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ARCHAEOLOGICAL PROSPECTION AND GROUND WATER HAZARD ASSESSMENT OF THE HAWARA PYRAMID, FAYOUM, EGYPT

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KEY WORDS

Hawara; ERT; TEM; archaeogeophysics, hydrogeophysics.

ABSTRACT

The present study utilizes the Electrical Resistivity Tomography (ERT) and Transient Electromagnetic (TEM) methods to investigate the Hawara Pyramid archaeological site, Fayoum, Egypt, located approximately 90 km south west of Cairo, and assess the impact of groundwater on the site's valuable foundations and preserved remains, particularly the Labyrinth mortuary temple complex and its surroundings to the south of the pyramid. The ERT measurements were carried out using the high-quality French device SYSCAL R2 (IRIS company, France).Twenty-five ERT profiles were conducted along the areas surrounding the pyramid. The 2D Electrical resistivity were processed with RES2DINV software. The TEM data were acquired at three sites comprising the pyramid, the Labyrinth, and the nearby cultivated land, measured by SIROTEM MK3 conductivity meter employing the coincident loop configuration. TEM data were inverted to a 1-D scheme using the TEMIX XL 4 program (2000), assuming layered-earth models. A careful analysis of the combined ERT and TEM results indicates the presence of some near-surface archaeological remains. It also indicates that the site suffers from a rising groundwater level that may impact it seriously. This threat has been attributed to the increasing agricultural activities where the flooding irrigation system dominates in the planted areas surrounding the pyramid site, eventually leading to continuous surface water infiltration and a rise of the subsurface water level.

Introduction

The Hawara area, a cemetery site located approximately 90 kilometers south west of Cairo in southeast Fayoum city, is home to the Labyrinth Mortuary Temple Complex, a site of significant archaeological importance. The complex, located south of the Hawara pyramid Fig. (1**)**, is considered as one of El-Fayoum's most crucial monuments. This pyramid, built by Amenemhat III (around 1855-1808 BC), the final major monarch of the 12th dynasty who is also buried there. Unlike other pyramids, it was constructed with a mud-brick core instead of limestone, a feature that adds to its historical significance. However, weathering has eroded its outer casing of limestone.

The pyramid, made of limestone rock base lies approximately 32 meters above sea level**,** is positioned in a unique way. Its face is towards the agricultural expanse of the Fayoum Valley to the west and the Bahr Wahba irrigation canal (**Brown 1892; Butzer 1976**). This unique positioning adds to the wonder and curiosity surrounding the Hawara Pyramid, making it a site of great interest and significance.

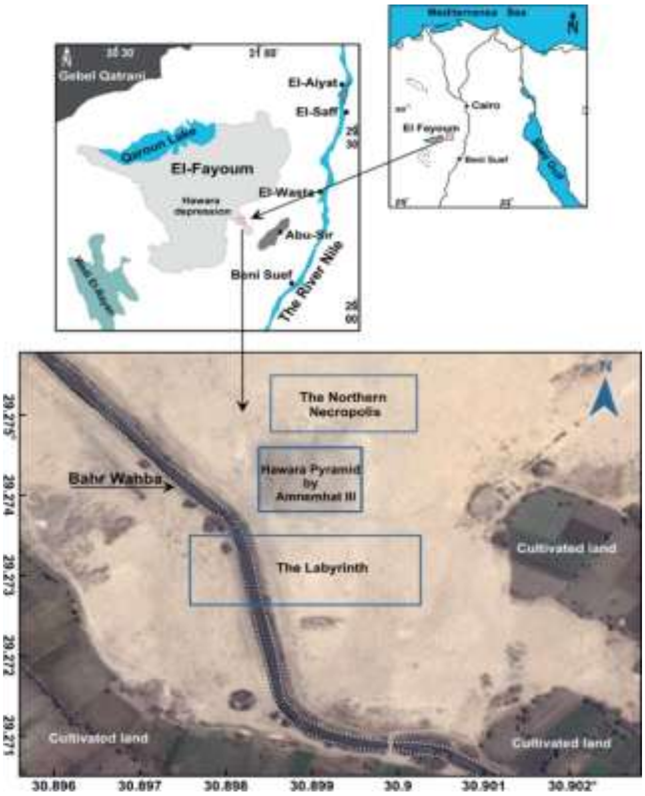

Fig. (1): Location of Hawara archaeological site (After **Abbas et al., 2023**).

Groundwater infiltrated the area around the Hawara Pyramid and the Labyrinth. According to **Petrie et al. (1912),** in 1889 only the lowest chambers of the tomb beneath the main pyramid foundation structure contained groundwater. Over time, especially in the 21st century, water has seeped into every room and the tunnel system. The internal structures of the pyramid are completely flooded at this time, and water was present 3.0 meters below the entry level **(Temraz and Khallaf 2016)**. Numerous researches focus on employing various geophysical techniques to uncover concealed archaeological sites across diverse geographic regions **(Abdel Fattah et al., 1993, Elkafrawy et al., 2021).** In this study, Electrical Resistivity Tomography (ERT) and Transient Electromagnetic (TEM) geophysical surveys have been conducted on the study area to explore the presence of near-surface archaeological remains, and define the subsurface water level in an attempt to identify the feeding sources of the groundwater affecting the archaeological targets at Hawara area.

Geologic setting

El-Fayoum region, a geological wonderland, has been the subject of extensive research by numerous geologists **(e.g., Said, 1962; Tamer, 1968; Swedan, 1986)**. The El-Fayoum province, with its four major depressions (Nile Valley, El-Fayoum, Hawara, and El Rayan) bordered by an Eocene limestone plateau, is a unique geological setting. The rock units in the El Fayoum region, ranging in age from Eocene to Quaternary. El-Fayoum depression, with its multitude of visible faults at its margins, is a sight to behold. These faults, trending in four directions: E-W, ENE-WSW, NNW-SSE, and NW-SE, with the latter being the most prevalent (**Swedan, 1986; Conoco, 1987**).

