Iraqi National Journal of Earth Science
www.earth.mosuljournals.com

Evaluation of Groundwater in Makhmur District for Irrigation Purposes Using Artificial Intelligence

Abid Mohammed Rashid Al-Saffah [1], Mohammed Hazim Sabry Al-Mashhadany [2*]
[1,2]*Department of Chemistry, College of Education for Pure Sciences, University of Mosul, Mosul, Iraq.*

Article information

Received: 12- Mar -2024

Revised: 13- May -2024

Accepted: 12- Jul -2024

Available online: 01- Jul – 2025

Keywords:
Irrigation
Fuzzy logic
Makhmour
SAR
Groundwater

Correspondence:
Name: Mohammed Hazim Sabry Al-Mashhadany

Email: mohammedhazemm@uomosul.edu.iq

ABSTRACT

Groundwater occupies the forefront in areas where there is no surface runoff from streams and rivers. Therefore, it becomes a natural resource that can be relied upon to develop the areas where it exists if investments are made rationally and thoughtfully, especially in agriculture. Groundwater is studied in the Makhmur district. The research objectives are to highlight the suitability of groundwater for irrigation using one of the methods of artificial intelligence by studying the chemical properties and calculating irrigation coefficients (PI, PS, SAR, MAR, KR, Na%, and RSC) and comparing them with the international standards, then the spatial distribution of irrigation coefficients for the study area is studied. The results of the irrigation classification using artificial intelligence, using the Fuzzy method, showed that 4 wells were classified as poor, 9 wells were very poor, and one well was unsuitable. The spatial distribution shows that the best places for FIGQ were in the West of the study area, in contrast to the southern region, where electrical conductivity increases significantly.

DOI:10.33899/earth.2024.147722.1245,

تقييم المياه الجوفية في قضاء مخمور لأغراض الري باستخدام الذكاء الاصطناعي

عبد محمد رشيد السفاح [1] ، محمد حازم صبري المشهداني [2]*
[2،1] قسم الكيمياء، كلية التربية للعلوم الصرفة، جامعة الموصل، الموصل، العراق.

معلومات الارشفة

تاريخ الاستلام: 12- مايو -2024
تاريخ المراجعة: 13- يونيو -2024
تاريخ القبـول: 12- أغسطس -2024
تاريخ النشر الالكتروني: 01- يناير -2025

الكلمات المفتاحية:
الري
المنطق الضبابي
مخمور
SAR
المياه الجوفية

المراسلة:

الاسم: محمد حازم صبري المشهداني
Email: mohammedhazemm@uomosul.edu.iq

الملخص

تحتل المياه الجوفية الصدارة في المناطق التي لا يوجد فيها جريان سطحي من الجداول والأنهار . ولذلك تصبح مورداً طبيعياً يمكن الاعتماد عليه لتنمية المناطق التي توجد فيها، إذا تم استثمارها بشكل رشيد ومدروس، خاصة في المجال الزراعي. تمت دراسة المياه الجوفية في قضاء مخمور . أهداف البحث هي تسليط الضوء على صلاحية المياه الجوفية للري باستخدام إحدى طرق الذكاء الاصطناعي من خلال دراسة الخواص الكيميائية وحساب معاملات الري (PI و Na% و KR و MAR و SAR و PS و RSC) ومن ثم مقارنتها بالمعايير الدولية. وتمت دراسة التوزيع المكاني لمعاملات الري لمنطقة الدراسة. أظهرت نتائج تصنيف الري باستخدام الذكاء الصناعي بطريقة Fuzzy أن 4 آبار صنفت بالفقيرة، و 9 آبار فقيرة جدا، وبئر واحد غير مناسب. وأظهر التوزيع المكاني أن أفضل الأماكن لـ FIGQ كانت في الجانب الغربي من منطقة الدراسة، على عكس المنطقة الجنوبية التي تزداد فيها التوصيلية الكهربائية بشكل ملحوظ.

DOI: 10.33899/earth.2024.147722.1245, ©Authors, 2025, College of Science, University of Mosul.

Introduction

Groundwater is an important natural resource in various parts of the Earth, especially in arid and semi-arid regions. Throughout human history, groundwater has been supplied by springs and wells. The issue of groundwater cannot be neglected in the study of a populated area. It is the main source that provides this region with the means of life, and without it, stability would have become impossible, as in the Makhmur district (Al-Mashhadany 2021). One of the artificial intelligence methods, namely fuzzy logic, was used to model the chemical elements in groundwater. Artificial intelligence is one of the computer sciences that aims to understand the complex mental processes that the human mind performs while thinking (Ataei et al., 2024). Then, translating these mental operations into equivalent computer operations increases the computer's ability to solve complex problems (Chidambaram, Prasanna et al. 2022). The process of fuzzification is the conversion of crips input values to fuzzy sets (Dhaoui, Agoubi et al. 2023). Then, the fuzzy rule laws, in which the relationship between the system's inputs and its outputs is determined, then the fuzzy inference engine (Bajić, Polomčić et al. 2017). It is responsible for the conclusion of the system's outputs from the system's inputs in a specific way according to the rule of fuzzy laws (Dhaoui, Agoubi et al. 2023). Finally, the process of converting to defuzzification is to convert the output to a digital image again. Fuzzy logic is based on one input (number of parameters) and one output. There are two models of fuzzy logic, namely Mamdani and Sagino; the first model is on which our research is dependent (Yazdi, Robati et al. 2024).

Spatial distribution maps of the study area are also used for irrigation coefficients. It gives a clear picture of suitable and unsuitable places for irrigation water for the study area. The study aims to highlight the suitability of groundwater in the study area by measuring chemical properties and calculating irrigation coefficients, and comparing them to international standards. Also developing a model to estimate groundwater quality for irrigation using fuzzy logic (Mallik, Mishra et al. 2021, Kuchelar, Ramesh et al. 2022).

