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Integration of 2D Resistivity Method and Water Quality Index to Evaluate Groundwater in Ramadi City, Iraq

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ABSTRACT

The study area is located in Ramadi City, western Iraq. Two methods are employed to evaluate the groundwater quality; first is Water Quality Index (WQI), and second is 2D resistivity method. A total of 20 groundwater samples are collected from wells in various locations from Ramadi City to evaluate its suitability for human consumption. Various physiochemical parameters are analyzed including pH, total dissolved solids, electrical conductivity, hardness, calcium, sodium, magnesium, chloride, sulfate, bicarbonate, and nitrate. The results are then compared with the standard limits for drinking water set by the Iraqi standard (ICOSQC, 2009). The results show that the values of the samples are within the acceptable limits for pH and NO_3^-, while most of the samples exceed the limits of the Iraqi standards. Groundwater quality is classified as poor to unsuitable for human drinking purposes based on WQI with a value range from 73.12 to 117.7. Three 2D resistivity profiles are utilized to delineate the groundwater contamination zone. The RES2DINV software employs a robust inversion method for processing and interpretation of 2D resistivity data. The 2D resistivity models indicate that the groundwater contamination zone exhibits a low resistivity value extending to a depth of 10 m. Both methods have identified sewage water and human activity as the primary contributors to groundwater contamination. Therefore, the treatment, management, and monitoring of the groundwater in Ramadi City are crucial to mitigate the environmental impacts on the health of society.

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تكامل المقاومة النوعية الكهربائية ثنائية الابعاد ومؤشر جودة المياه لتقييم المياه الجوفية في مدينة الرمادي، العراق

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الملخص

تقع منطقة الدراسة في مدينة الرمادي غربي العراق. تم استخدام طريقتين لتقييم المياه الجوفية؛ الاولى هي مؤشر جودة المياه (WQI) والثانية طريقة المقاومة النوعية الكهربائية ثنائية الابعاد. تم جمع عشرين عينة للمياه الجوفية لتقييم مدى صلاحيتها للاستهلاك البشري من الابار الموجودة في مناطق مختلفة من مدينة الرمادي. اجريت الفحوصات والتحليلات الفيزيائية والكيميائية على النماذج والتي تتضمن الرقم الهيدروجيني، مجموع الاملاح الذائبة الكلية، الايصالية الكهربائية، العسرة الكلية، الكالسيوم، الصوديوم، المغنيسيوم، الكلورايد، الكبريتات، البيكاربونات، والنترات. تمت مقارنة النتائج مع الحدود القياسية لمياه الشرب حسب المواصفة العراقية (ICOSQC, 2009). بينت النتائج الى ان قيم نماذج منطقة الدراسة ضمن الحدود المسموحة للرقم الهيدروجيني والنترات، بينما تجاوزت معظم العينات الاخرى حدود المواصفة العراقية. صنفت نوعية المياه الجوفية بالاعتماد على مؤشر جودة المياه على انها مياه ضعيفة الى غير ملائمة للاستخدام البشري بقيم بين 73.12 الى 117.7. تم استخدام ثلاث مقاطع مقاومة نوعية ثنائية الابعاد لتحديد منطقة تلوث المياه الجوفية. تم استخدام برنامج (RES2DINV) في معالجة وتفسير بيانات المقاومة النوعية ثنائية الابعاد. بينت مقاطع المقاومة ثنائية الابعاد وجود منطقة تلوث للمياه الجوفية تمتلك قيم مقاومية واطئة تمتد الى عمق 10 أمتار. حددت كلتا الطريقتين بان مياه الصرف الصحي والفعاليات البشرية هي المسبب الرئيس في تلوث المياه الجوفية. لذلك فان معالجة وادارة ومراقبة المياه الجوفية في مدينة الرمادي تعتبر اساسية للحد من التأثيرات البيئة على صحة المجتمع.

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Introduction

Water is a precious and vital resource for life on Earth, and its quality is critical for environment and human health. Ensuring good quality water for future generations requires protection permanently, both quantitatively and qualitatively (Al-Kubaisi *et al.,* 2021). Climate is an important factor affecting water quality in any region, and calculating the water balance is important for solving hydrological problems and changes (Al-Kubaisi and Al-Kubaisi, 2023). Working to manage and organize water resources to prevent fluctuations resulting from climate, especially rain and temperature changes, is needed (Al-Dabbas *et al.,* 2018). In general, water suitability is a very important matter and care must be taken effectively during our daily lives to use water safely (Al-Kubaisi *et al.,* 2023). Absolutely, the increased demand for groundwater resources in Ramadi City due to population growth, urbanization, and industrialization has led to overexploitation and contamination. Regular monitoring and assessment of groundwater quality is crucial for sustainable water resource management in the city.

Various methods have been developed to assess groundwater quality including physicαl, chemical, and biologicαl methods. One widely used method is Water Quality Index (WQI), which combines various water quality parameters to produce a single index value that reflects the overall water quality. The resistivity method is indeed a widely used geophysical technique for monitoring and evaluating possible groundwater and soil contamination due to its non – invasive nature, as it does not require drilling boreholes or collecting soil and groundwater samples (Thabit and Khalid, 2016; Nasir *et al.,* 2021; Al-Awsi and Abdulrazzaq, 2022; Ahmed *et al.,* 2022). This technique shows some benefits involving rapid data collection, low cost, and higher quality image of the subsurface structure (Dahline, 2001; Abed *et al.,* 2020, 2021; Al- Hetty *et al.,* 2021; Abbas *et al.,* 2022, 2024). Conductive materials such as sewage water with high level of organic matter and salts have lower electrical resistivity compared to cleaner soil and groundwater. The localized and defined spatial extend of sewage water contamination appears with low resistivity anomaly zones (Wang *et al.,* 2019).

