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GROUNDWATER EXPLORATION IN FRACTURED ROCKS USING TRANSIENT ELECTROMAGNETIC TECHNIQUE (TEM), WEST EL-MINIA, EGYPT

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استكشاف المياه الجوفية في الصخور المتشققة باستخدام طريقة الكهرمغنطيسية ، غرب المنيا ، مصر

الخلاصة: تعتبر ندرة الموارد المائية في مصر هي العقبة الرئيسية التي تواجه مشاريع التنمية، لا سيما في الأراضي الصحراوية، التي تغطي ٩٦% من الأراضي المصرية. تميل الحكومة المصرية إلى تنفيذ العديد من المشاريع التنموية الصحراوية للحد من الكثافة السكانية حول وادي النيل. يعتبر الامتداد الصحراوي غرب محافظة المنيا واحداً من المناطق التنموية الواعدة حيث نفذت وزارة الزراعة واستصلاح الأراضي مشروع استصلاح ٣٠٠٠٠ فدان بالقرب من منطقة الدراسة في اتجاه الغرب ضمن مشروع استصلاح المليون ونصف فدان. تقع منطقه الدراسة بين دائرتي عرض ٢٨,٣٤٨٨° و ٢٨,٥٥٧٦° شمالاً وخطي طول ٣٠,١٩٢٨° و ٣٠,٤٥٧٣° شرقاً. والهدف الرئيسي من هذه الدراسة هو فهم الامتداد الرأسي والأفقي للطبقات التحتسطحية وخاصة الطبقات الحاملة للمياه الجوفية في منطقة الدراسة. لتحقيق هدف هذه الدراسة، تم تنفيذ ٤٦ محطة TEM باستخدام جهاز TEM -Fast 48HPCعلي شكل شبكه في منطقة الدراسة، تم تحديد التكوينات الرئيسية الحاملة للمياه وهي طبقة الحجر الجيري المتشقق الحامل للمياه الجوفية والتي تتبع مكون سمالوط الذي ينتمي لعصر الايوسين الأوسط والذي يتكون من الحجر الجيري البحري المتشقق الضحل وتداخلات من الطفلة. سجلت ٢٩ محطة من أصل ٤٦ محطة وجود محتوي مائي في طبقة الحجر الجيري المتشقق. وتتركز هذه المحطات في الجزء الجنوبي الشرقي وتتبع الاتجاه العام شمال شرق−جنوب غرب وتتواجد أيضا في الجزء الجنوبي والغربي في بعض المواقع المتفرقة التي تم قياسها. مجموعه محطات القياس (TEM Stations) التي سجلت تواجدات المياه الجوفية في طبقة الحجر الجيري المتشقق تغطي حوالي ٦٠% من منطقة الدراسة والتي تعتبر أكثر المناطق تأثرا بالتشققات والكسور وهي أفضل الأماكن المقترحة لحفر ابار مياه جوفية منتجة.

ABSTRACT: *The scarcity of water resources in Egypt is considered to be the main obstacle to development projects, particularly in desert lands, which cover 96% of the Egyptian land. The government tends to carry out several development projects to reduce the population intensity around the Nile Valley.*

West El-Minia governorate desert fringes are one of the promising development areas where the Ministry of Agriculture and Land Reclamation carried out a 30,000-acre reclamation project near the study area included the 1,500,000 acres. The study area defined by the following coordinates, Latitudes 28.3488° N & 28.5576° N and longitudes 30.1928° E & 30.4573°E. The main objective of this study is to understand the vertical and horizontal extension of the subsurface succession and groundwater aquifer conditions in the study area.

To achieve the objective of this study, 46 TEM stations were carried out using the TEM-Fast 48HPC device. In the study area, the main water-bearing formations have been specified to be the fractured limestone aquifer of the Middle Eocene age Samalut Formation composed of shallow marine limestone with shale bed intercalations. 29 TEM stations out of 46 recorded the existence of water content in the fractured limestone aquifer, and these stations are concentrated in the eastern part and follow the NE-SW direction of faults, and recorded in a limited number of TEM stations in the western and southern parts of the study area.

The TEM stations recorded water in the limestone aquifer (Samalut Formation) cover about 60 % of the Study area that was almost regarded to be the most impacted area with fractures and faults. And these locations are suggested for drilling productive groundwater wells.

INTRODUCTION

Exploration of groundwater in fractured rocks is regarded as a challenge for geophysical techniques, particularly in arid areas with high resistivity surface layer. Direct current resistivity methods such as vertical electrical sounding and two-dimensional electrical imaging are regarded to be the most popular groundwater exploration techniques, but using these techniques in such circumstances is not so efficient, very difficult to apply and hard to obtain satisfactory fieldwork outcomes. In these conditions, transient electromagnetic (TEM) technique is considered to be a very powerful technique, it is AC current technique and does not require any direct contact with the surface layer. One of the most targeted aquifers in and around the study area is the fractured limestone of Samalut Formation. This formation is, in lithological terms, composed of hard, white, fossiliferous, fractured limestone with intercalations of shale and marl and controlled by a fault and fracture system network (Said, 1981). There is a leakage reported from the Nubian Sandstone aquifer and the Nile river water to the Eocene aquifer (Al Temamy and Abu Risha, 2016).

The area under consideration belongs to El-Minia governorate and considered as a promising area for sustainable development because it has several groundwater aquifers, Oligocene sandstone, Middle Eocene limestone, Nubian sandstone aquifer and Nile river (Hamed and Abu El maged, 2017; Yousif et al., 2018) in addition to the source of water from the Nile river. In the area under study, groundwater is found in fractured limestone formation belonging to the Eocene age, and water-bearing layer resistivity values rise with depth as a result of decreasing fracture density (Mahmoud and Kotb, 2017). Samalut Formation's fracture limestone is regarded to be of the main aquifer potential in the Western Desert, particularly West El-Minia and West Asyut, and it has a good water quality (Shabana, 2010; Al Temamy and Abu Risha, 2016).

