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A hydrogeophysical investigation of the Ain Mousa area, near Cairo, Egypt

S. A. Sultan · S. A. Mansour · F. A. M. Santos

Abstract The aim of this study was to determine the depth of the water-bearing strata in the Ain Mousa area and the source of the recharge. Five geophysical profiles were acquired and analyzed at four field stations. The interpretation of the geophysical data indicates that the study area consists of four geological units belonging to the Maadi Formation. The main water flows are through the intersection of two faults trending NW–SE and W–E. The hydrological studies included a hydrochemical analysis which indicated that the water is geologically recent and slightly saline.

Keywords Egypt · Faults · Fractures · Geoelectrical methods · Hydrogeology

Résumé L'étude présentée avait pour objectif de déterminer la profondeur de l'aquifère dans la région d'Ain Mousa ainsi que l'origine de ses recharges hydrauliques. Cinq profils géophysiques ont été réalisés ainsi que des analyses structurales sur quatre sites. L'interprétation des données géophysiques indique que la zone d'étude est constituée de quatre unités géologiques appartenant à la formation de Maadi. Le principal axe de drainage de l'aquifère se présente à l'intersection de deux failles de direction NW–SE et W–E. Les études hydrogéologiques ont comporté des analyses hydrochimiques qui ont indiqué que l'eau est géologiquement récente et légèrement salée.

Mots clés Egypte · Failles · Fractures · Hydrogéologie · Méthodes géo-électriques

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Introduction

The study area lies at the northeastern part of the Mokattam plateau, east of Cairo city. The Mokattam area has been extensively studied [see Moustafa et al. 1985, 1991; NARSS (National Authority of Remote Sensing and Space Science) 1997].

The Ain Mousa area is 160–180 m a.s.l. and about 60 m higher than Cairo city. The results of earlier geological and hydrological studies suggested that the water in Ain Mousa flows from fractures and joints in the dolomitic limestone unit of the Maadi Formation (EGSMA 2004). Subsequent chemical analysis revealed that this water is recent (900 years).

The aim of this study was to identify the source of the water flowing from Ain Mousa, to evaluate the thickness of the water-bearing unit and to determine the direction of the recharge water at Ain Mousa (Fig. 1).

Geology of the study area

The stratigraphic column in this area can be divided into four sedimentary units of the Maadi Formation of Middle Eocene age (Fig. 2). From top to bottom the units are as follows:
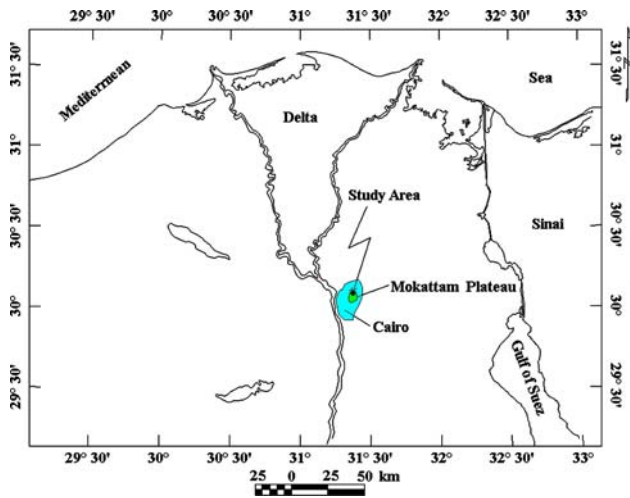
Fig. 1 Location of the study area

Fig. 3 Photograph showing the spacing of the joints and width of the fractures in the stronger strata located in the Wadi Ain Mousa area

(1) Upper carbonate unit, which is mostly formed of fossiliferous and sandy dolomitic limestone ranging in thickness from 25 m in the east (e.g. Wadi Ain Mousa) to 10 m in the west. Thin argillaceous limestone interbeds can be found in some parts. These dolomitic strata are strong, persistent and massive, forming prominent walls (Fig. 3);

