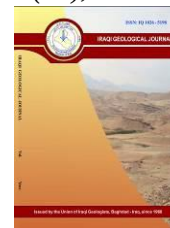




Iraqi Geological Journal

Journal homepage: <https://www.igi-iraq.org>



Hydraulic Characterization of the Quaternary Aquifer in Eastern Maysan, Southern Iraq: Insights from Pumping Tests and Geostatistical Analysis

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Received:
20 April 2026
Accepted:
28 June 2026
Published:
31 August 2026

Abstract

This study determines the hydraulic characteristics of the Quaternary aquifer in the eastern part of the Missan Governorate, southern Iraq. As a result of the increasing demand for water supplies, especially for agricultural purposes, in addition to droughts, groundwater abstraction has intensified, leading to declining groundwater levels. This requires determining the hydraulic characteristics of the aquifer and assessing its development potential. To obtain the hydraulic characteristics of the aquifer, pumping tests were carried out on nine selected wells. The results of the single and multi-well tests were interpreted using the Theis (1935) method and Cooper-Jacob (1946) analytical methods to obtain the hydraulic characteristics: Transmissivity, hydraulic conductivity, and Storativity. The pumping test data analysis revealed that the Quaternary aquifer is unconfined, with storativity values ranging from 0.006 to 0.1, indicating moderate to high storage potential. Spatial data analysis shows that hydraulic conductivity and transmissivity are highest in the eastern and northeastern parts of the area, where coarse gravel and sand of the alluvial fan are found predominate. Specifically, well W8 recorded the highest values, with transmissivity of about 556.65 m²/day and hydraulic conductivity of 11.05 m/day. Mapping of the spatial distribution of hydraulic characteristics of the aquifer (transmissivity, hydraulic conductivity, and storativity) highlights the northeastern part of the study area has the greatest groundwater potential. Overall, the aquifer is characterized by moderate to high hydraulic conductivity, underscoring its importance as a strategic water resource.

Keywords: Pumping test; Aquifer; Hydraulic conductivity; Wells; Missan Governorate; Hydrogeological; Specific capacity; Spatial analysis

1. Introduction

The determination of hydraulic characteristics is essential in the domain of groundwater hydrology due to their crucial role in describing aquifer behaviors and controlling groundwater flow dynamics. Hydraulic parameters such as transmissivity (T), hydraulic conductivity (K), and storativity (S) fundamentally characterize an aquifer's capacity to store and transmit water (Fetter, 2001). The amount of groundwater in any area is determined by the aquifer's appearances (transmissivity, hydraulic conductivity, and storativity), volume, and the wells' discharge (Amah and Anam, 2016; Liu et al., 2021). Lithological data and hydrogeological studies of aquifer properties are essential for the technical management and study of groundwater resources. Aquifer characteristics of subsurface formations play an important role in groundwater occurrence, distribution, movement, and storage (Islam, 2013).

These characteristics critically influence groundwater availability, well yield, aquifer recharge, discharge processes, and the overall sustainability of groundwater extraction. It is important to

DOI: <https://doi.org/10.46717/igi.2026.59.2B.11>

understand and quantify these properties so that scientifically sound groundwater management frameworks can be developed, including well design optimization, estimation of pumping responses to aquifers, assessment of recharge mechanisms, and protection from contamination and overexploitation (Kruseman and Ridder, 1994). Additionally, these hydraulic characteristics can be used for modeling groundwater flow and contaminant transport, which are essential for sustainable resource management and environmental protection. Effective groundwater management is based on accurate determination of hydraulic characteristics for the purpose of optimizing groundwater investments, preventing its depletion and maintaining ecosystem balance (Singhal and Gupta, 2010).

The eastern and northeastern parts of Maysan Governorate are largely dependent on groundwater and rainfall, in addition to the seasonal Al-Tayeb and Al-Diourj streams. In these regions, groundwater remains the primary water source for drinking, agriculture, domestic use, and industrial development (Al-Ghanimy et al., 2019). The increasing demand for groundwater due to the expansion of agricultural land has negatively impacted groundwater levels, particularly in the northeastern regions. Furthermore, given the arid conditions in Iraq, it has become essential to determine or calculate the hydraulic characteristics of the aquifer east of Maysan Governorate within the Quaternary deposits (Barwary, 1993). Analysis of well logs indicates that the aquifer is an unconfined type extending within the coarse Quaternary deposits of alluvial fan sediments, and its thickness depends on the thickness of these sediments. The most common method for determining hydraulic characteristics is pumping tests, although they are costly and time-consuming. However, it is more reliable than other field methods because it takes into account the heterogeneity and variation in aquifer conditions (Ali et al., 2022).

To determine the above characteristics, pumping tests were conducted on nine wells using both single-well and multi-well methods (Kruseman and Ridder, 1994). In addition to 23 wells from the archives of the General Authority for Groundwater, from the period (2019-2024), The hydraulic parameters were estimated using the Theis and Cooper-Jacob methods, and using (AQTESOLV software, version 4.50) to determine the values of the hydraulic parameters of the Quaternary aquifer in the study area. By assessing these characteristics, it became possible to identify promising areas for groundwater investment within a sustainable groundwater management framework based on scientific principles.

2. Materials and Methods

2.1. The Study Area

The study area is located in the east and northeastern Maysan Governorate, southern Iraq, between the latitudes of (32° 0' 0" - 33° 0' 0" N) and the longitudes of (46° 30' 0" - 47° 30' 0"). The study area covers an area of about 2729 km². It is bordered to the north by Wasit Governorate, to the east by the Abo-Ghrab region and the Islamic Republic of Iran, and to the west by the Tigris River. The major parts of the study area are flat and low terrain with a few isolated hills (Hamrin Hills) (Parsons, 1955). Three-quarters of the study area has a gentle slope and represents the southwestern parts of the study area. The remaining quarter is located in the eastern and northeastern parts and extends along the Iranian border and is interspersed with low convex folds interspersed with syn-valleys (Barwary, 1993). The elevation in the study area ranges from 17 to 96 m above sea level, Fig.1.

The study area represents the eastern parts of the Mesopotamian Plain (Abdulnaby et al., 2016). It consists of Quaternary (Holocene-Pleistocene) deposits covering an area of 2,519 km² and Tertiary deposits covering an area of 210 km², represented by the Al-Muqdadiyah Formation (Lower Bakhtiari), (Upper Miocene-Lower Pliocene). This formation comprises sandstone, mudstone, silty sand, and gravelly sand deposits, covering 8% of the study area (Jassim and Goff, 2006), Fig. 2. The Quaternary deposits consist of alluvial fan deposits, covering 11%, surface runoff deposits, covering 43%, and wind

deposits, covering 1%. (20%) floodplain deposits, covering a percentage of (7%), shallow depression filling deposits, covering a percentage of (6%), valley filling deposits, covering a percentage of (2%) , anthropogenic deposits, covering a percentage of (1%), fissure extension deposits, covering a percentage of (2%) of the study area (Jassim and Goff, 2006; Al-Jiburi and Al-Basrawi, 2011; Al-Saady et al., 2013).