Study area

Makhmur District is located in the southeast of Nineveh Governorate within the region's undulating plains, with an altitude of 270 meters above sea level, between latitudes (35.60213 – 35.83502) north and longitudes (43.35076 – 43.57904) east. The study area is bordered to the west by the Qarachog Mountains, to the East by the Tigris River, to the south by the Lower Zab, and to the north by the Upper Zab (Majeed, Al-Tawash et al. 2024). The area of the study area is 1000 km^2 in the area of Makhmur District, which is 2955 km^2, as shown in Figure 1 and Table 1. Due to the scarcity of water sources within the study area, most of its farmers depend on groundwater to irrigate their crops, while other parts depend on rainwater. The district is famous for its fertile soil, but it lacks irrigation projects that provide the opportunity to develop agriculture.

Given the lowest percentage of rainfall in the study area, the quantities of agricultural production often decline, especially grains, which depend mainly on rain during years of drought and scarcity of rain. The results obtained show that the average depth of the wells in the study area is 63 m. The lowest depth recorded, 25 m, is in well No. 9, located in the east of the study area. The maximum depth is recorded at 150 m at Well No. 11, located in the south of the study area (Table 1 and Figure 1). The wells are divided into three groups: the first near the Tigris River, the second near Mount Oarachog, and the third to the south of the study area.

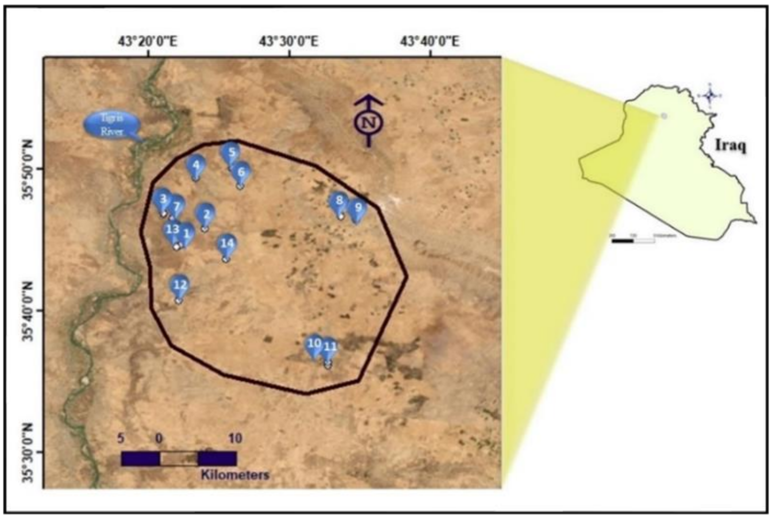


Fig. 1. Map showing the area of wells within the Makhmur district.

Table 1: Coordinates and depth of the studied wells.

Wells	E	N	Depth (m)
1	43.37091	35.74511	60
2	43.40050	35.76406	52
3	43.35076	35.78210	36
4	43.38896	35.82288	48
5	43.43205	35.83502	35
6	43.44224	35.81396	42
7	43.36158	35.77503	60
8	43.56078	35.77768	75
9	43.57904	35.77485	25
10	43.54614	35.60213	100
11	43.54553	35.60632	150
12	43.36875	35.67954	140
13	43.36722	35.74257	29
14	43.42544	35.72778	28

Experimental Work

The research method is based on using water analysis data from 14 wells in the study area between October 2023 and February 2024. The total number of samples is 140, with ten replicates. Clean plastic containers are used to collect and store samples. The samples are transferred directly to the laboratories of the University of Mosul to conduct chemical measurements within 24 hours to avoid errors that may result from the influence of environmental factors. Measurements are performed according to standard methods. They included pH, electrical conductivity (Portable device), cations such as calcium, magnesium (titration methods), sodium and potassium (flame photometry), and anions such as chloride (titration method), sulfate (Turbidity method), and bicarbonate (titration method)(E.W. Rice 2017) Irrigation coefficients are calculated based on the above measurements of cations and anions measured for each well, namely PI, PS, SAR, MAR, KR, Na%, and RSC (meq/l), as in the following equations (Westcot 1985):

$$PI = [Na + (\sqrt{HCO_3})/Ca + Mg + Na] \times 100$$

$$PS = Cl + 1/2\,SO_4$$

$$SAR = Na/\sqrt{Ca + Mg/2}$$

$$MAR = [Mg/Ca + Mg] \times 100$$

$$KR = Na/Ca + Mg$$

$$Na\% = [Na/Na + K + Ca + Mg] \times 100$$

$$RSC = (CO_3 + HCO_3) - (Ca + Mg)$$

Modeling irrigation coefficients using fuzzy logic

The MATLAB b2023 program is used for numerical analysis and building a Mamdani-type fuzzy logic system model with eight inputs divided into two groups and one output for each input, as illustrated in Figure 2. Then, entering the previous outputs as inputs and one output as the final result, as represented by FIGQ. Each entry is divided into a fuzzy set into five categories: Excellent, Good, Poor, Very Poor, and Unsuitable (Mallik, Mishra et al. 2021). The previous categories are divided based on choosing a membership activation function appropriate to the nature of the data using triangular membership functions. Each fuzzy set has a range of data (Al-Rashidi, Sabarathinam et al. 2023, Thabrez and Parimalarenganayaki 2023) (Figs. 2,3 and Table 2).