(2) Upper clastic unit, which is moderately strong, partly dolomitised marl with ferruginous and calcareous patches. Gypsiferous marly sands of varying thickness are present towards the base. The top of the unit is unconformable with the overlying strata; consequently, it frequently is red in colour;
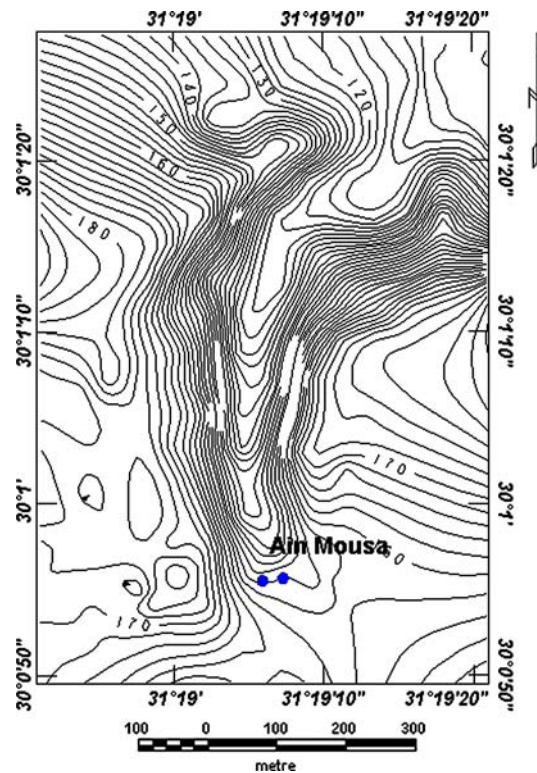

Fig. 2 Geological log of the Wadi Ain Mousa area

Fig. 4 Topography of the area

Fig. 5 Main faults dissecting the study area (F) and stations (S) where the fault and joint characteristics were measured (image from Landsat; U.S. Geographical Survey; http://ldcm.usgs.gov/landsat_home.php)

(2) Lower carbonate unit, which is an interbedded unit of sandy dolomitic limestone and gypsiferous marly sands;

Table 1 Distribution of the joints and fractures at Wadi Ain Mousa

Station	Numbers	Main trend	Inclination	Width (m)	Density (joints/m)
S1	150	E–W	Vertical	0–1.5	Three
S2	215	NE–SW	Vertical	0–0.2	Five
S3	115	E–W	Vertical	0–0.2	Three
S4	399	E–W	Vertical	0–0.1	Ten
S5	1200	NW–SE	Vertical	0–0.1	20 joints/m
Total	2099				

(4) Lower clastic unit, which consists mainly of shale over sandy marly limestones interbedded with shale.

The geomorphology of the study area is dominated by the Wadi Ain Mousa, which rises in elevation from approximately 110 m a.s.l. at its wider, northern part to some 170 m a.s.l. in the south (Fig. 4). Figure 5 shows the position of the faults in the region. The F1 fault lies in the northeastern part of the study area and has a NW–SE direction. It intersects the E–W F4 fault at the northern end of the Wadi. The structural disturbance caused localised fracturing of the dolomitic limestone, through which the ground water egresses at Ain Mousa (Fig. 6). The F2 fault is parallel to F1 and intersects the E–W F3 fault at Ain Mousa. As a result, there is again an increase in the density of fractures, through which deeper ground water rises,
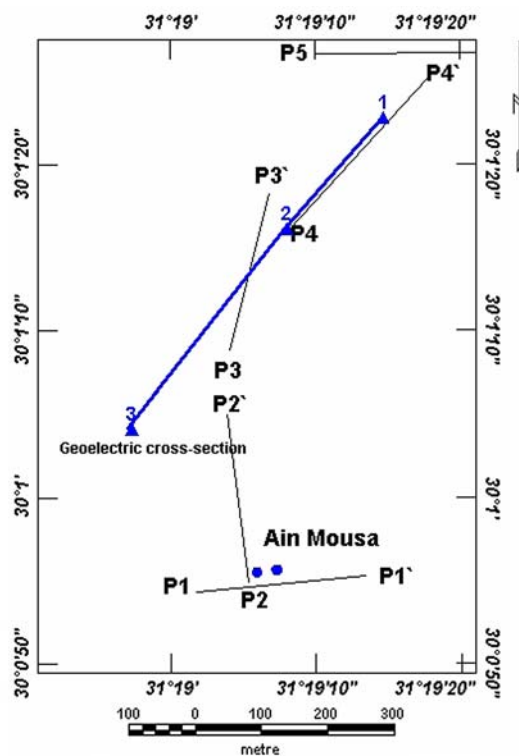