The study aims to evaluate the groundwater quality and determining the contamination areas in Ramadi City using the Water Quality Index (WQI) and resistivity method.

Location of Study area

Ramadi City is located in western Iraq, situated on the southern bank of Euphrates River and surrounded by a desert land scape (Fig.1). It has a flat topography with an average elevation of 57 m above sea level. The hydrology of the region is primarily influenced by the Euphrates River, which does not only run through the city, but also serves as the main water source for various purposes such as irrigation and drinking. Additionally, several wadis (seasonal streams) in the area that equipped with numerous groundwater wells, are subject to flooding during heavy rainfalls. Groundwater recharge in the city occurs through infiltration from the river and rainfall leading to fluctuations in the water table based on precipitation and extraction levels. The Quaternary deposits covering Ramadi City mainly consist of unconsolidated sedimentary deposits including gypsum soil and gypcrete above the Injana Formation (GCGW, 2001).

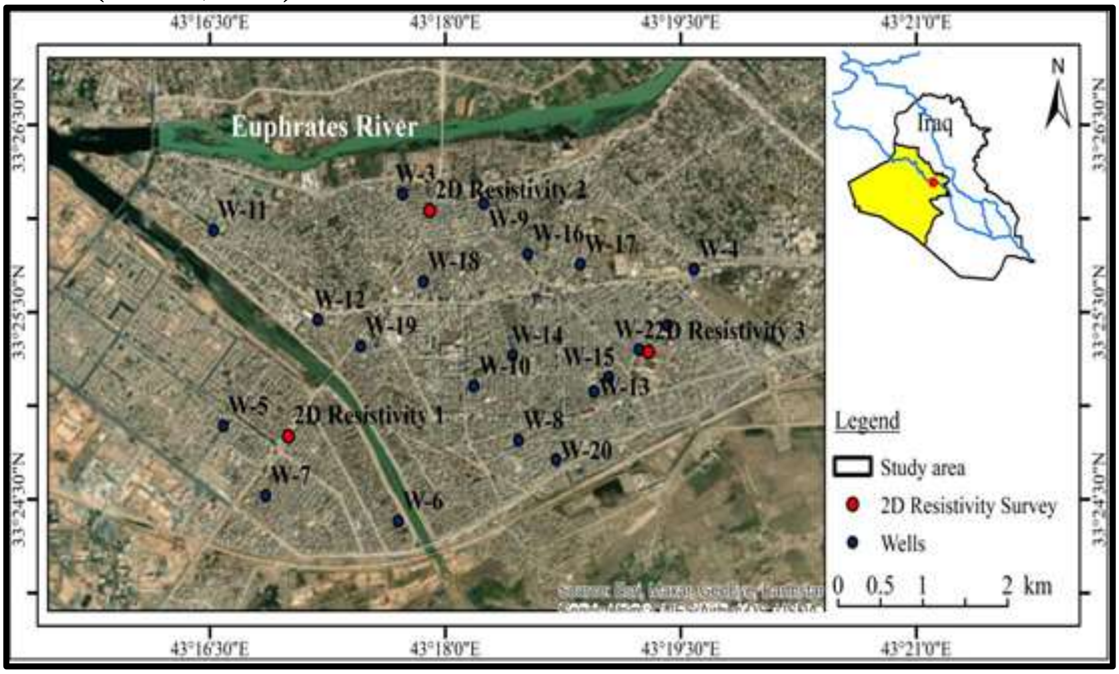

Fig. 1. Study area with groundwater well sampling and 2D resistivity survey.

Materials and Methods

Groundwater Sampling

Groundwater samples are taken from 20 wells situated in various areas within Ramadi City. Sampling location are marked using GPS to ensure accurate position, also their selection is based on the hydrogeological characteristics, proximity to contamination source, and availability of accessible groundwater wells (Table 1). The samples are analyzed for a variety of parameters including pH, TDS, EC, TH, Na^{+}, Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^{-}, Cl^{-}, and NO_3^{-}. These samples are transported to the central laboratory for Anbar water, and stored in two-liter plastic bottles. The results of these tests are used to determine if any corrective measures are needed to improve the water quality.

Table 1: Coordinates and depths of wells in the study area.

Wells	Longitude	Latitude	Well depth (m)
W-1	43° 19' 25.0000" E	33° 25' 25.7000" N	48
W-2	43° 19' 14.1000" E	33° 25' 17.9000" N	48
W-3	43° 17' 43.6000" E	33° 26' 07.8000" N	36
W-4	43° 19' 35.1000" E	33° 25' 43.7000" N	42
W-5	43° 16' 35.2000" E	33° 24' 53.5000" N	38
W-6	43° 17' 42.0000" E	33° 24' 23.0000" N	40
W-7	43° 16' 51.4000" E	33° 24' 31.2000" N	32
W-8	43° 18' 28.0000" E	33° 24' 48.8000" N	45
W-9	43° 18' 14.7000" E	33° 26' 04.7000" N	43
W-10	43° 18' 11.0000" E	33° 25' 06.3000" N	32
W-11	43° 16' 31.4000" E	33° 25' 56.2000" N	29
W-12	43° 17' 11.2000" E	33° 25' 27.5000" N	43
W-13	43° 18' 56.8000" E	33° 25' 04.5000" N	30
W-14	43° 18' 25.8000" E	33° 25' 16.1000" N	25
W-15	43° 19' 02.5000" E	33° 25' 09.1000" N	36
W-16	43° 18' 31.5000" E	33° 25' 48.6000" N	38
W-17	43° 18' 51.5000" E	33° 25' 45.3000" N	41
W-18	43° 17' 51.6000" E	33° 25' 39.8000" N	43
W-19	43° 17' 27.6000" E	33° 25' 19.1000" N	34
W-20	43° 18' 42.3000" E	33° 24' 42.7000" N	46

Water Quality Index (WQI)

The Water Quality Index is computed according to the drinking water quality principles proposed by IQS (2009). It serves as a crucial metric for evaluating the overall status of water quality. Horton (1965) was indeed one of the first researchers to propose the concept of WQI. The index is typically calculated using a weighted arithmetic index method.