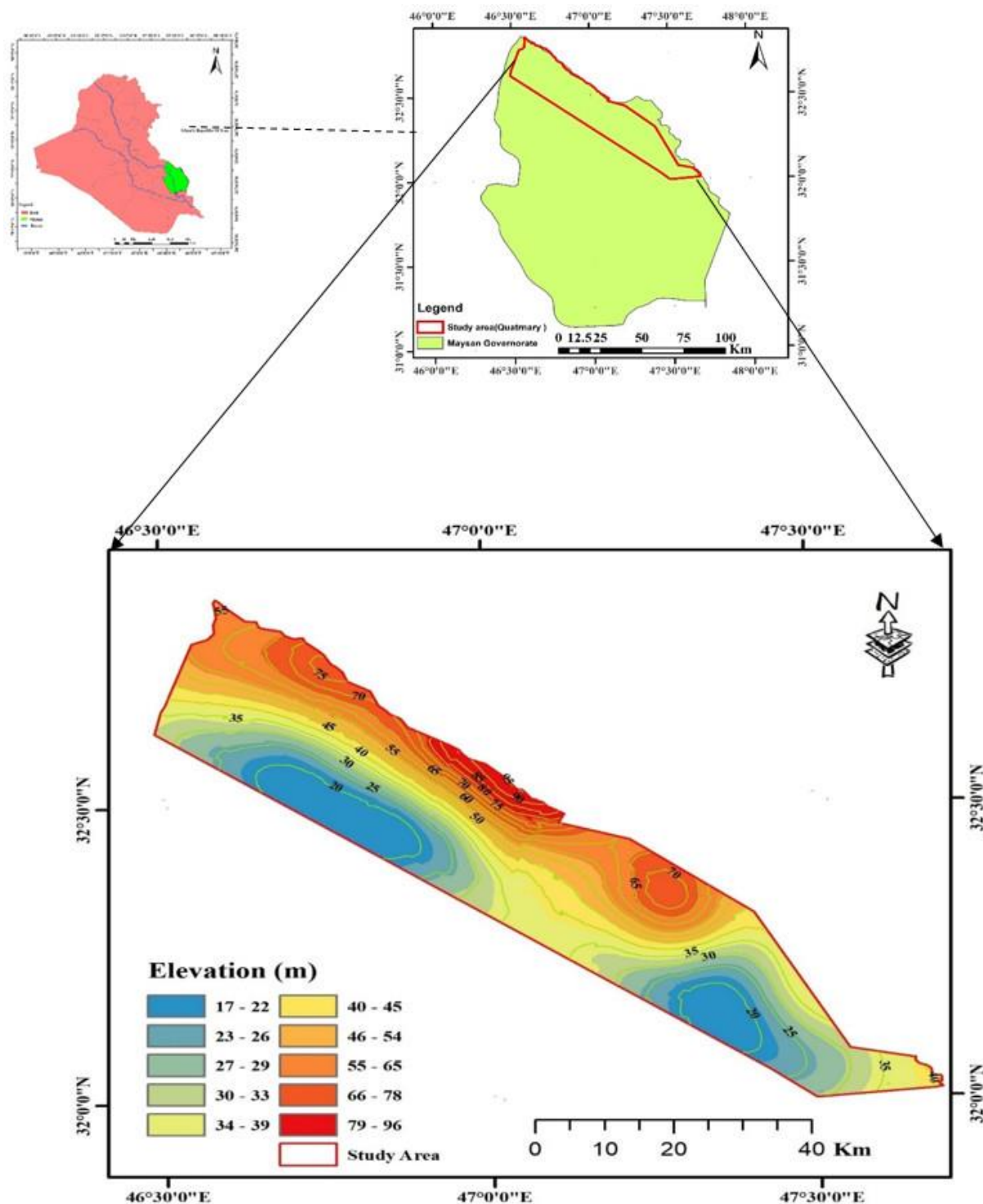


Fig. 1. Location of the study area

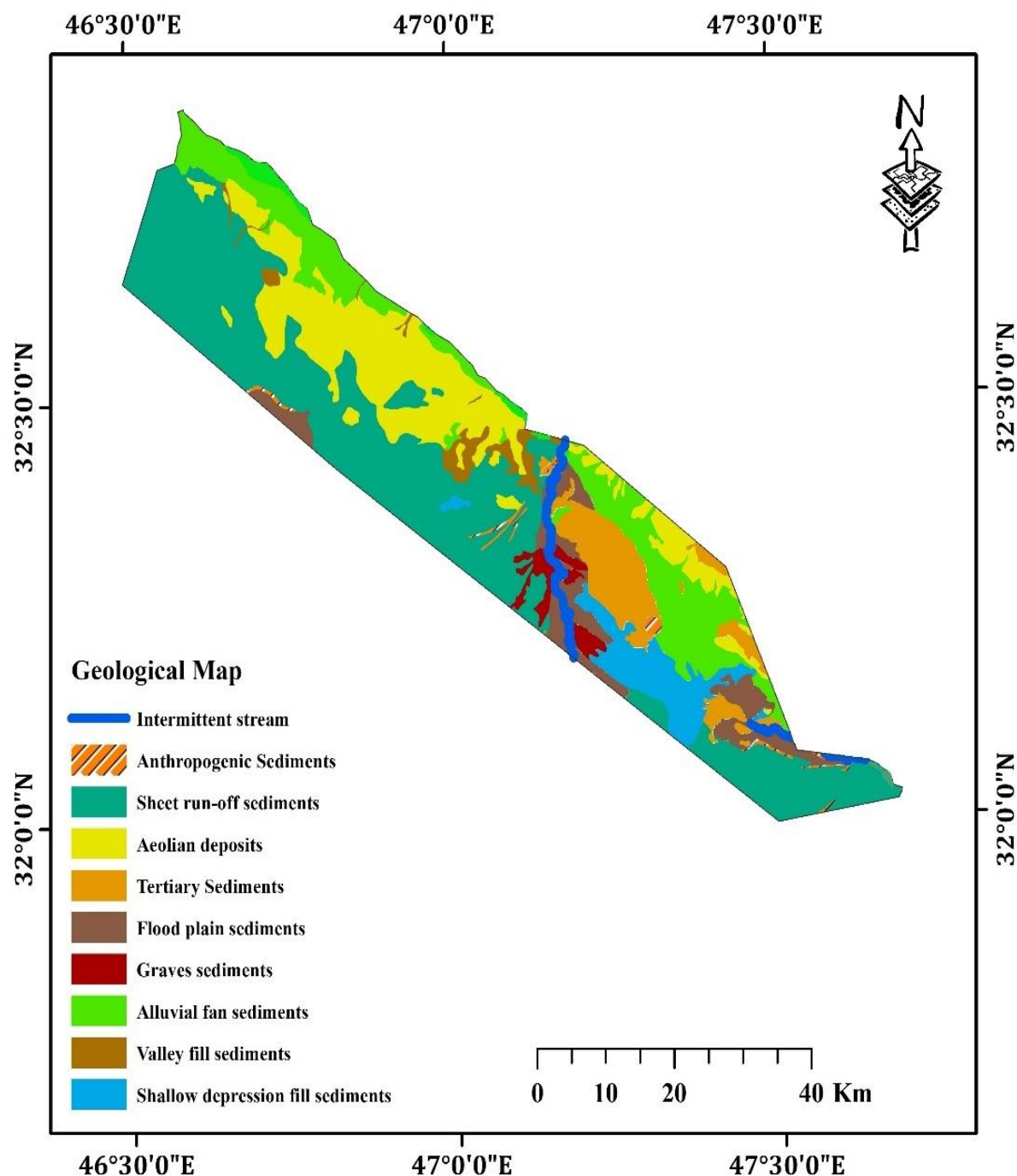


Fig. 2. Geological map of the study area

2.2. Data and Techniques Used

Tables 1, 2, and 3 present data for water wells across the area, including aquifer saturated thickness (b) in meters, hydraulic head (H) in meters, static depth to groundwater level (S.W.L.) in meters, and well flow rate (Q) in l/s. Data from eight newly drilled boreholes (Tables 4 and 5), along with available drilling reports, were used to construct a cross-sections along lines A-A' and B-B' (Fig. 3). The study of these cross-sections reveals that the type of aquifer is unconfined in consistent with the previous studies (Al-Saady et al., 2013; Al-Zubedi, 2022).

Table 1. Well discharge ($Q_{l/s}$) in the study area (provided by the General Authority for Groundwater)

Well no.	X	Y	SWL	E(m)	Q	Well no.	X	Y	SWL	E(m)	Q
w1	699210	3595837	31	96	5	w23	710405	3585678	21	68	13
w2	717674	3584128	15	70	13	w24	713404	3587430	22	69	19
w3	717074	3579481	14	58	26	w25	705011	3590065	11	59	13
w4	735692	3554241	10	29	8	w26	689809	3598290	55	98	19
w5	748134	3550212	11	41	26	w27	701464	3593238	12	61	5
w6	678024	3605571	16	49	26	w28	692030	3601021	58	102	5
w7	674609	3600369	6	25	5	w29	684734	3591406	1	30	8
w8	656255	3615484	17	42	19	w30	681440	3608131	48	94	13
w9	651277	3626127	20	62	26	w31	674265	3612292	19	67	13
w10	661063	3616549	24	48	13	w32	666958	3612706	29	54	13
w11	668761	3605435	14	60	8	w33	664895	3617822	27	53	19
w12	748861	3546497	11	36	8	w34	653236	3623637	19	61	26
w13	744351	3552399	12	33	13	w35	648280	3630934	24	65	26
w14	744425	3550602	12	31	19	w36	658333	3609968	7	27	26
w15	736526	3556157	12	33	13	w37	673723	3608318	16	64	26
w16	732189	3549930	4	25	8	w38	681666	3601991	14	46	26
w17	728297	3552828	4	23	8	w39	701821	3577811	9	43	8
w18	723739	3573013	5	36	19	w40	701418	3580764	7	46	8
w19	709048	3573333	5	43	5	w41	702769	3582628	8	54	5
w20	710807	3570968	4	40	8	w42	705204	3585375	9	56	19
w21	708404	3575751	3	39	8	w43	706692	3589142	10	57	13
w22	702381	3573604	11	39	8	w44	709525	3589367	29	70	8

