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Advancing Aquifer Monitoring: TDEM's Application in Seawater Intrusion Detection within Heterogeneous Coastal Aquifers of the Nile Delta

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Abstract

Coastal aquifers are vital freshwater sources worldwide, yet they are increasingly threatened by seawater intrusion due to over-extraction and climate change. The Nile Delta aquifer, one of the largest coastal groundwater reserves in the world, is particularly vulnerable to salinization, posing significant risks to agriculture, industry, and drinking water supplies. This exacerbates land salinization, infrastructure corrosion, and stresses the local economy. This study aims to explore the efficiency of the Time Domain Electromagnetic (TDEM) method in delineating seawater intrusion within coastal aquifers. The time domain electromagnetic method was used to collect 50 data points along a 50km profile perpendicular to the shoreline towards Mansoura City. Appropriate data processing techniques were applied to increase the signal-to-noise ratio and enhance the readability of data as the area has high cultural noise. Geophysical data inversion and interpretation showed the salt-fresh water boundary. Lithological data from the monitoring well allowed for the calibration of the geophysical model to ensure better results. TDEM data closely matched well data with an average error margin of 5%, showing seawater intrusion extending more than 40 km inland with a gradient nature. Intrusion depth varied between 10 and 20 meters. This confirms TDEM's effectiveness as a fast, cost-effective tool in mapping the salt-fresh water interface in the Nile Delta aquifer. While TDEM has been employed in various coastal settings, it hasm't been employed in the heterogenic nature of the Nile Delta aquifer. This research suggests integrating TDEM with the current monitoring network for tracking changes in aquifer parameters, challenging the complex nature of the area to provide successful results. This approach offers a foundation for improving groundwater management susceptibility and updating water policy.

Keywords: Groundwater salinization, Environmental Monitoring, Water Resource Management, Aquifer characterization, Hydrological hazards

Introduction

Population growth represents increased stress on water availability. This resulted in a continuous decrease in the individual share of water since 1990, placing Egypt with the lowest individual share of water per person in the world (Abd Ellah, 2020). Renewable water resources are limited in Egypt due to the defined share of Nile water as the main source of water. According to the FAO AQUASTAT database SDG 6.4.2 parameter, the level of water stress in Egypt is 141.17%, meaning freshwater withdrawals exceed renewable water resources, causing unsustainable utilization. This creates a high risk of resource depletion, environmental degradation, and long-term water scarcity, urging better water management practices. This makes the groundwater a precious resource that acts as a safety net for Egypt (Negm et al., 2019). The Nile Delta Aquifer is in direct contact with the Mediterranean Sea, which makes it subject to contamination with saltwater (Sefelnasr & Sherif, 2014)

Seawater intrusion is a widespread issue affecting coastal aquifers all over the world, as its progression is affected by external factors as groundwater pumping, irrigation and recharge operations, land use, and sea level rise, where the Egyptian coast is most vulnerable (Bear, 1999; El Raey et al., 1999). Groundwater salinity is affected by seawater intrusion, increasing seaward and depth-wise due to the increased density of more saline water naturally sinking due to gravity. (Sefelnasr & Sherif, 2014). This growing need for water is compensated by the unsystematic pumping of underground water by the villagers, which exceeds the replenishment rate of the aquifer. (Sherif, 1999). This process decreases the pressure in the freshwater zone and allows for saltwater to invade the aquifer. (Abd-Elaty & Polemio, 2023). In addition, the saltwater creates spikes of saltwater (Figure 1). With more surface area being mixed with salt water, the speed at which the saltwater diffuses into the aquifer increases (Zeidan, 2017).