In the research region, the subsurface stratigraphic column is capped by Quaternary sediments, which are extensively distributed throughout El-Fayoum province and consist of sand and gravel of various grain sizes, limestone pebbles, silt, clay, and gypsum. They result from alternating sedimentation and erosion throughout the Pleistocene and Holocene periods. These deposits rest directly on thick, vast Eocene limestone deposits extending to deeper depths. The geometry of the underlying limestone and deposition environment resulted in forming a thick Quaternary section in this region. At the same time, Middle Eocene limestones and marls (Mokattam Formation) create isolated patches in the area, one of which serves as the base of the Hawara pyramid (**Sweden, 1986**).

Methodology

Two geophysical methods, namely, Electrical Resistivity Tomography (ERT) and Transient Electromagnetic (TEM) were used. They are briefly introduced in the following paragraphs.

Electrical Resistivity Tomography (ERT)

2D electrical resistivity tomography, an active geoelectric technique, is renowned for its precision and reliability in measuring the electrical resistivity variation in the subsurface. This technique enables the classification of subsoil materials according to their electrical properties and lithological characteristics **(Dahlin, 2000; Martínez-Lo'pez et al., 2013)**. It can be considered continuous vertical electrical sounding (CVES), merged, or a combination of successive profiling with increasing electrode spacing **(Aizebeokhai, 2010)**. The method provides more precise and reliable results about subsurface resistivity distribution vertically and horizontally along the survey line (ERT profile) **(Loke, 2015)**.

In this study, the resistivity measure-ments were carried out using the high-quality French device SYSCAL R2 (IRIS company, France) with its exceptional resolution and deep penetration capabilities. The sequence measurements technique was applied to obtain a pseudo section during creation of 2D sequence of measurements. Twenty-five ERT profiles have been conducted along the free accessible areas surrounding the Hawara pyramid (nine profiles were conducted in 2019, and the remaining 16 profiles were conducted in 2021). In the field, three multi-node boxes with sixteen electrodes were used to measure each ERT profile with 48 electrodes, 235 meters in length, 5 meters between each two successive electrodes to give a penetrating depth of about 35 meters beneath the ground surface. Figure (2) shows the locations and directions of the conducted ERT profiles surrounding the pyramid.

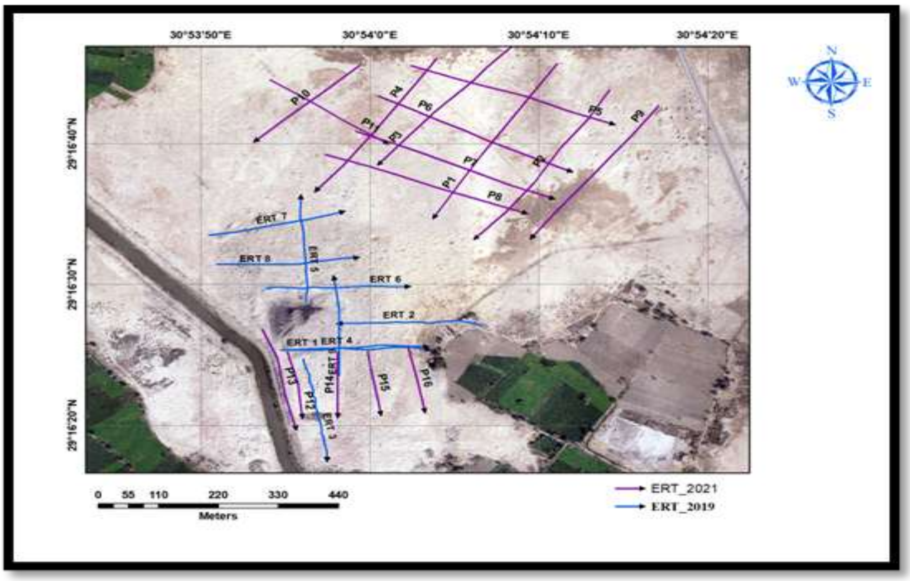

Fig. (2): Location of the conducted ERT profiles surrounding Hawara pyramid.

Transient Electromagnetic (TEM)

It is an inductive method involving a square loop often placed on the ground surface, which uses a high direct current running through it. A primary magnetic field will be produced by the current flowing through the surface loop and extending into the earth. When the primary field is absent, it measures the secondary field (**Nabighian and Macnae, 1991**).

In the present study, the TEM data were measured by a SIROTEM MK3 conductivity meter by applying the single loop configuration with a loop side length of 50 m. The data were recorded in composite mode through up to 30 time windows. Here 40, measuring stations arranged in a grid-like pattern Fig. (3) were defined to cover the entire archaeological site, including the pyramid, the labyrinth, the northern necropolis, and the surrounding cultivated land. The investigated area measures about 1500 x 2200 m, and the TEM measuring points were spaced at about 100-300 m in both E-W and N-S directions Fig.(3).

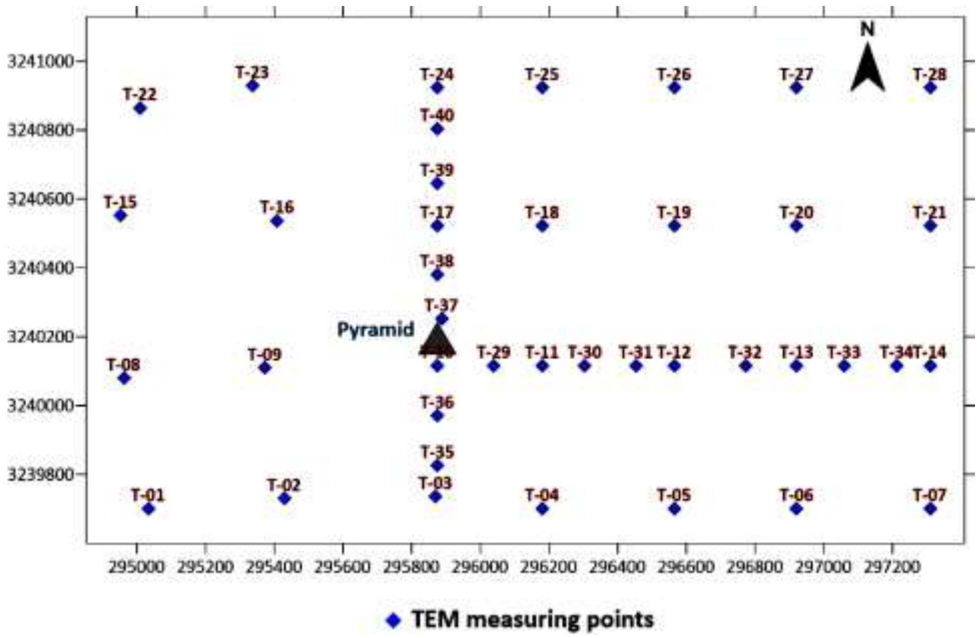

Fig. (3): Distribution of TEM measuring points at Hawara archaeological site.