Table 2. Saturated thickness of aquifer (b) in the study area (provided by the General Authority for Groundwater)

well no.	X	Y	Well Depth(m)	b(m)	well no.	X	Y	Well Depth(m)	b(m)
w1	674609	3600369	72	34	w34	651277.6	3626127.5	60	50
w2	678024	3605571	70	45	w35	661063	3616549	66	38
w3	681440	3608131	88	41	w36	668761	3605435	50	21
w4	670412	3608162	70	23	w37	748194	3548790	80	50
w5	658312	3614885	70	36	w38	710405	3585678	72	32
w6	659750	3616528	70	37	w39	705011	3590065	54	33
w7	655819	3616826	75	33	w40	692030	3601021	120	30
w8	652098	3620644	75	35	w41	701464	3593238	60	33
w9	656255	3615484	70	38	w42	708404	3575751	50	34
w10	652182	3622805	75	35	w43	7134047	3587430.3	70	39
w11	653446	3624753	75	43	w44	683894	3592525	45	27
w12	652519	3624942	75	43	w45	645889	3618011	75	29
w13	651277	3626127	70	41	w46	643032	3613248	70	28
w14	650191	3627361	70	40	w47	652147	3609557	75	28
w15	665187	3621907	90	53	w48	663947	3612653	80	39
w16	674214	3612390	80	55	w49	657121	3605747	70	30
w17	646613	3626442	60	34	w50	661725	3600270	70	24
w18	648426	3622209	48	29	w51	669067	3595680	75	21
w19	648231	3631038	60	42	w52	684968	3603379	90	40
w20	656552	3629983	80	55	w53	675337	3593960	90	22
w21	669816	3609036	50	21	w54	695234	3591526	80	32
w22	679496	3608740	85	44	w55	688778	3587398	42	24
w23	650220	3633027	80	52	w56	701584	3587293	60	26
w24	681495	3608665	88	47	w57	694493	3582424	50	20
w25	717074	3579481	72	50	w58	707511	3583165	60	27
w26	684734	3591406	45	24	w59	697139	3577344	40	25
w27	699210	3595837	84	40	w60	707617	3570783	40	19
w28	717674	3584128	68	38	w61	722751	3569195	50	44
w29	735692	3554241	42	27	w62	716401	3563480	36	20
w30	748134	3550212	80	50	w63	729313	3559882	60	25
w31	678024	3605571	66	55	W64	737991	3545277	50	54
w32	674609	3600369	70	25					
w33	656255	3615484	66	37					

Table 3. Hydraulic head(H) for the groundwater in the study area (provided by the General Authority for Groundwater)

Well No.	X	Y	S.W.L (m)	E (m)	H (m)	well no.	X	Y	S.W.L (m)	E (m)	H (m)
well 1	749628	3546009	11	36	25	well 28	658333	3609968	7	27	20
well 2	747805	3550010	11	41	30	well 29	659886	3616657	24	48	24
well 3	746340	3550790	11	33	22	well 30	656169	3615624	17	42	25
well 4	741643	3549878	9	32	23	well 31	675286	3605384	15	47	32
well 5	728297	3552828	4	16	12	well 32	674265	3612292	19	67	48
well 6	729881	3555993	3	27	24	well 33	665281	3621785	27	87	60
well 7	727879	3570344	5	33	28	well 34	650190	3627968	17	61	44
well 8	723739	3573013	5	36	31	well 35	646626	3626442	13	58	45
well 9	718475	3580938	16	62	46	well 36	651277	3626127	20	62	42
well 10	711996	3586497	21	69	48	well 37	653236	3623637	19	61	42
well 11	709048	3573333	5	43	38	well 38	652018	3620556	19	51	32
well 12	708296	3576007	3	39	36	well 39	699210	3595837	31	96	65
well 13	702381	3573604	11	39	28	well 40	732393	3567921	11	41	30
well 14	701625	3577360	9	43	34	well 41	739252	3552327	9	28	19
well 15	701418	3580764	7	46	39	well 42	716978	3583549	15	70	55
well 16	700133	3584214	5	47	42	well 43	643420	3612189	12	29	17
well 17	702125	3589215	6	56	50	well 44	646895	3618338	14	45	31
well 18	701464	3593238	12	61	49	well 45	653575	3604688	5	19	14
well 19	705011	3590065	11	59	48	well 46	663070	3598295	4	15	11
well 20	710348	3588653	28	66	38	well 47	725383	3560673	6	20	14
well 21	695085	3576480	5	36	31	well 48	673902	3591490	4	14	10
well 22	684734	3591406	1	30	29	well 49	684513	3582141	3	27	24
well 23	692030	3601021	58	102	44	well 50	737524	3545972	5	26	21
well 24	690009	3601870	50	96	46	well 51	721182	3558584	4	14	10
well 25	681069	3608417	48	94	46	well 52	723822	3567295	7	22	15
well 26	674216	3600137	6	25	19	well 53	717093	3568813	4	31	27
well 27	671143	3600349	4	26	22	well 54	709891	3565998	4	26	22

Table 4. Selected wells cross-section(A-A') drawing of Quaternary layers for the study area

Well no.	Coordinate		Depth (m)
	X	Y	
W1	693197	3575981	112
W2	718899	3578041	58
W3	734465	3550598	29
W4	740851	3548865	21

Table 5. Selected wells cross-section(B-B') drawing of Quaternary layers for the study area

Well no.	Coordinate		Depth (m)
	X	Y	
W1	696117	3595338	82
W2	678535	3604849	75
W3	654944	3615546	34
W4	648525	3622854	46

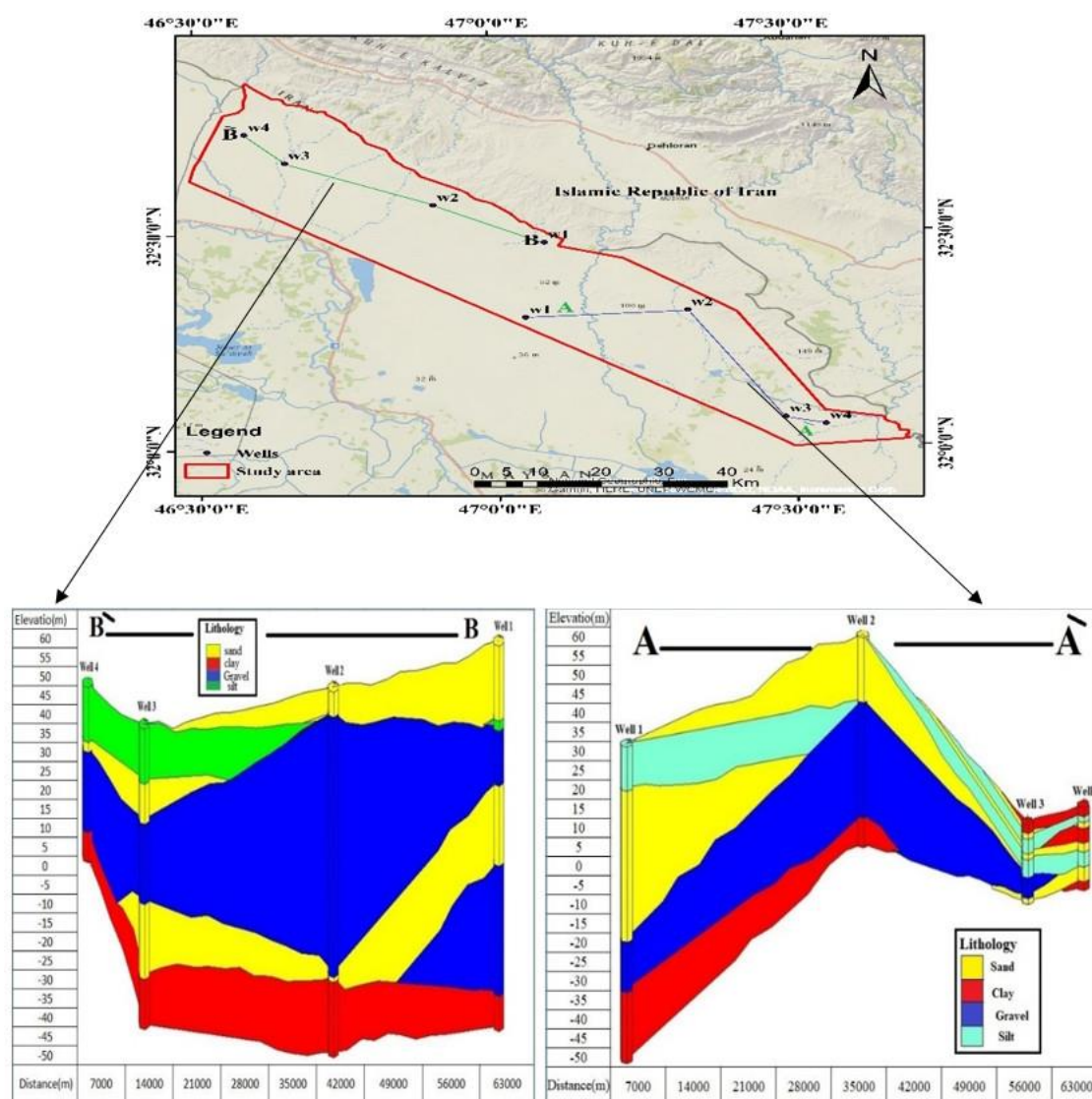


Fig. 3. Cross sections in the study area

Table 6 presents the fundamental statistical analysis of the data from Tables 1, 2, and 3. The spatial distribution of these variables and their significance in aquifer potential were also revealed by interpolating the H, S.W.L., Q, and b using the same data in Table 6.