1. Calculating the proportionality constant *K* using:

$$\boldsymbol{K = \frac{1}{\sum_{j=0}^{n} \frac{1}{si}}} \qquad (1)$$

Where, *si*: the permissible limit for the ith parameter; *n*: number of parameters.

2. Calculating the weight and relative weight *Wi* of the ith parameter using:

$$\boldsymbol{Wi = \frac{K}{si}} \qquad (2)$$

3. Calculating the sub-index of ith parameter *Qi* using:

$$\boldsymbol{Qi = \frac{1000Vi}{si}} \qquad (3)$$

Where, *Vi:* the monitored value of the ith parameter.

The quality rating for pH (*QpH*) is determined using the flowing equations:

$$QpH = 100\left[\frac{Vi - S}{Si - S}\right] \quad pH > 7 \qquad (4)$$

$$QpH = 100\left[\frac{S - Vi}{Si - S}\right] \quad pH < 7 \qquad (5)$$

Where, *S*: the ideal value of pH, considered equal to 7.

4. Calculating the WQI using equation (6):

$$WQI = \frac{\sum_{j=1}^{n} QiWi}{\sum^{nj=1} Wi} \qquad (6)$$

According to WQI, the quality of water for human drinking is categorized into five distinct classes (Table 2).

Table 2: Classification of water quality according to the WQI (Pei-Yue *et al.*, 2010).

WQI Value	0-25	26-50	51-75	76-100	> 100
Class	Excellent	Good	Poor	Very Poor	Unfit for human drinking purpose

The relative weights (Wi) for all parameters of the study area are calculated basaed on the Iraqi standard limits (ICOSQC, 2009) (Table 3).

Table 3: Relative weight (Wi) for the WQI parameters.

Parameters	**Limits (Si) ICOSQ, 2009**	**1/Si**	**K**	**Relative Weight (Wi)**
pH	8.5	0.1177	6.558	0.7715
EC	1500	0.00067		0.0043
TDS	1000	0.001		0.0065
TH	500	0.002		0.0131
Na	200	0.005		0.0327
Mg	100	0.01		0.0655
Ca	150	0.0067		0.0437
HCO_3	450	0.002		0.0145
SO_4	400	0.0025		0.0163
Cl	350	0.0029		0.0187
NO_3	50	0.02		0.131
		Σ= 0.15247		**Σ= 1.1178**

2D Resistivity Survey

The 2D resistivity technique has proven to be a successful and powerful tool in distinguishing the contaminated areas from clean areas, as well as in detecting the depth and moving direction of underground seepage. In Ramadi City, a 2D resistivity method is conducted to investigate the impact of sewage water contamination of groundwater quality and to identify the extent and depth of contamination plume.

Data are collected during the three 2D resistivity traverses in Ramadi City using SAS 4000 instrument (Fig. 1). Each 2D survey utilized a dipole-dipole array with 42 electrodes with a-spacing of 2 m, and an n-factor of 6. This configuration resulted in a total measurement line length of 82 m and a depth investigation of 17 m. Additionally, it provided a data coverage of 685 readings across the entire station. The survey is conducted in an area with a high probability of sewage water contamination due to the proximity of sewage discharge areas. The data acquired from the 2D survey are processed and interpreted using RES2DINV software robust inversion method. This inversion shows the variation in resistivity with depth and lateral distance. The initial stage involves the elimination of inaccurate data through two methods. The first method entails manually selecting flawed data points by creating configuration files (Fig. 2a). The second method involves an automatic static approach of removing data points using the RMS error option to enhance the overall RMS errors (Fig. 2b).