The study area is defined by the following coordinates, Latitudes 28.3488° N & 28.5576° N and longitudes 30.1928° E & 30.4573°E (Fig.1). It is bounded by Bani Mazar-Baharia Oasis road from the northern part, the southern border is the electricity power line and Darb El Robi road, from the East it is bounded by Cairo Asyout Western road, and from the west it is bounded by El Nashfa limestone plateau area. The total area covered by this research is approximately 380 Km^2. The study area characterized by arid climate hot and dry in summer and mild with rare rainfall in winter. Scarce precipitation does not exceed 6 mm/year. As non-invasive and cost-effective, geophysical exploration remains the first choice of aquifer mapping, particularly Transient Electromagnetic (TEM) method (Fitterman, 1987). Saturated fractures have a good electrical conductivity which makes them a good target for electromagnetic techniques. Electromagnetic sounding techniques are often ideally more suited to conductive target exploration than DC resistivity techniques (Fitterman and Stewart, 1986). Briefly, the main objectives of this research were as follow: a) combining geological, tectonic, hydrogeological, geophysical, and other data in order to create scenarios that can answer important research hydrogeologic questions, b) to determine depth, thickness and other aquifer properties, c) Identifying a high-potential groundwater target region based on existing groundwater data for groundwater pumping well planning. Due to insufficient knowledge of the fracture networks, it is hard to find steady sources for groundwater in hard rocks co0vering about 20 percent of the Earth's surface (Chandra et al., 2019). For effective groundwater targeting, efficient location of fracture zones in hard rocks is crucial and this goal will be accomplished in this research using TEM technology in combination with the study area's geological, geomorphological, hydrogeological and structural data.

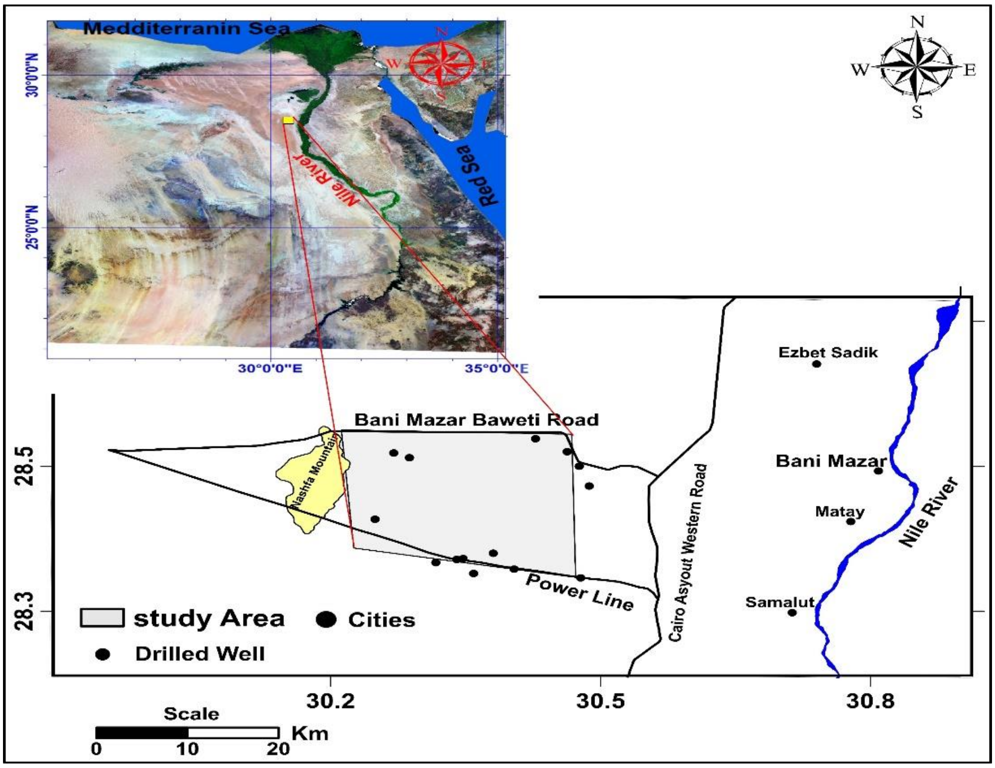

Figure 1: Location Map of the study area.

GEOMORPHOLOGICAL ASPECTS

The study area is considered to be the North Eastern part of the old Nile delta (Oligocene time) formed in the western desert. The geomorphic units of the study area can be easily subdivided as follows on the basis of a topographical map of 1:250,000 scale (Fig.2):

1- Structural Plateau: in the study area the structural Plateau composed of two geomorphic units:

A- Table Land: This geomorphic unit consists of hard limestone in some localities and chalky limestone in the others and covering the eastern part of the study area.

B- Isolated Hills: This geomorphic unit consists of hills elevated and standing on the plateau surface of the geomorphic unit located in the SSW direction of the study area.

2- Gravel Plain: it is the most common geomorphic unit in the central part, and it is composed of flint and limestone fragments gravel.

(Fig. 2 and 3) shows the Geomorphological map of the study area with the surface lineament and the elevation profile A-B respectively, From this map we can conclude that the study area is mainly affected by the structure in the eastern and western parts and it is recorded also from the elevation profile A-B, between the geomorphological units of the table land and the gravel plain in the east and between the gravel plain and the isolated hills in the west, which are more promising areas for groundwater aquifers.

GEOLOGICAL AND STRUCTURAL SETTING

The geological map of El Minya area after (Egyptian Geological Survey and Mineral Authority 2005) (Fig. 4) shows the geological units of the area which ranging in age from lower Eocene to Quaternary (Holocene). The geology of west El-Minia has been previously studied by many authors, (Said, 1962; Khalifa, 1981; Monsour and Philobbos, 1983; and Boukhary and Abd El Malik, 1983) studied the western desert stratigraphically and sedimentological. On the other hand, (Shata, 1953; Yousef, 1968; and Abd El-Aziz, 1994) studied the structure setting of the area. Yousif et al., (2018) concluded that the exposed rocks in the area under investigation are assigned to ages ranging from the Lower Eocene to Oligocene, and the following rock units are recognized from base to top: Minya Formation which composed of limestone with clay intercalations, Samalut Formation which composed of fractured chalky limestone with thin clay intercalations, Qatrani Formation which composed of gravelly calcareous sandstone and finally Katkut Formation consist mainly of a sequence of clastic deposit (siltstone and claystone), limestone fragments and gravels, respectively (EGSMA, 2005). Yousif et al., (2018) concluded the main trend of lineaments in the study area is NE–SW followed by NW–SE directions. Structural lineaments are concentrated in the vicinity of the study region to the east and northwest. Eocene rock exposures are extremely fractured by mostly linked cracks and joints. The study area affected by several faults and fractures lineament trends; the main lineament trend is NE-SW followed by NW-SE directions.