Table 6. Basic statistical analysis of data in Tables 1, 2, and 3

Statistical Parameter	Hydraulic head(H)m	Static water level (S.W.L) m	Discharge(Q)l/s	Saturated thickness (b) m
Minimum	10	1	5	19
Maximum	65	58	26	55
Mean	32	13	14	35.4
Median	30.5	10	13	34.5
Standard Deviation	13.5	12	7.46	10.3
Coefficient of Variation (%)	42.2	92.3	53.3	29

2.2.1. Pumping test

The most common method for determining aquifer hydraulic characteristics is to conduct an on-site hydraulic test (field test). However, this test is relatively expensive and time-consuming. While laboratory experiments are simpler and require less time, they do not accurately reflect the in-situ

hydraulic characteristics (Singhal and Gupta, 2010). The field investigation employed a suite of complementary hydrogeological and geophysical methods, encompassing slug tests, injection tests, and pumping tests for the direct assessment of aquifer hydraulic properties, alongside geophysical techniques including vertical electrical sounding (VES) (Akhter et al., 2022), geo-electrical measurements, ground-penetrating radar (GPR), and magnetic resonance sounding (MRS) for subsurface characterization (Ali et al., 2022). The pumping test is the most common and accurate method. It is also the only one that provides information on aquifer characteristics and well hydraulic performance simultaneously (Dashti et al., 2022).

The pumping tests were carried out in nine wells, (Table 7, Fig.4) and the dynamic water level, drawdown and recovery water levels were monitored in six observation wells (multiple well pumping test) screened at the same depth as the pumping wells w1, w5, w6, w7, w8, and w9, while wells w2, w3 and w4 were used for pumping and monitoring purposes single well pumping tests due to the lack of monitoring wells close to the pumping wells. The water level in the well was measured during the pumping test using an electric water-level meter, and the productivity of each well was determined by pumping rate.

Table 7. Pumping test of the wells in the study area

Well no.	X	Y	Depth (m)	Well no.	X	Y	Depth (m)
w1	699210.21	3595837.42	84	W6	674609.50	3600369.52	70
W2	717074.48	3579481.22	72	W7	656255.08	3615484.18	66
W3	735692.00	3554241.00	42	w8	651277.60	3626127.50	60
W4	748134.00	3550212.00	80	W9	661063.72	3616549.75	66
W5	678024.72	3605571.76	66				

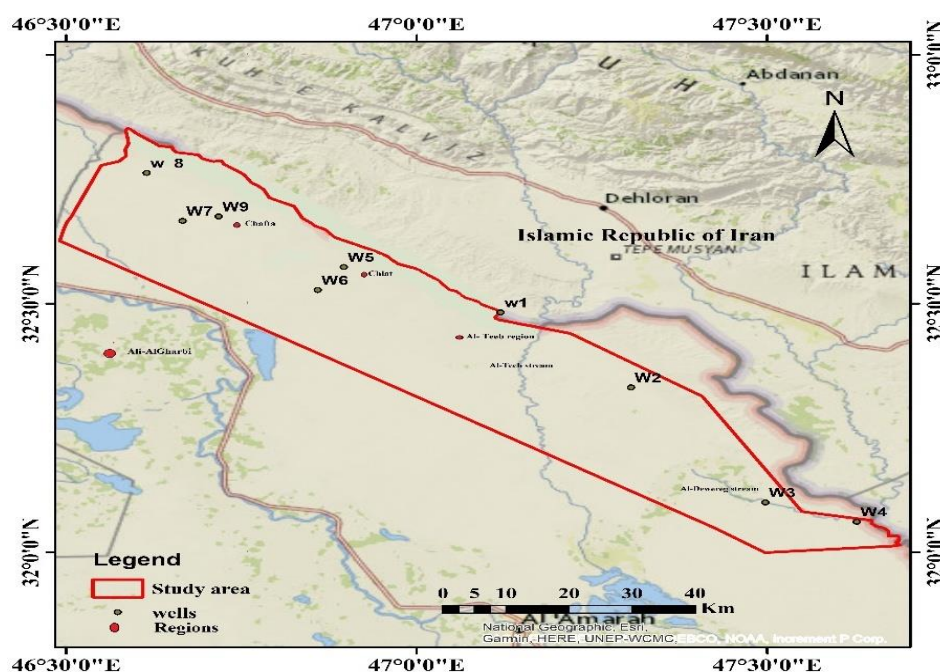


Fig. 4. Location of the pumping test wells in the study area

2.2.2. Pumping test analysis

In this study, the methods of Theis (1935) and Cooper-Jacob (1946) were used to analyze pumping-test data. Both methods were applied to compare aquifer parameters and evaluate the consistency of the estimated hydraulic properties.

- Theis (1935) method

Theis method is a foundational approach in hydrogeology for analyzing groundwater flow during a pumping test. Developed by Charles Theis in 1935, it provides a mathematical solution, known as the Theis equation, to describe how water levels (drawdown) change over time (Fetter, 2001).

Theis equations:

$$T = \frac{Q}{4\pi(h_0 - h)} W(u), \quad (1)$$

$$S = \frac{4Tut}{r^2}, \quad (2)$$

where: $h_0 - h$: drawdown (m), Q = constant pumping rate (m^3/d), T = transmissivity (m^2/d). $W(u)$: Theis well function. Theis parameter $u=r^2S/4Tt$, S : storativity of the aquifer (dimensionless), r^2 : distance between the pumping well and the observation well in (m) or pumping well radius. t : time since pumping.

-Cooper–Jacob (1946) method

Cooper and Jacob's (1946) solution can be applied to interpret pumping tests in both confined and unconfined aquifers. It is based on the Theis (1935) method and applies to a well that discharges at a constant rate from an infinitely large, homogeneous, and isotropic aquifer with uniform thickness. (Kruseman and Ridder, 1994). This method estimates two aquifer properties: T (transmissivity), S (storativity). The Cooper and Jacob (1946) equations are:

$$S=2.25Tt_0/r^2, \quad (3)$$

$$T=\frac{2.30Q}{4\pi\Delta s}, \quad (4)$$

Where:

S : storativity of the aquifer (dimensionless), T : is the transmissivity (m^2/d), Δs : the drawdown(m), Q : is the constant pumping rate (m^3/d), t_0 : is the time, where the straight line intersects the zero–drawdown axis (x-axis).

3. Results and Discussion

3.1. Statistical Evaluation of the Hydraulic Properties of the Aquifer

Analysis of the data in Table 6 shows that the hydraulic head (H) have a mean of 32 m and a median of 30.5m, ranging from 10 to 65 m. The standard deviation (13.5 m) and coefficient of variation (42.2%) indicate a significant spatial variation in hydraulic head among the wells in the study area due to variations in aquifer characteristics and recharge conditions. The static water level (SWL) exhibits greater relative variability, ranging from 1 to 58 m with a mean of 13 m. The high coefficient of variation (92.3%) indicates considerable fluctuations in groundwater levels across the study area, likely resulting from variations in pumping intensity, recharge rates, and local hydrogeological conditions. Pumping discharge rates ranged from 4 to 26 l/s, with an average of 14 l/s and a median of 13 l/s. A standard deviation of 7.46 l/s and a coefficient of variation of 53.3% indicate moderate variability, implying generally comparable productivity among the sampled wells. The aquifer thickness ranged from 19 to 55 m, with an average of 35.4 m and a median of 34.5 m. The relatively low coefficient of variation (29%) indicated that the aquifer thickness was relatively uniform across the study area compared with the other parameters. The statistical analysis of the static water levels (SWL) shows the greatest degree of variability among the parameters investigated, whereas aquifer thickness displays the least. This disparity underscores the dominant role of dynamic hydrological processes in groundwater fluctuations, in contrast to the comparatively stable geological constraints that dominate aquifer thickness.

3.2. Pumping Test Results

After conducting a pumping test on nine wells and using submersible pumps suitable for this purpose, the pumping results for the wells were analyzed according to the Theis and Cooper- Jacob methods. Pumping results listed in Tables 8–16, were analyzed using the program (AQTESOLV , version 4.50), and the results are summarized in Table 17.

