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ORIGINAL PAPER

Determination of the aquifers geometry in arid zones by using geoelectrical method

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Abstract Water resources in the Algerian South are rare and difficult to reach because they are often too deep. This is the case of Guerrara which is characterized by an annual precipitation average of less than 60 mm. The water supply is warranted from groundwater, frequently too deep and badly known. The main purpose of the present study is to determine the geometry of aquifer from geophysical data. Fourteen vertical electrical soundings covering the total surface area were carried out by using an arrangement of electrodes called "Schlumberger array." The length of the selected transmission line (AB) was 1,000 m, which allowed a vertical investigation reaching up to 160 m of depth. The analysis of the results shows that the prospected zone is characterized by the succession of layers with different electrical resistivities. A sandstone aquifer characterized by resistivities near 100 Ω m overcoming a limestone aquifer stronger with values that exceed 1,000 Ω m, separated by a conductive layer of clay with average resistivity of 15 Ω m. Distribution map of sandstones thickness shows the structural variations of this horizon allowing an estimation of its hydraulic potential.

Keywords Algerian South · Guerrara · Electrical prospecting · Arid zone

Introduction

Water reserves in the Sahara are mainly formed by the northern Sahara aquifers. This vast basin contains a groundwater system composed by two main superposed aquifers: the Intercalary Continental and Terminal Complex (OSS (Observatoire du Sahara et du Sahel) 2002). In the region of Mzab, the boundaries of these two aquifers are badly known and are associated with other aquifer levels. Noting also that the old oases were founded by the exploitation of water from wadis that crossed the region and water routing was done through seguias. These hydraulic structures, traditional and ingenious, allow recharging superficial aquifer under the oasis and irrigation is done as well. These last years have been marked by an overexploitation of the resource, which could jeopardize the existence of Seguias. To enable sustainability for this system, we proceeded a first step to the identification of different aquifer horizons present in the oasis of Guerrara.

Geophysical studies have attempted not only to relate resistivity to the hydraulic properties of the aquifer (Kelly 1977; Mazac et al. 1990; Cassiani and Medina 1997) but also as a means of assessing water quality (Mhamdi et al. 2006; Boughriba et al. 2006; Al-ahmadi and El-Fiky 2009).

The resistivity of the materials is a good indicator and marker of the nature and state of alteration. Thus the electrical prospecting methods have long been used in engineering geology and Geotechnical. These methods, both quantitative and qualitative, are based on the principle of Ohm's law: injecting a current at very low frequency in soil and potential measurement can be reflected back to the true resistivity of traversed formations (Bakkali and Bouyalaoui 2005).

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Geological and hydrological settings

The study area is located in the Algerian south at the Northeast of Ghardaïa between the latitudes 32°30′–33°30′ North and longitudes 4°25′–4°35′ East. It is limited by the wilaya of Djelfa to the North, Ouargla in the East, the daïras of Berrian and Bounora in the West, and the daïras of Zelfana and Al