The United States Environmental Protection Agency points out that chloride-rich water may present several issues, such as high blood pressure, a salty taste, the corrosion of piping, fixtures, and appliances, with potential blackening and pitting of stainless steel. (Wiltse & Dellarco, 1996). Agricultural land salinization caused by seawater intrusion poses a significant threat to food production. Salt can degrade buildings, roads, and water supply systems, increasing operational costs and reducing efficiency. This means saltwater intrusion places immense stress on the economic system, food chain and health system and thus should be considered as a major threat to our country (Mohamed, 2016). The Nile Delta represents 40% of crops, 50% of fish wealth and contributes 60% of industrial yield, which makes it a major contributor to the Egyptian economy (El Raey et al., 1999).

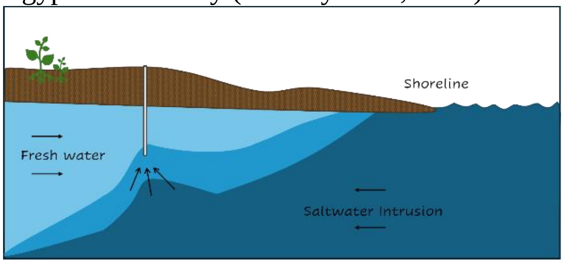

Figure 1 Illustration of saltwater intrusion in a coastal aquifer due to over-pumping of groundwater, altering the subsurface hydrodynamics and water quality. The fresh-saltwater interface is in a dynamic balance governed by hydrogeological conditions and human activities.

Previous studies aimed to determine the effect and extent of seawater intrusion on the Nile Delta aquifer using the time domain electromagnetic method as an efficient, cost-effective tool. The effect of seawater intrusion in the area was proven by (Ahmed et al., 2013) using chemical analysis of water samples obtained from several wells in the area. (Nofal et al., 2015) suggested the presence of a complex wedge system of four saline wedges intruding into the aquifer. The freshwater only exists in the top two wedges, with the rest of the reserve in the aquifer being saline and brackish. Later studies depended mostly on soil samples represented by Elsaid Saeed (2021) due to limited accessibility to well data. (Ding et al., 2020) introduced the possibility of using remote sensing data to predict seawater intrusion. More advanced remote sensing techniques combined with multivariate statistical analysis introduced by Abd El-Hamid et al. (2023) provided promising results in the area. These results can be limited by the capabilities of remote sensing data, low resolution and inaccessibility to detailed subsurface data, depending on indirect indications of seawater intrusion.

This study aims to determine whether the time domain electromagnetic method (TDEM) can be used to determine the seawater intrusion in this area. The approach is expected to provide the lateral and depth extent of seawater encroachment into freshwater based on previous work conducted in comparable settings (El-Kaliouby & Abdalla, 2015). The objective is to realize the efficiency of TDEM in providing models of the groundwater system at a site where seawater intrusion has occurred with accurate results. The results will contribute to the better management of coastal aquifers with changing saltwater extent and help and protect the essential water supplies and local economy.

Geologic settings

The Nile Delta aquifer is considered one of the largest groundwater reserves in the world. It is a coastal aquifer that lies under the delta region of Egypt, with a thickness ranging from 200 meters in the south to 900 meters along the shoreline (Sefelnasr & Sherif, 2014) Refilled by irrigation activities, it is a source of water in Egypt and a vast storage facility providing flexibility of management (Elbeih, 2016). The aquifer occupies the Quaternary and Late Tertiary deposits with a water table less than 1 meter below the surface, subjecting the water to various surface contaminants (Sharaky et al., 2016). Groundwater movement follows the general topography, moving from south to north, aquifer recharge sources include the Damietta Branch, flood irrigation water, and rainfall (Gamal et al., 2023).

