

Delineation of the fresh/salt water zones at a coastal Mediterranean area, West of Alexandria using electrical resistivity investigation

S. Abou Shagar^{*}, A. El-Fiky and Sh. Eid^{}**

^{}National Institute of Oceanography and Fisheries, Alexandria, Egypt.*

*^{**}Department of Environmental Sciences, Faculty of Science, Alexandria University-Egypt
Correspondent author*

Abstract

The present investigation aims to map the shallow Pleistocene aquifer and to demonstrate the impact of the human activities as well as the salt water intrusion phenomena on this aquifer Using the Schlumberger symmetrical co-linear configuration. Thirty five vertical electrical soundings were measured at the Agami area located to the west of Alexandria City, in the northern Mediterranean coastal area. The maximum current electrode distance was 200m giving maximum depth of penetration of about 60m. The investigation revealed that the resistivity of the fresh water-bearing layer is greater in summer than in the winter season. The depth to the fresh water-bearing layer is less in summer than in the winter season. This indicates that the infiltration of the sewagewater from the septic tanks plays a considerable role in such situation. The resistivity of the mixed water-bearing layer is greater in winter than in summer, due to the subsurface flow of the rainwater from the southern direction directly into this layer. Thus the depth of this layer is greater in summer than in winter season. Resistivity of the salt water-bearing layer is less in winter than in summer, due to the high salt-water intrusion rate in winter from the dynamics of the sea activity. Rising of the groundwater in the fresh water-bearing layer results from the hubhazard accumulation of waste disposal. This phenomenon will cause damage in the soil and then serious environmental problem in the shallow subsurface, which in turn will lead to damage the building foundations in this area

Keywords: Coastal Mediterranean, resistivity, salt-fresh water intrusion.

INTRODUCTION

The present work deals essentially with geophysical and hydrogeological investigations of the Agami area located west of Alexandria city at the northwestern Mediterranean coastal zone of Egypt. The area extends from the shoreline southward with a maximum distance of about 5km. (Fig. 1).

The northwestern coastal zone occupies a narrow strip lying between the Mediterranean Sea to the north and the tableland to the south. It extends westward from the Nile Delta to the Egyptian-Libyan frontiers. Geomorphologically, this area is divided into two unites, namely, a low altitude northern-coastal plain (of maximum elevation of about 40 m), characterized by the occurrence of a series of elongated ridges oriented parallel to the present coast and alternating with shallow depression areas and the southern higher tableland or the Marmarican homoclinal plateau extending from the northern Mediterranean coastal plain southward to the Qattara Depression (with maximum elevation of about 120 m). These two geomorphologic units are separated from each other by a narrow piedmont plain.

Intensive studies represented by geomorphological, geological, and hydrogeological have been carried out on the northwestern Mediterranean coastal zone. In addition some geophysical investigations using surface electrical resistivity method were carried out (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13 and 14). From the hydrogeological point of view, the northwestern Mediterranean coastal zone of Egypt has been studied by many authors (15, 16, 17, 18, 19, 20, 21, 22, 23 and 24).

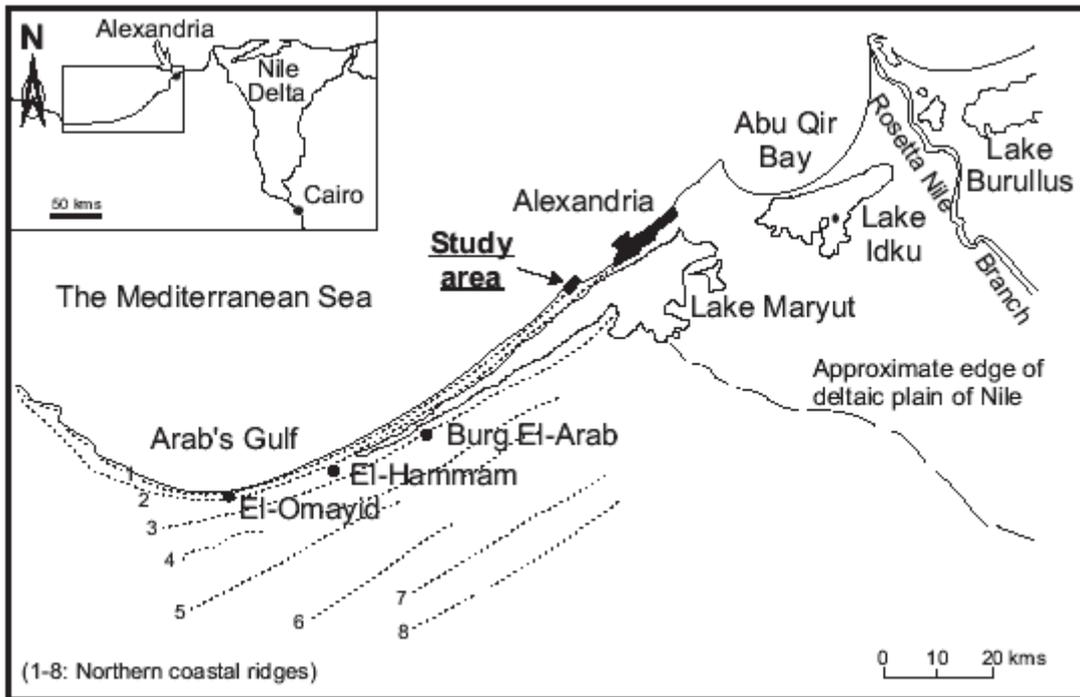


Figure 1: Location map of study area.

