NRIAG Journal of Astronomy and Geophysics (2016) 5, 323–333

National Research Institute of Astronomy and Geophysics

NRIAG Journal of Astronomy and Geophysics

www.elsevier.com/locate/nrjag

Shallow groundwater investigation using time-domain electromagnetic (TEM) method at Itay El-Baroud, Nile Delta, Egypt

H. Shaaban [a,b], **G. El-Qady** [b,*], **E. Al-Sayed** [b], **H. Ghazala** [c], **A.I. Taha** [b]

[a] *National University of Mineral Resources ûMiningý, St. Petersburg, Russia*
[b] *National Research Institute of Astronomy and Geophysics, Helwan, Egypt*
[c] *Geology Department, Faculty of Science, Mansoura University, Egypt*

Received 13 July 2014; revised 25 April 2015; accepted 30 May 2016
Available online 8 July 2016

KEYWORDS

Groundwater;
TEM;
Itay El-Baroud;
Nile Delta

Abstract The Nile Delta is one of the oldest known ancient delta, largest and most important depositional complex in the Mediterranean sedimentary basin. Furthermore, it is a unique site in Egypt that is suitable for accumulation and preservation of the Quaternary sediments. In this work we applied time-domain electromagnetic (TEM) method to investigate the Quaternary sediments sequence as well as detecting the groundwater aquifer in the area of study.

A suite of 232 TEM sounding at 43 stations were carried out using a "SIROTEM MK-3" time-domain electromagnetic system. A simple coincident loop configuration, in which the same loop transmits and receives signals, was employed with loop side length of 25 m. The 1-D modeling technique was applied to estimate the depth and the apparent resistivity of the interpreted geoelectrical data.

Based on the interpretation of the acquired geophysical data, four geoelectric cross-sections were constructed. These sections show that the Upper Quaternary sequence consists of three geoelectric layers. The Holocene Nile mud is separated into two layers: the agricultural root zone (Layer 1) and thick water saturated mud (Layer 2). The Upper Pleistocene sandy aquifer (Layer 3) is very complicated non-linear boundary. This aquifer is the most important unit since it is considered as the main water bearing unit in the study area.

1. Introduction

The Nile Delta is described as a wide spread flat area with a very low relief. It covers an area of about 12,500 km^2 which has been cultivated for several millennia. The Quaternary Nile sediments lie unconformably over the Pliocene or older sediments in the Nile Delta. The Nile trough possesses the most

* Corresponding author.
Peer review under responsibility of National Research Institute of Astronomy and Geophysics.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.nrjag.2016.05.004

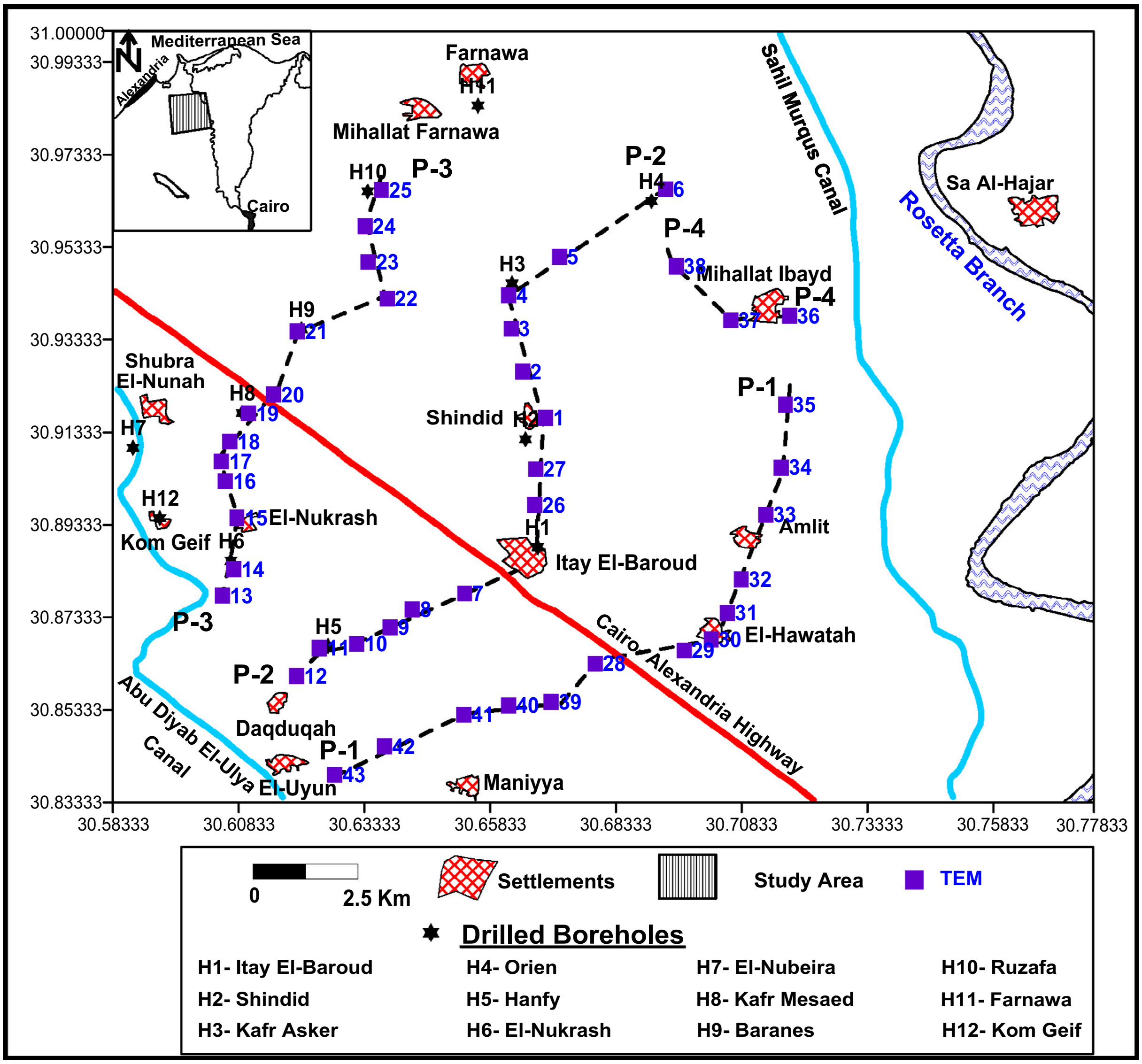

Figure 1 Location map with the drilled boreholes and TEM around Itay El-Baroud area, Nile Delta, Egypt.

complete record of Quaternary in Egypt where the sediments assume great thickness and are divided into several units, which are unconformably stratified (Said, 1981). According to Rizzini et al. (1978), the maximum thickness of the Quaternary succession attained in the Nile Delta is about 1000 m, with thinning southward and toward the fringes of the Delta. This thickness reaches about 500 m in the middle part of the Nile Delta.