Results and Interpretation

The ERT

The RES2DINV computer program, with its automatic generation of two-dimensional resistivity models of the subsurface, played a crucial role in refining the resistivity imaging field data. The result appears as rectangular blocks, which further was enhanced using the least square inversion, ensuring the highest level of accuracy in our resistivity models as it minimize the contrast between the measured and calculated resistivity models and instilling confidence in the precision of our results.

The final result, a product of rigorous processing, is not just an attempt but a successful endeavor to produce ideal images of what is present in the subsurface layers with a precise and reliable information about subsurface **(Loke and Barker, 1996)**.

Based on the resultant ERT profiles conducted at the area and its surroundings and the exatracted resistivity values across different profiles, it has been realized that the ERT profiles that cross the labyrinth area south of the pyramid show areas of very high resistivity values that appear in purple color and high resistivity values that appear in orange and yellow colors. These values could indicate an empty volume (Open cavity, Shafts, Halls, Rooms,…etc) that may reflect the presence of possible subsurface archaeological remains, as pointed by arrows in Figs (4 to 7). For example, the ERT N-S profile No. (3). shows two closures; both show high resistivity values compared to the surrounding (Fig. 4). The first closure has a width of 6 m at a depth approximately of 7.5 m and the second closure has also a width of 6 m at depth of 7.5 m. Another example is the ERT N-S profile No.12, located at the south of the pyramid, has one closure at the north with high resistivity values with a width of 4 m at depth 5 m Fig. (6).

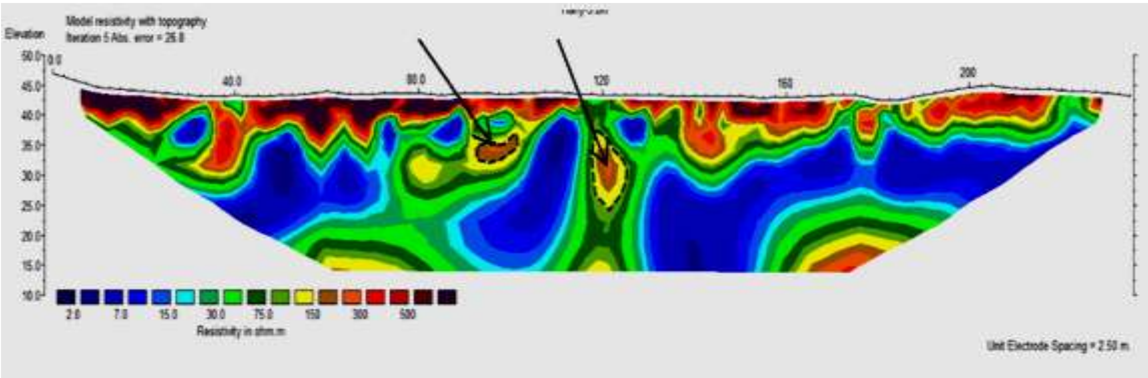

Fig. (4): Electrical resistivity tomography N-S profile No. 3 (survey conducted in 2019) located at the south of the pyramid.

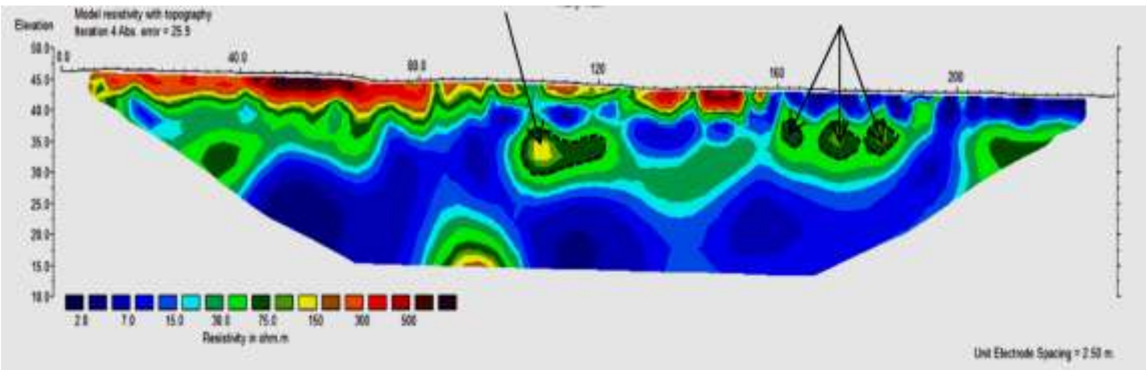

Fig. (5): Electrical resistivity tomography W-E profile No. 4 (survey conducted in 2019) located at the south of the pyramid.