Hydrogeologic setting

The important groundwater aquifers in the northwestern Mediterranean coastal zone are classified into the following categories:

The dune sand accumulations (Holocene)

This hydrogeologic unit consists of unconsolidated calcareous sand of high porosity. Such accumulations act as good local reservoirs for rainfall. They are tapped by a number of wells to yield water of low salinity.

The oolitic limestone (Pleistocene)

The oolitic limestone forms the most important aquifer in the region to the west of Alexandria. It covers the whole coastal plain forming elongate ridges. The oolitic limestone extends southward from the coastline to about 10 km in average.

The foreshore oolitic limestone ridge is characterized by less cementing materials compared with the inland ridges and hence it has more porosity. The flanks of the foreshore ridge are covered by loose foreshore sand accumulations, which permit direct infiltration and percolation of rainwater. The groundwater found in the oolitic limestone ridges originates either from direct infiltration and percolation of annual rainfall on the ridges or from the rainwater falling on the tableland located to the south.

The fissured limestone (Middle Miocene)

The Miocene formations, which form the underlying rocks of the whole area, are composed of limestone with few clay intercalations. Such limestone may be dolomitic, marly, clayey or chalky limestone according to the local conditions of sedimentation.

A small-scale homoclinal and synclinal folding and fissuring appear to be the most common structural features along the coastal zone. Consequently, the groundwater occurs in the form of separated sheets accumulated above the contact with the impervious clays alternating with the porous limestone. The Miocene formations have no relevance as aquifers eastward of El Alamein.

Groundwater conditions

Groundwater in the northwestern coastal zone occurs mainly under the following conditions:

The main water table

The only source of water supporting the main water table in the northwestern coastal zone is the localized rainfall directly precipitated on the coastal plain and the southern tableland. The free surface of the main water table has a level at or about the mean sea level up to about 20 km

Inland. The main fresh-water table forms a thin freshwater layer floating on the saline water. The hydrologic relation between these two water tables is controlled by the bouncy effects and the salt-water intrusion into coastal aquifers. Shata (25) pointed out that near the sea; the inflow of seawater maintains a dynamic equilibrium with a comparatively thin layer of fresh water existing on the upper surface of the salt water. Most of the wells and open trenches along the coastal zone depend on their supply from the main water table.

Under natural conditions, the fresh groundwater in the coastal aquifers is discharged into the sea at the beach face or seaward of the coastline. A balance or equilibrium tends to be established between the fresh groundwater and the salt water pressing in from the sea. Where coastal aquifers are over pumped, lowered by natural drainage, or natural recharge is impeded by construction or other activities, the groundwater level is lowered, thereby reducing the fresh water flow to the sea. A reversal or reduction of freshwater flow allows the heavier salt water to advance inland, which can seriously threaten the continued use of an aquifer as a water supply source.

Fresh water and seawater, being of different densities, when brought together under steady-state balance tend not to coalesce but to form a distinct interface (26 and 27). Because seawater intrusion however, represents a displacement of the miscible liquids in the porous media, the diffusion and hydrodynamic dispersion mix the two liquids and the interfacial surface becomes a transition zone of variable thickness (28).

The position of the interface between freshwater and salt water depends on a number of factors; flow rates, nature of the flow paths, high tide, and change in recharge. A change in any of these factors will cause the salt-water/fresh-water interface to migrate. Reduction of stream flow, over pumping or deepening of the open channels results in the landward migration of the seawater wedge (29) whereas the increased stream flow result in a seaward migration.

Geoelectrical resistivity survey

Many workers have used the geoelectrical resistivity method for groundwater exploration from whom are (30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40 and 41). The electrical resistivity method was used in the present work to obtain information about the depth to fresh/salt-water zones as well as their dynamics and the thickness of the fresh water-layer floating over the salt water.

In the present work, the ABEM A.C. Terrameter, model SAS 4000 was used for conducting the geoelectrical resistivity survey. Four cable reels, sixteen steel

electrodes and other accessories such as measuring tapes, GPS of the Germin type, etc. were used.

Schlumberger configuration was applied at the study area (Fig.1) twice during 2003; a first survey was conducted by the end of the winter season (May, 2003) and a second by the end of the summer season (October, 2003). The aim of such survey was to map the fresh/salt water zones and to observe any fluctuation of the fresh water depth in both seasons. Also, the reasons for any variation will be considered and related to possible environmental effects. Using collinear Schlumberger symmetrical configuration, thirty-five vertical electrical soundings (VES) were measured Fig. 2.

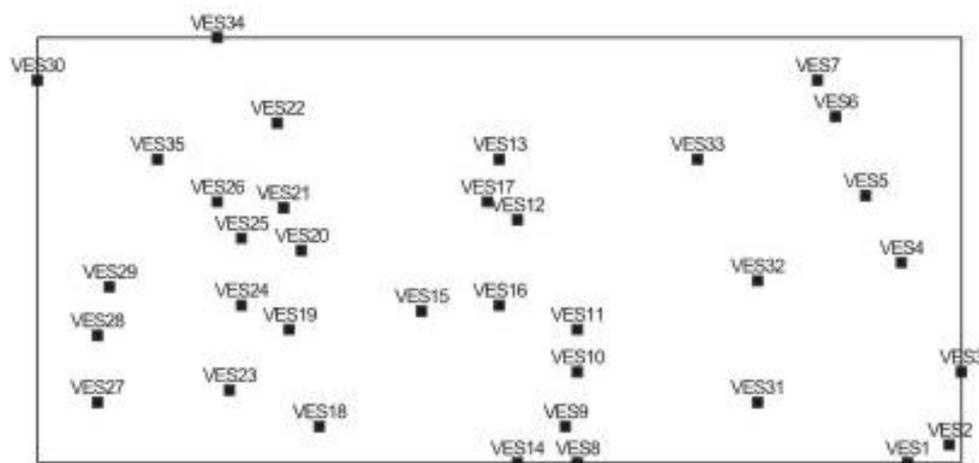


Figure 2: Location of the sounding points.