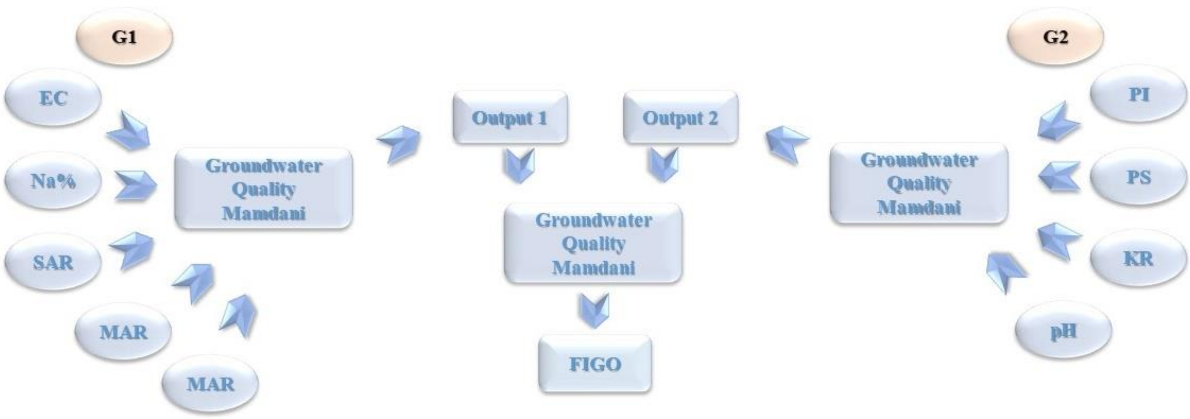


Fig. 2. Membership functions of the FIGQ.

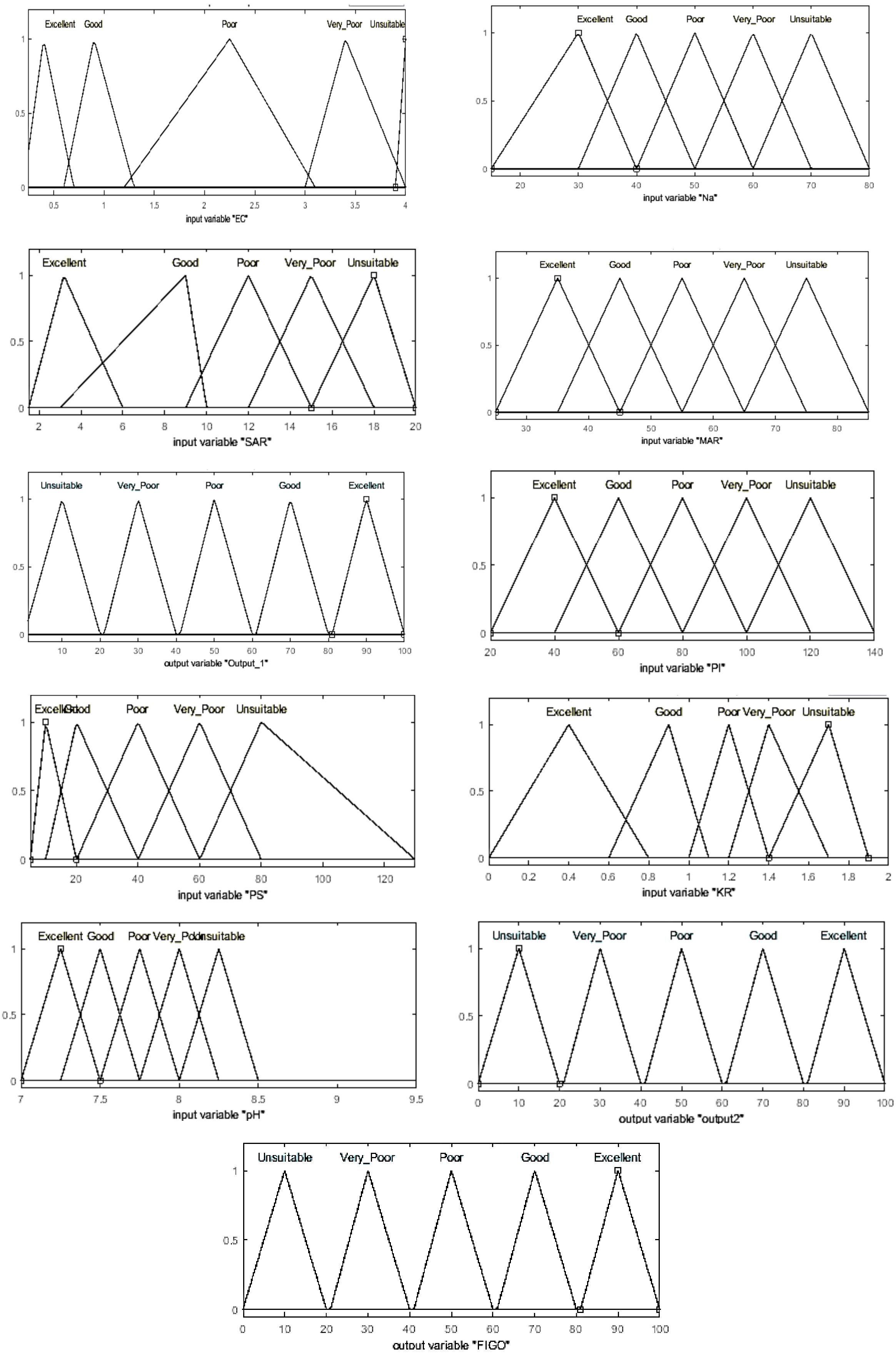


Fig. 3. Fuzzy set functions.