The area of study is located in the central-western part of the Nile Delta, west of Rosetta Branch, around Itay Al-Baroud city (Fig. 1). It lies between Latitudes 30°50′–31° N and Longitudes 30°35′–30°46′42″ E covering an area of about 435 km^2, mainly covered with cultivated lands. There are very few investigations which have been carried out on the Upper Quaternary sediments of the western part of the Nile Delta (e.g. El-Gamili and El-Mahmoudi, 1996; El-Gamili and Shaaban, 1993). The present paper is mainly concerned with the applications of the geophysical techniques in the form of electromagnetic method to investigate the Quaternary sediments sequence as well as detecting the groundwater aquifer in the area of study.

2. Lithostratigraphy

The Quaternary lithostratigraphy of the Nile Delta (Table 1) has been studied by many authors e.g. Attia (1954), Rizzini et al. (1978), Said (1981, 1990), Zaghloul et al. (1977, 1979) and El-Fayoumi (1987).

Rizzini et al. (1978) subdivided the Quaternary subsurface section in the Nile Delta into two rock units on the basis of their lithological composition. These include from base to top: Mit Ghamr and Bilqas Formations.

2.1. Mit Ghamr Formation

Said (1981) considered that Mit Ghamr Formation is coeval with the Prenile Qena Sands. It consists of quartzose sands

Table 1 Composite columnar section of the Quaternary succession of the Nile Delta and its hydrological characters (Modified after Rizzini et al., 1978).

Age		Formation	Average thickness (m)	Lithology	Hydrological Remarks		
					Farid, 1980	Serag El-Din 1983	Serag El-Din, 1990
Quaternary	Holocene	Bilqas	50		Clay Cap	Clay Cap Aquitard	Coastal sand dunes aquitard and Holocene aquitard
Quaternary	Pleistocene	Mit-Ghamr	700		Ground water aquifer	Main Ground-water Aquifer containing some subaquifers	Main Ground-water Reservoir including some subaquifers

and pebbles. The sands are medium to coarse grained. The pebbles are mainly quartzose but occasionally silicified limestone and chert pebbles are found. Thin beds of clay, silt and peat containing coastal or lagoonal fauna mark the upper levels of this formation. Mit Ghamr Formation has an average thickness of about 700 m in the northern delta, decreasing toward the south (Zaghloul et al., 1979). The lithofacies distribution of this formation shows distinct lateral lithologic variations ranging from sandy facies covering most of the delta to sandy shale in the northern marginal zones of the delta. Between these two types of facies, a narrow belt of shaly sand facies occurs (Serag El-Din, 1990). The riverine sediments of this formation appears in outcrops as Turtle backs in the midst of the agricultural fields representing the higher parts of eroded surface of this complex (Said, 1981).

2.2. Bilqas Formation

Bilqas Formation consists mainly of clay, silt and minor sand of riverine and flood basin deposits. The sediments are more calcareous and the deposition took place in lagoons and brackish swamps interrupted by beach sands in the northern parts of the Nile Delta (Said, 1981). Plant remains and peat layers have been encountered within the sediments of Bilqas Formation (Hegab and Bahloul, 1987). This formation represents the muddy cap of the Upper Quaternary sequence in the Nile Delta and varies in thickness from few meters in the southern part to slightly more than 30 m in the northern part of the Nile Delta and has a maximum thickness of about 77 m (Zaghloul et al., 1977). According to Said (1981), Bilqas Formation may be included within the Neonile sediments which are Late Pleistocene to Holocene.

The lithofacies of Bilqas Formation at the Nile Delta shows lithological variations ranging from clay and silt at the eastern and north central parts, sand dunes at the northern coastal areas to sandy facies to the south. These facies distribution may be attributed to the irregularity of the basin bottom during deposition and the density of the old Nile distributaries and hence their energy (El-Fayoumi, 1987).

3. Hydrogeology

As the electric resistivity of rocks is highly dependent on lithology as well as the water content and salinity, it is important to shed some light on the hydrological and hydrochemical conditions of the Nile Delta where the area of study is located.