METHODOLOGY

The Transient Electromagnetic (TEM) method is relatively young compared to other electromagnetic methods as it was created and refined in the mid-1980s. The TEM technique can be applied in many different configurations, direct electrical contact with the ground is not necessary and the depth within which it can be applied ranges from the top few meters to hundred meters (Kalisperi et al., 2018). The TEM method uses the direct current transmitted to the transmitter loop lying on the ground. A main, stationary magnetic field is created by the current. The direct current is turned off, inducing an eddy current system in the ground (Fig. 5) A) the transmitter current waveform and B) the current flowing in the ground. The current system will decay due to the ohmic resistance of the subsurface and cause a secondary magnetic field measured in an induction coil (the receiver coil) (Fitterman 1987). The electromagnetic field decay rate relies on the sub-surface resistivity distribution. In a conductive medium, the field decay is faster than in a resistive medium (Soupios et al., 2010). (Danielsen et al., 2013) provide a comprehensive description of the technique. The depths of interest in the study area lie within an interval between 80 meters to 250 meters for groundwater exploration in the different groundwater aquifers in the study area. The TEM method operates in the near-field of the source, where the sounding depth is controlled by the diffusion depth, depending on the transient time. Under favorable conditions, the sounding depth is usually 3-4 times the size of the transmitting-receiving magnetic antenna (loops) (Spichak 2015). This advantage enables the exploration of complex geological media with a high locality and depth. However, transient responses in magnetic loops are less sensitive to high resistance objects and cannot be used effectively for the sounding of geological structures consisting of thin resistive layers.

TEM-Fast 48 system from AEMR Ltd has been used for the data acquisition. A net of 46 TEM stations covering the whole study area have been conducted using the parameters in table 1. In order to improve the quality of the TEM measurements collected in the occurrence of noise, the induced current in the loop was set to 4A and the filter frequency was set to 50 Hz. The output of a TEM device was an approximately power law voltage decay curve. In order to interpret such data, the field data should be converted to apparent resistivities $\rho(t)$. 1X1D V.2 2008 software has been used for the processing and inversion step of the acquired data. The next step after calculating the resistivity data is the modeling of the interpreted data, where the primary objective is to understand the distribution of the subsurface conductivity in the study area. Usually TEM soundings are used to assist define aquifer characteristics and other subsurface structures.

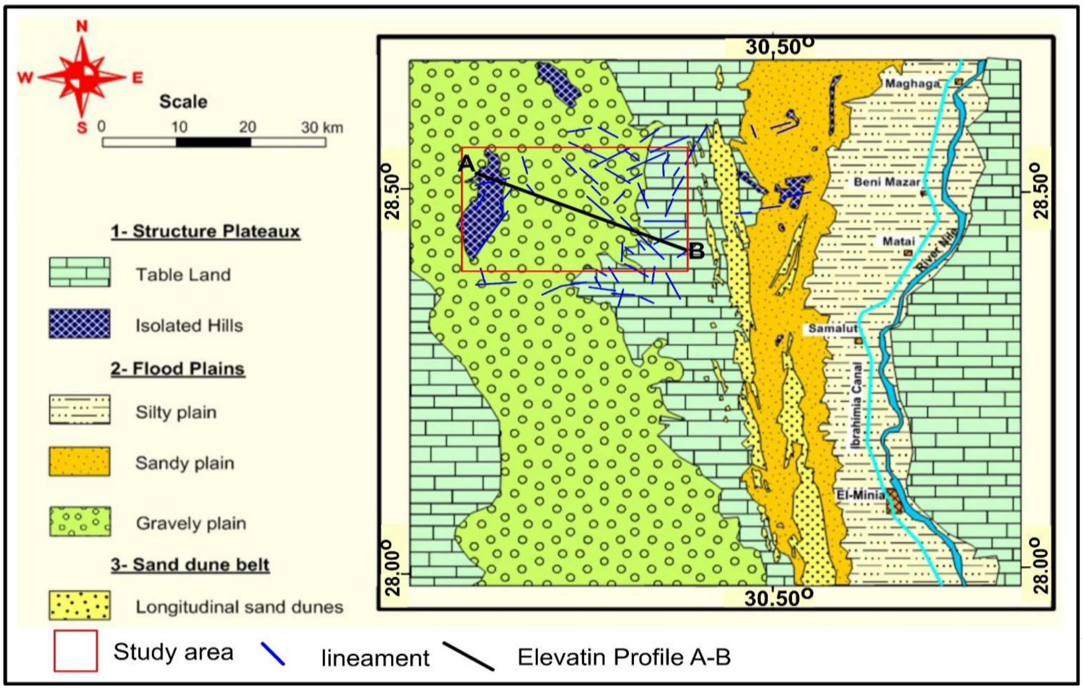

Figure 2: Geomorphologic map of the study area (after Shabana, 2010).

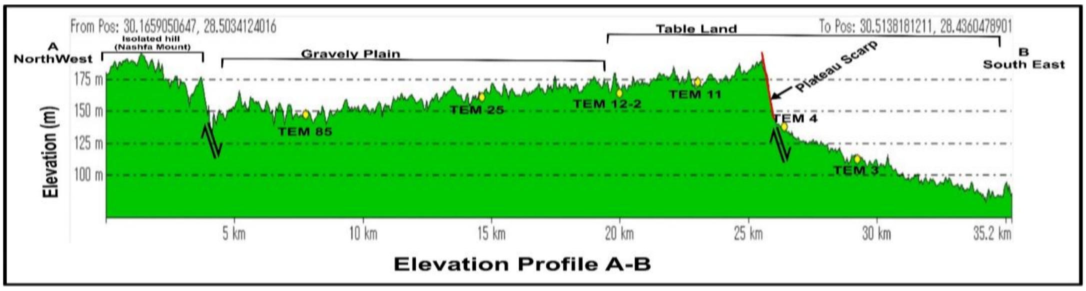

Figure 3: The Topographic features (Elevation profile) A-B.