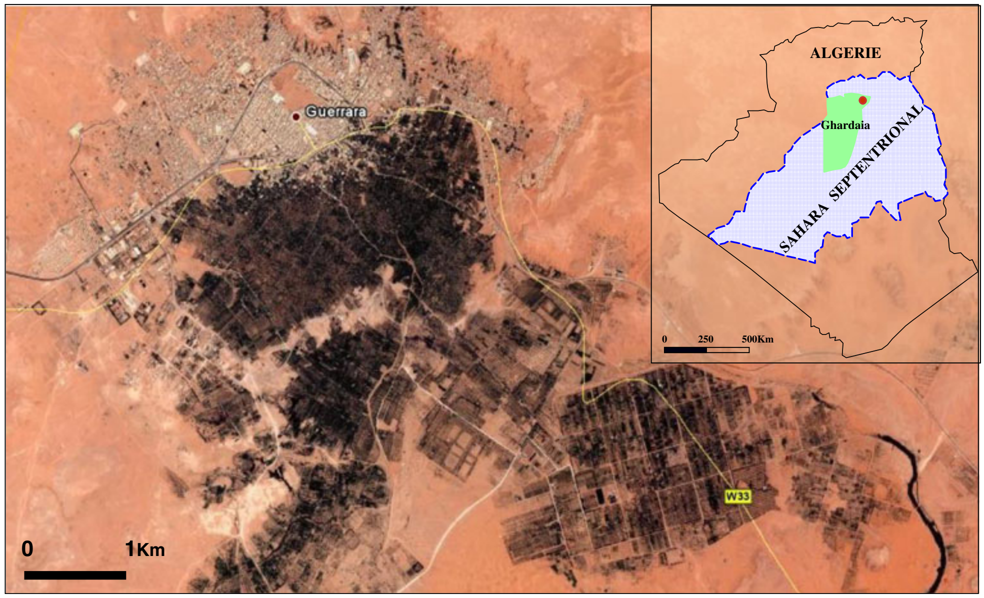

Fig. 1 Geographical location of the study area

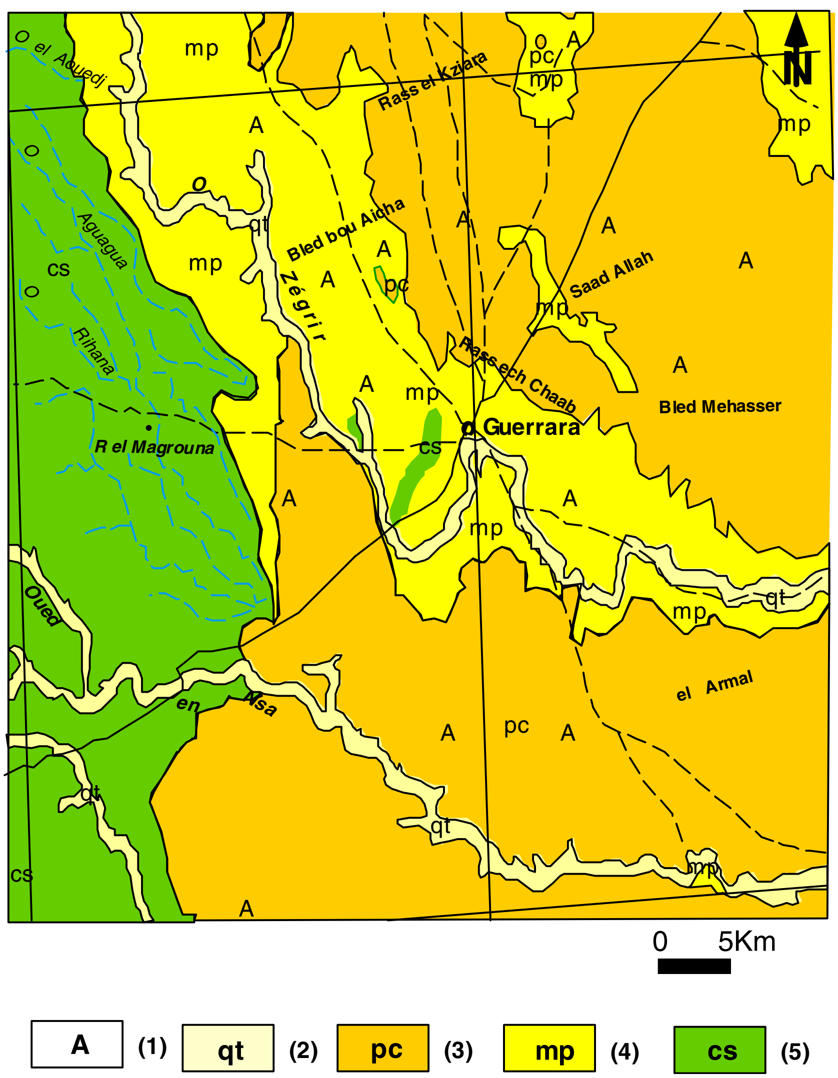

Fig. 2 Extract from geological map of Algeria 1/500000 (S.C.G. (Service de la Carte Géologique) 1952). (*1*) Actual alluvium; (*2*) Quaternary continental: alluvium, regs, terraces; (*3*) Pliocene continental: pudding, lacustrine limestone; (*4*) Pontian (locally equivalent to the Miocene continental); and (*5*) Upper Cretaceous marine

Atteuf in the South (Fig. 1). It extends on an area of more than 2,600 km^2.

Hydrologically, the area is traversed by the Zegrir Wadi which takes its source on the place called Ras Chaab, 152 km to the Northwest of Guerrara. It goes first from Northwest to Southeast up to Guerrara; 8 km of the city, it makes a hook with a right angle towards the Northeast, to move on to the oasis which was installed on the alluvia of the river, then it is diverted again in the Southeast towards el Hadjira (Dubief 1953)

The geological map of the region (Fig. 2) shows the following formations:

In the West appears the Secondary represented by limestone of upper Senonian. In the center, the Miocene formations of the Continental Terminal are consisting of a sand and sandstone alternation. Towards Bled El Mehasser, a breastplate limestone known as "hammada flagstone" forms a thick and very hard plateau and covers the continental terminal. The quaternary appears especially in form of alluvial deposits on the beds of wadi and closed depressions (Dayas).

Water resource is located mainly in two aquifers:

- The Intercalary Continental contained in the formations dates from Albian until the base of Barremian. The aquifer consists of detrital formations: sand, sandstone, clays with a dolomitic passage attributed to Aptien, and its thickness exceeds 500 m (Gautier and Gouskov 1951). The aquifer is surmounted by Cenomanian and Senonian lagoon forming the confining overlying layer.
- The Terminal Complex is a heterogeneous series including carbonated formations of the upper Cretaceous and detrital episodes of the Tertiary, mainly of Miocene (Busson 1970; Fabre 1976).