Table 2: Parameters for membership functions used in the FIGQ (Al-Saffawi and Al-Barzanji 2020)

parameter	standard	Unsuitable			Very Poor			Poor			Good			Excellent		
EC_{25}	2.9	3.9	4	26.53	3	3.4	4.0	1.2	2.25	3.1	0.6	0.9	1.3	0.2	0.4	0.7
Na%	60	60	70	80	50	60	70	40	50	60	30	40	50	15	30	40
SAR	9	15	18	20	12	15	18	9	12	15	3	9	10	1.5	3	6
MAR	50	65	75	85	55	65	75	45	55	65	35	45	55	25	35	45
Output 1	1-100	0	10	20	21	30	40	41	50	60	61	70	80	81	90	100
PI	75	100	120	140	80	100	120	60	80	100	40	60	80	20	40	60
PS	10	60	80	130	40	60	80	20	40	60	10	20	40	5	10	20
KR	1	1.4	1.7	1.9	1.2	1.4	1.7	1	1.2	1.4	0.6	0.9	1.1	0	0.4	0.8
pH	6.5-8.5	8	8.25	8.5	7.75	8	8.25	7.5	7.75	8	7.25	7.5	7.75	7.0	7.25	7.5
Output 2	1-100	0	10	20	21	30	40	41	50	60	61	70	80	81	90	100

Spatial distribution maps

Spatial distribution maps are obtained using the Kriging method within a GIS environment using ArcGIS 10.6 software developed by the Environmental Systems Institute (Al-Mashhadany 2022). The method is classified as one of the estimated spatial interpolation methods. The kriging method assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in surfaces. An exploratory statistical analysis of the data is accomplished. It consists of several steps, including exploratory statistical analysis of data, modeling of variables, and surface construction. It is most appropriate when we know that there is a spatially connected distance. It is often used in soil science, geology, and groundwater. When there is a spatial correlation, it is often used in soil sciences, geology, and groundwater (Hameed 2013, Mahammad, Islam et al. 2023).

Results and Discussion

The pH results of groundwater in the study area show that the values range between 6.6 - 7.9, and the standard deviation is relatively low (0.1 - 0.4). It is also within the normal permissible range for irrigation (6.5 – 8.5) as recommended by (Ayers 1999).

Table 3: Min., Max., Mean, and SD of the characteristics of the groundwater sources under study.

Wells		EC_{25}*	Na%	SAR	MAR	PI	PS	KR	pH	RSC
1	**Min**	1.95	25	2.1	29	31	7	0.3	6.9	-20
	Max	2.75	53	6.6	65	58	39	1.1	7.9	-12
	Mean	2.10	33	3.1	44	39	18	0.5	7.6	-15
	SD	0.25	9.3	1.4	15.0	8.8	9.9	0.3	0.3	2.7
2	**Min**	8.20	14	1.6	46	17	43	0.2	7.2	-52
	Max	11.63	47	9.1	59	49	77	0.9	7.6	-47
	Mean	9.87	41	7.4	50	43	55	0.7	7.4	-50
	SD	1.21	9.7	2.2	4.0	9.4	10.5	0.2	0.1	1.7
3	**Min**	2.62	21	2	27	27	9	0.3	7.1	-25
	Max	3.07	43	5.6	56	48	43	0.8	7.9	-20
	Mean	2.92	30	3.3	38	35	20	0.4	7.4	-23
	SD	0.16	6.6	1.1	9.5	6.4	12.1	0.2	0.3	1.7
4	**Min**	5.73	11	1.5	38	14	25	0.1	6.6	-68
	Max	8.86	25	3.9	56	29	42	0.3	7.5	-46
	Mean	7.53	22	3.2	47	25	34	0.3	7.1	-59
	SD	1.26	4.1	0.7	5.7	4.1	5.9	0.1	0.3	7.2
5	**Min**	7.37	28	4	40	31	27	0.4	7.0	-47
	Max	9.09	44	7.7	57	47	59	0.8	7.3	-40
	Mean	7.84	40	6.7	46	43	41	0.7	7.2	-44
	SD	0.67	4.8	1.1	5.2	4.6	9.7	0.1	0.1	2.2
6	**Min**	6.29	22	2.6	13	25	21	0.3	7.1	-43
	Max	7.60	48	7.3	66	51	62	0.9	7.5	-28
	Mean	6.66	35	4.8	33	38	37	0.6	7.3	-36
	SD	0.50	8.3	1.5	18.0	8.4	13.8	0.2	0.1	6.7
7	**Min**	2.04	13	1	44	19	11	0.2	7.1	-31
	Max	2.89	25	2.8	62	30	30	0.3	7.6	-17
	Mean	2.46	18	1.7	53	24	17	0.2	7.3	-24
	SD	0.36	4.7	0.6	5.4	4.2	7.8	0.1	0.1	4.9
8	**Min**	4.11	10	1.1	44	14	16	0.1	7.0	-48
	Max	6.21	25	3.3	56	28	53	0.3	7.3	-42
	Mean	5.63	19	2.4	48	22	31	0.2	7.2	-45
	SD	0.62	4.2	0.6	3.7	4.0	11.4	0.1	0.1	1.8
9	**Min**	3.84	14	1.6	20	18	16	0.2	6.8	-45
	Max	4.83	23	2.9	47	27	52	0.3	7.9	-31
	Mean	4.21	19	2.2	38	23	26	0.2	7.1	-38
	SD	0.28	2.8	0.4	8.0	2.9	10.6	0.0	0.4	5.2

10	**Min**	9.07	29	6.1	48	30	72	0.4	7.1	-107
	Max	31.61	68	22	76	69	178	2.1	7.7	-51
	Mean	21.79	50	14.5	67	51	127	1.1	7.4	-85
	SD	10.64	10.9	6.1	11.2	10.6	45.6	0.5	0.2	26.1
11	**Min**	3.60	19	2.6	47	22	42	0.2	7.4	-56
	Max	11.92	53	12.4	65	55	67	1.1	7.7	-46
	Mean	6.38	40	7.3	58	42	58	0.7	7.5	-52
	SD	2.20	9.2	2.6	5.9	9.0	7.7	0.2	0.1	3.2
12	**Min**	3.22	30	3.2	11	35	21	0.4	6.7	-26
	Max	4.33	48	6.6	53	52	33	1.0	7.8	-21
	Mean	3.53	36	4.3	27	41	26	0.6	7.5	-24
	SD	0.31	6.4	1.2	14.0	6.1	3.8	0.2	0.3	1.7
13	**Min**	2.73	24	2.2	32	31	10	0.3	6.9	-23
	Max	3.03	32	3.6	43	38	29	0.5	7.8	-17
	Mean	2.90	28	2.7	38	35	16	0.4	7.2	-19
	SD	0.09	3.4	0.5	3.7	2.9	5.8	0.1	0.2	1.9
14	**Min**	5.83	20	2.5	21	24	26	0.3	7.1	-46
	Max	8.41	48	9.2	42	51	61	0.9	7.6	-32
	Mean	6.65	38	5.9	36	41	44	0.6	7.3	-39
	SD	0.82	8.6	2.0	6.6	8.4	12.6	0.2	0.1	3.7