Fig. 6 Photo showing the flow of the water from Ain Mousa

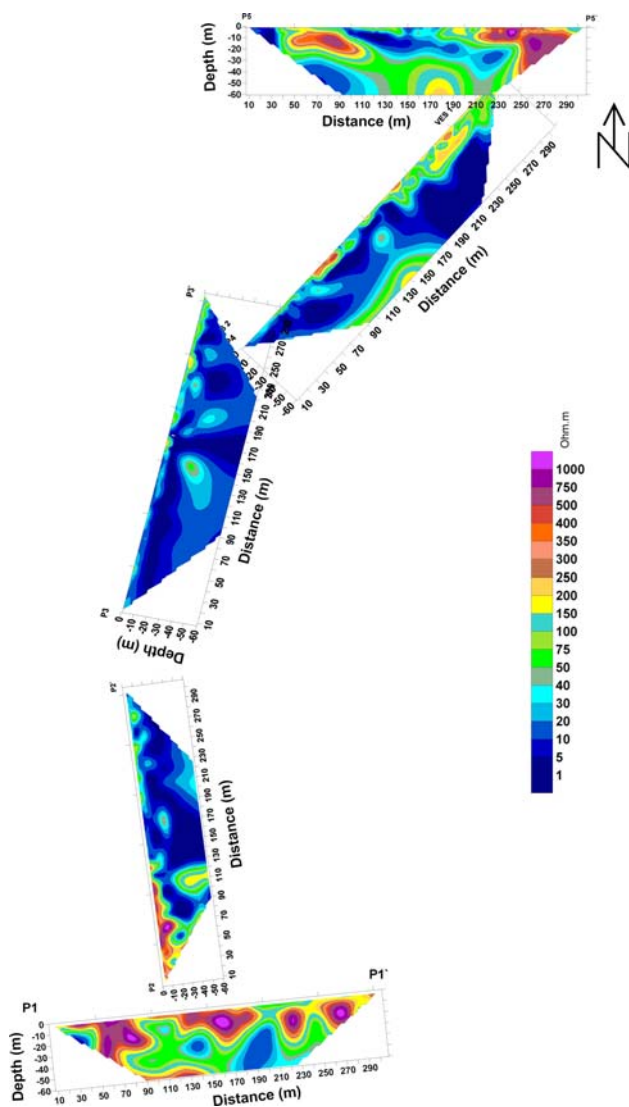Fig. 7 Location of the geophysical surveys

Fig. 8 Dipole–dipole resistivity model obtained from profiles P1–P1′, P2–P2′, P3–P3′, P4–P4′ and P5–P5′

particularly at the intersection of the faults. F4 and F5, F2 and F3 delimit the horst blocks, while the area between F2 and F5 is a graben downthrowing the SSE part of the area, which currently has a dip 4° to the north. F1 and F4 have a downthrow to the N/NE.

Table 1 summarises the main characteristics of the joints and fractures in the study area, as shown in Fig. 5. As indicated, the main trend is E–W with some NE–SW and NW–SE orientations. In general, the fractures are vertical and vary in width – in the case of F1, up to 1.5 m.

Data and interpretation

Five dipole–dipole resistivity profiles (315 m long) with electrode spacings of 5, 15 and 30 m were made in the

study area (Fig. 7). The data were acquired using a multi-electrode system and SYSCAL–ELREC-T equipment. The first dipole–dipole profile (P1) was acquired upstream of the Wadi, approximately 50 m south of Ain Mousa. Profiles P2, P3 and P4 were acquired in the Wadi and P5 in the downstream area. The results are shown in Fig. 8. In addition, vertical electrical soundings (VES) were made at an AB/2 spacing ranging from 1 to 200 m (Fig. 9).