Finally, an unconfined aquifer overcomes the Terminal Complex is contained in the Quaternary alluvia of the Zegrir Wadi and exclusively recharged by precipitations

Methodology

Electrical methods have been used to identify the nature and the geometry of the aquifer at depths of a few hundred meters. Electrical resistivity expressed in Ω m (or its inverse, conductivity expressed in practice in mS/cm, 1 Ω m corresponds to 10 mS/cm) and is widely used as a relevant parameter for hydrogeological studies. In addition, resistivity values are particularly sensitive to the porosity, the water content, the mineralization of the water and the nature of the rocks (McNeill 1980).

To determine the extent of aquifers, 14 vertical electrical soundings (VES) with a Schlumberger layout are carried out (Fig. 3). The maximum value of emission line AB chosen was 1,000 m, which allowed a vertical investigation reaching up to 160 m in depth.

Recorded resistivities are graphically represented in form of curves of apparent resistivity "ρ_a" according to the

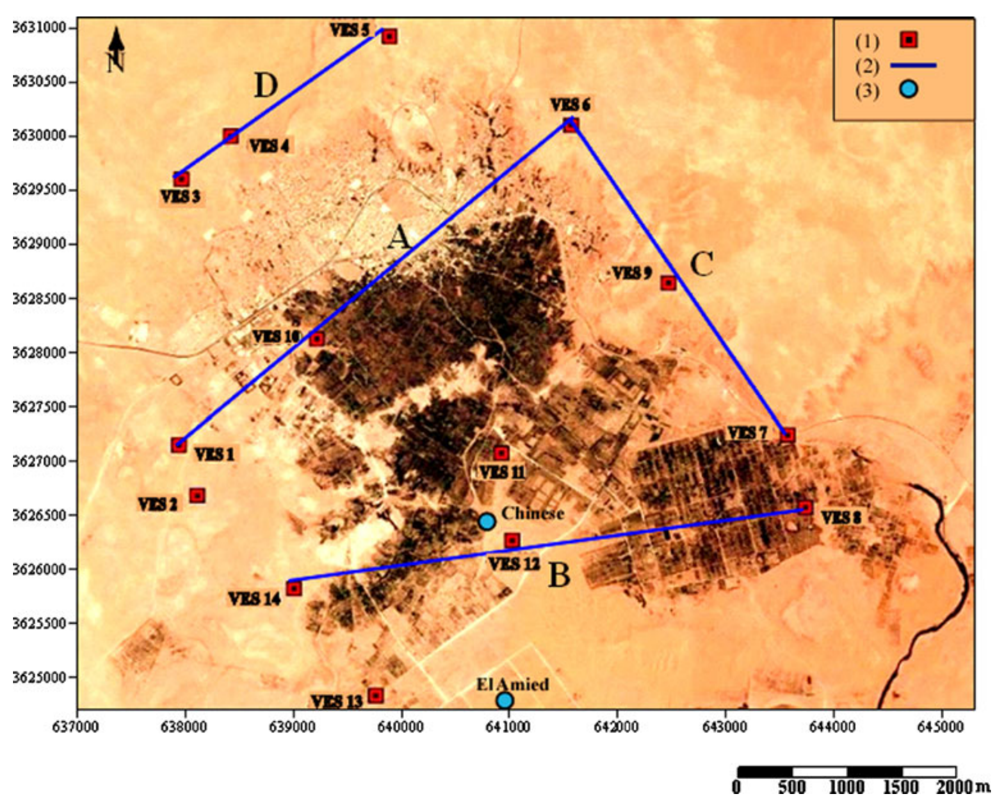

Fig. 3 Location map of vertical electrical soundings (*VES*). (*1*) VES vertical electrical sounding; (*2*) profiles; (*3*) drillings