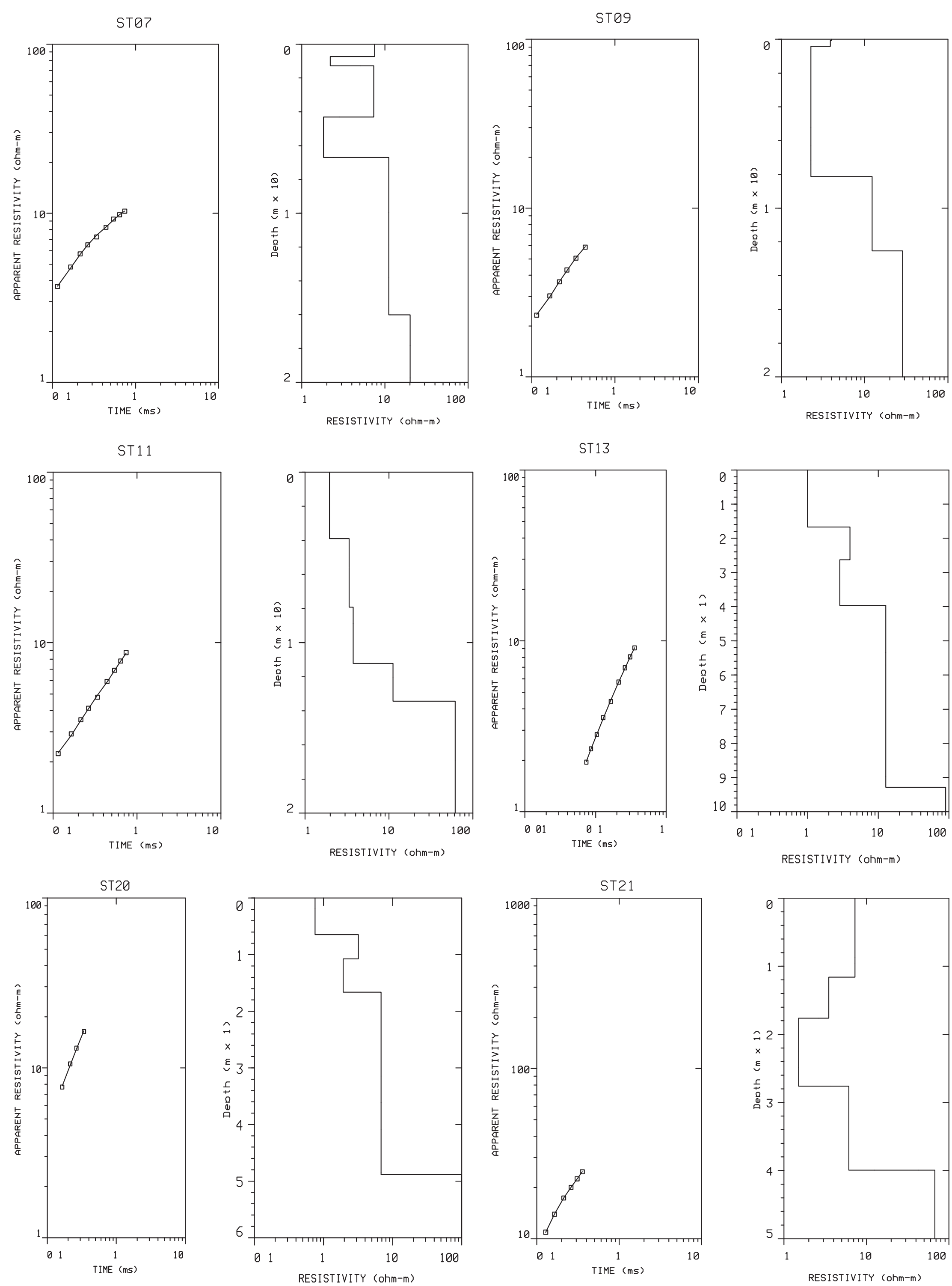

Figure 2 Examples of the inverted TEM soundings.

Hydrogeological and hydrochemical studies have been carried out on the Nile Delta aquifer in a regional scale by many authors e.g. El-Kashef (1981, 1983), Serag El-Din (1983, 1990) and Atwia et al. (1996).

The Quaternary succession in the Nile Delta was differentiated hydrogeologically into two water-bearing units. The upper cap muddy unit of Holocene age (Bilqas Formation) acts as aquitard. The lower thick sand unit of Pleistocene age (Mit Ghamr Formation) forms the huge main aquifer of the Nile Delta (Serag El-Din, 1983).

The first water-bearing unit represents a free-ground water aquifer with its water table separating an upper clayey aerated zone (root zone), and the underlying soil moisture zone that constitutes the muddy zone. Drainage and irrigation practice

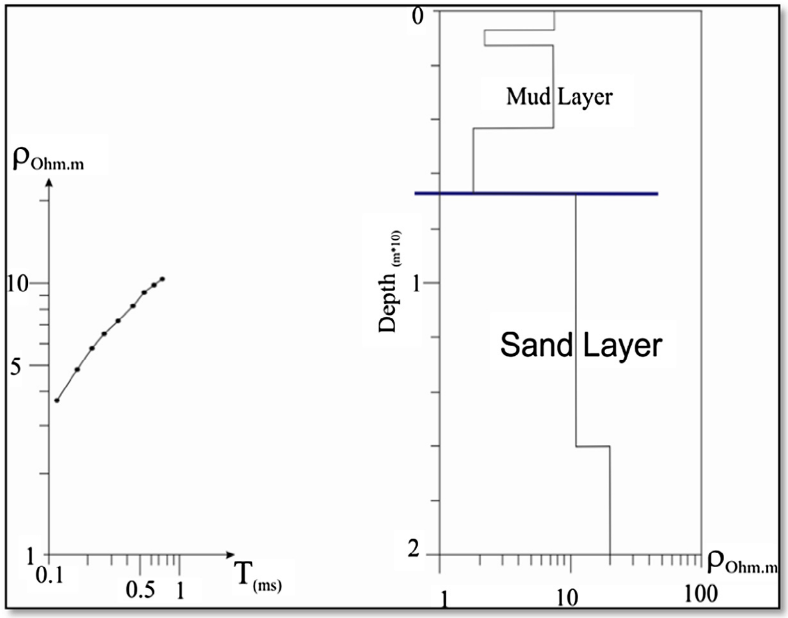

Figure 3 Typical example of the inverted TEM sounding.

affects these two zones as well as the level of the water table and its capillary fringe (El-Gamili and Shaaban, 1993). The depth of the water table controls the depth of the applied covered drainage system which is found to be around 1.4 m (El-Gamili and El-Mahmoudi, 1996).

The thickness of the aeration zone varies from less than one meter to four metes, especially in the northern parts of the Nile Delta. There is a very close relationship between the depth to water in the soil profile and the occurrence of surface water. In other words, the levels of the soil shallow groundwater are strongly controlled by the lithology, drainage conditions and the type of crop and hence the amount of the water needed for irrigation. The groundwater of the Nile Delta main aquifer is characterized by moderate to excessively high salinity. Whereas, the lower salinity values were observed in the southern parts of the Nile Delta region and in the parts close to the irrigation canals and branches of the Nile. The aerial distribution of salinity contents of groundwater at different depths shows a belt running parallel to the northern coast with very high salinity values more than (3200 ppm). South of this belt, low values of salinity content are observed and classified as high saline water (1440–3200 ppm). However, to the south, some spots of medium saline water (less than 480 ppm) are observed (Serag El-Din, 1990).