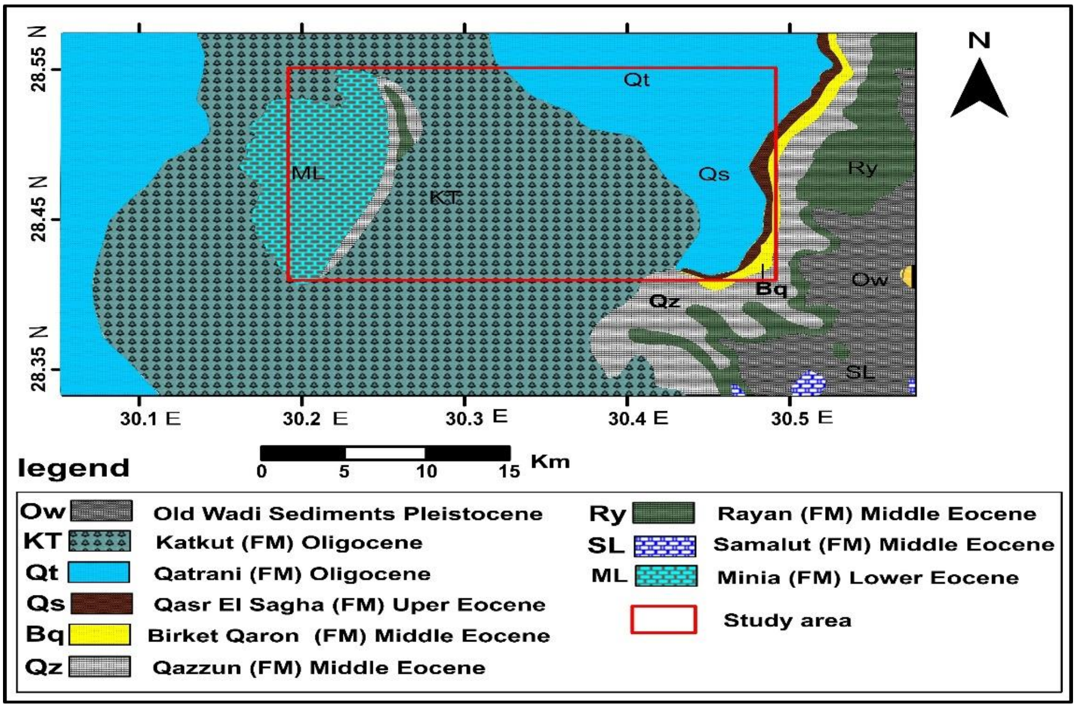

Figure 4: Geological map of the study area (modified after E.G.S.M.A 2005).

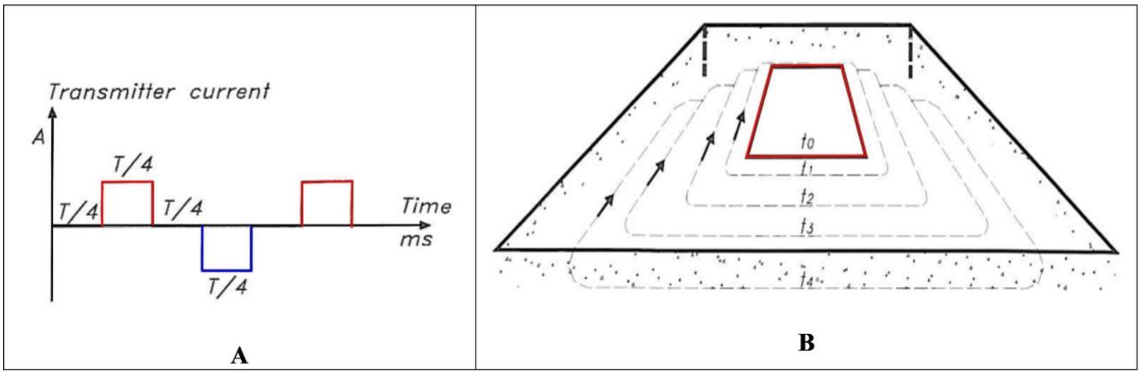

Figure 5: (A) Transmitter current waveform (B) Current flowing in the ground (after Gaetano Ranieri, 2000).

Table 1: TEM-Fast 48 used field parameters.

Parameters	Tx	Rx	Time (ms)	Stack	HVP	I (A)	F (Hz)
Value	200m*200m Copper loop	200m*200m Copper loop	7 & 9	5	11	1-2	50

Finally, the quality of the raw data was very good and the stations have been recorded several times for better quality. The RMS errors were 0.5 percent to 5 percent after the inversion. Figure (6) displays the location of the measuring stations, wells and the geoelectric cross-sections generated in the research area.

RESULTS AND DISCUSSION

According to the shapes of the curves, the number of segments of the TEM sounding curves divided qualitatively into three groups A, B, and C. Figure (7) displays examples of group A, B and C of the TEM curves in the study area. The curves showing the presence of four main segments in each curve of group A and B and 5 main segments of in group C curves. The curve type of group A is KH which represent 27% of the total number of curves and it is mainly recorded in Eastern and southern parts of the study area. Group B has the most dominant curve type in the study area which is KH with about 40% of the total number of curves and focused in the central northern Part and in the central part of the study area, and finally group C which has a QH curve type with about 37% of the total number and located in distinct localities in the extreme eastern, southern and northwestern parts of the study area. Figure (8) show the lithological succession of well 14 in the North Western part of the study area and an interpretation model of TEM 33. Table 2 shows the hydrogeological information of the drilled groundwater wells used to aid the interpretation process.

Four geoelectric cross-sections have been constructed for better understanding and presentation of the subsurface properties and groundwater availability (Fig. 6). Geoelectric cross-sections A-A ', B-B ', C-C ' and D-D' are shown in (Figs. 9, 10, 11 and 12). The most dominant trend of fractures and faults in the study area is NE-SW and NW-SE directions, this is why the cross-sections N-S and E-W directions were chosen to capture the structure in the study area. In the different cross-sections, six geoelectric layers were observed (A1, A2, B, C1, C2 and D) however the six layers were not recorded at some TEM stations due to variations in clay layer thickness and sub-surface electrical characteristics. Several wells with known geological succession and recorded logs for some of these wells have been used to assist in the process of creating the initial TEM data processing model and to assist in the process of interpreting the final models of the data collected.