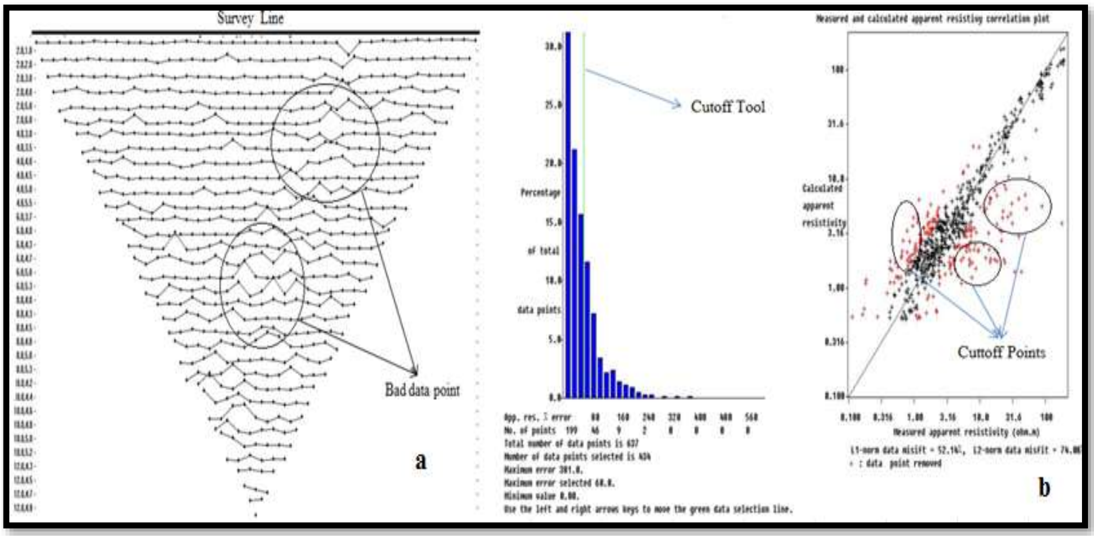

Fig. 2. Data processing through third 2D resistivity traverse.

Results and Discussion

Groundwater Quality Index (GWQI)

The GWQI values of water sample designated for drinking fell within the range of 73.12 to 117.7 (Fig. 3) indicating a classification from poor to unfit (Table 4). Both W15 and W20 fell into the poor category and could potentially be used as consumption after management. Though, wells 3, 4, 7, 8, 10, 11, 12, 13, 14, 16, 17, and 18 are rated as extremely poor. Furthermore, the GWQI values of wells 1, 2, 5, 6, 9 and 19 fall under the category of “unfit for human consumption” and exceed the permissible values due to elevated chloride, sulfate, total hardness, calcium and magnesium concentrations.

Table 4: GWQI Classification in the study area.

Wells	WQI Value	Class
W1	117.7	Unfit
W2	115.9	Unfit
W3	99.39	Very Poor
W4	93.21	Very Poor
W5	109.76	Unfit
W6	102.64	Unfit
W7	91.51	Very Poor
W8	90.74	Very Poor
W9	108.36	Unfit
W10	82.7	Very Poor
W11	75.62	Very Poor
W12	91.42	Very Poor
W13	95.36	Very Poor
W14	97.6	Very Poor
W15	73.97	Poor
W16	82.01	Very Poor
W17	95.9	Very Poor
W18	82.65	Very Poor
W19	103.41	Unfit
W20	73.12	Poor

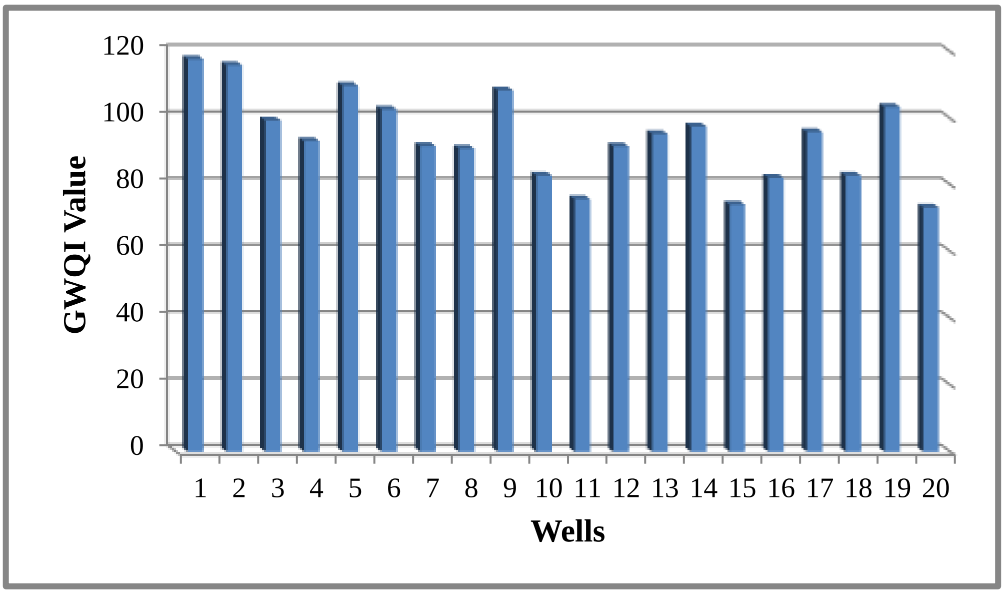

Fig. 3. GWQI values in the study area.

Physical Properties

The results show pH values between 7.1 to 7.6 (Fig. 4) indicating neutral to weakly alkaline water quality based on Komatina's classification (2004). The pH values fall within the limitation values of ICOSQC (2009). Additionally, Figure (5) illustrates a notable increase in Total Dissolved Solids (TDS) in most studied areas, especially in W1 and W2. This increase is due to human activity and mixed sewage water leading to various environmental issues. The TDS values range from 5100 and 9010 ppm categorizing the water as slightly brackish exceeding the permissible limit of 1000 ppm. Furthermore, the Electrical Conductivity (EC) values between 7123 to 14040 µS/cm signifying highly mineralized water due to salinity (Fig. 6). These EC values surpass the allowable ICOSQC limits. The Total Hardness (TH) ranges from 1817 to 3672 ppm in the study area (Fig. 7) indicating very hard water due to high sulfate concentration in groundwater.