Atwia et al. (1996) stated that, the quality of water in the Nile Delta aquifer is affected by the quality of water recharging the aquifer from surface water, thickness of the clay layer forming the top of the aquifer and seawater mixing.

4. Geophysical data

Electromagnetic methods have been extensively developed and adapted over the past three decades for the lateral and vertical mapping of resistivity variations. Electromagnetic methods can be broadly divided into two major groups: Frequency domain electromagnetic method and Time-domain electromagnetic method. Common for both of them is that they are controlled by the basic physics of the Maxwell Equations. In fact, one of them is simply the Fourier transform of the other (Kaufmann and Keller, 1983; Nabighian and Macanae, 1991).

The time-domain method is different from the frequency domain methods in two ways. Firstly, it is decaying secondary field as a function of time that is measured, and secondly the primary field is not present during the time measured. The primary field is thus not registered and there are no problems with separating the two field components. Because the secondary signal contains a wide range of frequencies the undesired noise cannot be filtered out. To obtain a high signal to noise ratio one must repeat the measurement several times to stack the data. In this way the stochastic electromagnetic noise level is reduced (Fitterman and Stewart, 1986).

Although the output of an electromagnetic survey is similar to that produced by electrical resistivity techniques, there are several advantages to the electromagnetic methods. They do not need direct coupling to the ground, they may provide higher resolution information and they may be cost effective. The side length of the loop depends on the desired depth of exploration. For shallow depths (less than 40 m) in relatively resistive ground, the length may be as small as 5–10 m. The TEM techniques are effective for determining electrical resistivity or conductivity of soils at different depths. Since electrical resistivity of soil correlates strongly with soil properties, TEM is a powerful tool for mapping soils and changes in soil types in that depth range. TEM is useful in mapping sand and gravel aquifers; clayey layers restricting groundwater flow, conductive leachate in groundwater; salt-water intrusion, and depth to bedrock (Fitterman and Stewart, 1986).

4.1. The time-domain electromagnetic method (TEM)

The transient electromagnetic method was originally developed in the seventies for mining exploration with the aim of

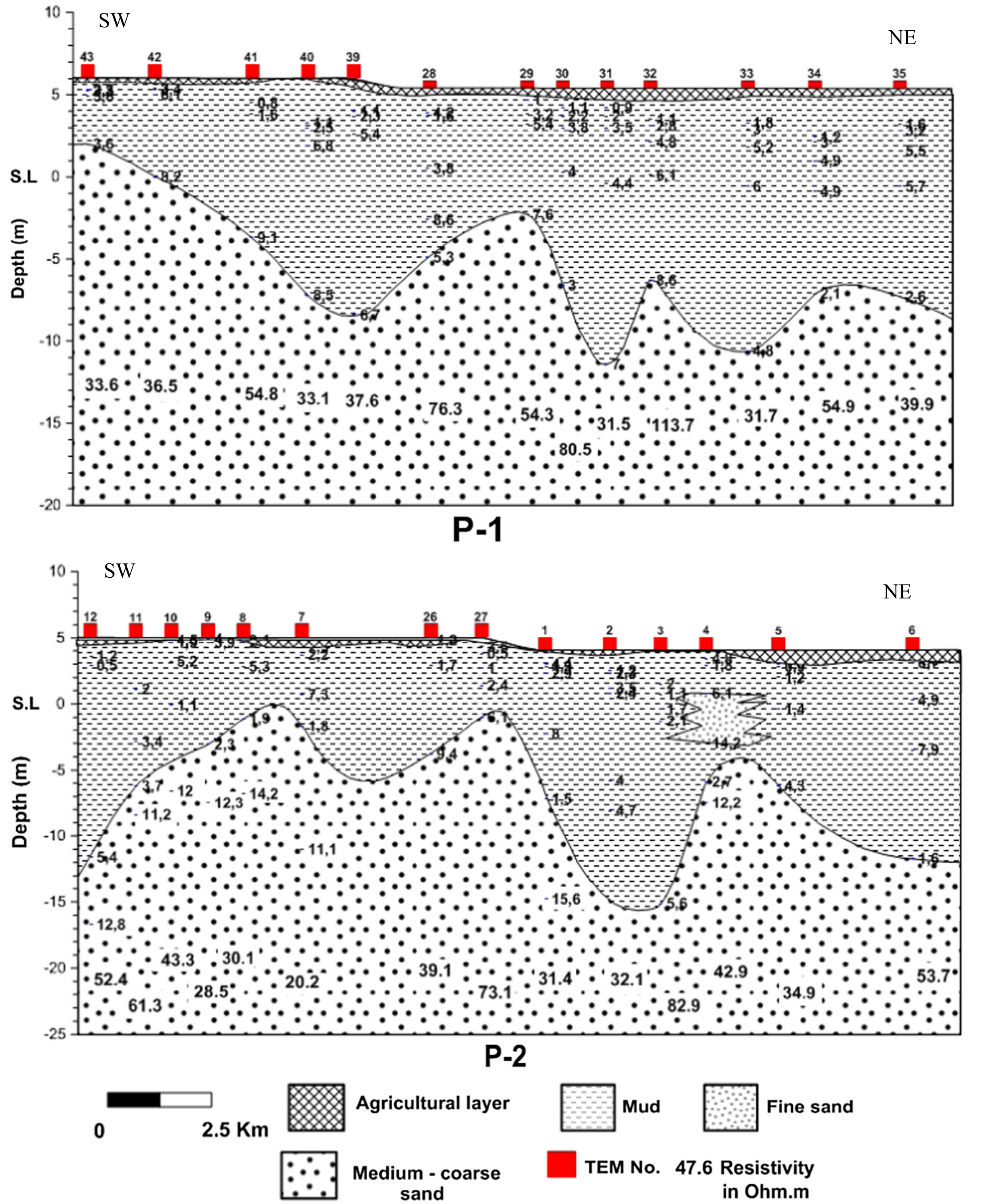

Figure 4 Geoelectric cross-sections based on the 1-D interpretations of TEM data for the profiles P-1 and P-2, Itay El-Baroud area, Nile Delta, Egypt.

identifying conducting ore deposits. Different authors had shown that TEM is very useful in identifying major aquifers, where large areas have been mapped by the method (e.g. Nabighian and Macanae, 1991; McNeill, 1990; Massoud et al., 2010 and Metwaly et al., 2010).