The relation between the maximum depth of investigation and the current electrode spacing has been studied (42, 36 and 43) by defining a term called the depth factor, "F" which is defined as the ratio of the depth to the midpoint parallel to the earth's surface of the study target (S) and the current electrode separation (L), where:

$$F = S/L$$

This depth factor has no direct relationship to the depth of current penetration, but some indirect relations may be present. The factors affecting F have been studied (44 and 45). These authors have calculated F as ranging between 1/3 and 1/4 of L. Roy and Apparao (42) have defined this factor as the depth, which contributes most of the signal measured on the ground surface and is determined by the position of both potential and current electrodes and equals 1/8 L. Roy and Elliot (26) have concluded a wide range of F which ranges between zero and 0.8 L. Thus, the current flows inside the earth's body reaching into variable depths of the investigation depend on the distance between the current electrodes and the type of soil penetrated by the current.

Different geological and hydrogeological information have been collected from some wells scattered in the study area. These information are used as guide during the interpretation of the different vertical electrical soundings. Flathe (30) concluded that

without a geological concept, an interpretation of geoelectrical measurements is almost impossible if the number of layers concerned exceeds three.

Data processing, analysis and interpretation

The distribution of the vertical electrical soundings in the study area is controlled by the topographic conditions, building distribution and the presence of guide water wells. The steps followed for treating the VES data are as follows:

- a) Carrying out matching technique of interpretation of the data.
- b) Using the results obtained from (b) as an initial model for carrying out (achieving) the automatic interpretation using special software.
- c) The application of both steps (b) and (c) did not give good results, when comparing the final model with the actual geologic information obtained from some wells drilled in the area.
- d) Zohdy's technique (45) was used to change each apparent resistivity value and half current electrode spacing ($L/2$) into true resistivity and depth values.
- e) When applying (e) the number of layers equals the number of digitized points.
- f) After that step, each group of strata having equal or nearly equal resistivity values is stacked together to form one layer.
- g) The obtained number of layers after stacking is taken as new initial model that is introduced into a soft ware prepared by Hemker (46) after the method described by Ghosh (47) to give the final model.

By applying the above-mentioned steps into consideration, each sounding point was subjected to qualitative and quantitative interpretation. All sounding curves obey the Q type, where continuous decrease in apparent resistivity values is observed, except for some local irregularities.

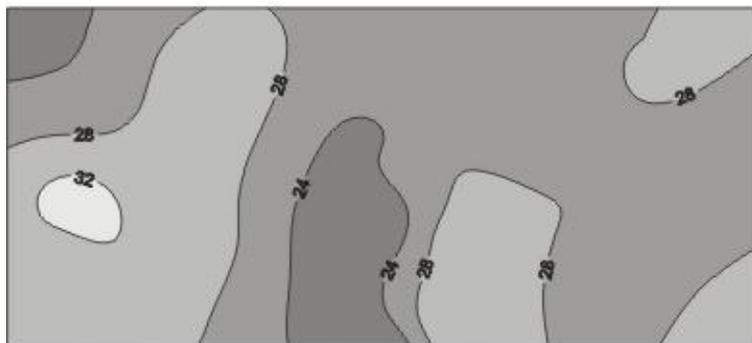


Figure 3a. Iso-resistivity map of the fresh water bearing layer (winter season).

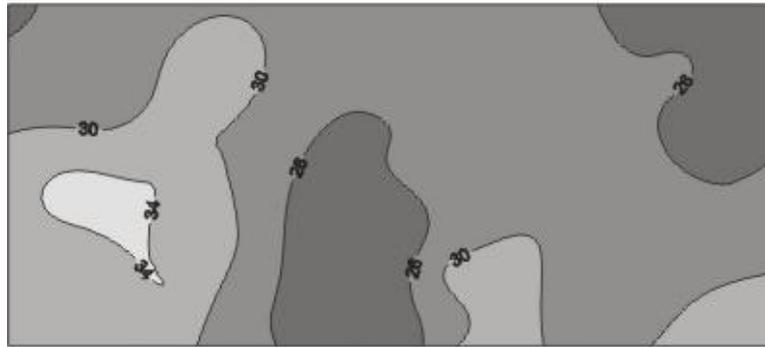


Figure 3b. Iso-resistivity map of the fresh water bearing layer (summer season).

Data analysis and discussion

Based on the quantitative results obtained from the interpretation of the measured 35 sounding points at the end of winter season, seven contour maps were prepared. Fig. 3a shows the iso-resistivity distribution of the freshwater-bearing layer, where three relative high (R1) and one low (R2) resistive zones are observed. Fig.4a shows the iso-resistivity pattern of the mixed water-bearing layer, where one main high resistive (R3) and three relative low resistive zones (R4) are observed. Fig. 5a shows the depth of the freshwater-bearing layer, that increases gradually toward the southeastern direction. Fig. 6a shows the depth of the mixed water-bearing layer, where the depth increases toward the southeastern direction with some local low depth zones scattered at the northern and western parts of the study area. Also a low depth zone extends N-S. Fig.7a shows the depth of the salt water bearing, where a gradual increase towards the southern direction with one local relative high depth zone (D1) is observed. The thickness of this freshwater-bearing layer is shown in Fig.8a, where two relative low thickness zones are observed (T1). The thickness of the mixed water-bearing layer is shown in fig. 9a. Two minimum zones are observed north and south of the study area with a high thickness zone between them.