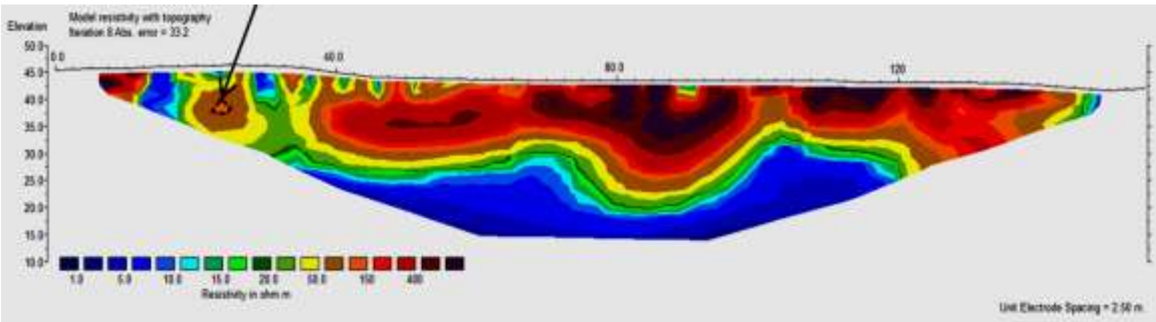

Fig. (6): Electrical resistivity tomography N-S profile No. 12 (survey conducted in 2021) located at the south of the pyramid.

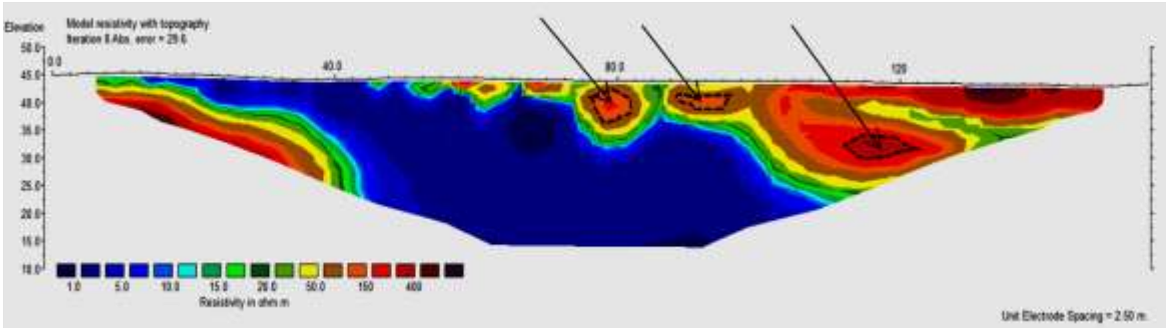

Fig. (7): Electrical resistivity tomography N-S profile No. 14 (survey conducted in 2021) located at the south of the pyramid.

The ERT profiles conducted to the north and northeastern of the pyramid show low resistivity values ranging from 1 to 10 Ω.m with blue color. These values indicate that the Hawara pyramid and its surrounding area may have been highly affected by wastewater seepage from the subsurface. It also indicates that the water flow follows in the same direction from the north and northeast of the pyramid as shown in Figs (8 & 9). This seepage may come from the old water plant with broken water pipes that existed at the northeastern corner of the area. This historical context, which is crucial for understanding the potential impact of the seepage, is a significant part of our work in preserving the pyramid's history and underscores the urgent need for further investigation. Besides, at the northeastern corner of the site, there is an old water plant with broken water pipes and a lot of water leakage in the subsurface soil.

The difference in resistivity values from the ERT profiles reveals that the area at the north of the pyramid is more affected by the water seepage than that to the south (Figs 8&10). For example, the ERT profile No.(6)., located to the north of the pyramid, shows low resistivity values (blue color in Fig. 8), while the ERT profile No.13. located beside the pyramid to the south shows very high resistivity values (purple color in Fig. 10).

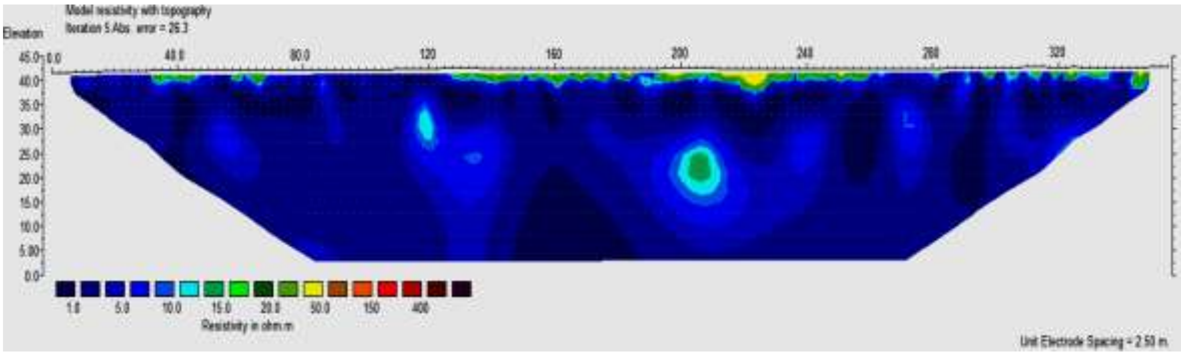

Fig. (8): Electrical resistivity tomography W-E profile No. 6 (survey conducted in 2021) located at the north of pyramid.

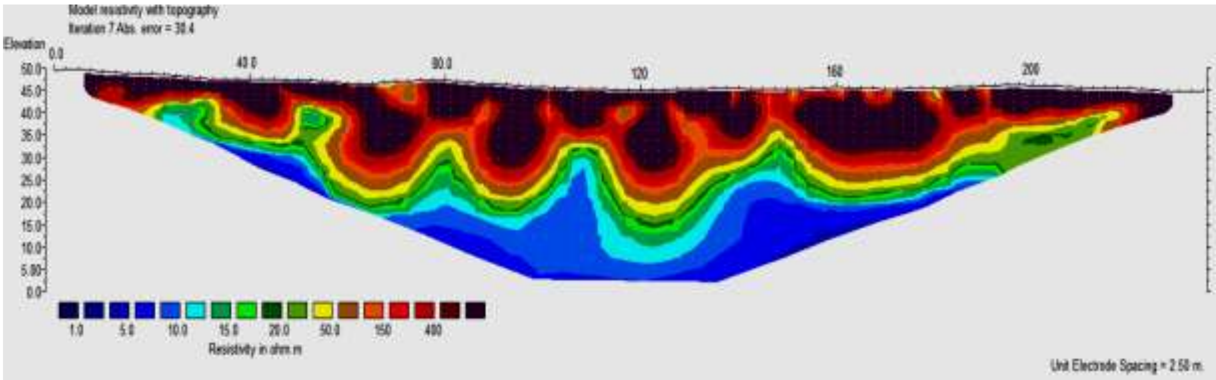

Fig. (9): Electrical resistivity tomography NE-SW profile No. 10 (survey conducted in 2021) located at the north of the pyramid.