The study area is located in the northeastern Nile Delta, covering a 50 km profile from the northwest border of New Mansoura City towards Mansoura (Figure 2). This region is composed of fluvial-deltaic deposits represented in thick sand Bilqas Formation deposited with Holocene age, topped with silty Bilqas Formation as valley deposits (Pennington et al., 2017). Based on this model, the Nile Delta aquifer has been defined by a simplified model, treating it as a homogeneous sand-gravel aquifer capped by a clay layer. This model divided the aquifer into a three-layered structure: an upper Holocene aquitard, a primary gravel-sand aquifer with intermittent clay lenses, and a lower Pliocene clay aquiclude that serves as the base (Negm et al., 2019). This representation suggested a continuous, uniform aquifer, with a gradual southward homogeneity, dipping at an average slope of 4 meters per kilometre. However, recent studies challenge this simplicity. The updated model reveals a more complex, "finger-like" configuration, with sand and clay layers alterations, varying both laterally and vertically (Nofal et al., 2015). This complexity in lithology arises from the dendritic drainage pattern system creating a multilayer aquifer, allowing the saltwater to invade some wedges more than others and creating lenses of salt and fresh water at various depths. (Nofal et al., 2015; Pennington et al., 2017).

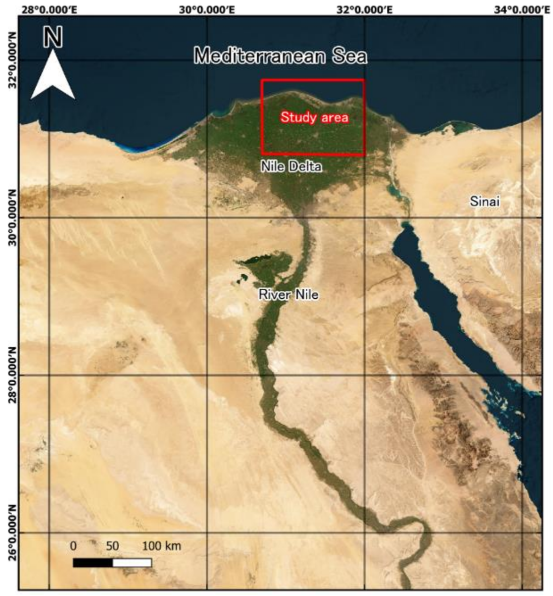

Figure 2 Satellite image of a part of Egypt including The Nilde Delta valley and River. The study area in located in the northern part of the east and middle delta within the jurisdiction of Damietta and Dakahlia Governerates.

The fluvial-deltaic origin of these deposits means that sedimentation patterns vary significantly across the profile. Near the shoreline, deposits are thicker, with sands and gravels providing primary pathways for groundwater flow, while inland, the clay content increases, reducing permeability (Coutellier & Stanley, 1987). This variability influences the rate and extent of seawater intrusion, as the saline front moves more readily through high-permeability sandy layers and is hindered by low-permeability clay zones (Stanley Andrew G., 1993).

This complex layering and variable lithology make it challenging to accurately predict the movement of seawater intrusion, as saline water can bypass certain layers through sand channels or be restricted by clay barriers (Zeidan, 2017). The aquifer's structure not only limits the predictability of traditional models but also calls for more sophisticated techniques to assess the freshwater-saltwater boundary accurately (Dawoud, 2004).

Figure 3 A satellite image of The Nile Delta showing the locations of RIGW National monitoring network modified after (Dawoud, 2004)

National Monitoring Efforts and Limitations

Egypt established the National Groundwater Quality Monitoring Program (NGQM) in 1998 to monitor both seawater intrusion and point pollution through wells (Figure 3). The design of this program faced a challenge to cover both problems with limited data and budget, adding stress on the model design.

Due to factors like geographical distribution, hydrogeological variability, population density, groundwater usage, and projected pollution loads, a relatively small number of wells were assigned to cover broad regions (Dawoud, 2004). Since the monitoring network was established, measurements have largely depended on the project's available budget. That, combined with the natural heterogeneity of the aquifer, made the model less reliable. Over time, funding declined. The network degraded. In many areas, testing stopped in most wells. We relied on data from three nearby wells that still provide recent readings. However, this information was clearly insufficient. As a results, we relied on water samples collected during recent construction activities in the area. The data show total dissolved salts (TDS) ranging from 2,650 ppm to 24,500 ppm. High salinity values were observed near the coast and at greater depths. For instance, Point 1 (15 m) recorded the highest salinity at 24,500 ppm. Deeper wells such as Point 7 (250 m) also showed elevated TDS (20,000 ppm), while inland and shallower points like Point 8 (30 m) had much lower concentrations (2,650 ppm). This pattern points toward both lateral and vertical salinity gradients across the region.