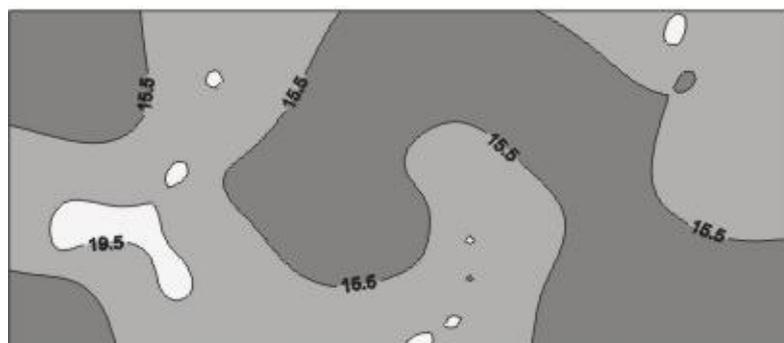


Figure 4a. Iso-resistivity map of the mixed water bearing layer (winter season).

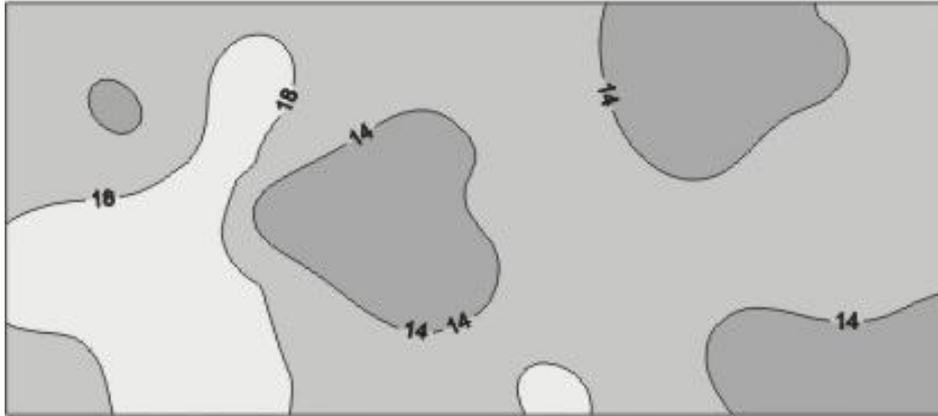


Figure 4b. Iso-resistivity map of the mixed water bearing layer (summer season).

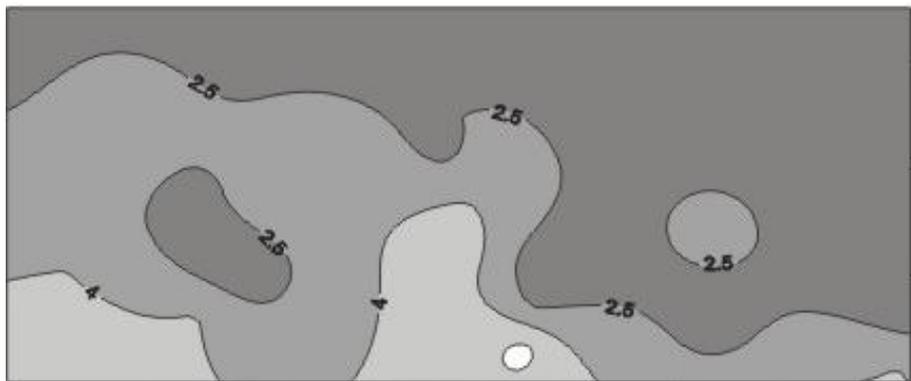


Figure 5a. Depth map of the fresh water bearing layer (winter season).



Figure 5b. Depth map of the fresh water bearing layer (summer season).



Figure 6a. Depth map of the mixed water bearing layer (winter season).

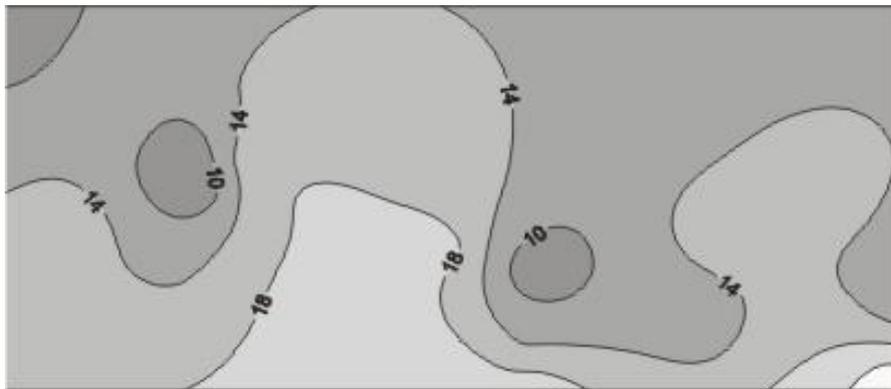


Figure 6b. Depth map of the mixed water bearing layer (summer season).