The rate of water flow was measured at three sites (Table 2). At the two main springs of Ain Mousa the flow rate was 70 m^3/h in the east and 30 m^3/h in the west. The third measurement was in the Wadi where the two main spring flows join. Hydrochemical and isotopic ©[14], H^2 and O^{18}) analyses were carried out on water samples from these sites; the results are summarised in Tables 2 and 3.

The interpretation of the dipole–dipole models calculated using RES2DINV software (2001) was made by correlating the geoelectrical results with the geological units based on the resistivity values for each unit. The model obtained from profile P1–P1′ (Figs. 7, 8) shows very high resistivity values at shallow depths. These high resistivity values (>500 ohm-m) correspond to the upper dolomitic limestone formation (upper carbonate unit), which ranges in thickness from 20 to 30 m. This unit is also recognised in profile P2–P2′, which has an average thickness of 18 m, but is not seen in profiles P3–P3′, P4–P4′ and P5–P5′. The upper clastic unit is identified in all the profiles, with resistivity values ranging from 1 to 40 ohm-m. The high resistivity values associated with the lower dolomitic limestone formation (lower carbonate unit) were recorded in the lower part of profile P1–P1′ and in the upper part of P4–P4′ and P5–P5′. However, the lower clastic unit is represented only in the lower part of P5–P5′.

The quantitative interpretation of the VES was carried out using a graphical method based on the two layer curves and generalised Cagniard graphs (Koefoed 1960). The results of manual interpretation were used as the initial models for the IPI2win software (2000) in order to compute the true depths and resistivities of the one-dimensional model for each VES curve (Fig. 9). The upper carbonate and upper clastic units are represented only in VES 3, while the lower carbonate and lower clastic units were identified at all VES sites. Figure 10 shows the geoelectrical cross section obtained from the VES models. The presence of the F6 fault can be identified between VES 2 and 3 as a downthrow towards VES 2.

Electrical resistivity is a useful parameter for characterising porous media. It is known that the electrical conductivity of porous media depends on the porosity, pore geometry, fluid saturation, fluid conductivity and surface morphology of the mineral grains. For saturated porous media, Archie (1942) proposed the following relationship between bulk (σ_b) and fluid (σ_f) conductivities:

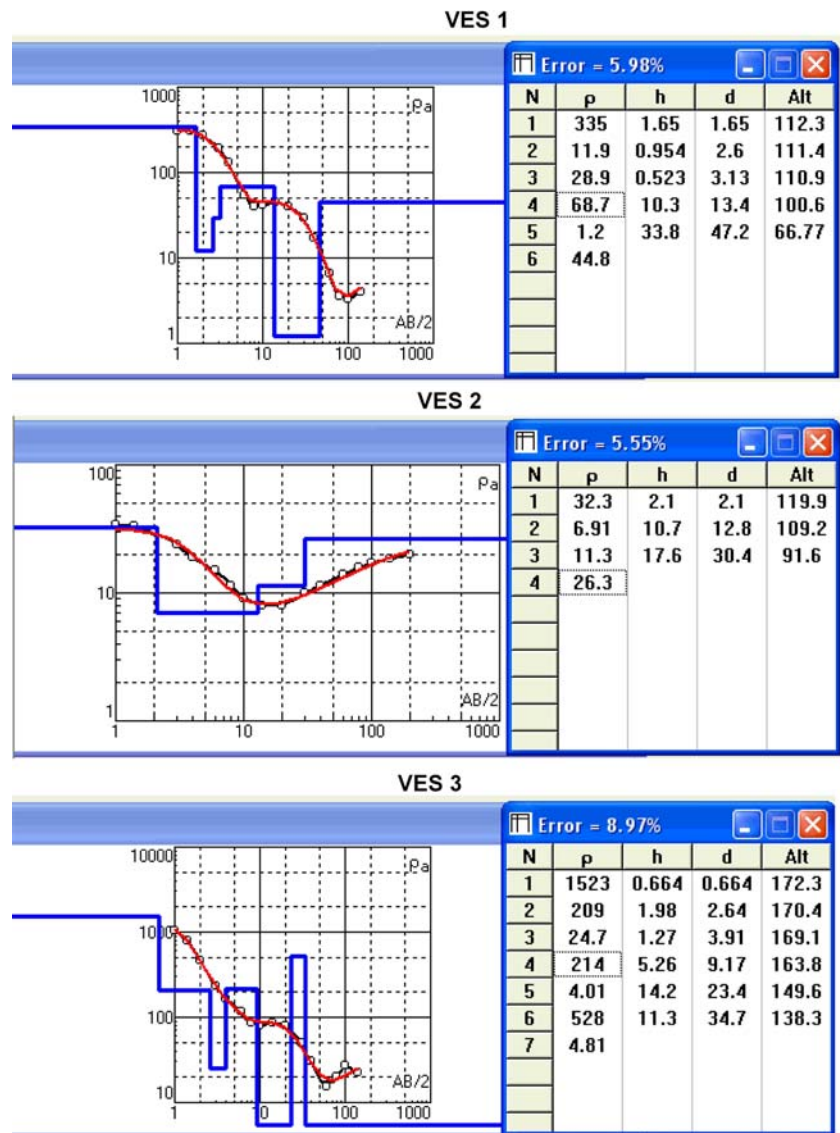**Fig. 9** Interpretation of the vertical electrical soundings (VES) data using IPI2WIN software (2000)

