill deposits is unknown, but it does not exceed a few meters [9].

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They deposits characterized being badly sorted, mainly due to alternating intense floods and abrupt drops in flow, which caused wide variation in grain size and composition. Lithologically, they are composed of gravels, sands, and silt; their size is decreasing downstream. The total thickness of the valley fill deposits is unknown, but it does not exceed a few meters [9].

3 Material and Methodology

To achieve the study objective, fieldwork was conducted, which required a set of materials. The use of topographic and geological maps at different scales, and the use of a GIS device to determine the locations of water wells that were investigated on-site during the field study in the area. These maps and GIS were used to determine the topographical elevations of these wells. Stratigraphic columns and Hydrogeological Data Bank, which were obtained from the General Commission of Groundwater in the Ministry of Water Resources [10], were also used to compare them with the investigated field data to determine the final information and data that can be used in this study. A set of computer programs, including Excel and Surfer, was used to input all data obtained and process data and information to produce contour maps related to the hydrogeological and hydrochemical characteristics of the unconfined groundwater aquifer.

4 Results and Discussion

4.1 Hydrogeological Properties of Aquifer

One of the most important requirements in hydrogeological studies is the identification of aquifer systems. This process relies on a combination of influencing factors, including tectonic, hydrodynamic, and geological aspects, to determine the characteristics and distribution of these aquifers [11]. Figure 1 demonstrates the geological map where the exposure of Quaternary deposits and Bai Hassan Formation, which indicates that the water-bearing layer was an unconfined aquifer, where Bai Hassan Formation layers compose this aquifer in the north-eastern side along the Iraq-Iran border, while an interbedding of different Quaternary deposits forms this aquifer all over the basin.

The unconfined aquifer begins with the Bai Hassan layers only in the groundwater recharge area located in the northeast of the basin. Then, Quaternary deposits, along with the Bai Hassan Formation, begin to form this aquifer all over the area of study, particularly in the central regions. The Quaternary deposits then become the main components of the aquifer in the western and south-western parts of the basin. The comparison of information collected in the field and stratigraphic columns verified the extension and nature of the unconfined aquifer in the area, as well as well depths recordings and groundwater levels. Table 1 shows the unconfined aquifer properties in the basin. Forty-seven wells were used in this study to obtain the hydrogeological characteristics of the aquifer's thickness, transmissivity, maximum yields, and groundwater flow. Figures 2-5 demonstrate these maps, respectively.

Table 1 Hydrogeological properties of unconfined aquifer in the area

Parameter	Number of values	Minimum	Maximum	Mean
Elevation (m)	42	60	185	113
Total depth (m)	47	32	121	73.65
Static water level (m)	47	0	25.5	8.01
Dynamic water level (m)	47	5.4	51.3	24.34
Water Table (m.a.s.l.)	42	39	185	104.8
Depth to water (m)	45	2	83	26.3
Thickness (m)	45	11	104	46.4
Maximum yield (m^3/day)	47	136	1551	655.6
Transmissivity (m^2/day)	47	7	773	112

The combined factors of tectonic settlement, topographic elevations, and geological situation directly influence the hydrological basin situation [12]. The studied area is characterized by mountainous highlands in the north-eastern parts, where the topographic elevations gradually decline towards the south, southwest, and west of the basin, as shown in Figure 1. This directly impacted the thickness of the unconfined aquifer, as shown in Figure 2, which represents a map of the aquifer thickness in the basin. The thickness of the unconfined aquifer increased in the north-eastern region and around the town of Mandali, while this thickness decreased in the south, west, and northwest of the basin, as shown in the map. As previously mentioned, the aquifer in the northern region consists of an interbedded layer of the Bai Hassan Formation and Quaternary deposits, while only Quaternary deposits form the aquifer at the remaining parts of the basin. This reflects a noticeable increase in the thickness of the aquifer in the groundwater recharge areas to reach the groundwater level, while this thickness decreases in the rest of the basin areas because the static water surface is closer to the ground surface and reduces the cost of drilling wells. The nature of the groundwater in the recharge area always becomes deeper than the transfer or drainage areas, which makes the water wells penetrate deeper in the recharge area and less in the rest of the groundwater basin [12, 13].