Table 8. Results of Drawdown test and Recovery to pumping well no.1

Drawdown test			Recovery test	
T(min)	D.W.L (m)	D.D (m)	T (min)	Recovery level(m)
1	31.17	0	1	31.71
2	31.20	0.03	2	31.66
3	31.25	0.08	3	31.62
4	31.29	0.12	4	31.59
5	31.32	0.15	5	31.55
10	31.43	0.26	10	31.47
15	31.49	0.32	15	31.42
20	31.53	0.36	20	31.39
30	31.58	0.41	25	31.37
40	31.61	0.44	30	31.35
50	31.64	0.47	40	31.32
60	31.66	0.49	50	31.3
90	31.69	0.52	60	31.29
120	31.72	0.55	90	31.26
150	31.73	0.56	120	31.24
180	31.77	0.57	150	31.23
210	31.77	0.6	180	31.20
215	31.77	0.61	190	31.17

Table 9. Result of Drawdown test and Recovery to pumping well no.2

Drawdown test			Recovery test	
T (min)	D.W.L (m)	D.D (m)	T (m)	Recovery level (m)
1	18.73	3.73	1	19.55
2	19.28	4.28	2	18
3	19.5	4.5	3	17.6
4	19.67	4.67	4	17.22
5	19.8	4.8	5	17
6	19.9	4.9	6	16.88
7	19.98	4.98	7	16.75
8	20.05	5.05	8	16.65
9	20.1	5.1	9	16.54
10	20.16	5.16	10	16.49
15	20.4	5.4	15	16.44
20	20.65	5.65	20	16.39
25	20.81	5.81	25	16.34
30	21.01	6.01	30	16.3
35	21.13	6.13	35	16.25
40	21.2	6.2	40	16.23
45	21.31	6.31	45	16.22
50	21.38	6.38	50	16.06
55	21.4	6.4	55	15.9
60	21.45	6.45	60	15.85
70	21.69	6.69	70	15.77
80	21.72	6.72	80	15.7
90	21.79	6.79	90	15.65
120	22.03	7.03	120	15.33
150	22.42	7.42	150	15.25
180	22.64	7.64	180	15.15
210	22.75	7.75	210	15.1
240	22.75	7.75	240	15.04
			270	15

Table 10. Results of Drawdown test and Recovery to pumping well no.3

Drawdown test			Recovery test	
T(min)	D.W.L(m)	D.D(m)	T(min)	Recovery level(m)
1	9.64	1.39	1	9.34
2	10.03	1.78	2	9.14
3	10.21	1.96	3	9.01
4	10.32	2.07	4	8.92
5	10.38	2.13	5	8.87
6	10.42	2.17	6	8.82
7	10.47	2.22	7	8.78
8	10.51	2.26	8	8.74
9	10.54	2.29	9	8.72
10	10.56	2.31	10	8.69
15	10.66	2.41	15	8.6
20	10.73	2.48	20	8.54
25	10.78	2.53	25	8.5
30	10.81	2.56	30	8.46
35	10.84	2.59	35	8.44
40	10.87	2.62	40	8.42
45	10.89	2.64	45	8.4
50	10.9	2.65	50	8.39
55	10.92	2.67	55	8.37
60	10.93	2.68	60	8.36
70	10.95	2.7	70	8.34
80	10.97	2.72	80	8.33
90	10.98	2.73	90	8.32
120	11.02	2.77	120	8.29
150	11.03	2.78	150	8.27
			175	8.25

Table 11. Results of Drawdown test and Recovery to pumping well no.4

Drawdown test			Recovery test	
T(min)	D.W.L(m)	D.D(m)	T(min)	Recovery level(m)
1	11.5	0.4	1	22.12
2	12.08	0.98	2	21.66
3	12.3	1.2	3	21.27
4	12.69	1.59	4	20.84
5	13.11	2.01	5	20.42
10	14.42	3.32	10	19
15	15.75	4.65	15	18.67
20	16.33	5.23	20	18.43
25	16.57	5.47	25	18.22
30	16.84	5.74	30	18.08
35	17.1	6	35	17.91
40	17.22	6.12	40	17.79
45	17.36	6.26	45	17.66
50	17.5	6.4	50	17.52
55	17.71	6.61	55	17.41
60	17.84	6.74	60	17.3
70	18.08	6.98	70	17.16
80	18.3	7.2	80	17.03
90	18.52	7.42	90	16.87
120	21.11	10.01	120	14.73
150	21.44	10.34	150	12.95
180	21.7	10.6	180	12.32
210	22.87	11.77	210	11.98
240	22.87	11.77	240	11.67
			270	11.33
			300	11.10

Table 12. Results of Drawdown test and Recovery to pumping well no.5

Drawdown test			Recovery test	
T(min)	D.W.L(m)	D.D(m)	T(min)	Recovery level(m)
0	18.44	0	0	21.85
1	18.84	0.4	1	21.32
2	19.13	0.69	2	21.05
3	19.3	0.86	3	20.88
4	19.45	1.01	4	20.74
5	19.57	1.13	5	20.63
6	19.69	1.25	6	20.53
7	19.78	1.34	7	20.45
8	19.86	1.42	8	20.38
9	19.92	1.48	9	20.32
10	20	1.56	10	20.26
15	20.27	1.83	15	20
20	20.45	2.01	20	20.84
25	20.51	2.07	25	19.7
30	20.6	2.16	30	19.57
35	20.69	2.25	35	19.47
40	20.72	2.28	40	19.4
45	20.84	2.4	45	19.33
50	20.89	2.45	50	19.23
55	20.95	2.51	55	19.13
60	21.03	2.59	60	19.05
70	21.12	2.68	70	18.92
80	21.17	2.73	80	18.82
90	21.31	2.87	90	18.73
120	21.55	3.11	120	18.55
150	21.71	3.27	150	18.44
180	21.77	3.33		
210	21.82	3.38		
240	21.85	3.41		
270	21.85	3.41		

Table 13. Results of Drawdown test and Recovery to pumping well no.6

Drawdown test			Recovery test	
T(min)	D.W.L(m)	D.D(m)	T(min)	Recovery level(m)
5	9.05	0.95	5	11.15
10	9.08	0.98	10	10.97
15	9.13	1.03	15	10.79
20	9.21	1.11	20	10.59
25	9.31	1.21	25	10.42
30	9.4	1.3	30	10.34
40	9.49	1.39	35	10.27
45	9.58	1.48	40	10.22
50	9.67	1.57	45	10.15
55	9.74	1.64	50	10.1
60	9.81	1.71	55	10.03
70	9.96	1.86	60	9.95
80	10.13	2.03	70	9.88
90	10.25	2.15	80	9.82
120	10.53	2.43	90	9.77
150	11.17	3.07	120	9.57
180	11.36	3.26	150	9.4
210	12.19	4.09	180	9.15
240	12.23	4.13	210	9.03
270	12.25	4.15	240	8.83
300	12.25	4.15	270	8.63
			300	8.45
			330	8.3
			360	8.2
			390	8.15
			420	8.10

Table 14. Results of Drawdown test and Recovery to pumping well no.7

Drawdown test			Recovery test	
T(min)	D.W.L(m)	D.D(m)	T(min)	Recovery level(m)
1	13.13	12.13	1	19.28
2	13.23	12.23	2	19.1
3	13.36	12.36	3	18.78
4	13.52	12.52	4	18.66
5	13.68	12.68	5	18.38
10	14.25	13.25	10	17.83
15	15	14	15	17.43
20	15.65	14.65	20	16.84
25	15.85	14.85	25	16.59
30	16.4	15.4	30	16.22
40	16.77	15.77	40	16.12
50	17.14	16.14	50	15
60	17.57	16.57	60	15.88
90	18.26	17.26	90	14
120	18.54	17.54	120	13.67
150	18.96	17.96	150	13.35
180	19.25	18.25	180	13.11
210	19.38	18.38	210	13
240	19.38	18.38		
270	19.38	18.38		

Table 15. Results of Drawdown test and Recovery to pumping well no.8

Drawdown test			Recovery test	
T(min)	D.W.L(m)	D.D(m)	T(min)	Recovery level(m)
1	14.08	0.08	1	15.81
2	15.03	1.03	2	15.5
3	15.54	1.5	3	15.28
4	15.68	1.68	4	15.2
5	15.78	1.78	5	15.1
10	16	2	10	14.96
15	16.14	2.14	15	14.83
20	16.21	2.21	20	14.76
25	16.25	2.25	25	14.68
30	16.31	2.31	30	14.65
40	16.35	2.35	40	14.56
50	16.41	2.41	50	14.50
60	16.48	2.48	60	14.46
90	16.55	2.55	90	14.37
120	16.62	2.62	120	14.3
150	16.68	2.68	150	14.28
180	16.71	2.71	180	14.25
210	16.71	2.71	210	14.2
			240	14.1
			270	14

Table 16. Results of Drawdown test and Recovery to pumping well no.9

Drawdown test			Recovery test	
T(min)	D.W.L(m)	D.D(m)	T(min)	Recovery level(m)
1	25.19	5.99	1	50.11
2	28	8.8	2	49.89
3	37	17.8	3	48
4	48.86	29.66	4	47.09
5	54.49	35.29	5	46.33
10	58	38.8	10	39
15	58.15	38.95	15	32
20	58.25	39.05	20	29.11
25	58.33	39.13	25	27.88
30	58.4	39.2	30	26.45
40	58.49	39.29	40	25
50	58.55	39.35	50	23.87
60	58.64	39.44	60	22.08
90	58.82	39.62	90	21.21
120	59.93	40.73	120	20.73
150	59.15	39.95	150	19.55
180	59.15	39.95	180	19.38
			210	19.20