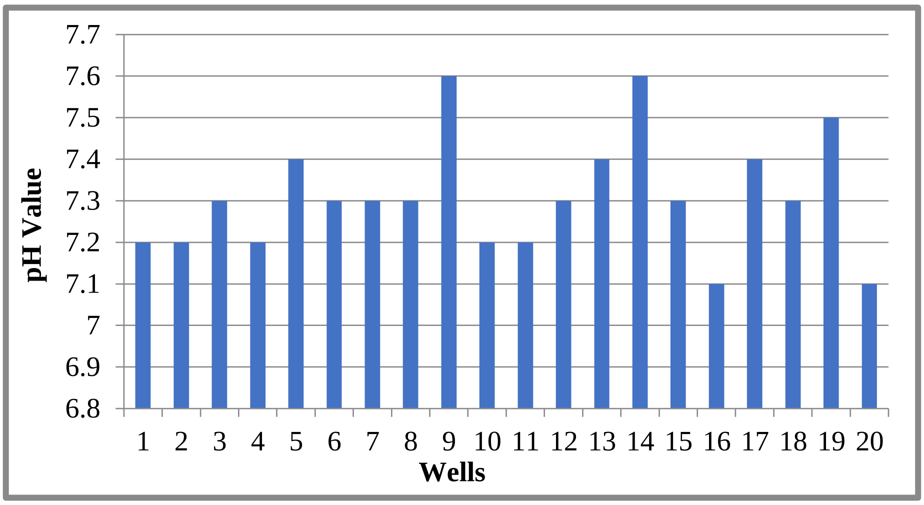

Fig. 4. pH value in the study area.

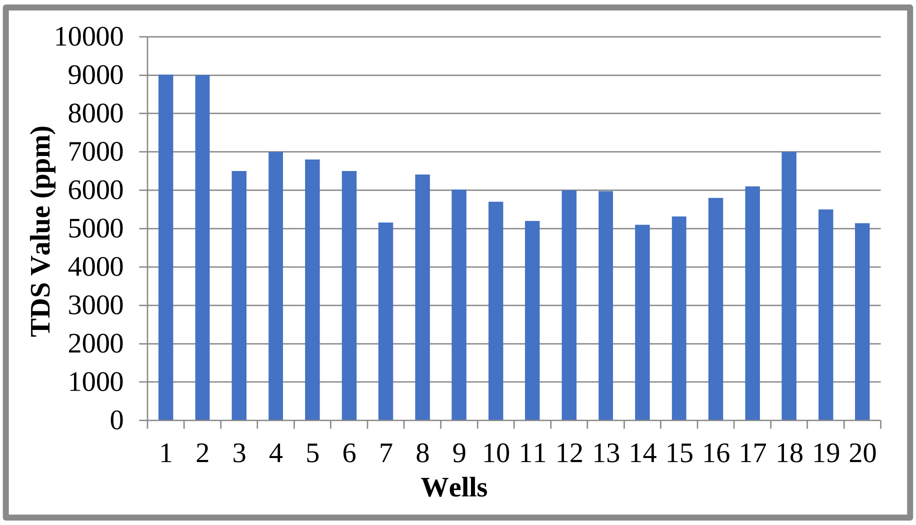

Fig. 5. TDS value in the study area.

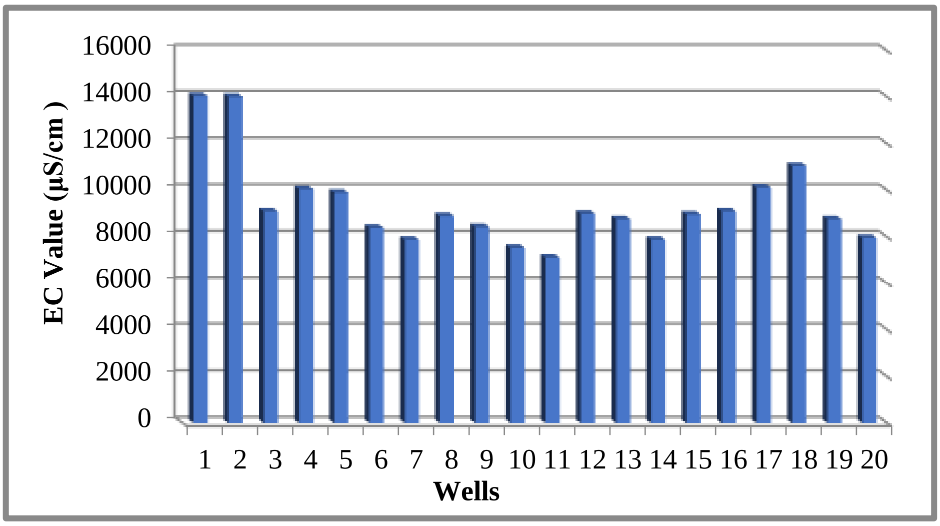

Fig. 6. EC value in the study area.

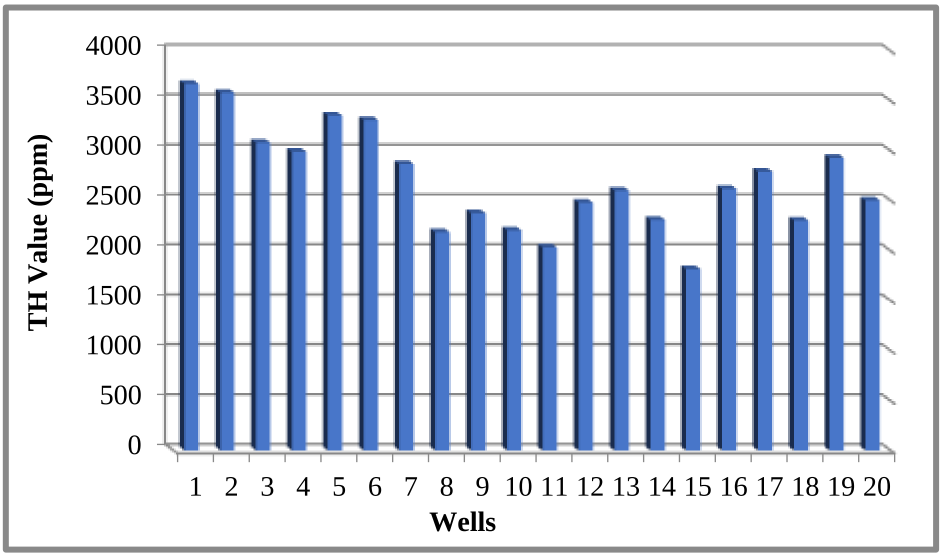

Fig. 7. TH value in the study area.