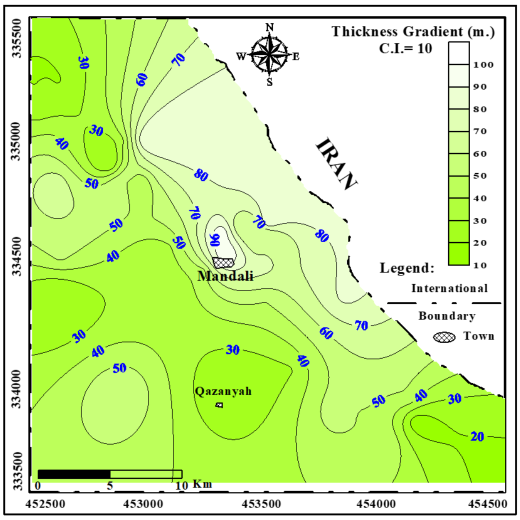

Figure 2 Thickness map of the unconfined aquifer

The hydraulic properties of the aquifers, represented by the transmissivity and storage coefficient, are greatly affected by the lithological nature of the rocks and sediments of the water-bearing layers, which directly depends on the type and texture of these deposits, as well as the degree of their sorting [14]. The nature of the Bai Hassan Formation, which is formed from layers of conglomerate and sandstone, is characterized by its symmetrical and regular layer extension in the northeast side of the area, which reflects good hydraulic properties for storage coefficient and transmissivity. This is observed in the eastern and northeastern regions, as shown in Figure 3.

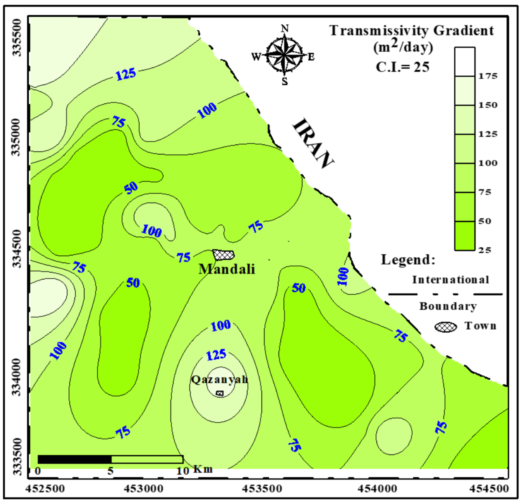

Figure 3 Transmissivity map of unconfined aquifer

In the western and southwest sides of the area, and specifically around the city of Qazaniya, high transmissivity values were observed. The unconfined aquifer in these areas formed from Quaternary deposits, which are characterized by poorly sorted deposits, especially in the northeastern parts. They begin to gradually transform into good sorting as we move towards the western part of the region, such that the permeability values increase. The eastern and northeastern parts of the basin represent groundwater recharge and surface runoff of rainwater, thus, transmissivity is directly affected and significantly decreased related to the continuous groundwater movement path in this area [14, 15].

The maximum yields map, as shown in Figure 4, shows the higher maximum yields of the unconfined aquifer in the southern area of the study area around Qazanyah town. The Geological situation and aquifer nature in the area, which consists almost of Quaternary deposits, affect on maximum yields. There is a direct, strong relationship between transmissivity and maximum yields related to the mixing of the deposits of various sorts of particles. This affects the hydraulic properties of the aquifer, thus, the unconfined aquifer in the recharge area has low values of maximum yields [16].