The geoelectric layers recorded in the research area can be divided into three main groups A, B and C as follows:

A. The first group of layers A divided into two layers composed of dry surface layers of sand and gravel turned to contain more clay content as follow:

- The first layer A1, has a lithological composition of sand and gravel with a thickness ranges from less than 1 meter at TEM 16 in the central Eastern part to 25.4 meter at TEM 46. This surface layer has a wide resistivity range from 20.55 Ohm.m at TEM 16 to 1772 Ohm.m at TEM 34 due to the lateral change in the sedimentary composition and layer compaction.
- The second layer A2, this layer, has been recorded at all TEM stations and consists of calcareous sandy clay layer with a range of resistivity between 25.3 Ohm.m at TEM 19 to 246 Ohm.m at TEM 33. The minimum thickness of the second geoelectrical layer starts from 12.7 m at TEM 17 while the maximum thickness of this layer at TEM 33 is 46.7 m.

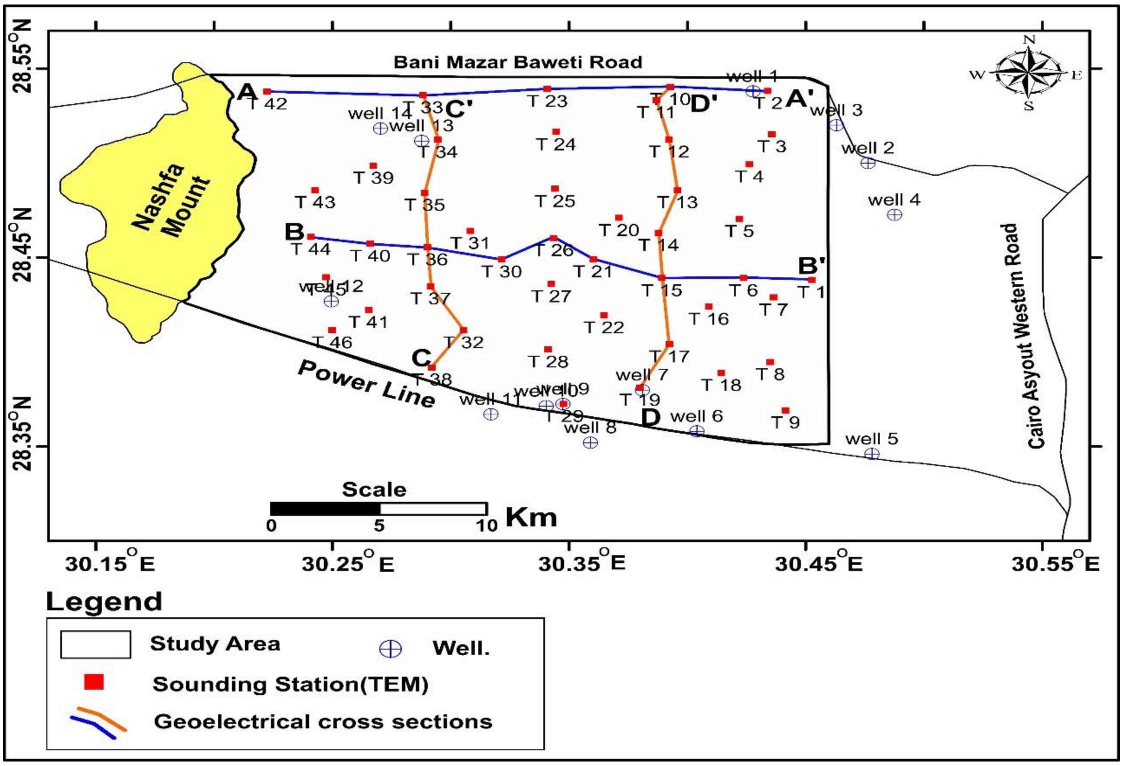

Figure 6: Location map of the TEM stations, Wells and Geoelectrical Cross-sections.

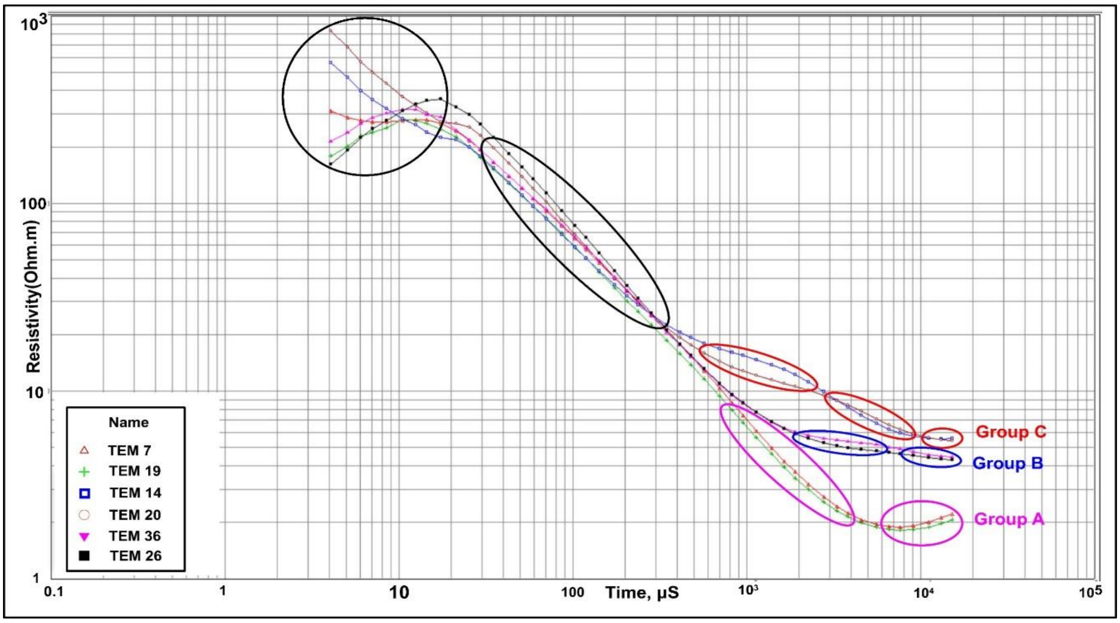

Figure 7: Examples of the TEM curve groups in the study area.