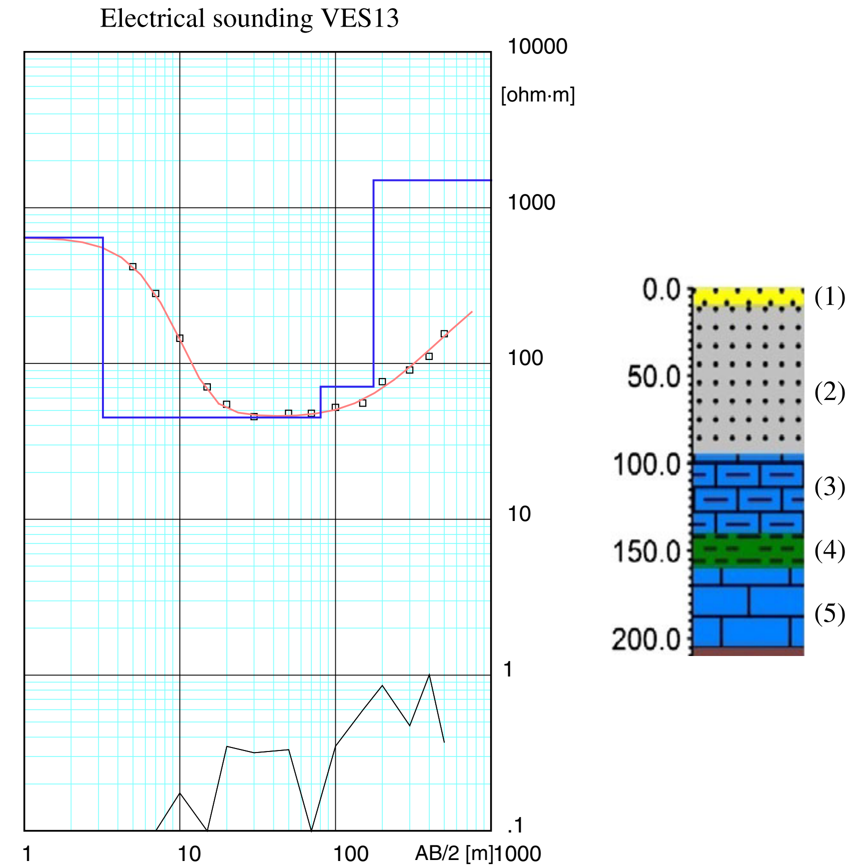

Fig. 4 Calibration of vertical electrical sounding VES 13 by "Guerrara sovietique" drilling. (*1*) Sand; (*2*) friable sandstone; (*3*) white limestone marl; (*4*) marl gray cracked; (*5*) fissured limestone

distances in a bilogarithmic coordinates system ρ_a=f (AB/2). The interpretation was made by using the software WinSev 6 which allows drawing the experimental curves of the surveys and gives two simulations (layered model and smooth model). The objective is to reduce to the maximum difference between the theoretical curve and the experimental one (the value of root mean square must be less than 5%).

Results and discussions

The apparent resistivity is a function of the true layer resistivities, their boundaries, and the location of the electrodes. If the substrata are homogeneous, the apparent resistivity is a good approximation of the true resistivity. The interpreted resistivity in terms of various geological formations is based on a resistivity-depth model that reproduces the observed resistivity from a depth sounding (Asfahani 2007).

The curves of electrical soundings allowed us to distinguish the succession of layers informing about the heterogeneity of the underground. From the comparison between the results of each survey interpretation given by the software and the data of the nearest drilling log, local resistivity scale can be established. The sounding VES13 is taken as example (Fig. 4). Interpretation of the results of this sounding (Table 1) shows a succession of heterogeneous formations which are from bottom to top: limestone, marly limestone, sandstone, and alluvia.

From the results of geoelectric soundings interpretation, correlated with lithological description logs we can set the following resistivity scale presented in Table 2.

A synthetic model shows a succession of layers with contrasted resistivities, composed upwards of:

- A first horizon with very high resistivities values (1,023–1,556 Ω m) representing limestones
- A layer of resistivities between 70 and 376 Ω m characterizing marly limestones
- A conductive level of resistivity oscillating between 4 and 35 Ω m corresponding to clays and sandy clays
- A more resistant horizon with values of 34–297 Ω m, it is about sandstone

Table 1 The results of electrical sounding "VES 13" interpretation

Resistivity (Ω m)	Thickness (m)	Depth (m)	Lithology
642	3.2		Alluvia (sands)
45	77	3.2	Sandstones
71	95	80	Marly limestone
1,492		175	Limestones

Table 2 Scale of local resistivity

Formation	Resistivity (Ω m)	Age
Coarse and dry alluvia	126–642	Quaternary
Sandstones	34–297	Mio-Pliocene
Clay and sandy clay	4–35	Mio-Pliocene
Marly limestone	70–376	Eocene
Limestones	1,023–1,556	Senonien

- A relatively resistant ground, with a resistivity that varies between 126 and 642 Ω m, corresponding to alluvia on the surface

Determination of the extension of the aquifers

To determine the distribution of the water level in space, we have made several resistivity maps. Each of which is related to a given depth, which will give an overview of potential aquifers localization.

Resistivity map AB=100 m, depth=16 m

The observation of the map (Fig. 5) shows a resistivity progressive increase of 20–105 Ω m; this latter value is located at Northwest, reflecting a passage from clays toward the alluvia.

In the South, the resistivity varies between 25 and 65 Ω m; it characterizes sands and sandstone of Mio-Pliocene.

At the level of the central zone and northeast, the resistivity is less than 20 Ω m corresponding to the friable sandstone of Mio-Pliocene outcropping in this part of the study area.