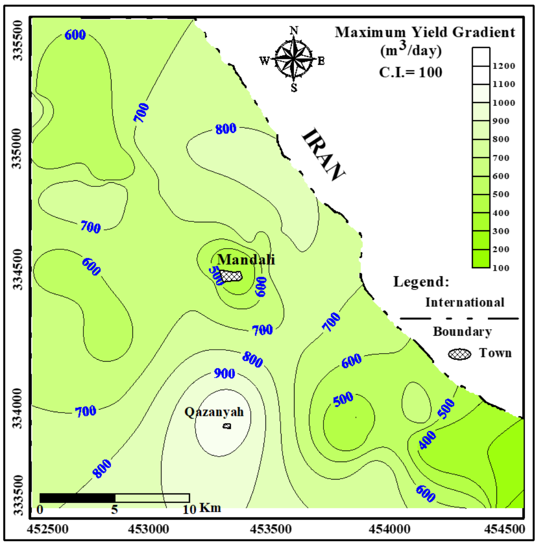

Figure 4 Map of the maximum yields of unconfined aquifer

Groundwater movement depends on the topographic slope in the unconfined aquifers. Figure 5 shows the groundwater movement map in the study area, where generally, groundwater flows from the eastern and northeastern regions, which are groundwater recharge areas near the foothills of the Hamrin Mountains, towards the southwest.

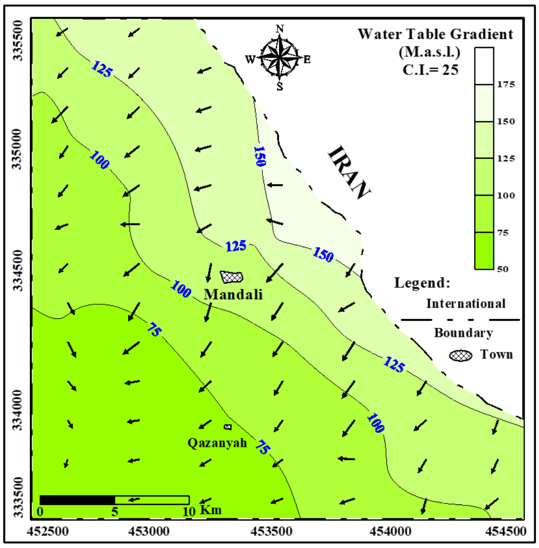

Figure 5 The unconfined aquifer flow net map

The exposure of the Bai Hassan Formation, which forms the aquifer, along with some Quaternary deposits in the eastern and northeastern regions, directly affects the groundwater movement through formation extension beneath the Quaternary deposits. The geological conditions, particularly the structural situation, in addition to the topographical gradient, play a fundamental role in the movement of groundwater from the recharge area towards the drainage area, which is often a water body [17, 18].

4.2 Hydro-geochemical Characteristics of Aquifer

The geological history of rocks, indications of groundwater recharge and movement in aquifers, as well as the storage coefficient, depend mainly and largely on hydro-chemical analyses of groundwater samples as crucial evidence [19]. Groundwater quality depends on many factors, including geology, source water quality, and land use type, and it is based upon the physical and chemical soluble parameters due to weathering from source rocks and anthropogenic activities [20–22]. Hydrochemical analytical data of groundwater properties are shown in Table 2. Forty-seven samples were analyzed to obtain the physicochemical parameters. The results of pH, electrical conductivity (EC), and total dissolved solids (TDS) showed a variation as represented by minimum and maximum values. The range of pH was (7) to (8.1), the EC of (400) to (9550) μmhos/cm, and TDS was (350) to (7434) mg/l. Accordance to references, the groundwater of unconfined aquifers is brackish to saline where (TDS $>$ 1000 mg/l) [23].