The TEM method is generally based on the simple physical fact that when a current in a coil is changed, a magnetic field is induced, and vice versa. Applying a current to a large coil creates a magnetic field, which is stable after some time. This interacts with the layers of the subsurface according to the

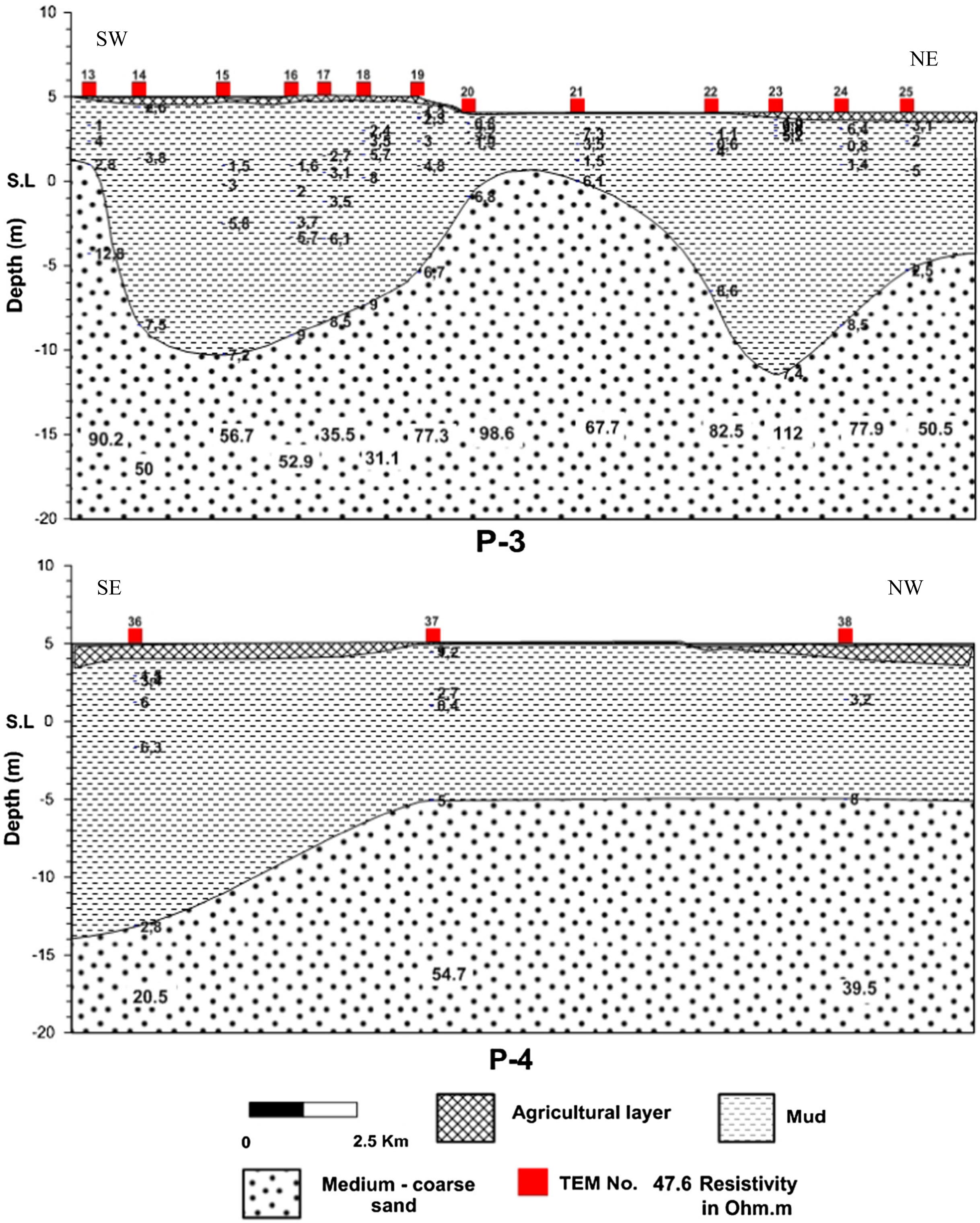

Figure 5 Geoelectric cross-sections based on the 1-D interpretations of TEM data for the profiles P-3 and P-4, Itay El-Baroud area, Nile Delta, Egypt.

capacitor theory and generates a secondary field which induces currents in the earth's layers. In conductive media the currents will diffuse more slowly. As the initial near-surface eddy currents decay, they in turn induce eddy currents at greater depths. The magnitude and rate of decay of those secondary currents depend on the conductivity of the medium, and on the geometry of the conductive layers. The TEM receiver measures the magnetic field created by those secondary currents. Measurements of the secondary field are typically made in the time range from 10 μs to 1 ms following the "turn-off" of