Table 1: TDS values of water sample and monitoring well data showing depth and TDS variation across the study area. Coastal and deeper points tend to show higher salinity

Point	Type	Depth	TDS	Latitude	Longitude
1	Water sampling	15	24500	31.478699	31.426046
2	Water sampling	35	6780	31.404750	31.499383
3	Water sampling	40	16200	31.421825	31.423809
4	Monitoring wells	250	7650	31.419531	31.363739
5	Water sampling	25	4710	31.407972	31.364450
6	Water sampling	25	7770	31.369006	31.475753
7	Monitoring wells	250	20000	31.363056	31.421667
8	Water sampling	30	2650	31.279604	31.298451
9	Water sampling	35	7560	31.201812	31.438938
10	Monitoring wells	200	11000	31.127372	31.363687

Methods

Time Domain Electromagnetic Method

This approach is a non-invasive, cost-effective method that does not need direct contact with the ground, which gives it the advantage of application in different terrain settings (Spichak, 2015). It can be used to detect the fresh and saltwater interface (Yang et al., 1999). The depth of investigation is controlled by the physical conditions of the area; a 25 m^2 square of wire was expected to reach a depth of 75 m (Zhdanov, 2009).Another set of data, represented in chemical analysis data from both deep and shallow wells in the area, was collected to draw a TDS profile. This profile aimed to investigate the trend in water salinity in the area shown in Figure 4.

Survey Design and Acquisition

Considering the extent of the saltwater intrusion, the TDEM stations were spaced at nearly 1km, avoiding possible obstacles as fish farms and inaccessible land. The stations were set to be perpendicular to the shoreline to guarantee that they cut through the fresh-salt water boundary. This resulted in 50 stations at a 50km distance from the northwest side of New Mansoura city to the northern boundaries of Mansoura city (Figure 5). The device used is a direct current transmitter and a receiver, both connected to a wire spread on the ground as a square with 25m side length that was expected to reach up to 75m, which may decrease due to soil salinity. The device used was an AIE-2 Measuring System (TDEM), comprising the TDEM-200 transmitter, TEM-IP receiver, and a control unit. This allowed us to record the decay curve at 0.1, 1 and 10 voltages (Figure 6).

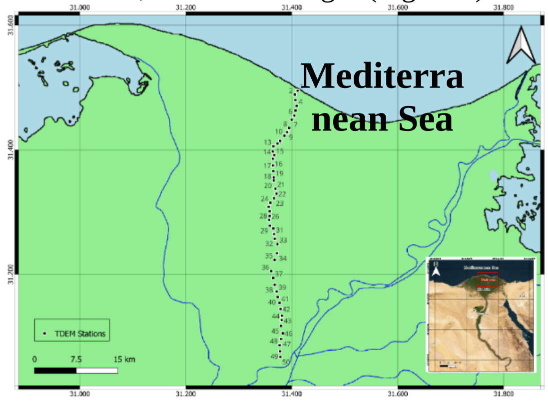

Figure 4 TDEM stations starting at the shoreline at western New Mansoura (Station 1), extending perpendicular to the shoreline ending at Mansoura city borders (Station 2).

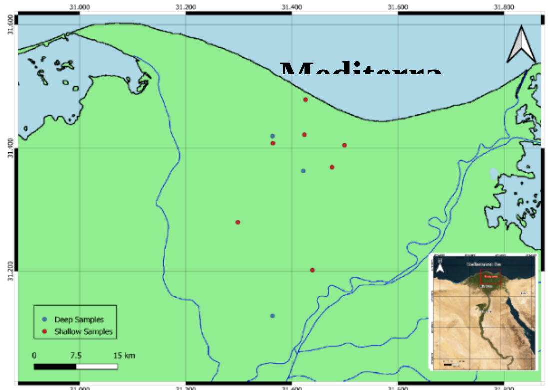

Figure 5 Shallow water samples collected from architectural projects in the area with an average depth of 35m and the deep samples collected from existing monitoring wells with an average depth of 250m.