The hydraulic parameters (T, K, and S) derived from the pumping tests reveal significant insights into the nature of the Quaternary aquifer and indicate a complex and heterogeneous hydrogeological system, as evidenced by the varying results of the pumping test analysis. The high-productivity zone is represented by wells 1, 8, and 9 : Well 8 stands out with the highest values ($T \approx 559 \text{ m}^2/\text{d}$ and $K \approx 11.1 \text{ m/d}$). This suggests that these wells are located within alluvial fan deposits composed of thick, well-sorted sandy gravel, providing the highest groundwater potential. The low-productivity zone is represented by Wells 4 and 6. Well 4 shows remarkably low values ($K \approx 0.27 \text{ m/d}$). This indicates a facies change where the aquifer material transitions into finer sediments, such as silty sand or clayey lenses, which significantly restrict groundwater flow. The storativity(S) values provide critical evidence regarding the aquifer's confinement status; wells (1, 5, 6, 7, 8, and 9) show (S) values ranging from 0.1 to 0.3. These are typical values for an unconfined aquifer, where water was released through the gravity drainage of pores. Wells 2 and 3 show lower (S) values (0.003–0.03). This indicates leaky or semi-confined conditions in these specific locations, likely caused by localized overlying silt or clay layers (confining units) within the Quaternary sediments.

Table 17 and Fig. 5 show that a clear relationship can be observed between the plotted drawdown behavior and the estimated aquifer characteristics from both the Theis (1935) and Cooper–Jacob (1946) methods. The graphs for most wells show good agreement between observed data and model fits, as demonstrated by the table, which shows that transmissivity(T) and hydraulic conductivity (K) values from both methods are very close. For example, Wells 5, 6, 8, and 9 in the table have nearly identical (T) values, and their corresponding graphs show a strong alignment between the Theis type curves and the Cooper–Jacob straight lines, indicating relatively homogeneous hydraulic behavior, and dependable late-time data. The graphs in wells 1, 3, and 7 show minor deviations, particularly at early or late times, which correspond to the table's low transmissivity values. These differences suggest that the Cooper–Jacob method, which is based on late-time linear trends, may overlook some early-time dynamics that the Theis method captures more effectively. This is particularly evident in the Theis plots, where curvature and late-time drawdown drop (observed in multiple wells) suggest boundary effects or aquifer heterogeneity.

Table 17. Hydraulic characteristics of pumping results

Well No.	Solution method	T(m ² /d)	K(m/d)	S
1	Theis (1935)	306	7.64	0.1
	Cooper-Jacob (1946)	263	6.57	0.1
2	Theis (1935)	296.2	5.92	0.01
	Cooper-Jacob (1946)	275.1	5.92	0.03
3	Theis (1935)	217	8.03	0.01
	Cooper-Jacob (1946)	244.3	9.04	0.003
4	Theis (1935)	13.11	0.26	0.5
	Cooper-Jacob (1946)	14.02	0.28	0.4
5	Theis (1935)	306.8	5.57	0.1
	Cooper-Jacob (1946)	306.8	5.57	0.1
6	Theis (1935)	29.4	1.17	0.1
	Cooper-Jacob (1946)	29.9	1.19	0.1
7	Theis (1935)	129.3	4.30	0.1
	Cooper-Jacob (1946)	141.16	4.71	0.1
8	Theis (1935)	554.3	11.09	0.3
	Cooper-Jacob (1946)	559	11.18	0.3
9	Theis (1935)	169.9	9.43	0.1
	Cooper-Jacob (1946)	174.2	9.6	0.1

The graphs reflected the variability in storativity (S) values as shown in Table 7. Wells 2 and 3, for example, show significant differences in (S) between the two methods, which corresponds to the observed curvature in their Theis plots and the less perfect linearity in the Cooper-Jacob plots. This confirms that storativity is more sensitive to early-time data, which is not fully represented by the Cooper-Jacob approach.

Additionally, the plots show that the transmissivity values vary widely between wells, with well 4 having a very low value and well8 having a very high value, evident in the graphs through differences in slope and drawdown magnitude. Wells with high transmissivity (Well 8) show gentler slopes and smaller drawdown changes, while low transmissivity wells (Well 4) show steeper responses.

Overall, Table 17 supports the graphical interpretation by confirming that both methods yield consistent transmissivity and conductivity values, while differences in storativity and curve behavior highlight the limitations of the Cooper-Jacob method and the more comprehensive nature of the Theis solution.

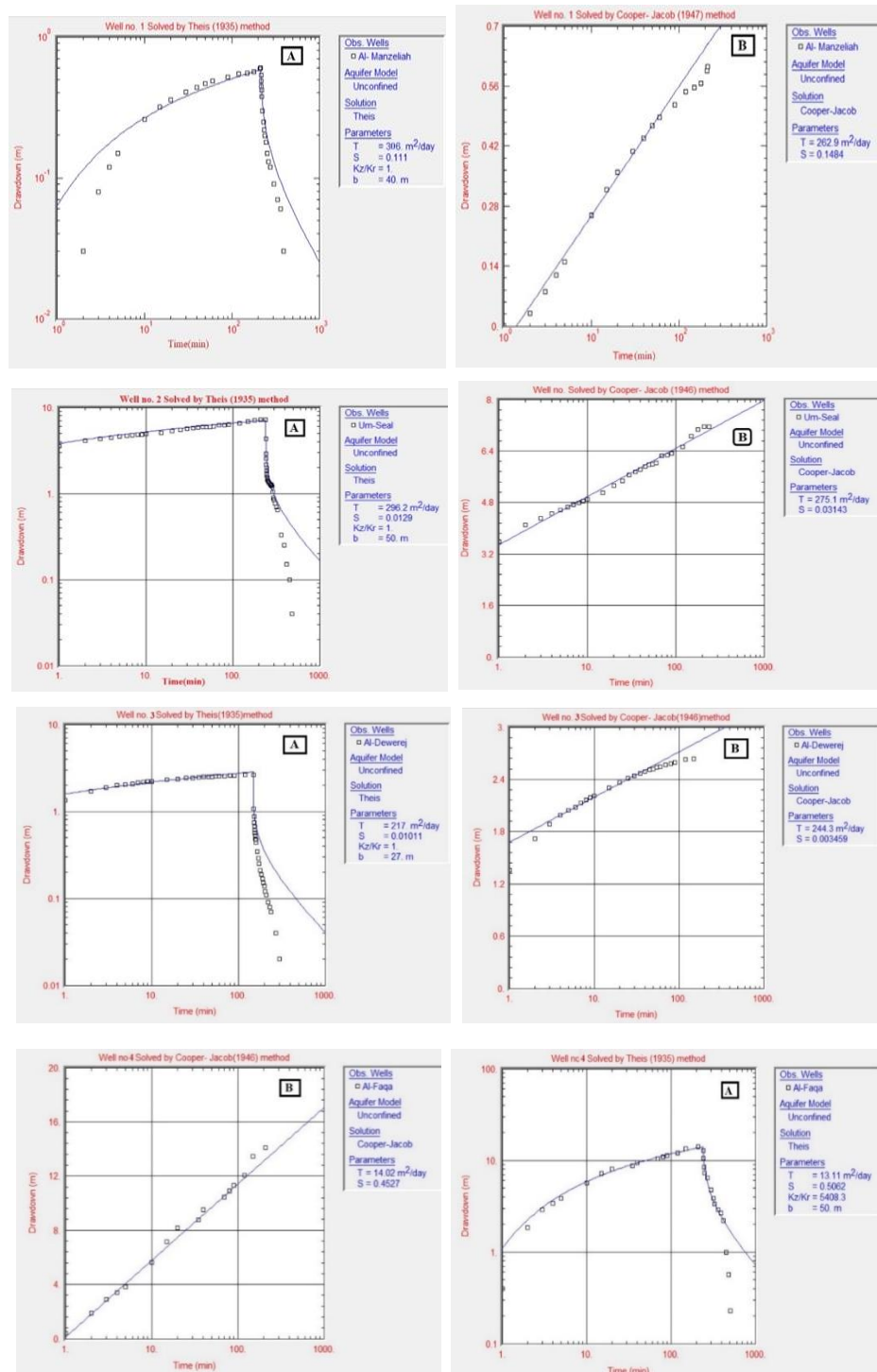


Fig. 5. Curve fitting of pumping test analysis (w1,w2,w3 and W4)