Chemical Properties

Figure (8) shows the concentrations of Ca^{+2}, Mg^{+2} and Na^{+} of the water samples. Calcium concentrations in the study area range from 336 to 780 ppm. Human activities and wastewater are considered to be the major sources of calcium ions in well water. All sample values exceed the allowed ICOSQC limits. Since dolomite dissolves slowly, magnesium ions (Mg^{+2}) are of lower concentrations than calcium ions and sodium ions. Magnesium concentrations between 234 to 420 ppm. All sample values are above the ICOSQC standard limit (50 ppm) (Fig. 8). Sodium is highly water-soluble and difficult to precipitate. Salt intrusion, mineral deposition, and wastewater all contribute sodium to water (WHO, 2017). In the study area, sodium concentrations range from 678 ppm to 1360 ppm. Figure (8) shows that all sodium values in the water samples exceed the allowable limits.

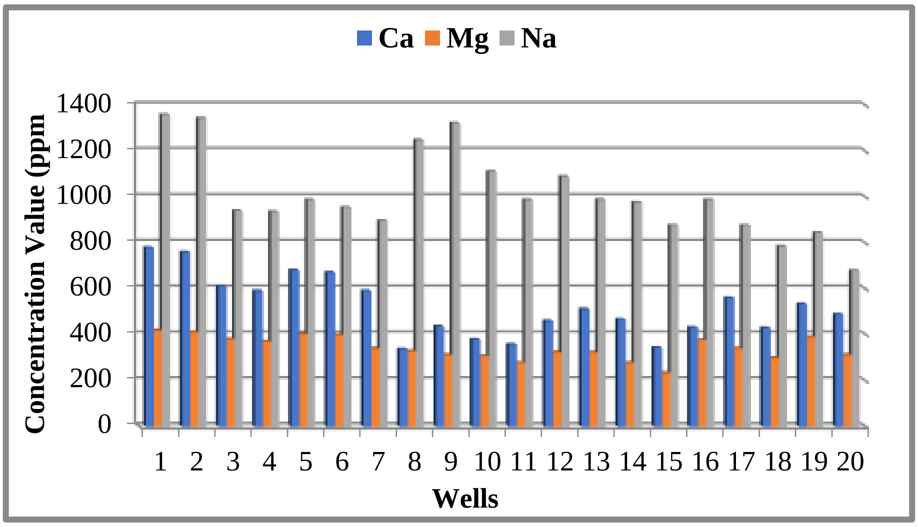

Fig. 8. Ca, Mg, and Na Concentrations in the study area

Chloride (Cl^{-}) is present in all types of water due to its large quantity and rapid water solubility. Chloride salts over 100 mg/l in combination with calcium and magnesium give the water a salty taste and increase its corrosiveness. Chloride values in this study range from 1334 to 2040 ppm (Fig. 9). Sulfate (SO_4^{-2}) is considered significant element issue in water quality affecting the odor and piquancy of water used (Bouslah *et al.,* 2017). The sulfate values are between 1078 and 2480 ppm. These high sulfate values are due to infiltration of wastewater, which dissolves the gypsum soil and secondary gypsum that cover the study area. All readings exceed the allowed (400) ppm limit (Fig. 9).

Bicarbonates (HCO_3^{-}) are considered the source of alkalinity in water, meaning that they are all bicarbonate, carbonate, and hydroxide ions. The bicarbonate level ranges from 550 to 1190 ppm, which surpasses the acceptable limit for consumption. In the study area, the nitrate concentration (NO_3^{-}) is found to vary between 10 and 17.2 ppm. However, all sample readings remain below (50) ppm as the maximum contaminant level (Fig. 10).

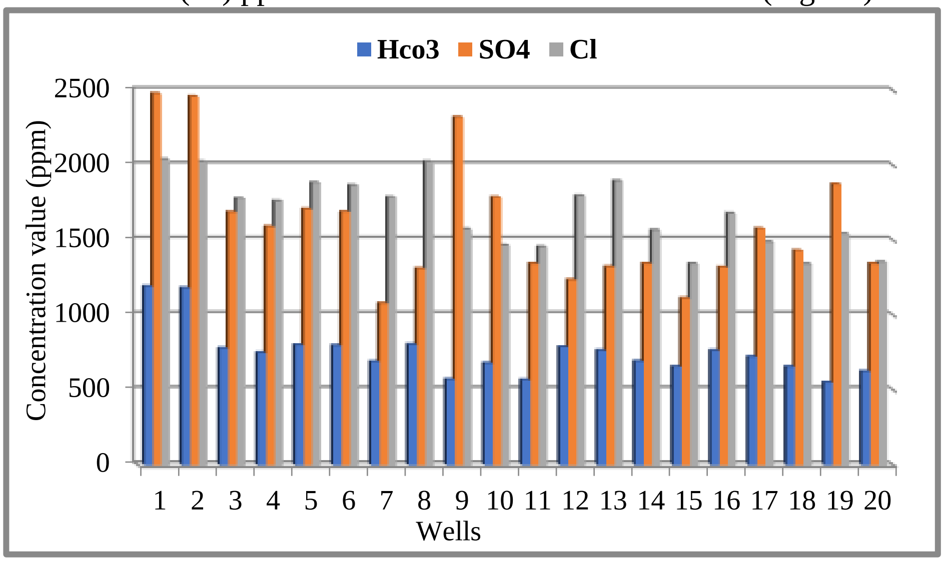

Fig. 9. HCO_3, SO_4, and Cl Concentrations in the study area.