Table 2: Hydrogeological data of the groundwater wells.

Well No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Of fractured limestone Aquifer	L.S	L.S	L.S	L.S	L.S	L.S	L.S	L.S	L.S	L.S	L.S	L.S	L.S	L.S
Salinity (PPM)	2296	1770	2076	896	1197	1370	1150	2272	2140	1475	1884	-	3500	2157
Water Depth (M)	193	70	77.7	92	44.32	77.33	-	104.9	117	140	111	215	-	230

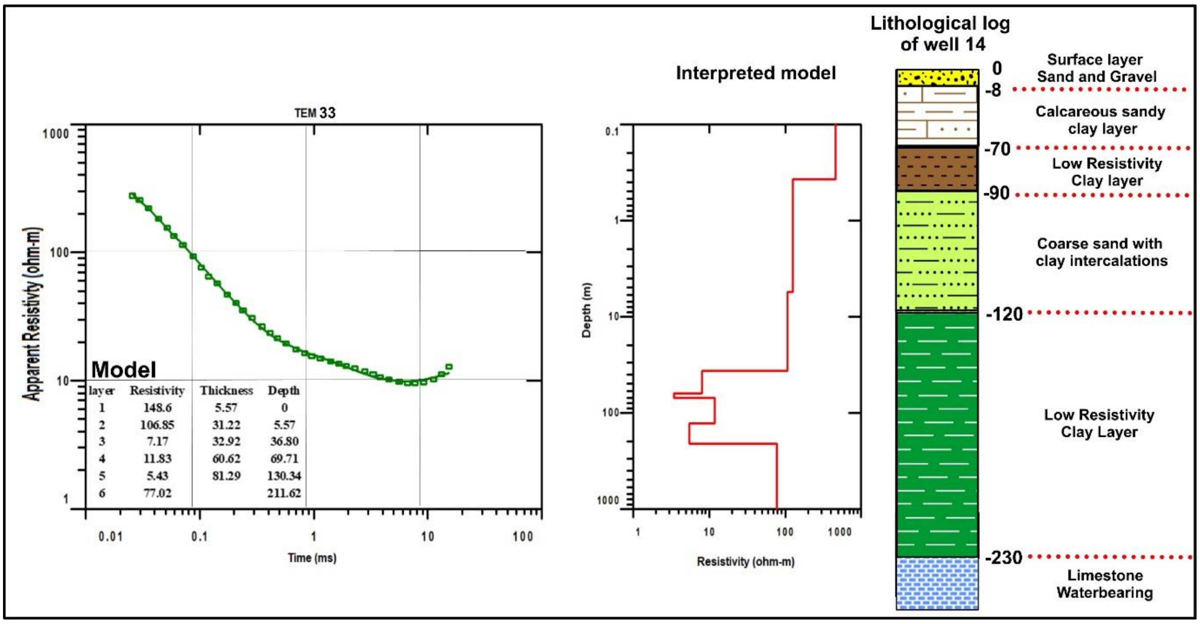

Figure 8: lithological succession of Well 14 and TEM 33 interpretation model.

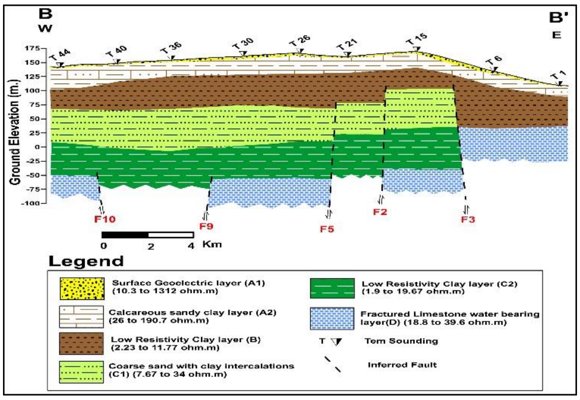

Figure 9: Geoelectric cross-section A-A'

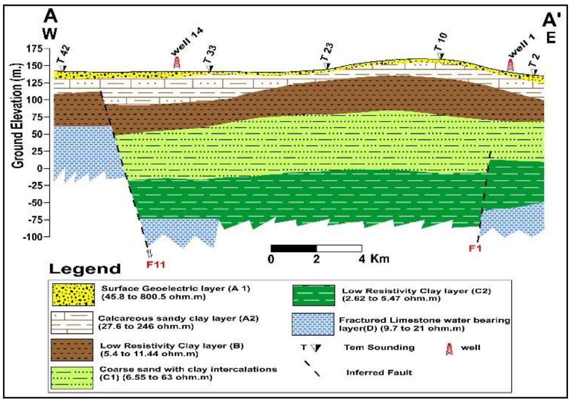

Figure 10: Geoelectric cross-section B-B'

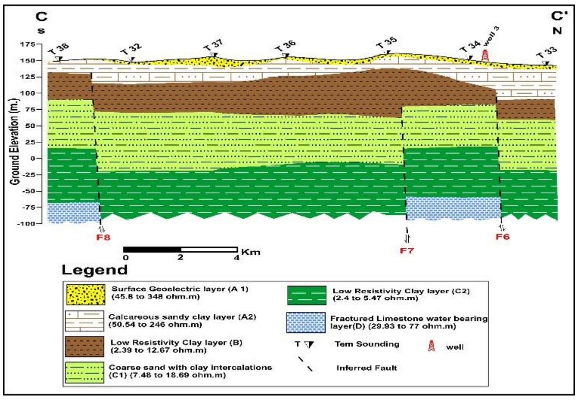

Figure 11: Geoelectric cross-section C-C'.