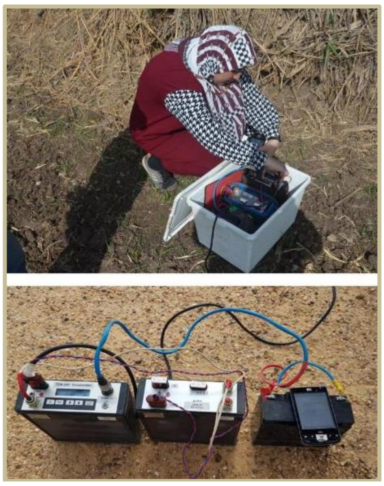
Figure 6 . Field setup for Time-Domain Electromagnetic (TDEM) data acquisition. (Top) Configuring the receiver and connecting the loop. (Bottom) AIE-2 Measuring System, including a power source connected to the transmitter, and loop connections for signal generation. A phone-like unit controls the survey parameters and operation.

Data Processing and Inversion

One challenge encountered was cultural noise due to municipal infrastructure, which interfered with the recorded decay curves. Noise distortion was particularly noticeable in the deep sections at some stations, necessitating the removal of these segments. A summation of the three decay curves at different voltages was calculated at each station, resulting in a higher signal-to-noise ratio. Some readings had to be manually adjusted to guarantee less ambiguities during the inversion process (Figure 7). According to the initial investigation of the data, a smooth inversion algorithm was applied to the processed data, utilizing a smoothing factor of 0.01 and a depth smoothing factor of 2, and an initial 4-layer model, which was edited whenever necessary. A fitted model with an average 5% error margin, which was supervised to ensure a reasonable geological fitting model. The resulting inverted pseudo-section figure (8) showed a wedge of decreased resistivity that has maximum thickness at the shore and decreases gradually as we proceed to the south with increasing depth. The data represented in Table 2 shows variation in resistivity in ohm.m (Ω.m) against layer thickness in meters. Station (1) is the first station on the seashore towards the north and Station (50) is the last station towards the south at Mansoura city. The values show a general decrease in resistivity with depth, suggesting increased salinity and increasing towards the south as fresh water prograde invading the saltwater zone into the more brackish layer.