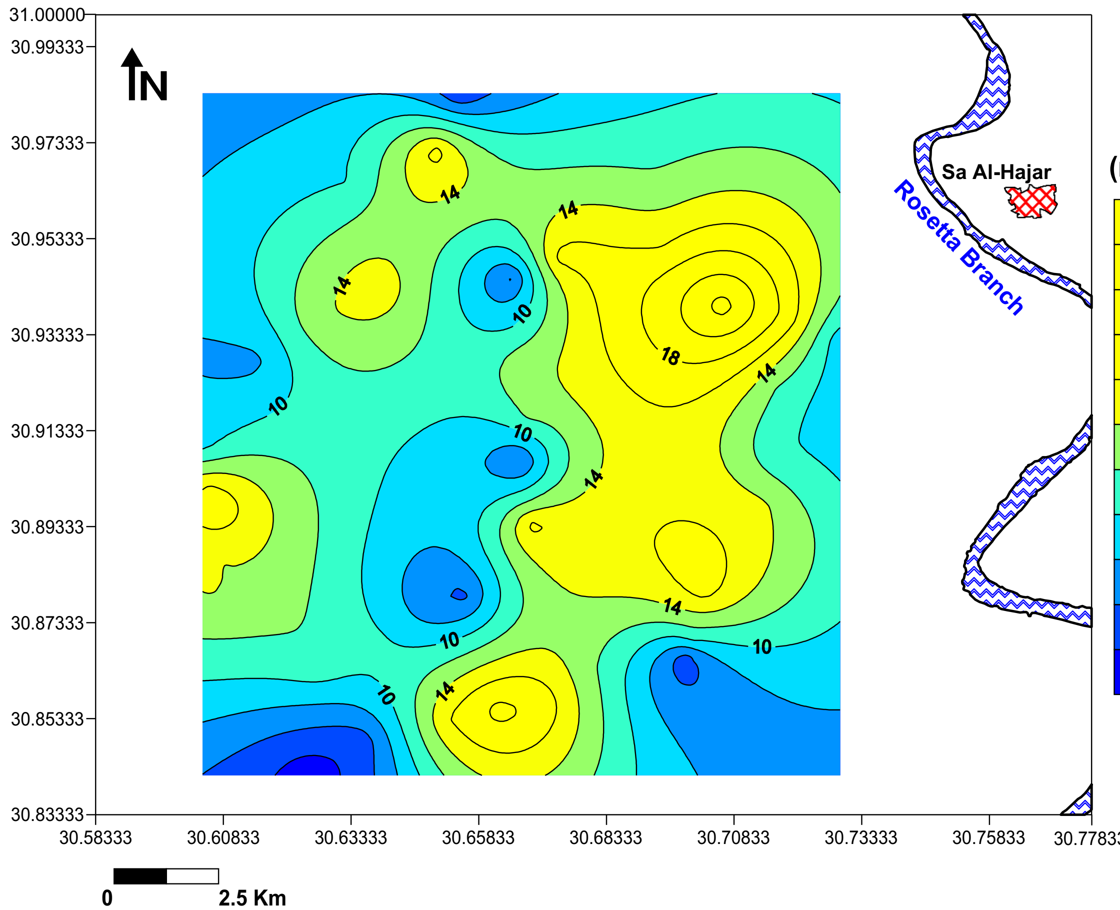

Figure 6 Iso-pach map for the Holocene Nile mud, Itay El-Baroud area, Nile Delta, Egypt.

the primary field. For deeper exploration in conductive section, the time of measurements can extend up to one second. Because measurements are made while the transmitter current is turned off, more sensitive measurements of the secondary filed can be made (McNeill, 1990).

4.2. Data acquisition

A suite of 232 TEM sounding were carried out at 43 stations (Fig. 1), using a simple coincident loop configuration, in which the same loop transmits and receives signals. The loop side length was 25 m. In all sites, the measurements were repeated four or five times. Delay times used were in the range of 20–40 ms. The best signal-to-noise data sets were chosen for further processing and interpretation. TEM data were acquired using SIROTEM MK-3 Conductivity meter.

5. Processing and interpretation of TEM data

There are many ways in which TEM data can be processed and these are largely dependent upon which instrument is used to acquire the original data. Most of TEM systems record the transient voltage at a number of discrete intervals during the voltage decay, after the applied current is switched off. In each time the current is applied and then stopped, measurements are taken; when the current is applied again and switched off, a repeat set of measurements is taken. This process may be repeated many tens of times at a given location where all the data are being logged automatically. Consequently, these many data can be processed to improve the signal-to-noise ratio. Commonly, the data are normalized with respect to the transmitter current or other system parameter, and the effects of the time decay may be amplified in compensation by normalizing the observed field at each point with the respective primary field value at the same point (Metwaly et al., 2010; Massoud et al., 2010).

The available geological information has been used to make the initial models for 1-D inversion of the TEM data using TEMIX XL V4 (1996) program. Then, a trial and error modeling was applied to the comparable data sets to give a single model that satisfies both TEM and boreholes data sets. Figs. 2 and 3 show typical example of the inverted TEM soundings. The shallow parts of all models are controlled by the relatively dense suites of boreholes data. In contrast, the deeper parts of these models are constrained by both boreholes and TEM data, with emphasis on the TEM data, which provides the highest resolution information.

5.1. Geoelectric resistivity cross-sections

The geoelectric resistivity cross-sections can be considered as vertical slices through the subsurface, which show the lateral