Resistivity map AB=300 m, depth=50 m

The iso-apparent resistivity lines (Fig. 6) indicate the presence of three areas:

- The first in North, one observes a gradual increase of resistivity that varies between 100 and 250 Ω m toward the Western zone. These are limestone formations which according to the cross-sections constructed in the region approach the surface and outcrops at West.
- In the South, resistivity varies between 50 and 160 Ω m. The already drilled wells in the area near the VES 12 and 14, show the following formations: hard sandstone and sandy clay of Mio-Pliocene. One also notes the existence of marly limestone in the lithological description log of the "Chinese" drilling in the neighborhood of the VES 11 where resistivity is over 60 Ω m.
- At the central area, old palm grove, the resistivity do not exceed 50 Ω m, indicating the presence of Mio-Pliocene sandstone.

Resistivity map AB=600 m, depth=100 m

It shows the presence of three areas distributed according to the values of resistivity (Fig. 7):

In the Northwest, at VES3 and VES4, the resistivity values are high, exceeding 300 Ω m, indicating the presence of limestone formations.

From the center to the east, at VES5, VES6, VES7, VES9, and VES10, the resistivities are relatively low, not exceeding 100 Ω m characterizing the marly limestones, indicated by the logs of drillings.

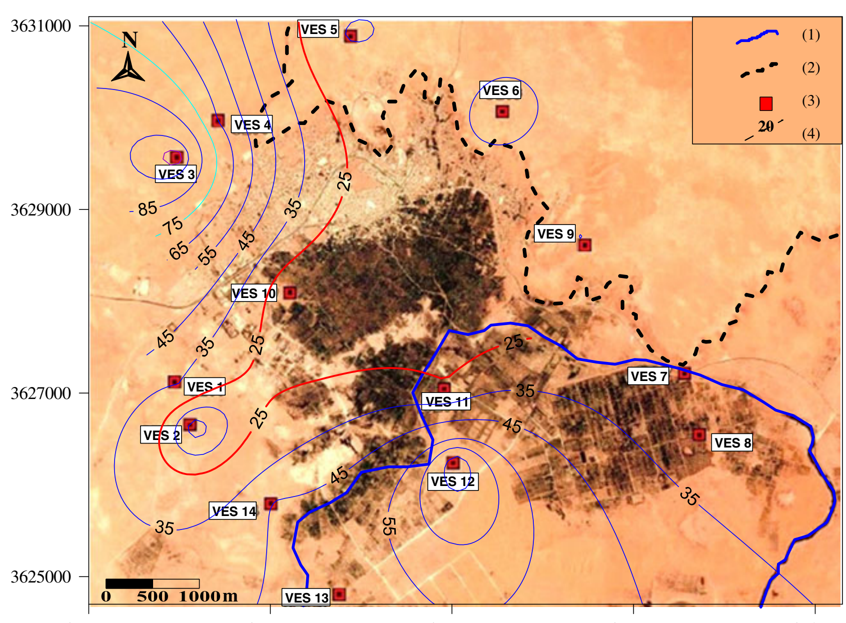

Fig. 5 Apparent resistivity map (AB=100 m). (*1*) Wadi; (*2*) limit of limestone plateau; (*3*) *VES* vertical electrical sounding; (*4*) Iso-resistivity curve

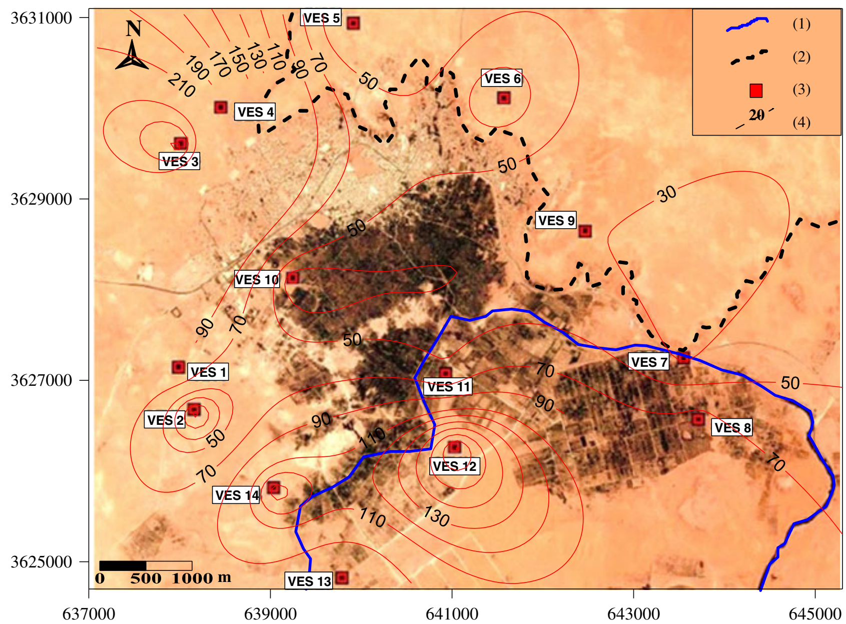

Fig. 6 Apparent resistivity map (AB=300 m). (*1*) Wadi; (*2*) limit of limestone plateau; (*3*) *VES* vertical electrical sounding; (*4*) Iso-resistivity curve

Finally, in the South and Southwest, the resistivity varies between 150 and 260 Ω m, indicating the presence of limestone.