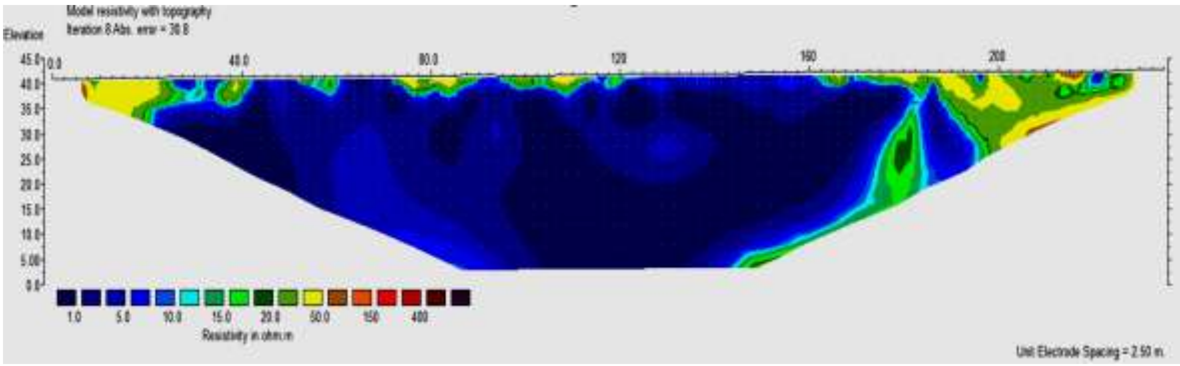

Fig. (10): Electrical resistivity tomography N-S profile No. 13 (survey conducted in 2021) located beside the pyramid to the south.

Figures (11 & 12) show that the area to the south of the pyramid is highly affected by the seepage of the underground water coming from the east direction (cultivated land) toward the pyramid.

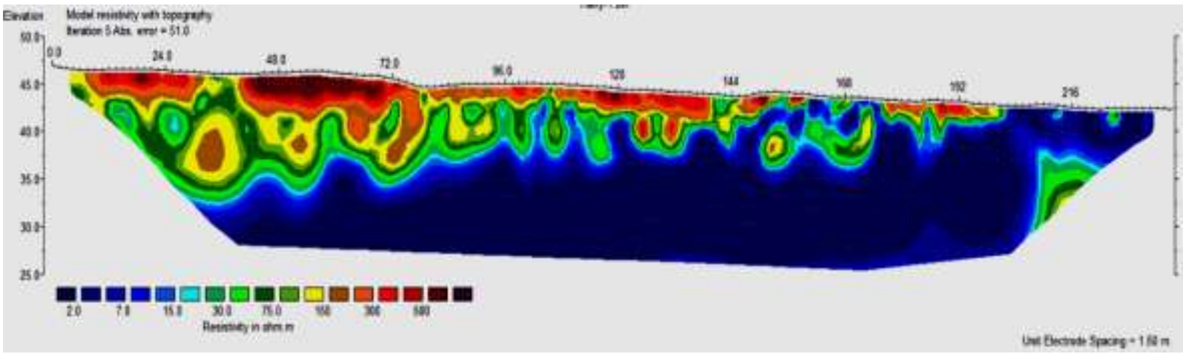

Fig. (11): Electrical resistivity tomography W-E profile No.1 (survey conducted in 2019) located at the south of the pyramid.

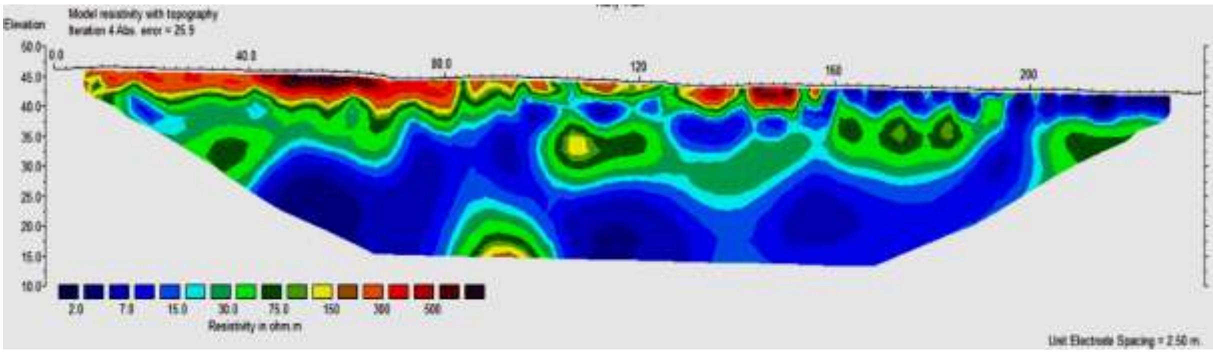

Fig. (12): Electrical resistivity tomography W-E profile No.4 (survey conducted in 2019) located at the south of the pyramid.

The TEM

The TEM data at the Hawara archaeological site were inverted to a 1-D scheme using the TEMIX XL 4 program (2000), assuming layered-earth models. Several criteria were tested to select the most appropriate starting model for the TEM data processing, including the number and thickness of the layers. The best model should provide minimum error, maximum fit, and best matching with the available geological information**.** After data inversion, a set of models was produced that gave information about the geoelectrical parameters of the subsurface section. Selected examples of the TEM sounding curves and the corresponding models are shown in Figs (13&14).