*ds/m, Sodium Absorption Ratio (SAR), Percent Sodium (%Na), Residual Sodium Carbonate (RSC), Permeability Index (PI), Potential Salinity (PS), Kelly's Ratio (KR), Magnesium Absorption Ratio (MAR).

Figure 4 shows that there is a relative decrease in pH values in the northeast of the study area. This explains the high values of bicarbonate ions in the same place. These results are consistent with the findings of (Ramesh and Srinithi 2014), where pH values decrease with the increase in bicarbonate concentration in groundwater.

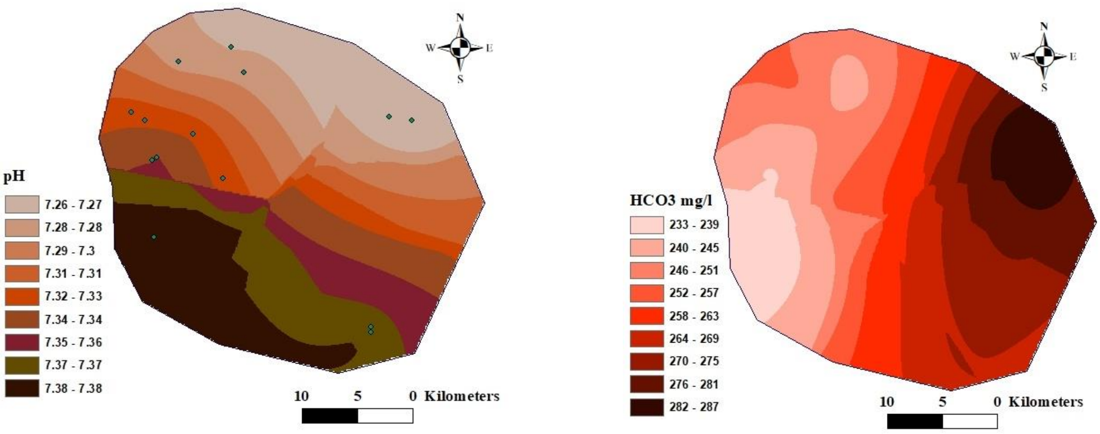


Fig. 4. Spatial distribution of pH and HCO_3^-

Water samples contain high concentrations of dissolved ions. The results show a wide variation in the values of the degree of electrical conductivity, as they range between (1.95-31.61) ds/m, and the SD± range between (0.09-10.64). The values are high at Well No. 10 (Riwalih village) due to farmers not using it at the beginning of the sample collection. After using the well, the electrical conductivity value decreases to 9.21 ds/m. Spatial distribution maps show the high electrical conductivity in the southernmost part of the study area (Mather 2020, Al-Mashhadany 2021) (Fig. 5).

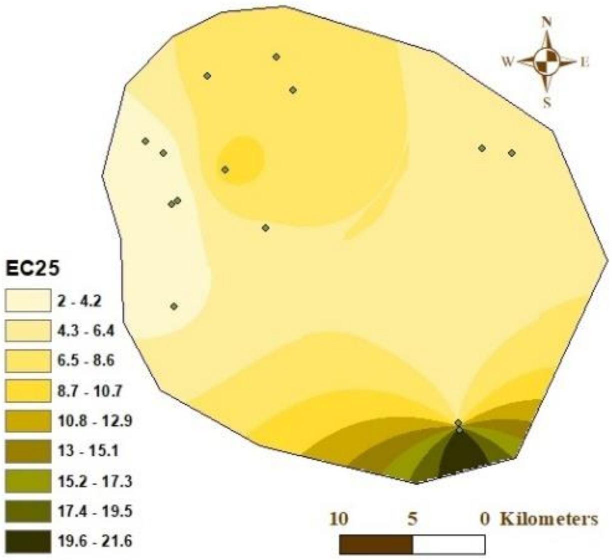
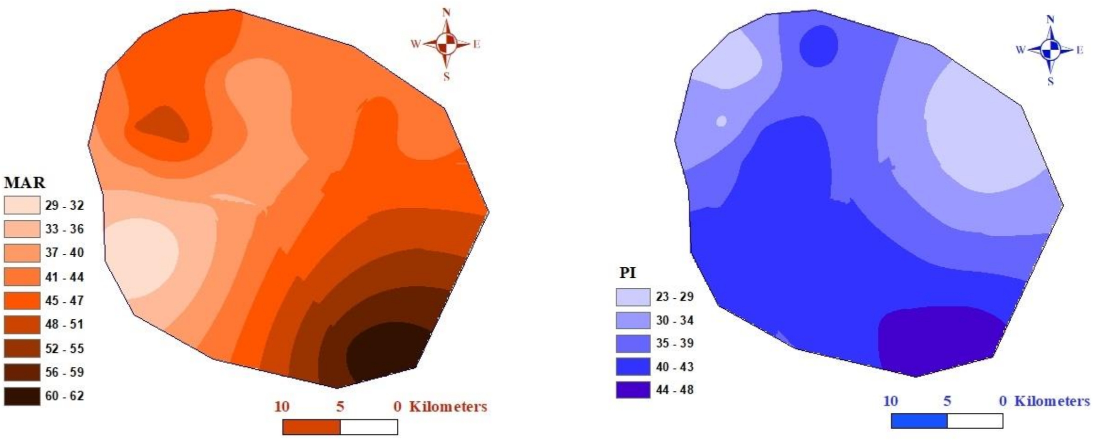


Fig. 5. Spatial distribution of EC_{25}.