Fig.3b shows the iso-resistivity pattern of the fresh water-bearing layer by the end of summer season. Inspection of this map shows two relative high resistivity zones (R5) and two relative low resistivity zones (R6). Fig.4b shows the iso-resistivity of the mixed water-bearing layer, where three relative low resistivity and one high resistivity zones (R8 and R7, respectively) are observed. Fig. 5b shows the depth contour of the fresh water bearing-layer. Two low depth zones (D2) and two high depth zones (D3) are detected. Fig.6b shows the depth of the mixed water bearing-layer with two relative low and two relative high depth zones (D4 and D5, respectively). Fig.7b shows the depth of the salt water-bearing layer with two relative high thickness zones (D6). Fig. 8b shows the thickness of the freshwater-bearing layer, where two alternative low thickness zones (T3) and three high resistive zones distributed from east to west are detected. Fig. 9b shows the mixed water-bearing thickness, where two maximum thickness zones are detected northward and southward (T4).

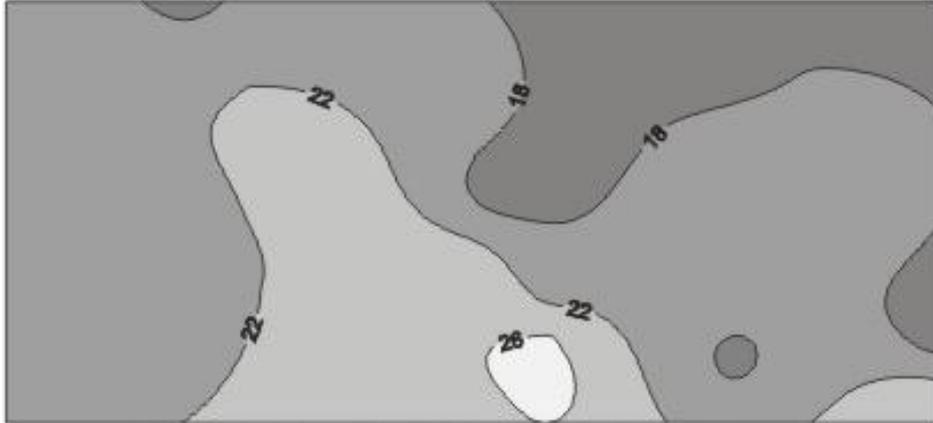


Figure 7a. Depth map of the salt water bearing layer (winter season)

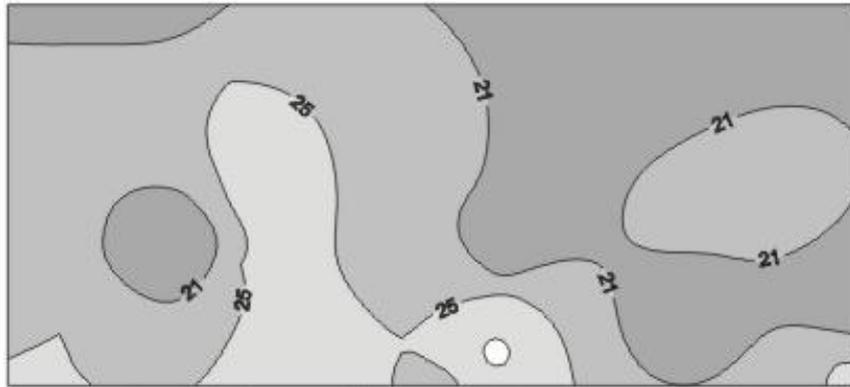


Figure 7b. Depth map of the salt water bearing layer (summer season).

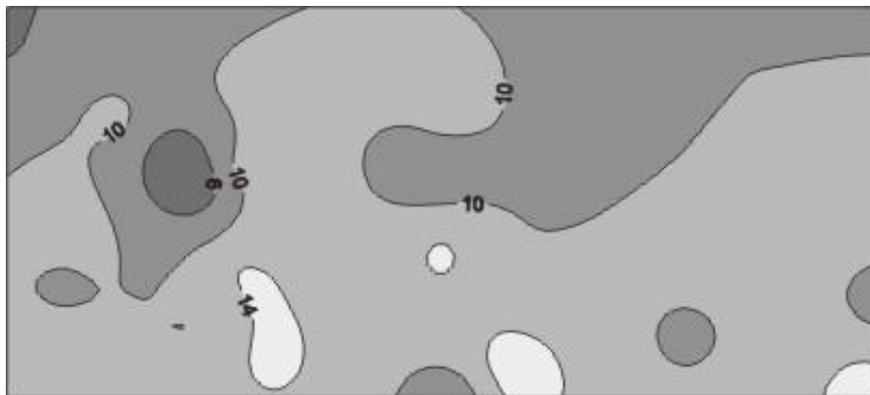


Figure 8a. Thickness map of the fresh water bearing layer (winter season).