The previous interpretation, combined with stratigraphic data of drillings, allowed the realization of subsurface geoelectrical model. Two sections from different directions are discussed.

Subsurface geoelectrical section along profile B

This section (Fig. 8) shows the following lithological succession: it's a resistant sandstone atop, then below it formations consisting of clay with resistivity that varies between 12 and 24 Ω m, then a more resistant layer from 80 to 108 Ω m characterizing sands. The bedrock of this section consists of limestone which resistivity varies from 1,028 to 1,145 Ω m.

Subsurface geoelectrical section along profile C

The superposition of various horizons (Fig. 9) is noticed: in depth the resistivities vary between 1,023 and 1,142 Ω m, characterizing the limestones, the latter are surmounted by

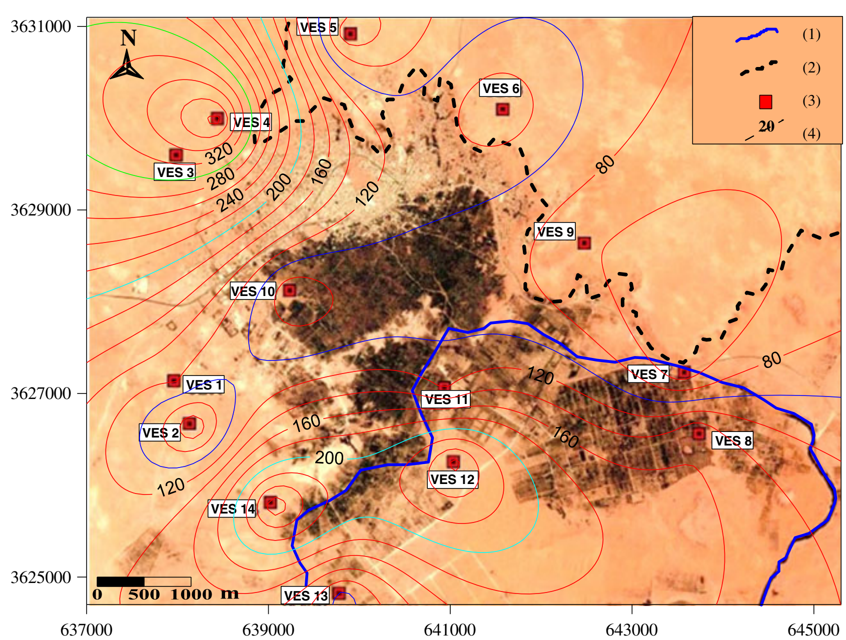

Fig. 7 Apparent resistivity map (AB=600 m). (*1*) Wadi; (*2*) limit of limestone plateau; (*3*) *VES* vertical electrical sounding; (*4*) Iso-resistivity curve