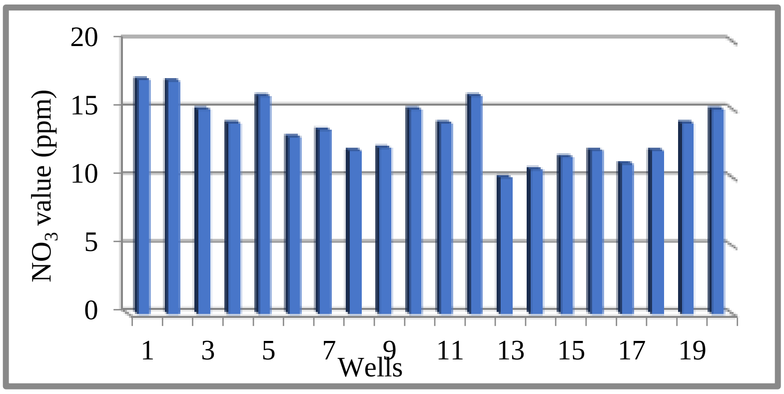

Fig. 10. NO_3 value in the present study.

2D Resistivity Inversion

The 2D resistivity models show a distinct low resistivity zone corresponding to sewage water contamination. The contamination plume extended to a depth of approximately 10 m. The resistivity values in contamination zone are significantly lower than those in the uncontaminated zone indicating the presence of mobile water and dissolved ions.

The 2D resistivity model for three traverses can be delineated into two primary zones (Fig. 11). The upper zone exhibits high resistivity values of more than (204) Ω.m with a thickness of approximately 1.5 m. This zone can be associated with the surface soil with no groundwater contamination. The second zone, extending from 1.5 m to 9 m in depth, is characterized by two distinct subzones; the first represents intermediate resistivity values ranging from 69 to 204 Ω.m suggesting areas of groundwater contamination. The second subzone reveals low resistivity anomalies with values ranging from 2.74 to 23.7 Ω.m. The resistivity anomalies represent areas of groundwater contamination due to intrusion of sewage water.

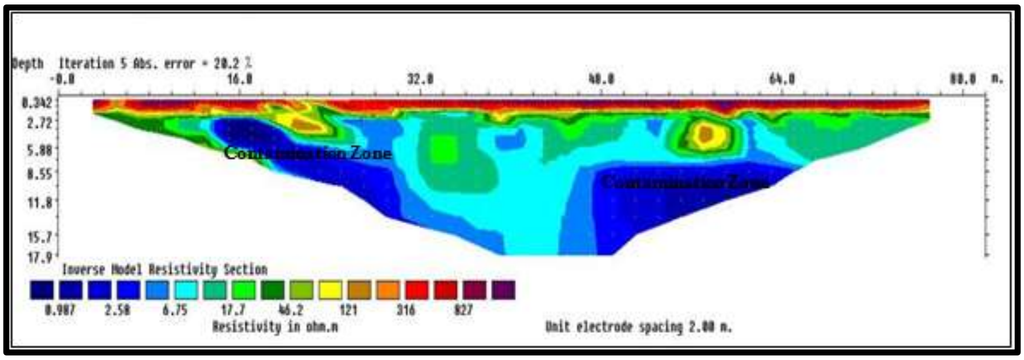

Fig. 11. 2D inversion model for first traverse.

Figures (12 and 13) represent 2D inversion model for the second and third traverses respectively. These models indicate that groundwater contamination zone is characterized by low resistivity values ranging from 0.987 to 17.7 Ω.m and 1.27 to 22.9 Ω.m with a depth extending approximately to 10 m.

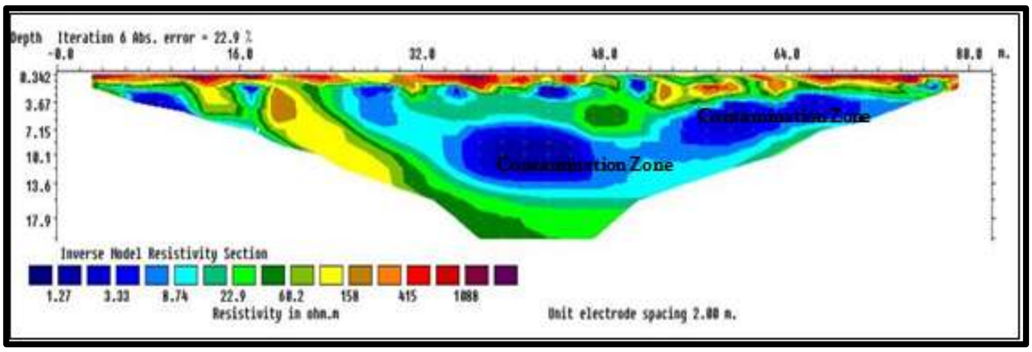

Fig. 12. 2D inversion model for second traverse.