Table (3) shows that the SAR values are between (1 - 22) with a mean ranging from (1.7 - 14.5) according to the classification of the Food and Agriculture Organization. Most of the well's water in the study area is within the permissible limits for irrigation. Therefore, it is not expected that problems related to the sodium adsorption rate will arise when used, except for Well No. (10) (Akintola, Bodede et al. 2017). The harmful effect expected to occur when using high SAR water is the absorption of sodium onto the colloidal surfaces in the soil and its replacement with magnesium and other cations. Causing a decrease in the rate of soil permeability (Todd 1980) hardening of the soil at the surface, and damage to germination processes. The concentrations of irrigation standards Na%, MAR, KR, PS, and PI range between (10-68, 11-76, 0.1-2.1, 7-178, and 14-69), respectively. The highest concentrations are in well No. 10, and the lowest are in well No. 8 for Na%, KR, PI, and SAR, well No. 7 for PS, and well No. 12 for MAR. The significant increase in the PS value is due to the significant increase in the sulphate value due to the influence of the geological conditions within the Fatha Formation (Middle Miocene) (Al-Mashhadany 2021), whether in terms of its presence in groundwater reservoirs, or within the rock formations through which the filtered water passes to those underground reservoirs (Al-Mashhadany 2021, Majeed, Al-Tawash et al. 2024). Figure 6 shows that the spatial distribution pattern of irrigation coefficients is very similar to the spatial distribution pattern of the degree of electrical conductivity. Well No. 10 constitutes a place where dissolved ion concentrations are high on the northeastern side near Mount Qarachog, and on the western side of the study area, where the groundwater is affected by the waters of the Tigris River. Its rise in the south is mainly due to the depth of the well and the direction of water movement from north to south.



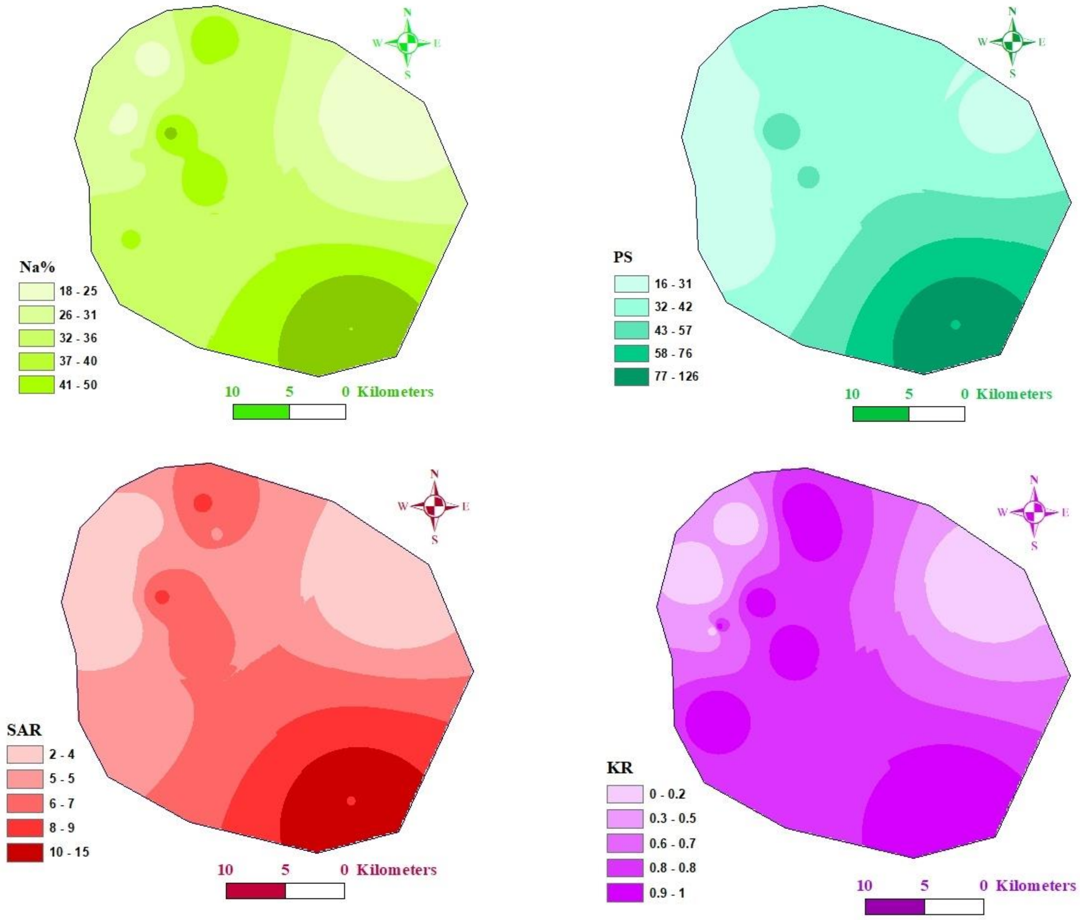


Fig. 6. Spatial distribution of MAR, PI, Na%, PS, SAR, and KR.

(FIGQ) It is calculated using one of the methods of artificial intelligence, fuzzy logic, by taking into account various factors. Based on the specifications and usage restrictions shown in Table 2. The water in Wells No. (1, 3, 7, and 13) are classified as poor, while wells No. (2, 4, 5, 6, 8, 9,11, 12, and 14). They are very poor. The results also show that there is one well, No. 10, whose water is of low specifications for irrigation purposes and is unsuitable (Table 4).