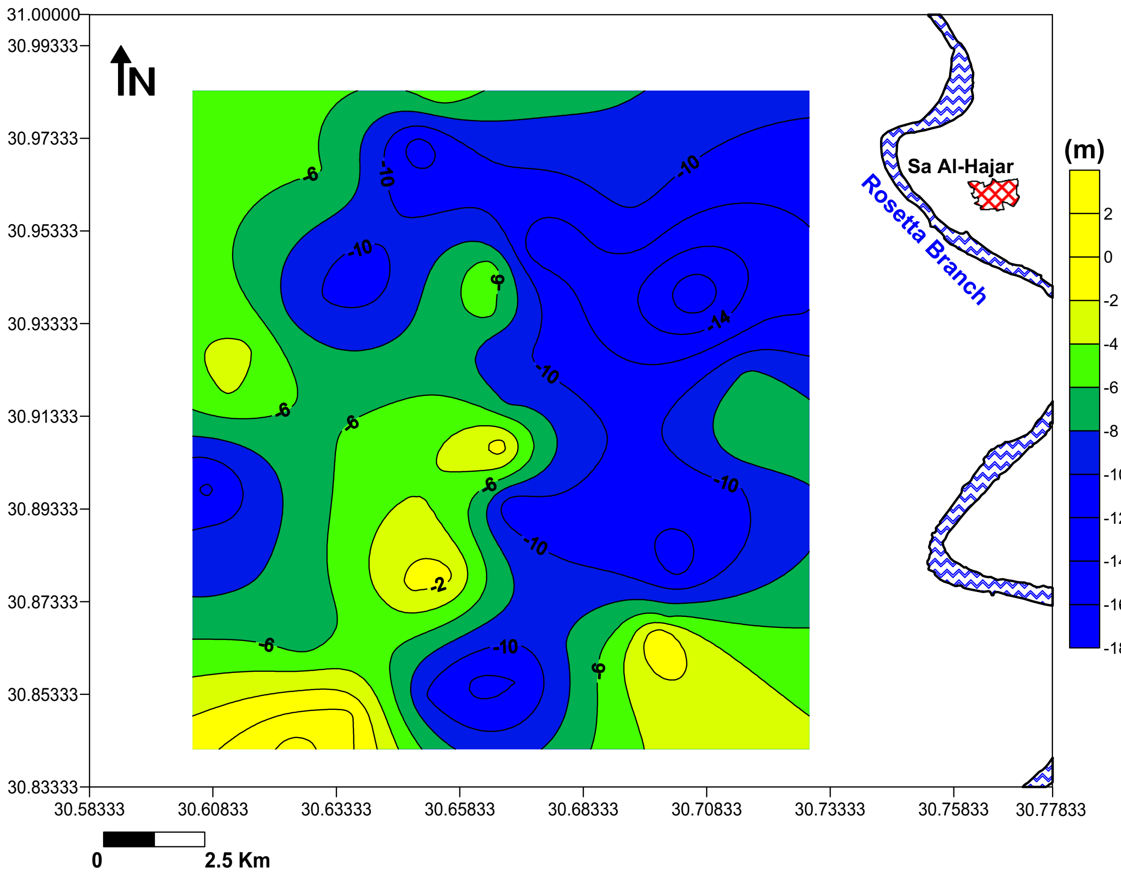

Figure 7 Paleotopographic contour map of the top surface of the Pleistocene sand inferred from TEM data, Itay El-Baroud area, Nile Delta, Egypt.

and vertical subsurface resistivity distribution. The results obtained from the calibration of one-dimensional TEM data with all drilled boreholes data and geological information, are used to construct four detailed geoelectric cross-sections. These sections elucidate the variations inherited both vertically and laterally in the electrical resistivity and their corresponding geological units of the Late Quaternary subsurface sediment. These sections; directed roughly in E-W direction, can be considered as lithoresistivity stratigraphic sections. Each of the cross-sections is discussed separately below.

Four geoelectrical cross-sections were constructed using 1-D inversion results illustrated in Figs. 4 and 5 to portray the variations inherited both vertically and laterally in the electrical resistivities and their corresponding geological units of the Late Quaternary subsurface sediments. The study area is dissected with some surface water canals that cause infiltration to the water in the subsurface that in turn reflected on the resistivity of the subsurface. Three predominant lithofacies are well identified by their corresponding resistivity values; the topmost facies of Holocene Nile mud, the water saturated Holocene mud and the underlying Pleistocene sands.

- The topmost geoelectric layer (Unit 1) is generally thin of variable thickness ranging from 0.4 to 1.2 m. The electric resistivity of this unit ranges from 5.4 to 50.8 Ω m. At some parts, the resistivity has large values due to the existing of sandy clays. This correlated with the aeration zone and represents the cultivated or agricultural layer.
- The second geoelectric layer (Unit 2) consists of water-saturated mud with varying thickness ranging from 2.8 to 22.8 m. this geoelectrical unit has resistivity values ranging from 1 to 9.8 Ω m. However, at some localities this unit contains sandy lenses of small dimensions having relatively high resistivity values (up to 31 Ω m) such as at VES's 8, 19, 24 and 34.
- The third geoelectrical layer (Unit 3) represents the Pleistocene sand which is the main aquifer in the study area. This layer shows higher resistivity values compared with the overlying units ranging from 10.4 to 60.9 Ω m.

5.2. The subsurface maps

The results of interpretation of the TEM data are used to determine total thickness of the Holocene mud cap (Bilqas Formation) above the underlying Pleistocene sand. The thickness of the Holocene mud facies (Fig. 6) ranges from 2.8 to 22.8 m. The maximum thickness (greater than 18 m) is encountered at the northwestern, western, eastern and southern parts of the study area. These localities correspond to depressions within the underlying Pleistocene sand.

The elevation (above sea level, ASL) of the top surface of the late Pleistocene sand approaches +2.8 m at the southern part of the area, while the minimum elevation about −17.8 m at northeastern part of the study area (Fig. 7). The considerable variation in the elevation reveals the presence of several local highs and lows. This is mainly due to the meandering of the old river branch and the associated depositional environment of that branch.

6. Conclusion

The geophysical tools provide useful methods to explore the near surface geology of the study area. Four geoelectric cross-sections were constructed to discriminate the investigated subsurface sequence of the study area. These geoelectric cross-sections indicate the salient geologic features of the study area as summarized below:

1. **The Holocene Nile mud** is differentiated into two layers of characteristic resistivity ranges due to variable aeration, water and ionic contents as well as man made effects. **The first layer** represents the agricultural or root zone (geoelectric unit 1), which is effected by irrigation and drainage system of the investigated sites that gives an observed variation in resistivity values. **The second layer** (geoelectric unit 2) is generally saturated with irrigation water from the agricultural fields, canals and drains. The resistivity values are generally lower than the above zone, due to the existence of relatively thick mud saturated with water. The variation in resistivity values is due to the existence of compact mud. The Holocene mud facies constitutes the cap of the Pleistocene sandy aquifer. Within the second layer, there is a sand lense embedded within the Holocene mud.
2. **The underlying Late Pleistocene sands** (geoelectric unit 3) are characterized by irregular surface with local highs and lows. These local highs represent buried Geziras sand.

The thickness of the Holocene mud facies ranges from 2.8 to 22.8 m. The maximum thickness is encountered in the northwestern, western, eastern and southern parts of the study area. These localities correspond to depressions within the underlying Pleistocene sand. These depressions were possible sites for the defunct Holocene channels.

The elevation of the top surface of the Late Pleistocene sand (relative to the present sea-level) approaches +2.8 m at the southern part of the area, while the minimum elevation about −17.8 m at northeastern of the study area. The considerable variation in the elevation reveals the presence of several local highs and lows.

Acknowledgments

Sincere thanks for all of NRIAG stuff, who helped in acquiring the geophysical data using NRIAG facilities. The authors are indebted to the anonymous reviewers who greatly enhance the manuscript through their comments.

References

Attia, M.I., 1954. Deposits in the Nile Valley and the Delta. Geol. Surv. of Egypt. Mines & Quarries Dep. Cairo. 356p.