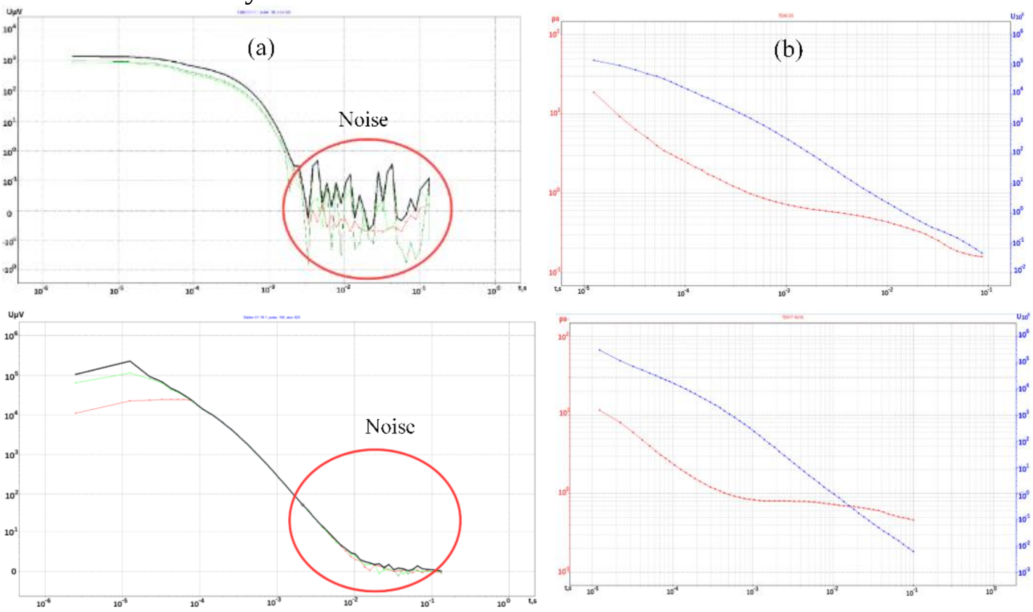

Figure 7 The TDEM decay curve at different voltages reading showing two station readings of the raw preprocessed data with cultural noise at (a) and the processed curves at (b). processing techniques includes removing highly distorted data at the end of profile

Table 2: Variation of resistivity (Ω.m) with depth across stations from the seashore to Mansoura city, illustrating the transition from saline to freshwater conditions.

	Station (1)		Station (10)		Station (20)		Station (30)		Station (40)		Station (50)	
	Ω.m	H	Ω.m	H	Ω.m	H	Ω.m	H	Ω.m	H	Ω.m	H
Layer 1	35.506	1.195	6.024	2.529	4.286	4.574	8.078	12.195	49.46	2.82	52.029	6.634
Layer 2	1.224	0.78	1.014	2.978	1.16	3.447	4.972	5.655	3.77	2.44	13.193	19.162
Layer 3	0.36	1.989	0.339	4.997	0.427	34.658	2.062	13.433	1.3	46.63	5.377	40.122
Layer 4	0.467	40.859	0.478	33.567	0.0496	17.245	1.357	22.653	0.24	20.22	2.693	55.842

To further enhance the reliability of the TDEM data, the results were cross-valid with well data obtained from the monitoring network established by the RIGWA institute. This integration included comparing both lithological and chemical analysis for the calibration of the TDEM model to assess the reliability of the model.

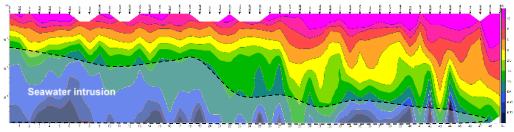

Figure 8: Inverted pseudo-section of TDEM data illustrating resistivity data in ohm.m on y-axis against distance starting at station (1) to the right towards the north at shoreline to station (50) southward to the left. Seawater intrusion shown as a descending wedge represented with resistivity less than 1 ohm and colors ranging from dark green to blue

Results

Based on TDEM data, the observed depth of penetration varied significantly across the study area, influenced by local salinity levels. In more saline areas, the penetration is restricted to about 60 meters; in less saline zones, this goes up to 80 meters.

The inverted section (Figure 9) showed three distinctive layers according to their resistivity, which was cross-validated with a geologic section obtained from a nearby well. The surface sand layer showed high resistivity, which was either dry or irrigated with fresh water. This layer increase in thickness towards the south corresponds to the increase of the water table depth.

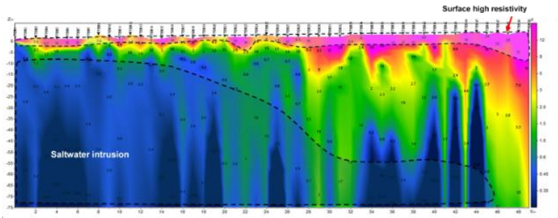

Figure 4: Inverted resistivity section along the profile, displaying resistivity values (Ω·m) with depth. The X- axis represent the stations from 1 to 50 and the Y-axis represent depth in (m). Warmer colours indicate higher resistivity zones, while cooler colours represent lower resistivity regions

Beneath, alternating sand and mud layers displayed moderate resistivity variations, with sand-dominant sections showing higher resistivity compared to clay-rich areas. The saltwater intrusion was revealed as a very low resistive zone with resistivity values between 0.1 and 3 ohm-m, extending inland from the coastline.