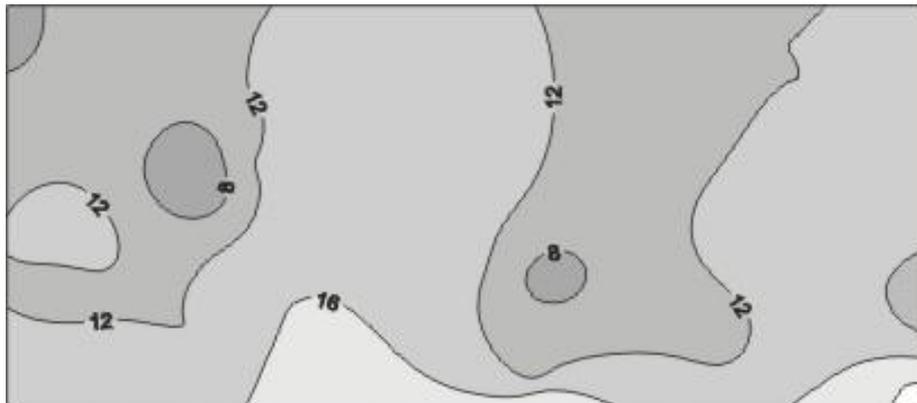


Figure 8b. Thickness map of the fresh water bearing layer (summer season).

The comparison between the results obtained in summer and winter seasons reveals the following ; regarding the iso-resistivity maps of the fresh water bearing layer in winter and summer seasons (Figs. 3a and 3b, respectively), the contour line pattern is nearly the same with a slight increase in the resistivity values in the summer season. The maximum values are found to be 32 and 34 Ohm-m in winter and summer seasons, respectively. Comparison of the iso-resistivity maps of the mixed water bearing-layer in winter and summer seasons (Figs. 4a and 4b, respectively) shows variations in the contour line pattern with an increasing in resistivity values all over the area in winter season, where the three scattered zones in Fig. 4b are combined in one zone (R4) in Fig. 4a. Comparison of the depth maps of the fresh water bearing-layer of the two seasons (Figs.5a and 5b) shows different contour line pattern with a decrease in depth values of about 0.5m in winter season. Comparison of the depth map of the mixed water-bearing layer in both seasons (Figs. 6a and 6b) shows similar contour line pattern with an increase in depth values of about one meter in summer season. This result differs from that obtained from the depth map of the freshwater bearing layer. Comparison of the salt-water bearing layer depth map of winter and summer seasons (Figs. 7a and 7b) shows an increase in the depths in summer season than in the winter. The thickness of the fresh water-bearing layer in winter is greater than in summer as shown in Figs. 8a and 8b, respectively. The thickness of the mixed water-bearing layer in winter is greater than in summer as shown by Figs. 9a and 9b, respectively. The study area is characterized by its close position with respect to the Mediterranean Sea, as well as its position as a new urban area extending westward of Alexandria harbor. The shallow subsurface layers may be affected by either the sea wave and tidal action or by infiltration of the contaminated mix coming from the hazardous septic tanks scattered in the study area. The seawater intrudes southward and causes rising of the ground water level and increases the mixed and salt water bearing layer thickness. Leachate from the septic tanks also causes rising of the freshwater level with an increase in organic matter content rather than the from seawater intrusion.

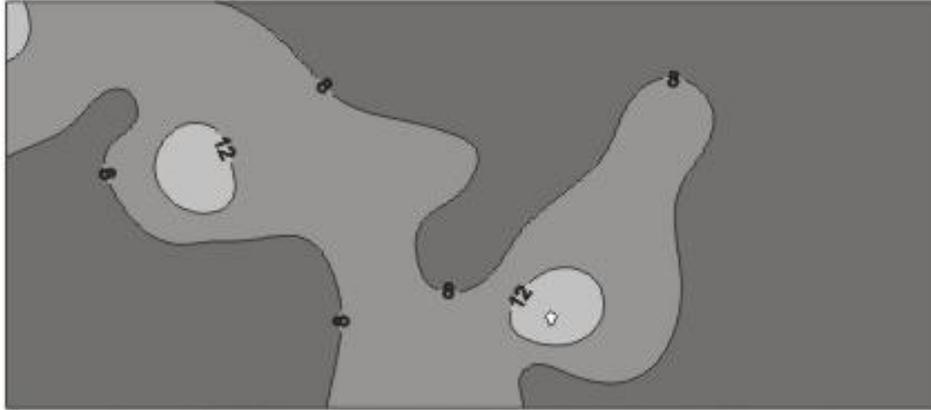


Figure 9a. Thickness map of the mixed water bearing layer (winter season).

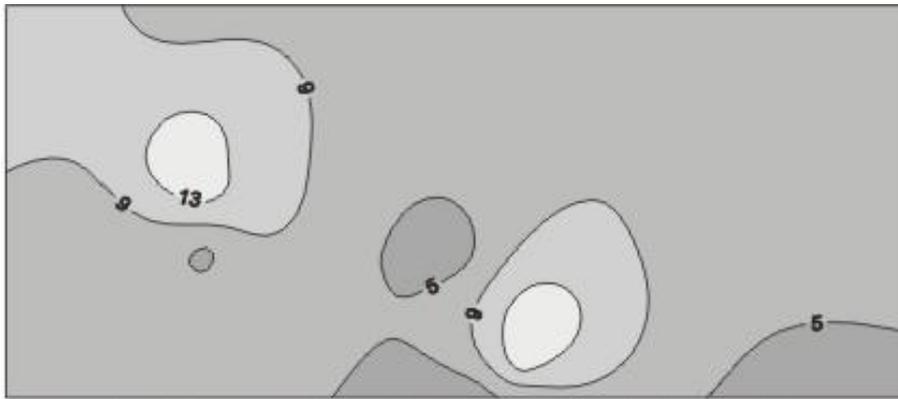


Figure 9b. Thickness map of the mixed water bearing layer (summer season).