The best-filtered models have been used to construct four resistivity and three thickness maps showing each layer's resistivity distribution and thickness variation (Figs 15 & 16). These maps show that the investigated section comprises four geoelectrical units (layers). The first (uppermost) unit shows moderate resistivity values representing the partially statured, near-surface layer with thickness values ranging from 1.5 m at the northeastern part to about 10 m at the southwestern part. The second and third units exhibit low resistivity values with variable thicknesses ranging from 2 to 28 m for the second unit and 60-112 m for the third unit. These units could be correlated with sandy clay sections saturated with water with variable clay and/or water content. The fourth unit shows higher resistivity values than the second and third units with undetermined thickness. This layer could be correlated with the Eocene fractured limestone with high water content (Figs. 15 &16). These findings have practical implications for understanding and managing geological formations.

The TEM data results extracted the groundwater level from the sea level, as presented in Fig. (17). The groundwater table attained its maximum elevation of 41.5 m asl at the eastern and northeastern parts of the site, while the minimum water table elevation of 30 m asl is encountered at the southwestern parts.

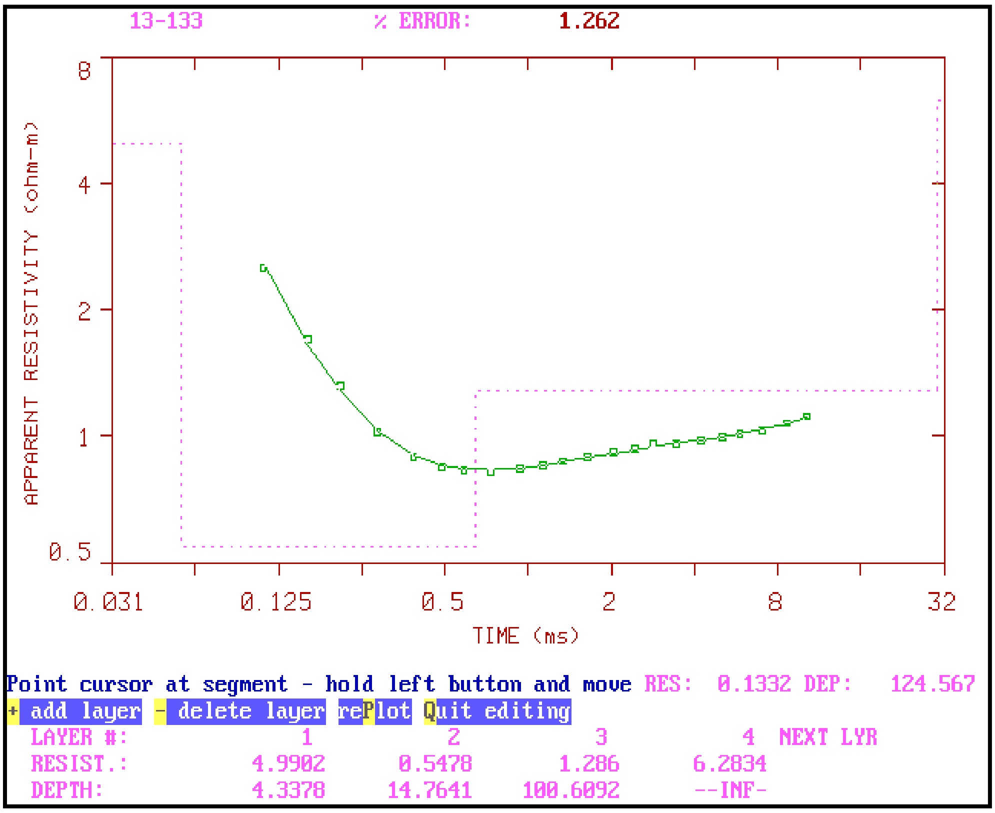

Fig. (13): 1-D model obtained from TEM data inversion at station 13.

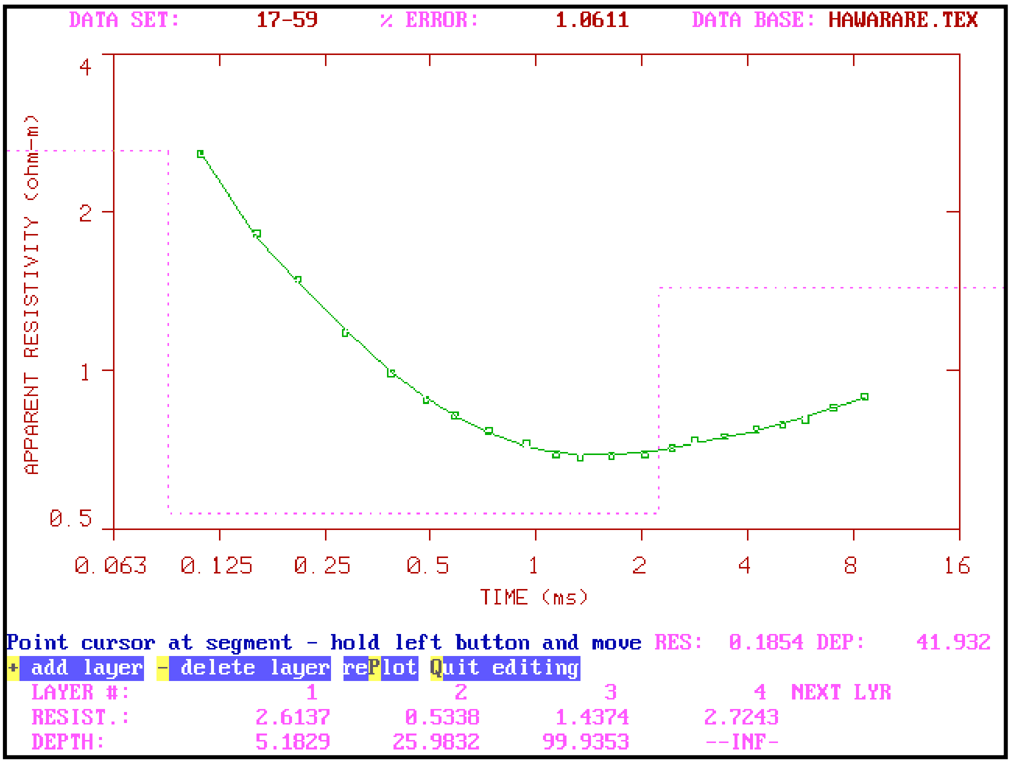

Fig. (14): 1-D model obtained from TEM data inversion at station 17.