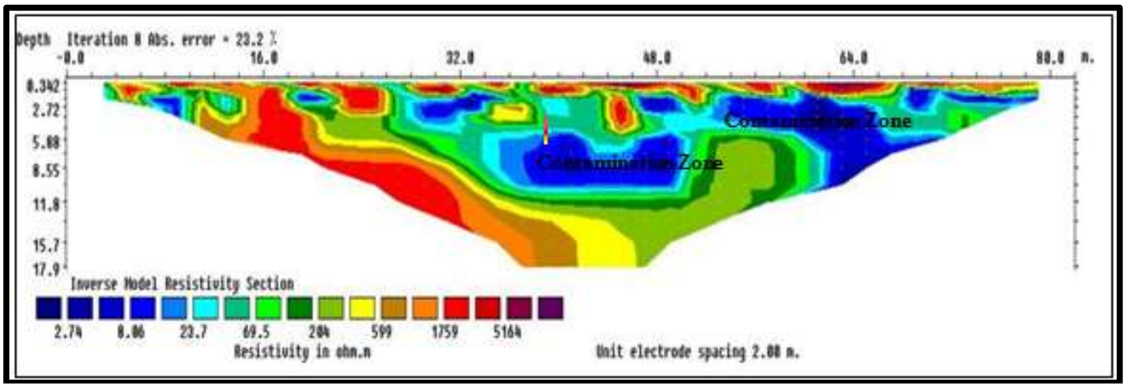

Fig. 13. 2D inversion model for third traverse.

The water levels in Ramadi City vary from 2 to 7 m based on measurement of water in wells (Fig. 14). This variation is due to the presence of sandy silt lenses forming suspended water or perched aquifers in the Quaternary sediments as a result of the intrusion of rainwater and sewage water.

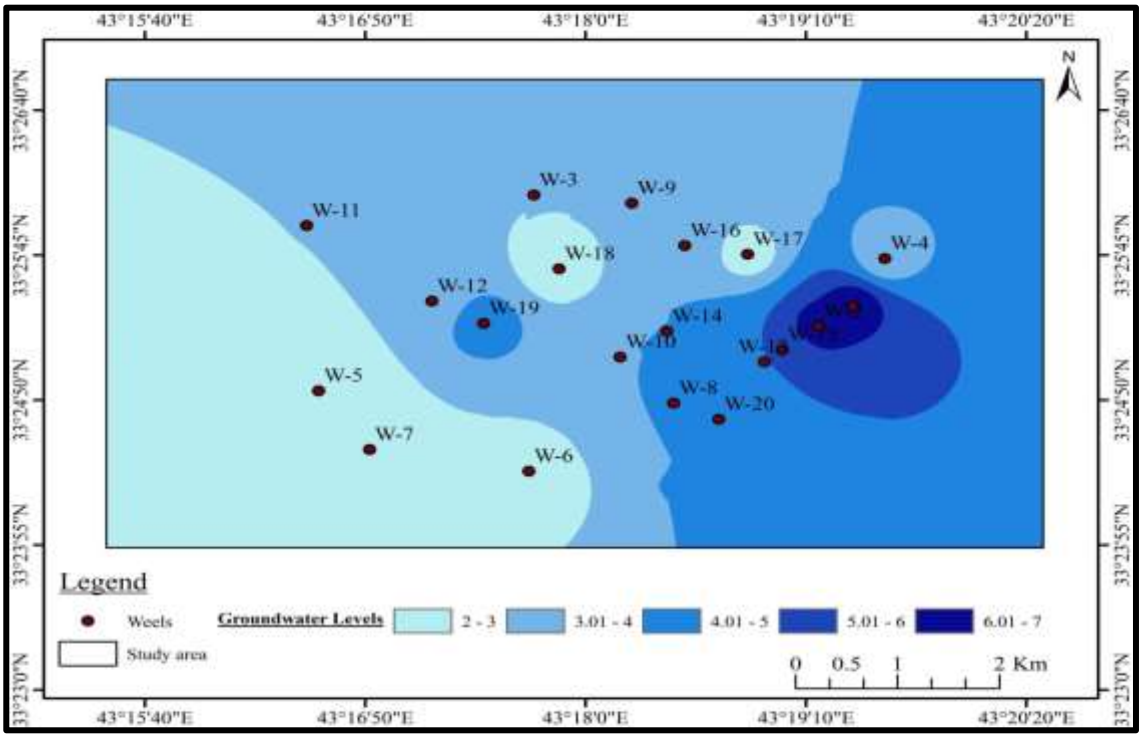

Fig. 14. Groundwater levels in Ramadi City.

Conclusion

1. The 2D resistivity models have revealed a clear low resistivity zone that corresponds to sewage water contamination. This contamination plume has been observed to extend to a depth of approximately 10 m.

2. The physicochemical analysis shows that the groundwater has a neutral to weakly alkaline pH, slightly brackish water due to TDS, high mineralization based on EC, and is classified as very hard in terms of total hardness (TH). Based on the chemical analysis, the predominant cations in the water samples are ordered as follows: $Na^+ > Ca^{+2} > Mg^{+2}$. Additionally, the main anions follow this sequence: $Cl^- > SO4^{-2} > HCO3^-$.

3. According to the WQI scale classification, the groundwater samples in Ramadi City are classified as poor to unfit showing that all the groundwater samples are not suitable for drinking purposes without treatment.

4. The elevated major element values in the water samples indicate that the main source of contamination is attributed to sewage water system leakage and human activities.

5. The city needs to take steps to recover the quality of its groundwater such as implementing better sewage water management practices and improving the infrastructure of water supply.

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