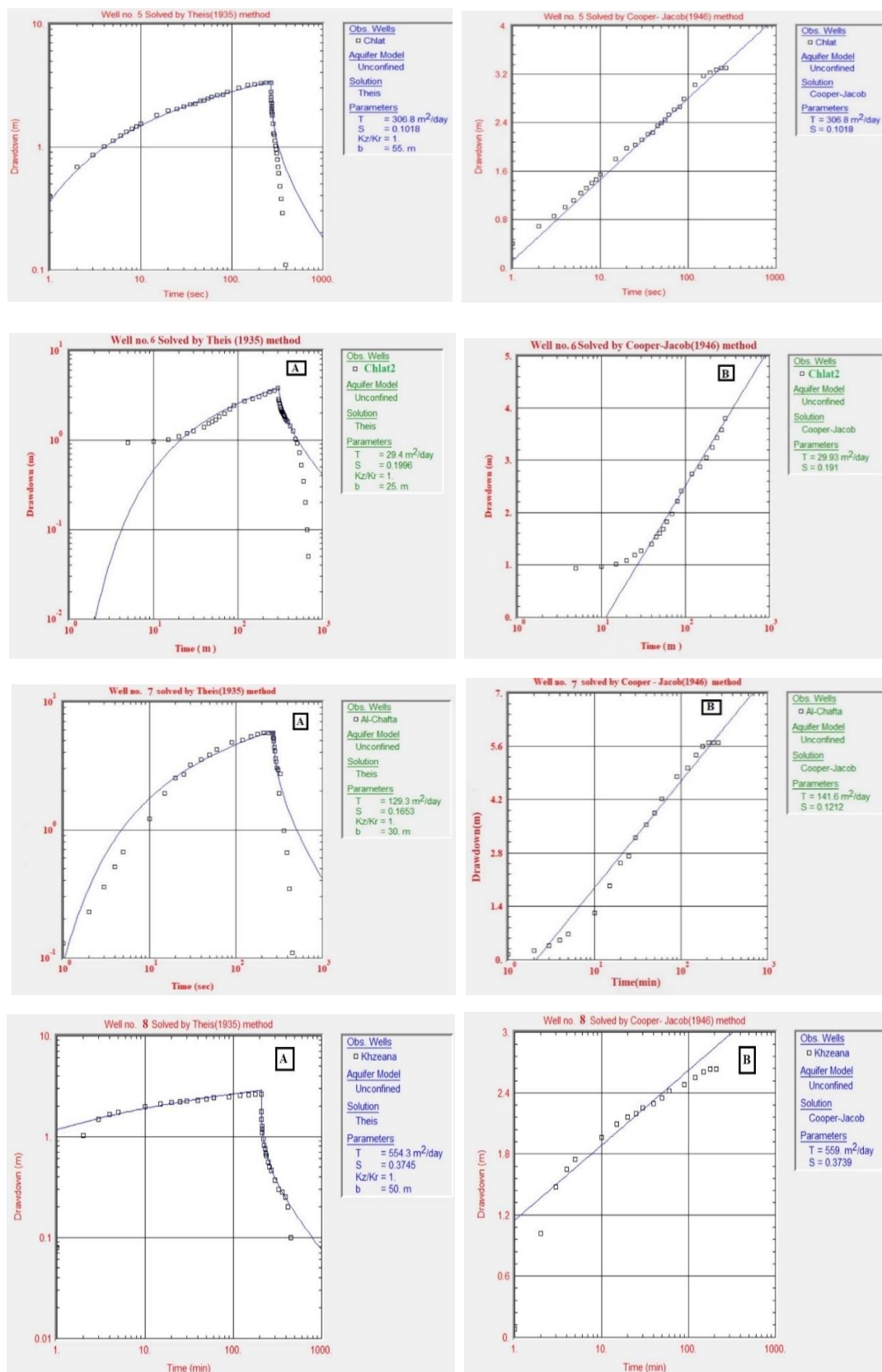


Fig. 5. Continue (w5, w6,w7and w8)

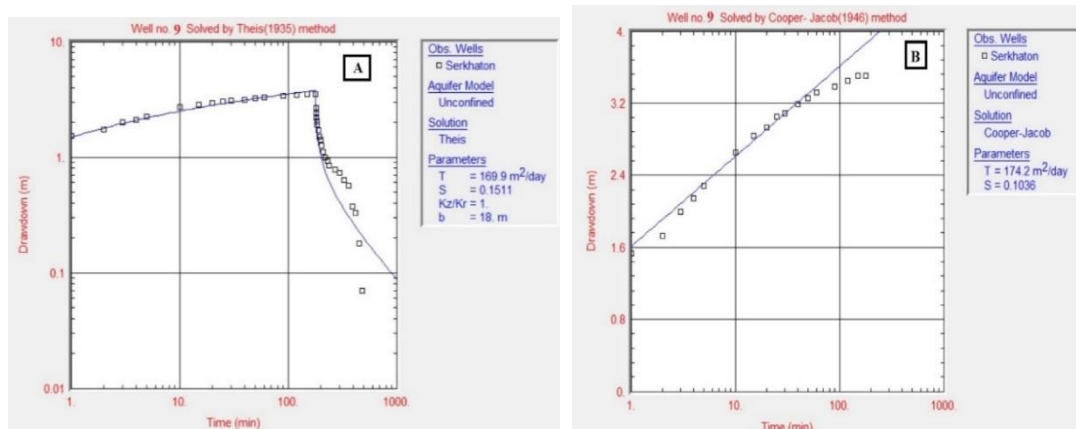


Fig. 5. ... Continue well (w9)

3.3. Spatial Distribution of Aquifer and Aquifer Hydraulic Characteristics

The spatial distribution of aquifer characteristics in the study area is shown in Fig. 6. Spatial distribution analysis reveals significant variation in the productivity (Q) of wells distributed throughout the study area, ranging from approximately 5 L/s to 26 L/S, Fig. 6a. This range reflects differences in the potential for groundwater exploitation within the aquifer, with the highest productivity in the northeastern and eastern parts of the study area, ranging from 17 to 26 l/s. This is attributed to the thickness of the aquifer in these areas. Well productivity decreases in the western and southeastern parts due to the reduced thickness of the saturated aquifer.

The significant variation in saturated aquifer thickness(b), ranging from approximately 19 to 55 m (Fig. 6b), reflects differences in groundwater storage capacity within the aquifer, with the highest thicknesses in the northeastern and eastern parts of the study area, ranging from 39 to 55 m, characterized by alluvial fan deposits. The saturated aquifer thickness gradually decreases towards the western parts. In these peripheral areas, saturated aquifer thickness typically ranges from 19 to 27 m. The reduced saturated thickness is attributed to a combination of factors, including low recharge rates and variations in the underlying sediment types, particularly the alluvial fans that mark the eastern end of the study area. These areas generally support lower groundwater storage volumes compared to the central, northeastern, and eastern parts of the study area.

The groundwater depth (SWL), Fig. 6c, shows considerable variability, with values ranging from 1 to 60 m. with spatial variations attributed to disparities in hydrogeological controls, specifically, recharge mechanisms, pumping stress, subsurface lithology, and topographic configuration. The southern and western parts of the study area are characterized by relatively shallow groundwater depths ranging approximately from 1 to 8 m. In the central parts of the study area, groundwater depths generally range between 8 and 20 m. In contrast, the northern and northeastern sectors exhibit the greatest groundwater depths, ranging from about 30 m to 60 m. This spatial pattern suggests a general increase in groundwater depth from the southern part of the study area toward the northern and northeastern directions.

The hydraulic head (H) of groundwater in the study area reveals a distinct gradient, declining from the east and northeast toward the west and southeast, which reflects the prevailing direction of groundwater flow, Fig. 6d. The eastern and northeastern region exhibits the highest hydraulic head values, ranging from approximately 47 to 67 m. The central part of the study area, the hydraulic head gradually declines to 27-35 m, reflecting a transitional hydraulic gradient and indicating groundwater flow along from zones with high hydraulic head towards zones with low hydraulic head, the hydraulic head continues to decline, reaching values of approximately 10–16 m in the west and southeast.