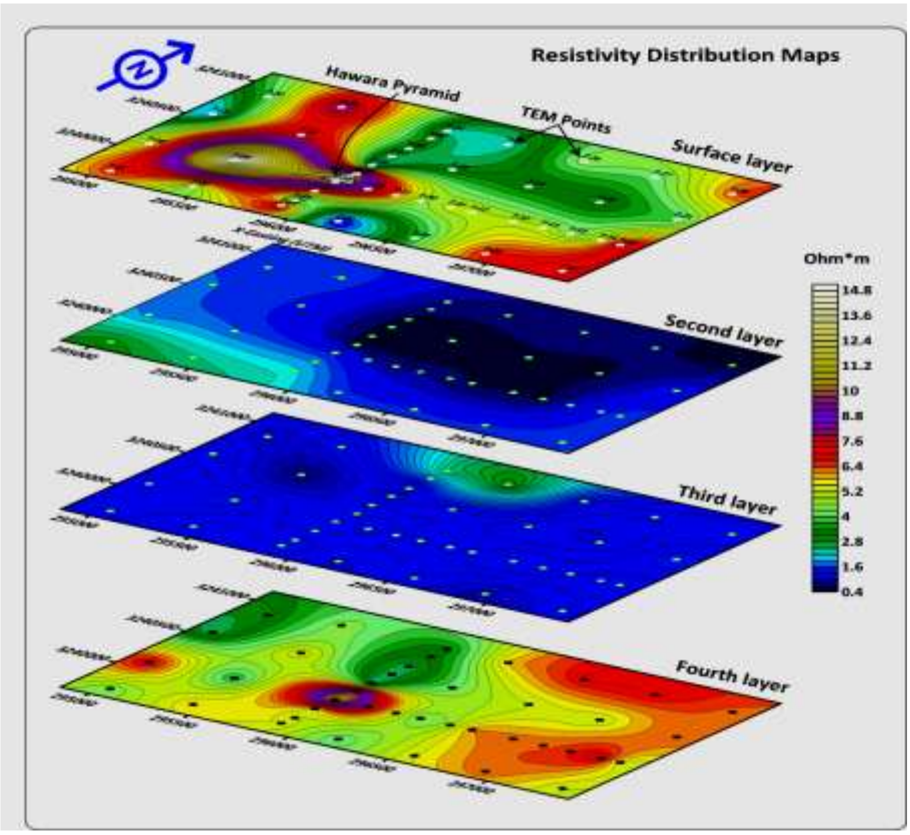

Fig. (15): Resistivity distribution maps in the investigated area.