Table 2 Rate of water flow from Ain Mousa springs

Spring name	Rate of flow	
	m³/h	m³/day
Eastern Ain	70	1,680
Western Ain	30	720
Mixed	130	3120

Table 3 Analysis of waters samples from the Ain Mousa area

O¹⁸ (% vs. SMOW)	H² (% vs .SMOW)	C¹⁴
2.39	16.42	900 YBP

SMOW, Standard mean ocean water; YBP, years before present

$$\sigma_b = a\,\sigma_f\varphi^m \tag{1}$$

or

$$1/F = a\,\varphi^m \tag{2}$$

where a and m are parameters that are assumed constants for a certain type of rock, φ is the porosity and F is the formation factor. Equation 1 assumes that surface conduction is negligible when compared with electrolyte conduction. If that is not the case, Eq. 1 has to be modified to include those effects. Sen et al. (1988) proposed an empirical law relating porosity with bulk conductivity,

$$\sigma_b = \varphi^m[\sigma_f + \mu_{DL}\,m_s\,Q_v/(1 + CQ_v/\sigma_f] + EQ_v \tag{3}$$

where Q_v is the clay charge contribution per unit pore volume (expressed in meq/ml), μ_{DL} is the mobility of the

Fig. 10 Structure of the area and the relationship between the VES profiles

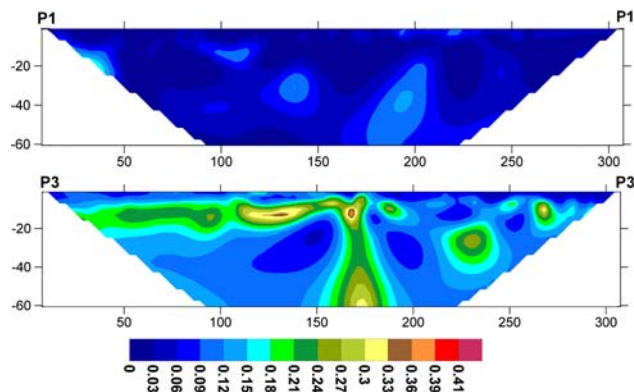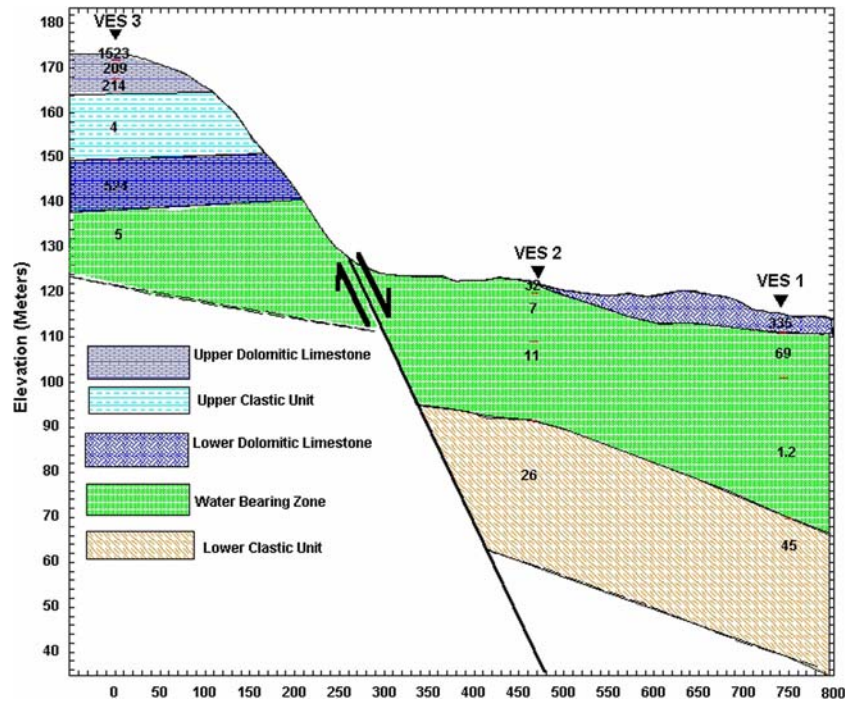**Fig. 11** Two dimensional porosity distributions obtained from the dipole–dipole sections P1–P1′ and P3–P3′ using Sen et al.'s (1988) model

ions and m_s is a surface tortuosity factor. C is a constant that depends on rock geometry and the effective mobility of cations near the surface (Sen et al. 1988). Sen and his co-authors found that their core data fitted well with μ_{DL} $m_s = 1.93 \times m$ Sl/mol, $CQ_v = 0.7$ S, $EQ_v = 0$, $Q_v = 2.04$ and $m = 2$. Thus, these values were adopted in our study. The fluid conductivity was measured at the two sources of Ain Mousa and at the mixing point of the two sources. The results for the eastern, western and mixed sources were 14.5, 8.2 and 12.7 mS/m, respectively. The calculations were carried out for the five dipole sections assuming the conductivity values from the bulk conductivity in Eq. 3.