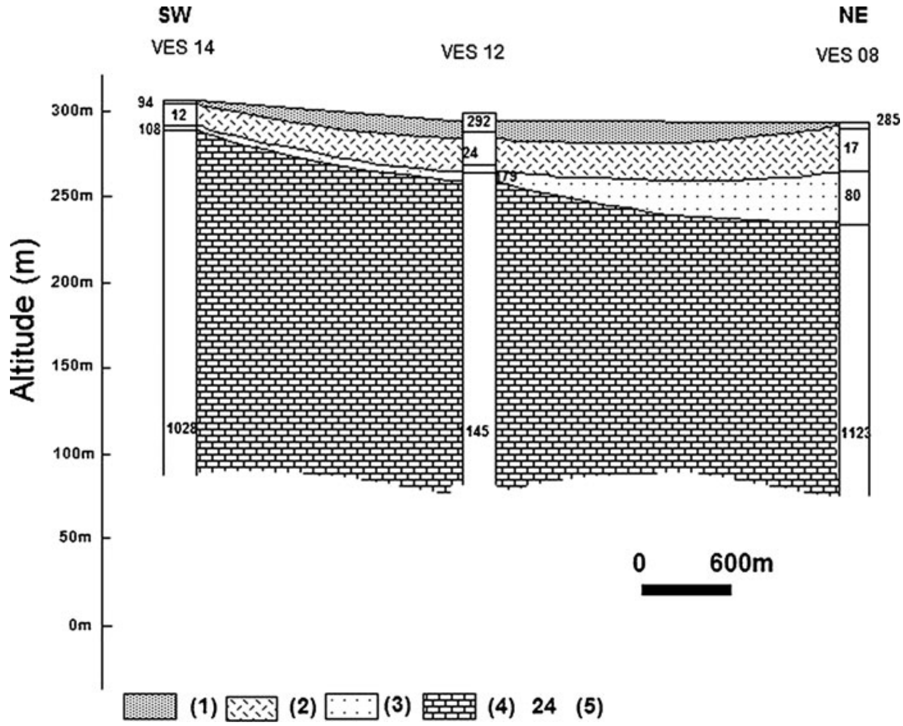

Fig. 8 Subsurface geoelectrical section along profile B. (*1*) Mio-Pliocene sandstone; (*2*) Mio-Pliocene clay; (*3*) Mio-Pliocene sand; (*4*) Senonian limestone; (*5*) Formation resistivity (in Ohm meter)

clays with a resistivity that does not exceed 35 Ω m. However the thickness of this layer of clay decreases and disappears by going toward the Northwest. The sandstones of resistivity that varies between 76 and 92 Ω m, overcome the clays and disappear in a steep slope toward the Southeast. They are replaced by coarse and dry alluvia (295 Ω m). In the Northwest, the sandstones are covered by a layer of clay with low resistivity between 4 and 17 Ω m.

Extension of aquifers

The interpretation results, in particular established geo-electric sections, show a heterogeneity of Mio-Pliocene. It consists of sandstones and sands, clays, marls, and limestones. The sandstones occupy summit position.

These sandstones are the base of the shallow aquifer and present a variable thickness (Fig. 10); the latter is of 15 m

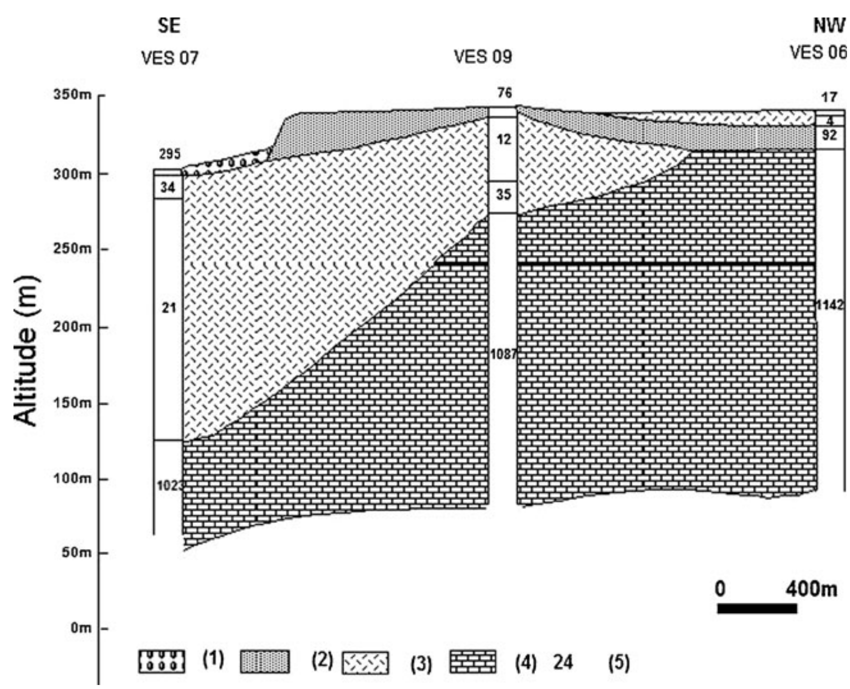

Fig. 9 Subsurface geoelectrical section along profile C. (*1*) Alluvial coarse dry; (*2*) Mio-Pliocene sandstone; (*3*) Mio-Pliocene clay; (*4*) Senonian limestone; (5) formation resistivity (in Ohm meter)