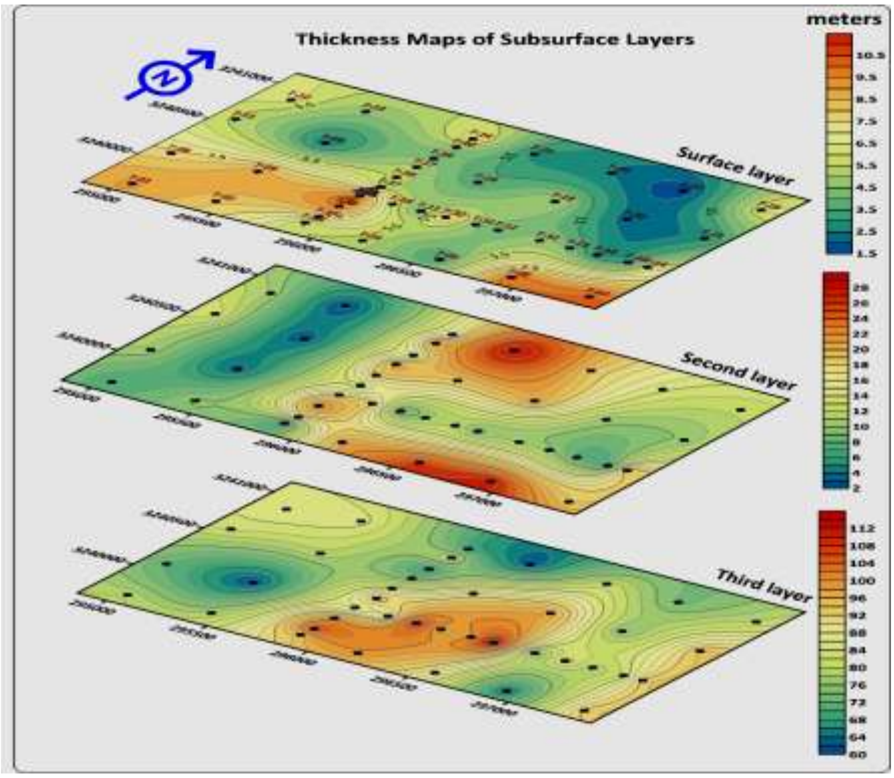

Fig. (16): Thickness variation of the identified layers at the study area

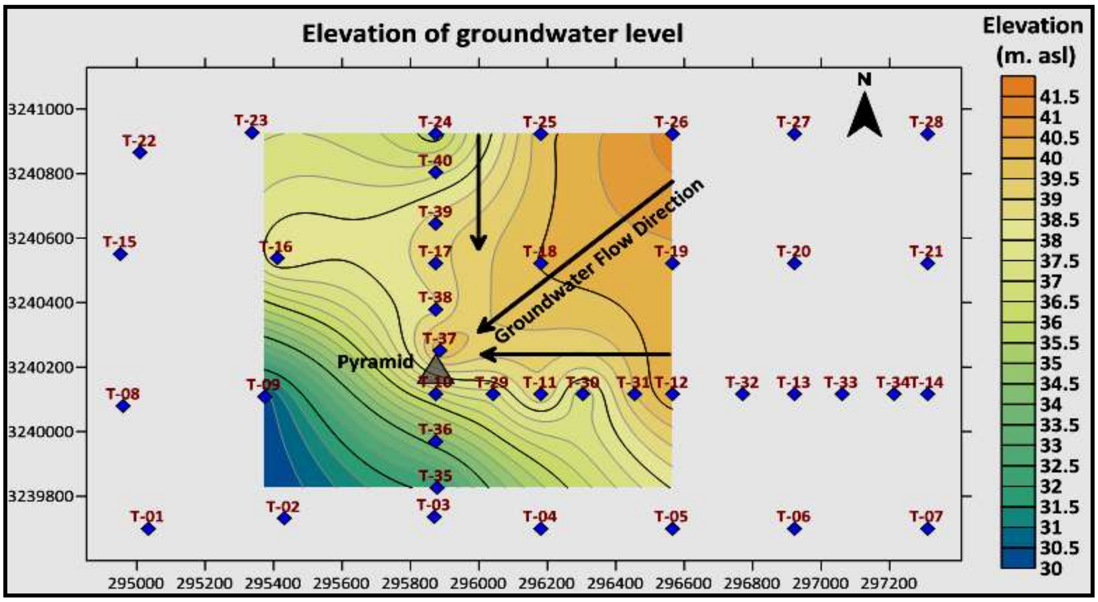

Fig. (17): Elevation of groundwater level at- and around Hawara Pyramid.

The water table elevation difference we've observed is a significant indicator of the feeding source of subsurface water invading this area, primarily located in the eastern and northeastern parts (Fig. 17). These areas can be considered recharging zones. The water level is found at a shallow depth (1.5 m) at the recharge area and a deeper depth (10 m) at the discharge area. The excess water at the recharge zones percolates into the subsurface and moves southwestward, invading the subsurface bedrock of the pyramid. This finding is in line with the ground truth, where intensive cultivations occupy the eastern part of the site with flood irrigation. The agreement of our assumption with the ground truth further validates the reliability of our study. Additionally, at the northeastern corner of the site, an old water plant with broken water pipes is causing water leakage in the subsurface soil, highlighting the urgent need for better water management practices.

Summary and conclusion

The application of both Electrical Resistivity Tomography (ERT) and Transient Electromagnetic (TEM) geophysical prospection methods at the Hawara site in Fayoum Province has proven valuable in detecting subsurface archaeological remains and elucidating the sources of water intrusion affecting this significant heritage site. Results from 25 ERT profiles conducted in the accessible areas south of the pyramid and across the labyrinth area, with pseudo-sections generated from 2D sequences of measurements, revealed high resistivity anomalies in the upper sections. These anomalies may indicate the presence of archaeological remains, which require further verification through standard excavation methods. Additionally, the ERT profiles indicated low resistivity values in the northern and northeastern parts of the area, suggesting potential water seepage. This is because the effect of the water seepage originates from the northeast, likely due to an old water plant with broken pipes**.** Another water source is the cultivated land east of the pyramid.

The Transient Electromagnetic (TEM) survey was conducted with 40 measuring points arranged in a grid-like pattern to cover the pyramid, the labyrinth, the northern necropolis, and the surrounding cultivated land, spaced approximately 100-300 meters apart in both E-W and N-S directions, has been instrumental in identifying the source of the invading water seepage. The water level in the recharge area to the east and northeast was found at a shallow depth of approximately 1.5 meters (with a water table elevation of 41.5 meters above sea level), while the discharge area in the southwestern part was at a deeper depth of approximately 10 meters (with a water table elevation of 30 meters above sea level). This indicates that the invading water seepage originates from the nearby cultivated land surrounding the pyramid, discharging its irrigation water towards the southern part of the pyramid, causing flooding and seriously threatening its foundations. Immediate solutions to mitigate this problem and protect the pyramid from further deterioration include adjusting the irrigation system of the surrounding cultivated land to drip or spray irrigation instead of flooding and dewatering the pyramid area, and initiating a monitoring system for observing the groundwater level.

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التنقيب الأثري وتقييم مخاطر المياه الجوفية لهرم هوارة، الفيوم، مصر

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في هذه الدراسة تم استخدام التصوير المقطعي للمقاومة الكهربية (ERT) و الطرق الكهرومغناطيسية (TEM) لتوصيف موقع هرم هوارة الأثري، الفيوم، مصر، والذي يقع على بعد حوالي ٩٠ كم جنوب غرب القاهرة، وأيضا عمل تقييم لتأثير المياه الجوفية على أساسات هذا الهرم ذو الأهمية والبقايا الأثرية المحفوظة المحتمل تواجدها في مجمع المعابد الجنائزية (المتاهة) والمناطق المحيطة بجنوب الهرم. تم استخدام الجهاز الفرنسي العالي الجودة SYSCAL R2 (IRIS company, France) في قياسات ERT حيث تم أخذ خمسة وعشرون بروفايل حول المناطق المحيطة بالهرم، تم عمل معالجة لبيانات الكهربية باستخدام برنامج RES2DINV. قياسات TEM أخذت في ثلاث مواقع تشمل الهرم والمتاهة المحيطة به و أيضا المناطق الزراعية القريبة باستخدام جهاز SIROTEM MK3 conductivity meter في شكل حلقيconfiguration loop ، بينما تم استخدام برنامج TEMIX XL 4 (2000) لمعالجة بيانات TEM و ذلك للحصول على نماذج تعبر عن الطبقات الموجودة.

من خلال التحليل الدقيق للبيانات الكهربية و الكهرومغناطيسية تم التعرف على وجود بعض البقايا الأثرية قريبة من السطح و أيضا ملاحظة أن الهرم و ما حوله يعاني من ارتفاع في منسوب المياه الجوفية مما قد يؤثر عليه بشكل خطير. يرجع هذا التهديد الى تزايد الأنشطة الزراعية حيث ان نظام الري بالغمر هو المتبع في المناطق المزروعه المحيطة بالهرم التي بدورها تؤدي الى تسريب المياه السطحية بشكل مستمر و أيضا ارتفاع في منسوب المياه الجوفيه.