The results suggest that profiles 1 and 5, carried out perpendicular to the main Wadi direction, have porosity

values ranging from 0 to 20%, while profiles P2, P3 and P4, carried out along the Wadi, have porosities ranging from 0 to 36% (Fig. 11). However, these values should be taken only as a rough estimation as a number of the parameters in Eq. 3 have not been measured.

Discussion and conclusions

The faults crossing the study area are mainly vertical and facilitate both the downward passage of water and, in some cases, upflow from deep aquifers into the Ain Mousa area.

The dipole–dipole resistivity section P1–P1′ (which intercepts fault F3 around coordinate 200 m) shows that the water flowing through the upper dolomitic limestone at the western part of the profile (where low resistivity values are observed) recharges the western Ain Mousa, while the eastern part (exhibiting low resistivity values due to water saturation) is connected with the eastern Ain Mousa recharge.

The upper dolomitic limestone present in the north-western part of Ain Mousa is dry (VES 3), suggesting that the water sources are located in the western and eastern part of the Ain Mousa. The P1–P1′ profile indicates a very low porosity (0–20%) suggesting that the upper limestone unit has only secondary permeability. The low resistivity (high porosity) zone in profile P3–P3' around coordinate 170 m is associated with fault F6.

The thickness of the water-bearing unit increases in sections P2–P2′, P3–P3′ and P4–P4′ where resistivity

values are very low and the porosity is likely to be about 36%. The thickness of the water-bearing unit decreases at section P5–P5′, suggesting that water flow is through the F1/F4 faults.

The results of our hydrochemical and isotope measurements indicate that the water of the Ain Mousa is geologically recent (about 900 YBP) and slightly saline.

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