CONCLUSIONS

The integrated investigation of the above-mentioned results in the study area has revealed the following concluding remarks; 1- The resistivity of the fresh water-bearing layer is greater in summer than in winter season; 2- The depth of the freshwater-bearing layer is less in summer than in winter season; 3- This indicates that the infiltration of the sewage water from the septic tanks appears to play a considerable role in such a situation; 4- Regarding the mixed water-bearing layer, it is clear that the resistivity of this layer is greater in winter than in summer, due to subsurface flow of the rainwater from the southern direction direct into this layer. Thus the depth of this layer is greater in summer than in winter season; 5- The resistivity of salt the water-bearing layer is greater in winter than in summer due to the high salt-water intrusion rate in winter as a result of the dynamic action of the sea; 6- The rising of the fresh water level may result from the incorrect seepage disposal and sea water intrusion from beneath. This phenomenon could cause damage in the soil and then lead to serious environmental problems for the buildings in this area.

REFERENCES

- [1] Abdallah, A.M., 1966, "Stratigraphy and structure of a portion in the north Western Desert of Egypt, U.A.R. (El Alamein-Dabaa-Qattara-Moghra area) with reference to its economic potentialities", Geol. Surv. Egypt, Paper no. 45, 19 pp.
- [2] El Shamy, I.Z., 1968, "The geology of water and soil resources in El Dabaa area, western Mediterranean coastal zone, U.A.R.", M.Sc. Thesis, Fac. Sci., Cairo Univ., Egypt, 112 pp
- [3] El Senussi, M.Y. and Shata, A., 1969, "Geomorphological and morphopedological aspects of Umm El Rakhm area (west Marsa Matruh, Egypt)", Bull. Inst. Desert, Cairo, **19**(1), pp. 31-61.
- [4] El Shazly, M.M. and Shata, A., 1969, "Geomorphology and pedology of Mersa Matruh area (western Mediterranean Littoral zone)", Bull. Inst. Desert, Cairo, **19**(1), pp. 1-28.
- [5] Ismail, M.M. and Selim, A.A., 1969, "Stratigraphy of the Salum area, Western Desert, U.A.R.", Bull. Fac. Sci., Alex. Univ., **9**, pp. 309-330.
- [6] El Fayoumy, I.F. ; Taha, A.A. and Shata, A., 1974, "Morphopedology of Mersa Matruh-Sidi Barrani area, western Mediterranean coast, Egypt," Bull. Fac. Sci., Mansoura Univ., **2**, pp. 149-165.
- [7] Misak, R.F., 1974, "Geomorphology and geology of the area between El Dabaa and Ras El Hekma, Western Mediterranean coastal zone, Egypt.," M.Sc. Thesis, Fac. Sci., Ain Shams Univ., Egypt, 144 pp.
- [8] Selim, A.A., 1974 "Origin and lithification of the Pleistocene carbonates of the Saluwestern coastal plain of Egypt," J. Sediment. Petrol., v. 44, pp. 70-78.
- [9] Cherif, O.H.; Bassiouni, M.A. and Ghanima, S.A., 1975 "Stratigraphy, paleoecology and climates of the Neogene and Quaternary of the Mersa Matruh area, north Western Desert, Egypt.," Ann. Geol. Surv. Egypt. **5**, pp. 137-147.
- [10] Ismail, M.M.; Selim, A.A. and Taha, A.A., 1977, "Matruh-Barrani carbonate sediments petrography and diagenesis.," Bull. Fac. Sci., K.A.U., v. 1, pp 145-160
- [11] Abdel Kader, S.A., 1978, "Petrology and mineralogy of the surface Tertiary and Quaternary deposits in the area between Ras El Hekma and Mersa Matruh, western Mediterranean coastal zone, Egypt," M.Sc. Thesis, Fac. Sci., El Azhar Univ., Egypt.
- [12] Hassouba, A.H., 1980, "Quaternary sediments from the coastal plain of northwestern Egypt (from Alexandria to El Omayid)," Ph.D. Thesis, Imperial College, London, 320 pp.