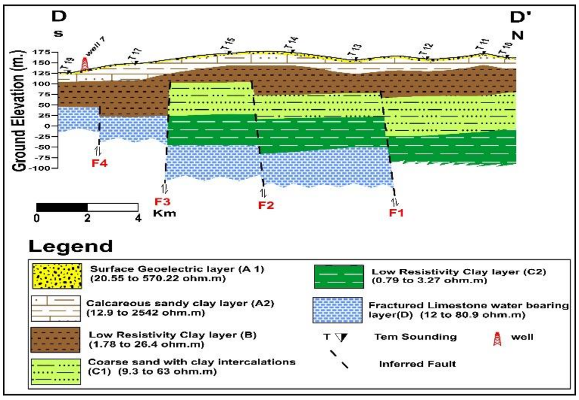

Figure 12: Geoelectric cross-section D-D'.

B. The second group of layers divided into 3 layers B, C1 and C2 which composed of a sequence of clay, limestone and sand layers as follow:

- The third layer (B), is the last layer of the dry zone (layers A1, A2 and B) composed of clay deposits with limestone intercalations. This layer is considered as a marker bed in the study area with rang of resistivity 1.8 Ohm.m at TEM 19 to 26.4 at TEM 11 and thickness from 27.4 m at TEM 46 to 100.4 m at TEM 8.
- The fourth layer (C1), this layer composed of coarse sand mixed with clay intercalations. The resistivity range of this layer 3.3 Ohm.m at TEM 3 and 38 Ohm.m at TEM 25 and thickness between 47.6 m at TEM 14 and 91.6 m at TEM 46.
- The Fifth layer (C2), this layer is the second clay layer in the succession with a range of resistivity from 2 Ohm.m at TEM 28 and 9.6 Ohm.m at TEM 22 and thickness ranging between 47.4 m at TEM 45 and 88.1 m at TEM 14. The top 5 layers A1, A2, B, C1 and C2 belong to the Oligocene age Qatrani formation which composed of calcareous sandstone with clay intercalations.

C. The last geoelectrical layer D, it is the water bearing fractured limestone formation belongs to the middle Eocene age (Samalut Formation). This layer is not recorded in all the TEM stations in the study area. The resistivity range of this layer is between 5 Ohm.m at TEM 2 and 80 Ohm.m at TEM 34 and the depth to the surface of this layer is between 191.1 m at TEM 2 and 235.7 m at TEM 11.

Table (3) shows the recorded geoelectric layers parameters in the study area.

Groundwater condition:

As it is noticed from the geo-electrical cross-sections, the Eastern and Northwestern parts of the study area are strongly affected by faults and lineaments, as mentioned earlier in the geological and structural maps of previous studies, some of these faults have been verified by this research as follows:

Table 3: The resistivity ranges, thickness, and depths of the recorded geoelectric Layers.

Layer	Resistivity range (Ohm.m)		Thickness Range (m.)		Depth Range (m.)		Lithological Description
	Min-	Max-	Min-	Max-	Min-	Max-	
Layer A1	10.3	1312	0.14	25.41	0	0	Surface Layer (sand and gravel)
Layer A2	12.9	2542	11.01	55	0.14	37.8	Calcareous sandy CLAY layer
Layer B	1.78	26.4	27.4	100	15	88.5	Low resistivity CLAY layer
Layer C1	6.55	63	47.6	117.5	54	134.6	Coarse SAND with clay intercalations
Layer C2	0.79	19.7	17.5	111.5	118	221.4	Low resistivity CLAY layer
Layer D	8.78	80	------	------	191	235.7	Fractured LIMESTONE (Water-Bearing)

Two faults recorded along the Cross-section A-A', F11 between TEM stations 33 and 42 in the north western part of the study area and F1 common between A-A' and D-D' cross-sections. Five faults recorded along the cross-section B-B' which are F2, F3, F5, F9 and F10. The cross-section C-C' recorded 3 faults F6, F7 and F8. The faults number F1, F2, F3 and F4 are recorded along the cross-section D-D' and F2, F3 and F4 are common between cross sections B-B' and D-D'.

Geological structure controls the groundwater potentiality and recharge in the fractured limestone aquifer. It is noticeable that the water-bearing fractured limestone is not recorded in the entire study area, in some instances, there is a large difference in the water level between very near water wells indicating that the water content of this layer is highly controlled by the fracture density. In some cases, very close water wells, one of which contains water in fractured limestone and the other is completely dry.

Fig. 13 shows the contour map of the upper surface of the fractured limestone aquifer, inferred faults and a dominant flow direction in the North West and to the center of the study area. The water level in the Eocene aquifer is ranging between 60 and -80 m. The depth to the surface of this aquifer generally increase to the central part of the study area and decreases to the south east and North West. It is well noticed from the contour map that not all of the TEM stations recorded water bearing limestone and the water bearing limestone recorded only in TEM stations focused in the south west and north east of the study area and this area is the most affected area with structure lineaments and faults. (Fig. 13) shows the TEM stations recorded the limestone aquifer which are 29 TEM stations out of 46 and 17 TEM stations did not penetrate the clay layer in the central part of the study area.

As we can see in (Fig. 14), the resistivity of the water bearing limestone ranging from less than 10 Ohm.m to about 80 Ohm.m, the south eastern and north western part has a moderate resistivity 30 to 65 ohm.m which indicate good quality water content, while the central and extreme western parts has low resistivity values indicating the high clay content and low water quality. The fractured limestone aquifer does not cover the entire study area and is only recorded in 29 TEM stations, and these locations are concentrated in the eastern part and follow the NE-SW direction of faults, and recorded in a limited number of TEM stations in the western and southern parts of the study area.

The groundwater salinity measured from the water samples ranging between 2157 ppm and 3500 ppm. Based on the resistivity values of the fractured limestone aquifer the water quality of the aquifer increases in north-east and south-west portions.