Table 2 Hydro-geochemical characteristics of aquifer in the area

Parameter	Number of values	Minimum	Maximum	Mean
Ph	25	7	8.1	7.62
Ec (mcomh/cm)	47	400	9550	2675
TDS (mg/l)	47	350	7434	2121
Na (mg/l)	47	22	1541	286.6
Ca (mg/l)	47	57	664	303.4
Mg (mg/l)	47	17	678	88.57
SO_4 (mg/l)	46	137	3700	1046
Cl (mg/l)	42	26	2378	285.9
HCO_3 (mg/l)	47	62	500	151.7
NO_3 (mg/l)	33	1	44	12.6
SAR	44	0.42	23	4.25

The variation of groundwater sources recharge and ionic exchange activities affects groundwater salinity directly. Several factors play an effective role in this variation. The main factors are the recharge and drainage areas, rock type, depth of aquifer, and the path of groundwater movement. As long as groundwater recharge, infiltrated waters reduce the groundwater salinity concentration due to dilution and ionic exchange, and mixing processes between groundwater and the recharged water [24, 25]. Figure 6 demonstrates the groundwater salinity distribution map of the unconfined aquifer in the area.

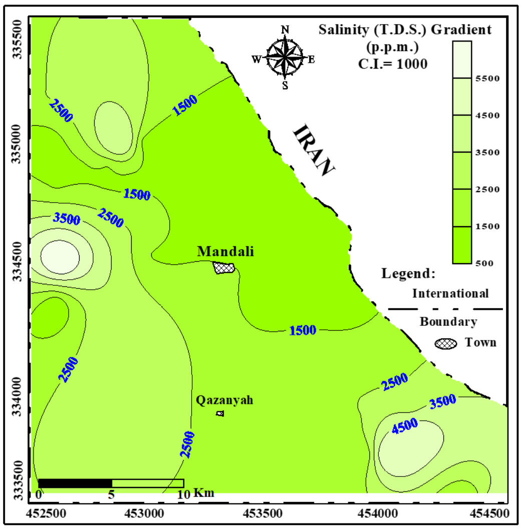

Figure 6 Salinity distribution map of unconfined aquifer

The salinity and ionic concentrations show low values in the area of recharge near the international border, where Bai Hassan formation is exposed on the surface. The continuous movement of groundwater away from the recharge area towards the discharge area in the western and south-western parts of the area will lead to an increase in the concentration of salinity due to the continuous ion exchange activities. In the eastern part of the area near the international border, as shown in Figure 1, the Quaternary deposits consist of slope deposits which are composed of gypsiferous material, causing the groundwater salinity and ionic concentrations highly values.

4.3 Groundwater Origin and Types

To determine the origin of water, especially groundwater, a set of hydrochemical formulas has been relied upon, which are directly based on the concentrations of chemical elements present in groundwater samples. The most important of these elements are chloride, sodium, and sulfate ions, measured in epm% [26]. According to the Kurlov formula [27], which depends on the positive and negative ionic concentrations measured in epm%, the groundwater quality can be determined in this research. The groundwater in the unconfined aquifer in the study area was characterized to be brackish to saline (TDS>1000 mg/l), as mentioned previously, while the origin of groundwater was continental as a result of its presence in an unconfined aquifer, which is composed of continental layers that were deposited in a continental deposition environment. Surface water infiltrates into the groundwater aquifer continuously during water surplus within the groundwater recharge areas in the eastern and northern-east area of the basin, which indicates the origin of this groundwater. Table 3 shows the origin and the three major groundwater types as recorded as: calcium sulphate, sodium chloride, and sodium sulphate, with two samples of magnesium chloride and calcium bicarbonate were found. The Quaternary deposits with gypsiferous material provide groundwater with diluted calcium ions, while Bai hassan and other types of Quaternary deposits provides the groundwater with diluted sodium and magnesium ions in ionic exchange activities.