Moving southward from station 29, about 24 km inland, resistivity started to increase, which showed that the groundwater transitioned into the brackish zone, which could potentially be a water resource. Further to the south, the apparent decrease in the value of resistivity would seem to be related to decreased salinity rather than changes in sediment type, since this trend was observed from both sandy and clay-rich sections.

The TDEM profile was compared with lithological data from wells provided by the Research Institute of Groundwater (RIGW) to assess the influence of saline and freshwater on resistivity measurements. The obtained section supported the predictions of the TDEM data of layer stratigraphy, eliminating the possibility that the resistivity difference is caused by lithological differences rather than fluid salinity.

To check this observation, we compared the TDEM profiles with the lithological data of the wells of RIGW. The results were quite consistent, meaning the variation in resistivity is controlled by the salinity of the fluids rather than by lithology. This was further supported by the TDS determinations shown in Figure 10, giving very high concentrations in the northern parts of the profile, topping 20000 ppm, while southward it gradually decreased to about 3000 ppm. This pattern no doubt has shown the extent of seawater intrusion in the study area.

TDEM profile length, along with insufficient well control, restricted resistivity-salinity calibration in the studied locations. As a result, determining the extent of the fresh-saline water interface is still debatable due to the gradual nature of the intrusion, resulting in a wide area of brackish water.

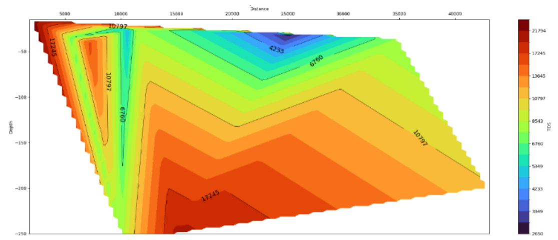

Figure 10: Total dissolved salts profile along the study area from the North (right) to the south (left) perpendicular to the shoreline

Discussion

This paper focuses on the dynamics of seawater intrusion in the Nile Delta aquifer and demonstrates the effectiveness of TDEM in mapping the salt-freshwater boundary. Saltwater intrusion is inferred inland, transitioning to brackish water and eventually freshwater further south. The resistivity variations observed are controlled by salinity differences rather than lithological complexity, which has been validated using well data. The identified brackish zone could support irrigation or industrial use, reducing freshwater demand.

While TDEM was successful in defining these limits, poor conditions such as cultural noise, sparse well data and insufficient funding prevented the determination of the freshwater boundary with enough accuracy. The transitional nature of the saline-brackish zones makes it difficult to define a more precise salt-freshwater interface. Although we managed to collect data from local wells and some soil samples, the regulation on water data and the scares recent well data made it challenging to validate the model with the expected certainty. This data could have been enough to conclude a reliable model, but the area has a high heterogenic lithology that controls aquifer parameters and seawater intrusion in the area which makes it challenging to interpolate data and calls for further research for specific sites or projects. The complex lithology of the area, high power line network and scattered urban residential complexes created a simple electromagnetic noise enough to disturb the data in some stations and prevented readings in others altogether.

Despite these limitations, TDEM showed a promising and economically viable non-invasive technique for coastal aquifer monitoring, while the characterized brackish zone provides possible use for non-potable purposes. This issue is not unique—many coastal aquifers in Mediterranean countries experience similar challenges. The outcomes here could likely be adapted in those regions with relatively low effort and cost. And beyond that, the tool helps guide decision-makers as it offers a practical way to set up a basic, cost-effective monitoring network—especially in areas where data is scarce—by mapping the region and identifying both hazard zones and preliminary salinity levels.