Figure (4) shows the Matlab rule viewer used in Output 1, and the following figure shows the surface graph of the interaction between EC_{25}, Na% SAR, and MAR variables, with the score of the water quality as an example.

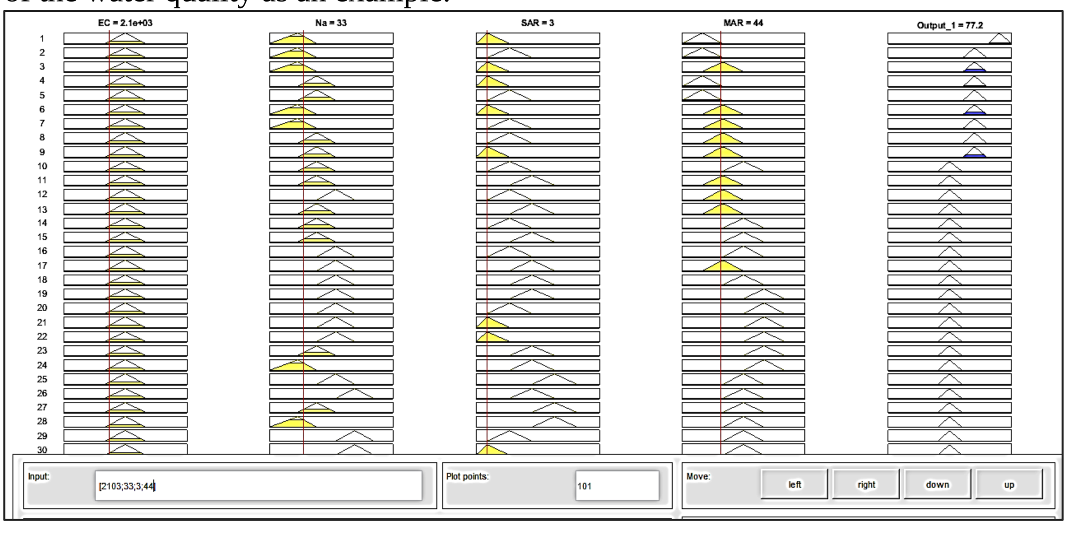


Fig. 7. Matlab rule viewer showing the inputs and the one output.

Table 4: Results of the FIGQ index for wells in the study area.

Wells	Output 1	Output 2	FIGQ
1	Poor	Poor	Poor
2	very Poor	Poor	Very Poor
3	Poor	Poor	Poor
4	very Poor	Poor	Very Poor
5	very Poor	Poor	Very Poor
6	very Poor	Poor	Very Poor
7	Poor	Poor	Poor
8	very Poor	Poor	Very Poor
9	very Poor	Poor	Very Poor
10	very Poor	Unsuitable	Unsuitable
11	very Poor	Very Poor	Very Poor
12	very Poor	Poor	Very Poor
13	Poor	Poor	Poor
14	very Poor	Poor	Very Poor

Figure 8 shows the spatial distribution of the FIGQ index in the study area and the significant effect of the degree of electrical conductivity on the spatial distribution pattern. FIGQ decreases in the southern regions, unlike in western areas.

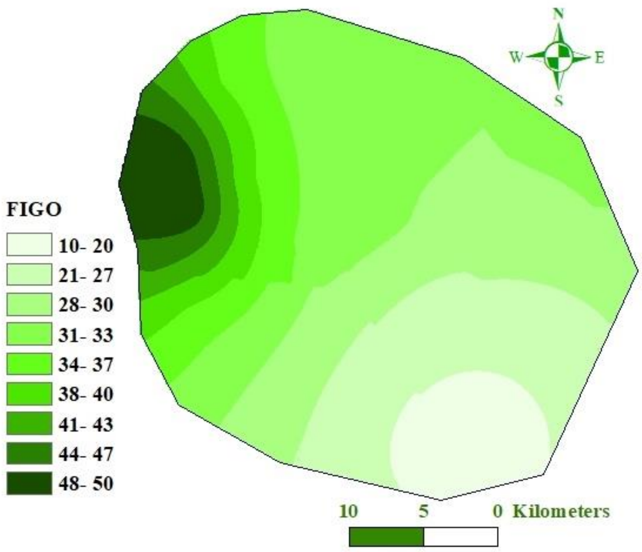


Fig. 8. Spatial distribution of FIGQ.

Conclusions

This study includes the development of a new index called Fuzzy Irrigation for Groundwater Quality (FIGQ). It provides a simple representation of the large-scale and complex variables that govern the overall quality of groundwater intended for use in irrigation. Eight water quality parameters are used: PI, pH, PS, SAR, MAR, KR, Na%, and EC_{25} as important index parameters for FIGQ to evaluate the quality of groundwater sources. The results of using the FIGQ groundwater quality index for irrigation are 28.57% poor, 64.28% very poor, and 7.14% unsuitable. The results obtained can contribute to the success of irrigation in the study area, as they provide information about the availability of wells suitable for irrigation. It is possible to create a model of fuzzy logic for water livestock and poultry.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

References

Akintola, O., Bodede, A., Appah, O., and Kolawole, A., 2017. Hydrogeochemical Evaluation of Groundwater Quality at Federal College of Forestry, Ibadan, Southwestern Nigeria, Journal of Sustainable Environmental Management 9: pp. 21-32 DOI: https://doi.org/10.1016/j.envres.2022.112679.

Al-Mashhadany, M.H.S., 2021. Application of the CCME Water Quality Index to Evaluate the Groundwater Quality of Shouira Village for Drinking and Domestic Purposes in Nineveh Governorate. IOP Conference Series: Earth and Environmental Science, IOP Publishing DOI: https://iopscience.iop.org/article/10.1088/1755-1315/722/1/012029/pdf.