Table 3 Groundwater types of aquifer in the area

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	1	7.4	1.92	8.5	0.73	2.16		
Maximum	19	28.8	15.83	46.87	9.57	12.42	Ca-Sulphate	34
Mean	7.64	15.44	5.84	20.1	4.67	4.67		
Minimum	10.43	7.1	5.58	4.8	2.67	2		
Maximum	41	33.2	18.33	47.14	42.5	4.83	Na-Sulphate	3
Mean	29.26	17.183	10.14	21.81	17.5	3.13		
Minimum	8.95	6.6	5.25	2.85	5.126	2.77		
Maximum	67	27.8	10.42	35.93	66.98	2.96	Na-Chloride	3
Mean	30.88	14.72	7.47	14.01	28.38	2.90		
	45.48	9.02	45.5	77.08	40.78	4.13	Mg-Sulphate	1
	1.13	5.9	1.42	4.16	0.98	6.13	Ca-Bicarbonate	1

4.4 Groundwater Utilization

The 47 analyzed groundwater samples, as shown in Table 4, indicated that only six samples of groundwater could be used for human purpose, twenty eight samples are qualified to be used in agriculture while forty four samples indicate to be used for animal purposes. Salinity that reflected by cations and anions caused by groundwater contamination in some area of the Mandali basin due to concentrations increasing.

Table 4 The utilization of groundwater in the studied area

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	No.*	Utilization
No. of samples	25	47	47	47	47	47	42	47	46	33	44		
Minimum	7	400	350	57	17	22	26	62	137	1	0.42		
Maximum	8.1	9550	7434	664	678	1541	2378	500	3700	44	23		
(WHO. 2011) [29]	6.5-8.5	-	1000	75	125	200	250	200	250	50	-	6	Human Purposes
(IQS. 2001) [30]	6.5-8.5	-	1000	50	50	200	250	200	250	50	-		
Standard FAO/1989 [31]	-	-	2000	40	5	20	30	10	20	-	15	28	Irrigation Purposes
Standard FAO/1989 Poultry + Livestock [31]	-	5000	-	-	250	-	-	-	-	100	-	44	Animal Purposes

Note: * Number of suitability wells

According to some previous studies and reports conducted in areas near Mandali basin, it seems that the nature of the soil in the area and the depth of the groundwater qualify the groundwater widely in agricultural utilization. The soil formed from medium-grained sand, silt, and clay of Quaternary deposits that retains only 20% of the irrigation water, as agricultural lands are irrigated with limited quantities daily to preserve the nutrients needed by cultivated plants.

Also, the nature of cultivated plants often tolerates irrigation water with high salt concentrations, while the topographical slope acts as a factor that helps accelerate in accelerating the drainage process [28].

5 Conclusion

The interbedded of Bai Hassan formation and Quaternary deposits produced the unconfined aquifer in the Mandali basin. The obtained hydrogeological properties reflected by the mean thickness, transmissivity, and maximum yields were (46) m, (112) m^2/day and (655) m^3/day, respectively. These properties reflect a suitable aquifer to be used for several purposes.

According to topographic situation of the basin, the direction of groundwater movement in the unconfined aquifer begins from north-eastern towards south-western part in the studied area. Two locations were found where groundwater salinity has risen causing contamination levels in these two location, to the west and in the eastern parts of the basin near Iraqi- Iranian international border. The salinity gradually increased from recharge area towards discharge area.

The hydro-geochemical characteristics of groundwater in the unconfined aquifer, which are determined by the values of physicochemical parameters, indicate the continental origin of brackish to saline groundwater. The dominant type of groundwater was calcium sulphate. The utilization of groundwater according to the international standards showed that some wells could be used for human benefit, while twenty-eight samples could be used for irrigation. Almost all samples of groundwater can be used for animal purposes. The assessment of hydrogeological conditions and hydro-geochemical characteristics of the unconfined aquifer produced a qualified location to increase well drilling. This location is situated in the central area between Mandali and Qazanyah towns, where the aquifer thickness, transmissivity, and maximum yields increase, while salinity decreases.

Conflicts of Interest

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

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