Conclusion

This study proves that the time domain electromagnetic method is a cost-effective tool for delineating seawater intrusion to guarantee the continuity of the monitoring process in the Nile Delta aquifer. We managed to map seawater intrusion with proximity to what was determined by well data, showing intrusion extending landward up to 24km. This survey extended to 50km and reached a depth of 60m, which can be increased by increasing loop size, time and power. These changes to survey configuration have a small effect on cost but yield better results. Processing cultural noise from the data was deemed to be challenging using traditional software and inversion techniques, but showed promising potential for more advanced techniques, such as deep learning-based noise filtering (e.g., convolutional neural networks, CNNs) and unsupervised clustering algorithms (e.g., K-means, DBSCAN) for noise identification, which could enhance signal extraction. Additionally, Bayesian inversion and physics-informed neural networks (PINNs) implemented in Python offer promising alternatives for improving resistivity inversion accuracy in complex environments. However, due to the limitations in computational expertise at the time of this study, traditional processing methods were employed. Accordingly, we recommend the integration of available well data and TDEM surveys to manage seawater intrusion with the sustainability of groundwater resources and using more advanced processing techniques. based on TDEM survey data, protected areas where groundwater use is restricted can be set to protect against further intrusion.

Data Availability Statement

Well data that was used in this research is a combination of published data in research and new updated data that can be requested from the Research Institute of Groundwater (RIGW) in Egypt. Time domain electromagnetic data is the property of the authors acquired through field surveys. The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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الملخص العربي

عنوان البحث: تطوير مراقبة الطبقات المائية الجوفية: تطبيق طريقة الزمن-المجالي الكهرومغناطيسي (TDEM) في كشف تسرب مياه البحر ضمن الطبقات الساحلية غير المتجانسة في دلتا النيل

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تُعدّ الطبقات الجوفية الساحلية مصدرًا حيويًا للمياه العذبة على مستوى العالم، إلا أنها تواجه تهديدًا متزايدًا بتداخل مياه البحر نتيجة الإفراط في سحب المياة وتغير المناخ. ويُعد خزان دلتا النيل أحد أكبر الخزانات الساحلية للمياه الجوفية في العالم، وهو عرضة بشكل خاص لتداخل مياة البحر، مما يشكل تهديدًا كبيرًا للزراعة والصناعة ومصادر مياه الشرب، ويزيد من تملّح التربة وتآكل البنية التحتية، مما يفاقم الضغوط على الاقتصاد المحلي. تهدف هذه الدراسة إلى استكشاف كفاءة طريقة المجال الكهرومغناطيسي (TDEM) في تتبع تسلل مياه البحر داخل الطبقات الجوفية الساحلية. تم استخدام هذه الطريقة لجمع خمسين نقطة بيانات على امتداد مسار طوله ٥٠ كيلومترًا عموديًا على خط الساحل باتجاه مدينة المنصورة. وقد طُبّقت تقنيات معالجة مناسبة لزيادة نسبة البيانات إلى الضوضاء وتحسين وضوحها نظرًا لارتفاع الضوضاء في المنطقة. وأظهرت عملية إقلاب البيانات الجيوفيزيائية وتفسيرها الحدود الفاصلة بين المياه المالحة والعذبة، كما أتاح توفر بيانات الطبقات من آبار المراقبة، معايرة النموذج الجيوفيزيائي للحصول على نتائج أكثر دقة. وأظهرت البيانات تطابقًا وثيقًا مع بيانات الآبار بهامش خطأ متوسط قدره ٥%، مما يكشف عن تداخل مياه البحر لأكثر من ٤٠ كيلومترًا إلى الخزان تدريجياً، وقد تراوح عمق التداخل بين ١٠ إلى ٢٠ مترًا. وتؤكد هذه النتائج فعالية TDEM كأداة سريعة ومنخفضة التكلفة في رسم حدود تداخل المياه المالحة والعذبة في خزان دلتا النيل. وتقترح هذه الدراسة دمج TDEM مع شبكة المراقبة الحالية لتتبع التغيرات في خصائص الخزان الجوفي، مما يوفر أساسًا لتحسين استراتيجيات إدارة المياه الجوفية.