Atwia, M.G., Khalil, J.B., El Awady, M.M., Habib, M.M., 1996. Hydrochemistry and water quality of groundwater in the central part of the Nile Delta, Egypt. Egypt. J. Geol. 41 (2B), 743–764.

El-Fayoumi, I.F., 1987. Geology of the Quaternary Succession and Its Impact on the Groundwater Reservoir in the Nile Delta Region, Egypt. Bull. Faculty of Science, Mansoura University.

El-Gamili, M.M., El-Mahmoudi, A.S., 1996. Implications of geophysics to the geoenvironmental and engineering aspects in the Nile Delta, Egypt. In: Proceeding of the First International Conference on Role of Engineering Towards Better Environment (RETBE, 96), vol. 1, Alex. Univ., Faculty of Engineering, pp. 305–318.

El-Gamili, M.M., Shaaban, F.F., 1993. A geophysical evaluation of the depth and thickness of the capillary fringe in the Holocene sediments of the Nile Delta, Egypt. Mu'tah J. Res. Stud. Mutah Univ., Jordan 8 (4), 173–195.

El-Kashef, A.I., 1981. Technical and ecological impacts of the high Aswan Dam. J. Hydrol. 53, 73–84.

El-Kashef, A.I., 1983. Salt-water intrusion in the Nile Delta. J. Groundwater 21 (2), 160–167.

Fitterman, D.V., Stewart, M.T., 1986. Transient electromagnetic sounding for groundwater. Geophysics 51, 995–1005.

Hegab, O., Bahloul, M., 1987. On the occurrence of Peat in the subsurface Holocene sediments of the Nile Delta and its geotechnical implications. Egypt. J. Geol. 31, 73–83.

Kaufmann, A.A., Keller, G.V., 1983. Frequency and transient sounding. Methods in Geochemistry and Geophysics, vol. 16. Elsevier Publ. Co., p. 685.

Massoud, U., Santos, F., El Qady, G., Atya, M., Soliman, M., 2010. Identification of the shallow subsurface succession and investigation of the seawater invasion to the Quaternary aquifer at the northern part of El Qaa plain, Southern Sinai, Egypt by transient electromagnetic data. Geophys. Prospect. 58, 267–277.

McNeill, J.D., 1990. Use of electromagnetic methods for groundwater studies. In: Ward, S.H. (Ed.), Geotechnical and Environmental Geophysics, Vol. 1: Review and Tutorial, Society of Exploration Geophysics Investigations No. 5, pp. 107–112.

Metwaly, M., El-Qady, G., Massoud, U., El-Kenawy, A., Matsushima, J., Al-Arifi, N., 2010. Integrated geoelectrical survey for groundwater and shallow subsurface evaluation: case study at Siliyin spring, El-Fayoum, Egypt. Int. J. Earth Sci. (Geol Rundsch) 99, 1427–1436. http://dx.doi.org/10.1007/s00531-009-0458-9.

Nabighian, M.N., Macanae, J.C., 1991. Time-domain electromagnetic prospecting methods. In: Nabighian, M.N. (Ed.), . In: Electromagnetic Methods in Applied Geophysics, vol. 2. Society of Exploration Geophysics, pp. 427–514.

Rizzini, A., Vezzani, F., Cococcetta, V., Milad, G., 1978. Stratigraphy and sedimentation of Neogene-Quaternary section in the Nile Delta area (A.R.E.). Mar. Geol. 27, 327–348.

Said, R., 1981. The Geological Evaluation of the River Nile. Springer Verlag, New York, Heidelberg, Berlin, 151p.

Said, R., 1990. The Geology of Egypt. Balkema Publ., Rotterdam, Netherlands, p. 734p.

Serag El-Din, H.M., 1983. Geological and Geochemical Studies on the Nile Delta Aquifer, Egypt. M. Sc. Thesis, Faculty of Science, Mansoura Univ. Egypt, 235p.

Serag El-Din, H.M., 1990. Geological, Hydrogeological and Hydrological Studies on the Nile Delta Quaternary Aquifer. Ph. D. Thesis, Faculty of Science, Mansoura University, Egypt, 300p.

TEMIXL XL V4, 1996. Temix V. 4 user's manual, interprex, 468p.

Zaghloul, Z.M., Taha, A.A., Hegab, O.A., El-Fawal, F.M., 1977. The Neogene-Quaternary sedimentary basins of the Nile Delta, Egypt. J. Geol. 21, 1–19.

Zaghloul, Z.M., Taha, A.A., Hegab, O.A., El-Fawal, F.M., 1979. The Plio-Pleistocene Nile Delta sub-environments, stratigraphic section and genetic class. Ann. Meet. Geol. Surv. Egypt 23, 282–291.

Further reading

Bietak, M., 1996. Avaris: The capital of the Hyksos; Recent excavations at Tell El-Daba. The Trustees of the British Museum. British Museum Press, 98p.

Diab, M.Sh., 1982. Groundwater pollution in the Quaternary aquifer under the Nile Delta, Egypt. J. Geol. Special Vol. Part 2, 135–144.

El-Gamili, M.M., Hassaneen, A.Gh., El-Mahmoudi, A.S., 1990. Geoelectric resistivity contribution to the mode of the occurrence of sand islets (Turtle Backs) in the Nile Delta, Egypt. In: Van Den Brink (Ed.), The Nile Delta in Transition: 4th-3rd Millennium B. C., pp. 269–287.

Frihy, O.E., El-Fishawi, N.M., El-Askary, M.A., 1988. Geomorphological features of the Nile Delta coastal plain, a review. Acta Adriat. 29 (1/2), 51–65.

Hemdan, G., 1980. In: The Character of Egypt (in Arabic), vol. 1. Alam El-Kotob, Cairo, 841p.

Sandford, K.S., Arkell, W.J., 1939. In: Paleolithic man and the Nile valley in the Lower Egypt, vol. 36. Chicago University, Oriental Institute. Pub., 105p.

Stanley, D.J., Warne, A.G., 1993a. Nile Delta, Recent geological evolution and human impact. Science 260, 628–634.

Stanley, D.J., Warne, A.G., 1993b. Sea level and initiation of predynastic culture in the Nile Delta. Nature 363, 435–438.