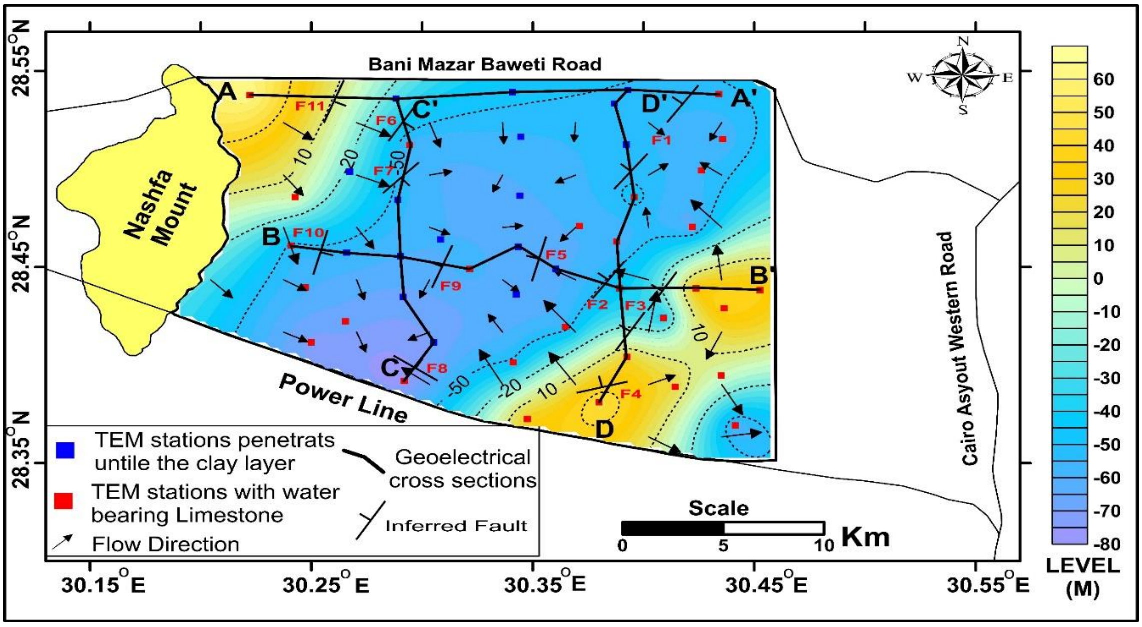

Figure 13: Contour Map of the upper surface of the fractured Limestone Aquifer (D), Flow direction, faults and TEM stations recorded water content.

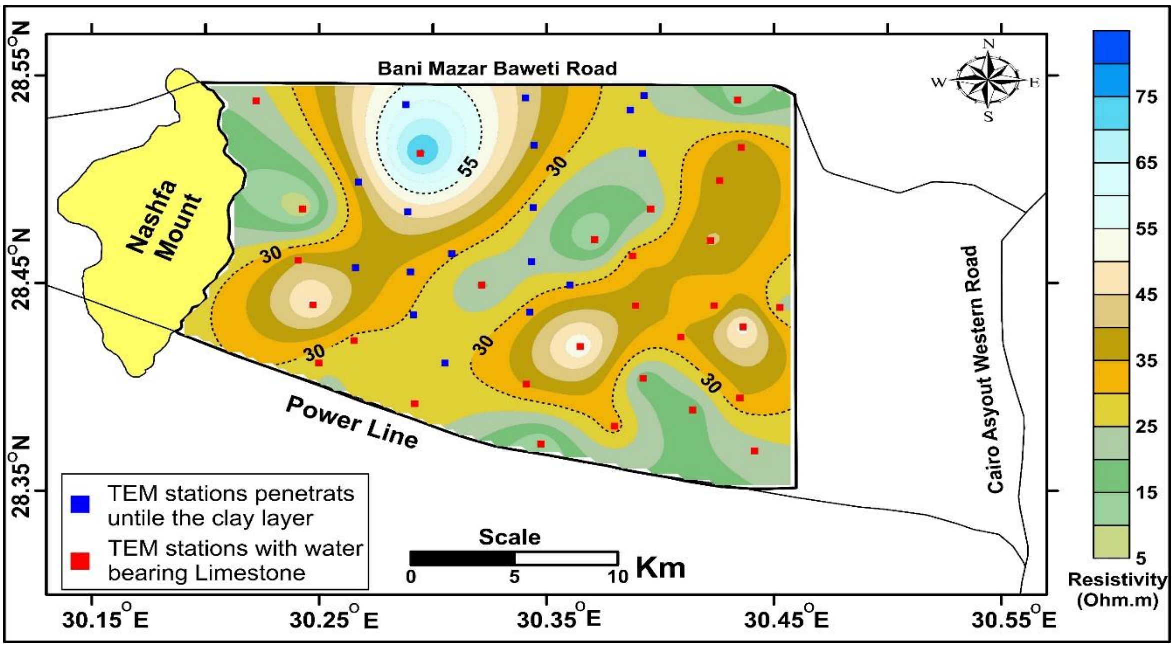

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Figure 14: Iso resistivity (D) contour map of the fractured limestone.

Table 4: Best locations and Depth for drilling groundwater wells.

TEM stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**14**	**15**	**16**	**17**	**18**
Expected water depth	74	209	207	221	215	104	81	150	235	215	180	179	168
TEM stations	**20**	**22**	**28**	**29**	**30**	**34**	**38**	**41**	**42**	**43**	**44**	**45**	**46**
Expected water depth	205	222	217	144	223	212	230	204	80	197	197	202	205

CONCLUSION

The Transient Electromagnetic Method (TEM) is a very powerful technique for groundwater exploration in arid regions and in fractured rock aquifers. Therefore the TEM technique can easily identify potential zones of groundwater, horizontal and vertical extension, also, potential geological structures affecting water-bearing layers and play an important role in the process of aquifer recharge.

Based on this study the water-bearing formation in this area is the fractured limestone of middle Eocene, as stated earlier, this layer's water content is strictly controlled by fractures and faults influencing this layer. This phenomenon makes the water content of this layer concentrated in some places and missed in others even though it is very near to water-bearing areas, making the decision to drill groundwater wells in places away from the decided locations very difficult. The presence of water content in this layer is observed by 29 TEM stations and confirmed with the drilled wells data, these stations are concentrated in the eastern part following the NE-SW direction and in some locations in the western portion which contain high density of fractures and faults as noticed in (Fig. 13 and 14).

RECOMMENDATIONS

The fractured limestone aquifer is not continuous in the whole study area and its presence is controlled with the presence of fractures, joints and faults and its density. The availability and water quality of the limestone aquifer increases toward the northwest and south east directions in the study area due to the increases of the fracture intensity in these parts as we mentioned before from the previous structure and geological studies. The best locations for drilling groundwater wells are the southeastern and northwestern parts of the study area, Table 4 shows the best selected locations for drilling productive groundwater wells in the middle Eocene fractured limestone aquifer and the expected depth of the groundwater.

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