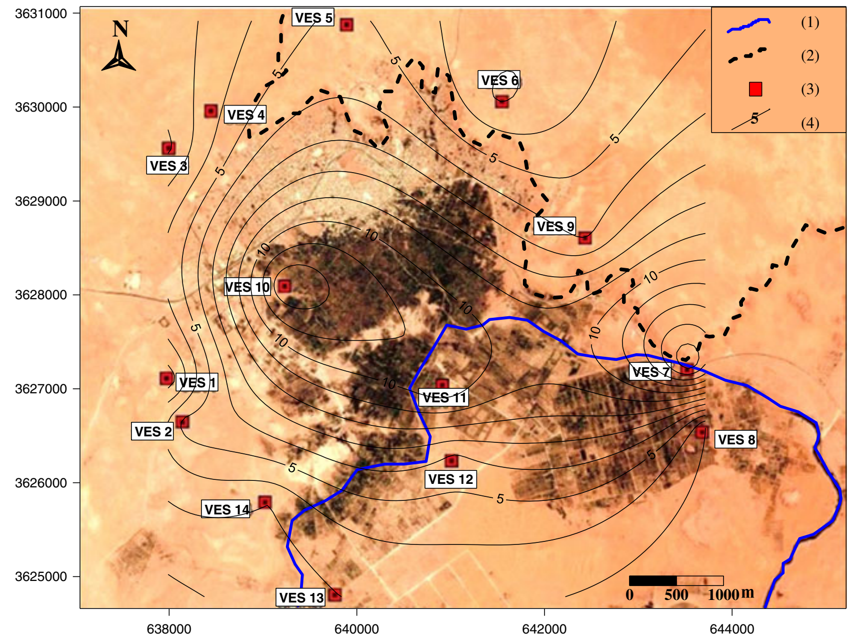

Fig. 10 Iso-thickness map of sandstones. (*1*) Wadi; (*2*) limit of limestone plateau; (*3*) *VES* vertical electrical sounding; (*4*) Iso-thickness curve

(maximum) at the old palm grove (VES10) and Dayat El Amied (VES7). The lowest thickness is located at the North and East of Guerrara confirmed by the vertical electric survey VES6 where the hammadian limestone flagstone forms a plateau that exceeds the oasis of 50 m in altitude.

Note that the thickness of sandstones is related to the shape of the Zegurir Wadi which draws a meander whose center is occupied by the oasis. In this context, the wadi has eroded the tender formations and deposits its contributions at the meanders. Thus, the limestone flagstone constitutes a barrier in this site and the flow of waters becomes low.

The limestones are the second-resistant horizon likely to contain water reserves. Map of the isobaths of this horizon (Fig. 11) shows that the depth of this aquifer top decreases from East to West.

One notices in the Northwestern part of the study area, a depth of limestone lower than 40 m at the vertical electrical soundings: VES1, VES2, VES5, and VES6.

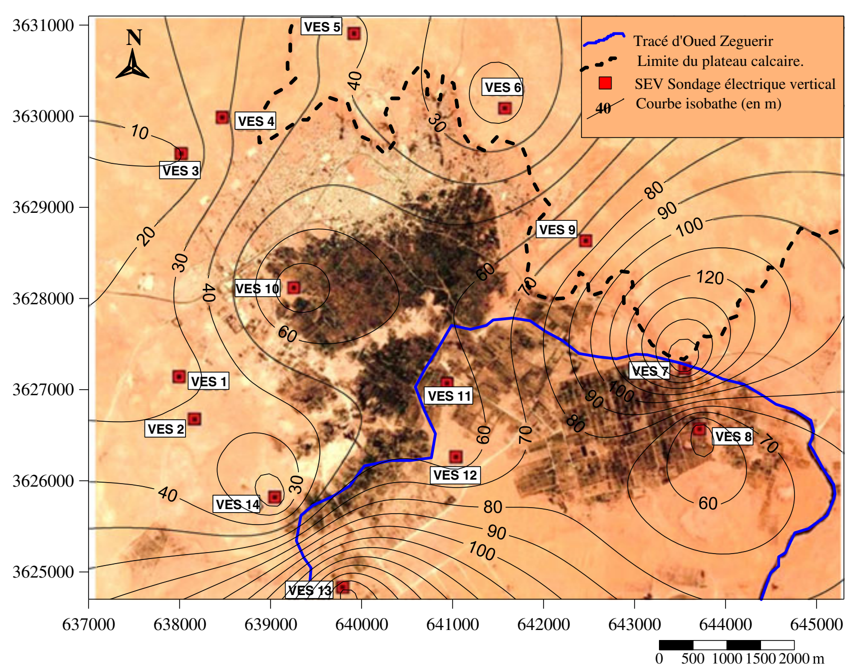

Fig. 11 Iso-bathes map of limestones. (*1*) Wadi; (*2*) limit of limestone plateau; (*3*) *VES* vertical electrical sounding; (*4*) Isobath curve

In the old palm grove, the depth of the limestone formations is between 50 and 70 m (VES10, VES11, and VES12). However, we observe in the new palm grove, in the South and Southeast, a great depth of limestones under the alluvial deposits.

Conclusions

The results achieved by this geophysical prospection show the lithological heterogeneity of the Terminal Complex system in the region of Guerrara. It consists of two main aquifers: the Mio-Pliocene detrital and limestone of Senonian.

The interpretation of electrical soundings allowed the drawing of an isopach map of sandstone. The latter shows that the thickness is variable; it is maximum (15 m) at the old palm grove and Dayat El Amied while it is minimum in the North and the East of Guerrara City. However, the water potentials in this formation remain insignificant.

The limestones are the second horizon which has reserves of good quality water. The isobaths map of this horizon shows that the depth of the roof decreases from East to West. It is less than 40 m to the Northwest and between 50 and 70 m in the old palm grove. However, it is important in the South and the Southeast. That is why one recommends the realization of drilling in the Northwestern zone for the exploitation of Senonian water.

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