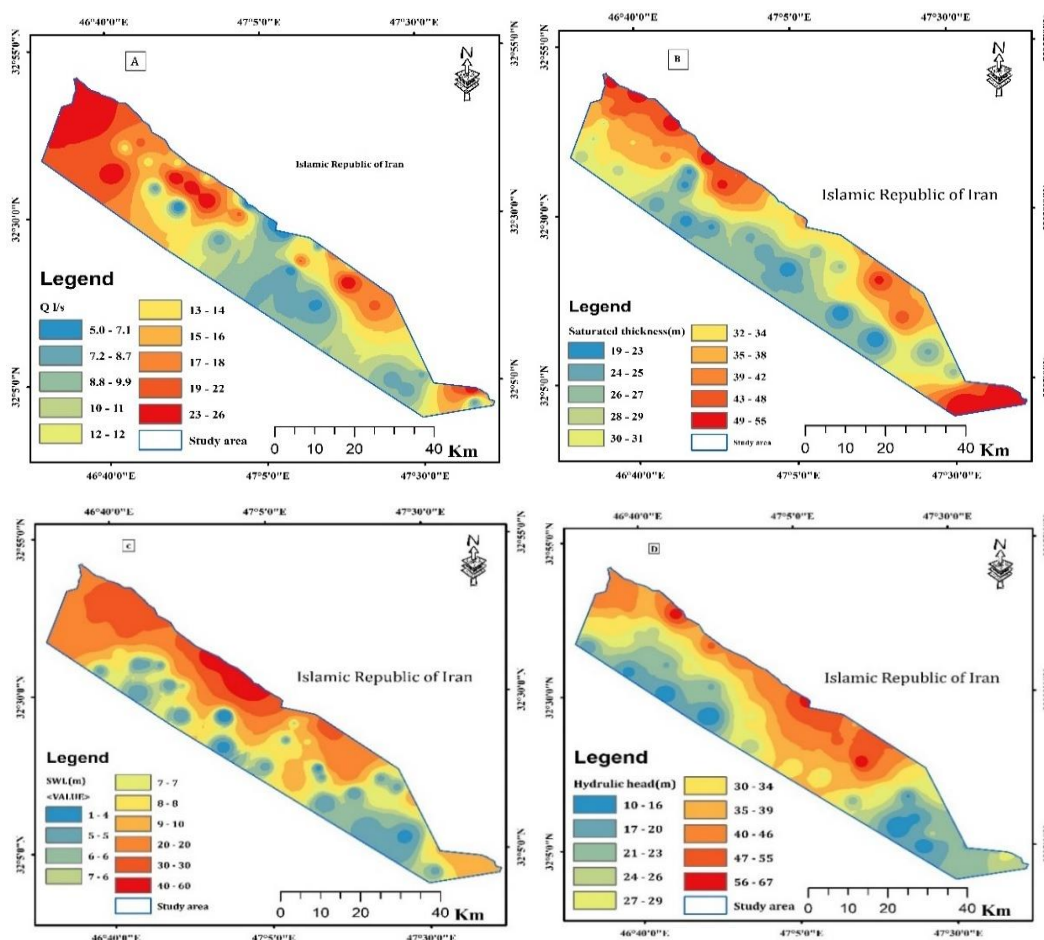


Fig. 6 Spatial distribution of aquifer characteristics data a) Well discharge, b) Saturated thickness, c) Static water levels, d) Hydraulic head

The hydraulic characteristics of the aquifer derived from pumping tests (9 wells), Table 7, and archival data from 23 wells distributed throughout the study area were used as input to reveal the spatial distribution of these characteristics. The spatial distribution of transmissivity (T), Fig. 7a reveals considerable heterogeneity. Transmissivity increases gradually from the northern and northeastern parts of the study area to the central and southern sectors. High transmissivity values (260–610 m²/d) characterize the northern and northeastern zones. Moving west and southward, transmissivity gradually declines to low levels (18–110 m²/d), indicating possible lithological variations or structural heterogeneity within the aquifer.

Fig. 7b, shows high storativity (S) values in the northeastern part of the region indicate zones with greater porosity and permeability, which range from 0.2 and 0.3, and are represented by alluvial fans of coarse sediments, making them favorable for groundwater storage and extraction. Moving toward the central and southwestern parts, the storativity gradually decreases, ranging from (0.04 to 0.03), suggesting the presence of finer-grained sediments such as clay or silt, which limit water storage and movement. This northeast-to-southwest declining trend highlights a possible geological or depositional gradient influencing aquifer properties. Additionally, isolated low-storativity pockets within moderate zones point to local heterogeneity in subsurface conditions.

The spatial distribution of hydraulic conductivity (K), Fig. 7c reveals significant heterogeneity, with values ranging from 0.55 to 6.7 m/d. The highest hydraulic conductivity values (5.4 – 6.7 m/d) are concentrated mainly in the northeastern part of the study area. Another relatively high conductivity is observed in the eastern and southeastern parts of the study area, suggesting highly permeable deposits,

represented by alluvial fans. In the central parts the hydraulic conductivity was moderate, which ranged between (4.7 – 5.8m/d). The lowest hydraulic conductivity values (approximately 1.5–4.1 m/d) are mainly observed in several scattered zones along the western and southwestern parts of the study area, which are characterized by fine-grained deposits .

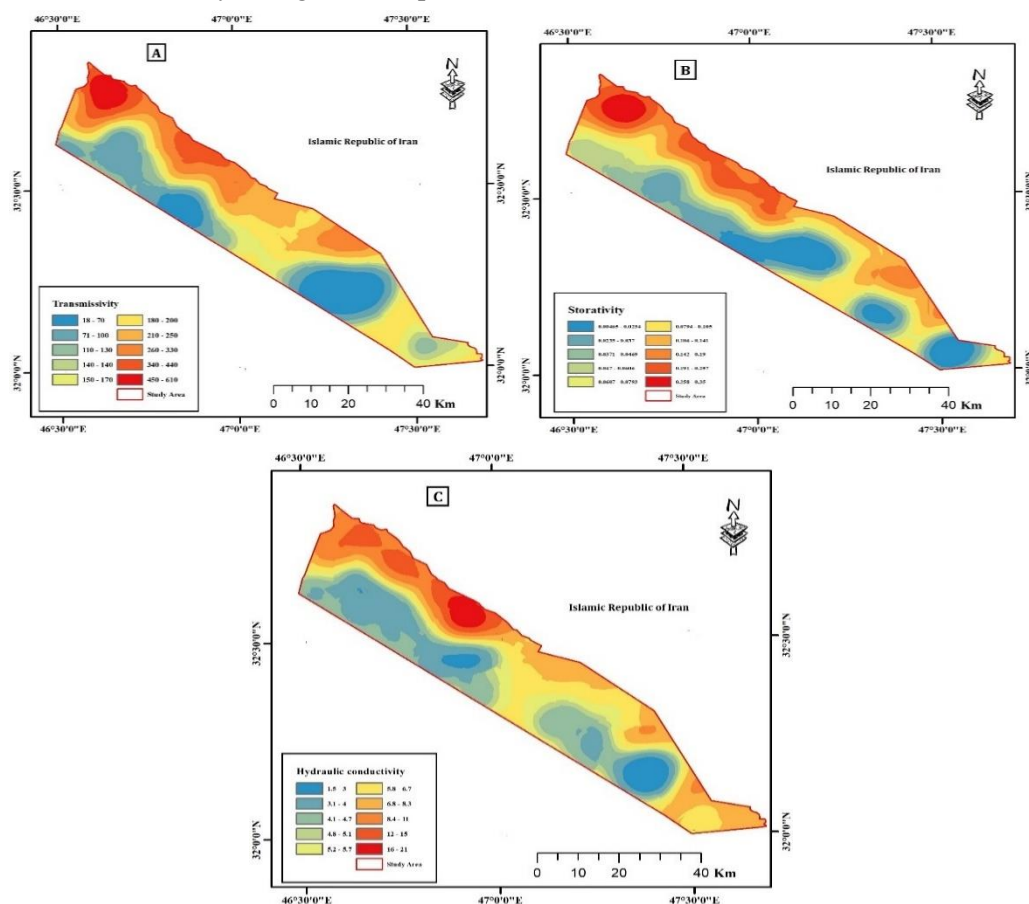


Fig. 7. Spatial distribution of aquifer hydraulic characteristics a) Transmissivity, b) Storativity, c) Hydraulic conductivity

4. Conclusions

The aquifer is unconfined, based on the storativity values, and the aquifer exhibited favorable hydraulic properties, characterized by moderate to high transmissivity and hydraulic conductivity values, with transmissivity (T) ranging from approximately 13 to 559 m²/day, hydraulic conductivity (K) ranging from 0.26 to 11.18 m/day, storativity (S) indicating good groundwater storage capacity, which ranged from 0.003 to 0.10; these values confirm that the aquifer has a significant ability to transmit and store groundwater. Hydraulic head, aquifer thickness and static water levels show considerable spatial variability in the study area, The results reveal a highly heterogeneous aquifer system, with strong spatial variation in hydraulic parameters. This heterogeneity is mainly controlled by lithological differences, particularly the contrast between coarse alluvial fan deposits and fine-grained sediments. The northeastern and eastern parts of the study area represent the most productive zones, due to the dominance of coarse sand and gravel deposits associated with alluvial fan deposits. While the western and southwestern parts show lower productivity due to finer sediments such as silt and clay, and reduced aquifer thickness, which restricts groundwater flow. The aquifer represents a strategic and sustainable groundwater resource for the region. However, increasing demand and overexploitation require careful groundwater management, controlled pumping strategies, and protection of high-potential zones from depletion

Author Contributions: CRediT**Declaration of Competing Interest****Acknowledgments**

I would like to express my sincere gratitude to all the staff of the Groundwater Department in Maysan, especially Dr. Fadhil Qasim Jabbar, the department director. I also extend my thanks to the Geology Department at the University of Basra for their continued support, and to the professors who will review the research to ensure its professional quality.

Funding Sources

This research did not receive any specific funding from any donor, whether public, commercial, or non-profit.

Data Availability

The data supporting the findings of this study are publicly available. Access to the data may be requested from the responsible author under the appropriate terms and conditions

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