Al-Mashhadany, M.H.S., 2021. Assessment the Suitable of the Groundwater for Civil Uses in Kakhirta Village, Al-Ayadiyah Subdistrict, Iraq. Journal of Physics: Conference Series, IOP Publishing DOI: https://iopscience.iop.org/article/10.1088/1742-6596/1879/2/022060.

Al-Mashhadany, M.H.S., 2021. Evaluation of the Wells Water Quality for Irrigation in Ein Al-Husaan Village, Talafar District, Iraq, Materials Today: Proceedings 42: 2756-2761 DOI: https://doi.org/10.1016/j.matpr.2020.12.717.

Al-Mashhadany, M.H.S., 2022. Valuation of Groundwater Contaminated with Nitrates and human health Risks (HHR) Between Villages of Sinjar and Tal Afar Districts, Iraq, Pakistan Journal of Analytical & Environmental Chemistry 23(2): 277 DOI: http://doi.org/10.21743/pjaec/2022.12.10.

Al-Rashidi, A., Sabarathinam, C., Samayamanthula, D.R., Alsabti, B., and Rashid, T., 2023. Groundwater Management for Agricultural Purposes Using Fuzzy Logic Technique in an Arid Region, Water 15(14): 2674 DOI: https://doi.org/10.3390/w15142674.

Al-Saffawi, A.Y. and Al-Barzanji, A.J., 2020. Application of the Sub-Index Model for Valuation Water Quality for Irrigation Uses: A Case Study of Groundwater in Al-Rashidiya Area, North of Mosul City of Iraq." Science Archives 1(2), pp. 61-67 DOI: http://dx.doi.org/10.47587/SA.2020.1203.

Ayers, R.S. and Westcot, D.W., 1999. The Water Quality in Agriculture. Rome, Italy, UFPB. Studies FAO Irrigation and Drainage.

Bajić, D., Polomčić, D., and J. Ratković, D., 2017. Multi-Criteria Decision Analysis for the Purposes of Groundwater Control System Design, Water Resources Management 31: pp. 4759-4784 DOI: https://doi.org/10.1007/s11269-017-1777-4.

Chidambaram, S., Prasanna, M., Venkatramanan, S., Nepolian, M., Pradeep, K., Panda, B., Thivya, C., and Thilagavathi, R., 2022. Groundwater Quality Assessment for Irrigation by Adopting New Suitability Plot and Spatial Analysis Based on Fuzzy Logic Technique, Environmental Research 204: 111729 DOI: https://doi.org/10.1016/j.envres.2021.111729.

Dhaoui, O., Agoubi, B., Antunes, I. M., Tlig, L., and Kharroubi, A., 2023. Groundwater Quality for Irrigation in an Arid Region—Application of Fuzzy Logic Techniques, Environmental Science and Pollution Research 30(11): pp. 29773-29789 DOI: https://doi.org/10.1007/s11356-022-24334-5.

Rice, E.W., Eaton, A.D., Editors, 2017. Standard Methods for the Examination of Water and Wastewater, American Public Health Association, American Water Works Association, Water Environment Federation.

Hameed, H., 2013. Water Harvesting in Erbil Governorate, Kurdistan Region, Iraq: Detection of Suitable Sites Using Geographic Information System and Remote Sensing, Student thesis Series INES DOI, https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=3737025&fileOId=3737039.

Kuchelar, P., Ramesh, S. B., Sudhir, S., and Kaliaperumal, A., 2022. Assessment of Groundwater Quality Around the Pallavaram Urban Solid Waste Dumpsite Using GIS, Environmental Quality Management 32(1): pp. 265-277 DOI: https://doi.org/10.1002/tqem.21902.

Mahammad, S., Islam, A., and Shit, P.K., 2023. Geospatial Assessment of Groundwater Quality Using Entropy-Based Irrigation Water Quality Index and Heavy Metal Pollution Indices, Environ Sci Pollut Res Int 30(55): pp. 116498-116521 DOI: https://doi.org/10.1007/s11356-022-20665-5.

Majeed, A., Al-Tawash, B., and Ali, H., 2024. Evaluation of Groundwater Using The Water Quality Index (WQI) In Hawija Area, Kirkuk, Northern Iraq, Iraqi National Journal of Earth Science (INJES) 24(1): pp. 156-180 DOI: https://doi.org/10.33899/earth.2023.141207.1097.

Mallik, S., Mishra, U. and Paul, N., 2021. Groundwater Suitability Analysis for Drinking Using GIS Based Fuzzy Logic, Ecological Indicators 121. https://doi.org/10.1016/j.ecolind.2020.107179

Mather, C.C., 2020. Dolomite Formation Within Groundwater Systems of Arid Northwest Australia, Unpublished PhD Thesis, University of Western Australia DOI, https://research-repository.uwa.edu.au/en/publications/dolomite-formation-within-groundwater-systems-of-arid-northwest-a.

Ramesh, K. and Srinithi, K., 2014. Hydrochemical Characteristics of Groundwater in Mayiladuthurai Block of Nagapattinam District, Tamil Nadu, DOI: http://sphinxsai.com/2014/ch_vol6_no14/4/(5698-5708)%20014.pdf.

Thabrez, M. and Parimalarenganayaki, S., 2023. A Fuzzy Synthetic Evaluation Based Groundwater Quality Classification for the Irrigation Purpose: A Case Study From Tumkur District, Karnataka, India, DOI: https://doi.org/10.21203/rs.3.rs-2964486/v1.

Todd, D.K.,1980. Groundwater Hydrology. USA, Wiley: Hoboken.

Westcot, R.S.A., 1985. Water Quality for Irrigation and Drainage 29(1).

Yazdi, S.H., Robati, M., Samani, S., and Hargalani, F.Z., 2024. Assessing the Sustainability of Groundwater Quality for Irrigation Purposes Using a Fuzzy Logic Approach, Environmental and Sustainability Indicators 22: 100342 DOI: https://doi.org/10.1016/j.indic.2024.100342.