- [13] Mersal, M.A.G., 1982, "Geological studies on Matruh area, northwestern part of Egypt," M. Sc. Thesis, Fac. Sci., Alex. Univ., Egypt, 152 pp.
- [14] El Asmar, H.M., 1991, "Old shorelines of the Mediterranean coastal zone of Egypt in relation with sea level changes," Ph.D. Thesis, Fac. Sci., Mans. Univ., Mansoura, Egypt, 219 pp.
- [15] Abdel Mogheith, S.M., 1968, "Hydrogeochemical studies in Burg El Arab and vicinities," M.Sc. Thesis, Fac. Sci., Ain Shams Univ., Egypt, 109 pp.
- [16] Swidan, A.S., 1978, "Water budget analysis for the northwestern coastal zone of the Arab Republic of Egypt," Ph.D. Thesis, Fac. Sci., Cairo Univ., Egypt
- [17] La Moreaux, P.E., 1970, "Groundwater resources of the northern coastal zone, U.A.R.," Univ. Alabama, USA, 107 pp.
- [18] Taha, A.A.M., 1973, "Geology of water supplies of Matruh-Barrani area (northwestern[Mediterranean coastal zone, A.R.E.)," Ph.D. Thesis, Fac. Sci., Alex. Univ., Egypt, 253 pp.
- [19] Guindy, Kh.A., 1989, "Hydrogeology of the coastal zone between El Ameriya and El Hammam," Ph.D. Thesis, Fac. Sci., Ain Shams Univ., Egypt, 151 pp.
- [20] Atwa, S.M.M., 1979, "Hydrogeology and hydrogeochemistry of the northwestern coast of Egypt," Ph.D. Thesis, Fac. Sci., Alex. Univ., Egypt, 225 pp.
- [21] Abu El Ella, A.M., 1987, "Geological and hydrogeological studies for El Dabaa Nuclear Power Plant Station, north Western Desert, Egypt," M.Sc. Thesis, Fac. Sci., Cairo Univ., Egypt, 193 pp.
- [22] Eweida, E.A.; Fayed, L.A.; Hassan, E.A. and Abu El Ella, A.M., 1989, "Groundwater contamination at El Dabaa site.," 1st Conf. Geoch., Alex. Univ., pp. 595-603.
- [23] El Ramly, I.M. and Abdel Fattah, A., 1991, "Rainfall-soil conservation as an important tool for rangeland management along the Western Desert coastal region, Egypt. Document submitted to the first workshop on Rahabilitation and Development of Siwa Oasis and the Western Desert coastal region,"
- [24] Farag, M.H., 1995, "Major ion characterization of coastal saline groundwaters in the area between El Hammam and Bahig," Bull. Fac. Sci., Alex. Univ., v. 35, no. 2, pp. 417-432.
- [25] Shata, A., 1970, "The geomorphology, pedology and hydrogeology of the Mediterranean coastal desert of U.A.R.," Symposium on the geology of Libya, Tripoli, Libya, pp. 431- 446.
- [26] Ghyben, W., 1889, "Nota in Verband met de voorgenmen put Amsterdam," Tijds. K. Institute Ing., The Hague, p. 21.
- [27] Herzberg, B., 1901, "Die Wasserversorgung einiger Nordseebüder," J. Gasbeleuchtung und Wasserversorgung, **44**, pp. 815-819, 842-844.

- [28] U.S. EPA 1973, "Identification and control of pollution from salt-water intrusion," Washington, D.C.
- [29] Cooper, H.H., JR., Kohout, F.A., Henry, H.R. and Glover, R.E., 1964, "Sea water in coastal aquifers," U.S. Geol. Surv. Water Supply Paper 1613-C, pp. 70-84.
- [30] Flathe, H., 1976, "The role of a geological concept in geophysical research work for solving hydrological problems," *Geoexploration*, **14**, pp. 195-206.
- [31] Meidav, T., 1960, "An electrical resistivity survey for groundwater," *Geophysics*, **25**, pp. 1077-1093.
- [32] Kelly, S.F., 1962, "Geophysical exploration for water by electrical resistivity," *J. New Engl. Water Works Assoc.*, **76**(2), pp. 118-189.
- [33] Keller, G.V. and Frischknecht, F.C., 1966, "Electrical methods in geophysical prospecting," Oxford Pergamon Press, 183 pp.
- [34] Topfer, K.D., 1976, "Representation and interpretation of resistivity mapping data in groundwater prospecting in Zambia," *J. Geophys.*, **42**, pp. 147-158.
- [35] Cosentino, P., Cimino, A. and Riggio, A.M., 1978, "Time variations of the resistivity in a layered structure with unconfined aquifer," *Geoexploration*, **17**, pp. 11-17.
- [36] Roy, K.K. and Elliot, H.M., 1981, "Some observations regarding depth of exploration in D.C.," electrical method. *Geoexploration*, **19**, pp. 1-13.
- [37] Abdel Fattah, Th., 1984, "Combination of electrical resistivity and seismic refraction measurements for groundwater exploration," Ph.D. Thesis, Kiel Univ., West Germany, 165 pp.
- [38] Hassan, B.H., 1984, "On electric and electromagnetic methods for groundwater parameters determination," M. Sc. Thesis, Cairo Univ., Egypt.
- [39] Awad, W.K. and Girgis, M.M., 1985, "Goelectric study for groundwater at El-Hemma area, Northern Sinai. E.G.S," *Proc. of 4th Ann. Meet.*, pp. 25-42.
- [40] Boulos, F.K.; El Sherif, A.F. and Basta, N.Z., 1986, "Geophysical investigation of groundwater midway Cairo-Suez Road, Egypt. E.G.S," *Proc. of 4th Ann. Meet.*, pp. 14-24.
- [41] Abdel Fattah, Th.; El Nekhaily, A.; Mesbah, M.A. and El Raey, M., 1988, "Exploration for groundwater resources at Es-Sadat City," *Symp. Environ. Sci. (UNARC), Alexandria*, pp. 86-101.
- [42] Roy, A. and Apparao, A., 1971, "Depth of investigation in direct current methods," *Geophysics*, **36**, pp. 943-959
- [43] Abdel Fattah, Th., 1994, "Current penetration and depth investigation in Schlumberger configuration (field applications)," *Bull. Fac. Sci., Qena, Egypt*, **2**(2), pp. 41-48.

- [44] Frohlich, R.K., 1967, "The depth penetration of dipole arrays compared with Schlumberger arrangement," *Geoexploration*, **5**, pp. 195-204.
- [45] Zohdy, A.A.R. and Jackson, D.B., 1969, "Application of deep electrical soundings for groundwater exploration in Hawaii," *Geophysics*, **34**, pp. 584-600.
- [46] Hemker, C.J., 1984, "Vertical electrical sounding model interpretation program. Amsterdam, The Netherlands,"
- [47] Ghosh, D.A., 1971, "The application of linear filter theory to the direct interpretation of geoelectrical resistivity sounding measurements," *Geophys. Prosp.*, **19**, pp. 192-217.