*Geofísica Internacional (1997), Vol. 36, Num. 3, pp. 191-200*

# Geophysical investigations of the vadose zone in the Valley of Hermosillo aquifer, Sonora, Mexico

Birgit Steinich[1], Isabel Simón[1], J. Andrés Chavarría[2] and Luis E. Marín[3]
[1] *Instituto de Geología, UNAM, Mexico City, Mexico.*
[2] *Facultad de Ingeniería, UNAM, Mexico City, Mexico.*
[3] *Instituto de Geofísica, UNAM, Mexico City, Mexico.*

Received: February 6, 1997; accepted: April 13, 1997.

## RESUMEN

En el Valle de Hermosillo, Sonora, México, siete sondeos tipo Schlumberger y tres sondeos azimutales fueron realizados con el fin de investigar la zona vadosa del acuífero del Valle de Hermosillo. Este acuífero costero consiste de material aluvial y es considerado como libre en su parte superior. El estudio de los sondeos muestra que los cambios laterales de las resistividades pueden ser interpretados relativos a un 'valor de fondo' de 100 Ωm. Los valores de la resistividad menores de 50 Ωm fueron encontrados cerca de la costa y de los centros urbanos e industriales de Hermosillo y Miguel Alemán. Estos valores relativamente bajos pueden estar reflejando la presencia de agua de mala calidad en los poros por la irrigación con aguas subterráneas afectadas por intrusión salina, con aguas negras no tratadas, y/o con aguas subterráneas contaminadas con aguas negras de procedencia industrial y doméstica. Basado en la Ley de Archie, la porosidad se estimó en un valor aproximado de 25%. Los sondeos azimutales muestran que existe anisotropía de la resistividad en la superficie; sin embargo, ésta disminuye con la profundidad, por lo que se propone que se debe al arreglo de los granos del suelo relacionado con la infiltración del agua de irrigación.

**PALABRAS CLAVE:** Valle de Hermosillo, zona vadosa, sondeos de resistividad, salinización del suelo.

## ABSTRACT

Seven Schlumberger soundings and three azimuthal soundings were conducted in the Valley of Hermosillo, Sonora, northwestern Mexico, in order to investigate the vadose zone above the Valley of Hermosillo aquifer. This coastal aquifer system, which is considered unconfined in its upper part, consists of alluvial material. The resistivity soundings show that lateral changes of the resistivity can be interpreted with respect to a 'background' value of 100 Ωm. Resistivity values less than 50 Ωm were found near the coast and near the population centers Hermosillo and Miguel Alemán. These relatively low values may reveal the presence of low quality pore water due to irrigation with ground water mixed with brackish ground water from sea water intrusions and with untreated sewage, or as a result of pollution by domestic and/or industrial sewage. The porosity of these low resistivity areas was estimated to be on the order of 25 %, based on Archie's law. Azimuthal resistivity surveys show that there is only superficial resistivity anisotropy which may be related to a rearrangement of grains by infiltrated irrigation water.

**KEY WORDS:** Valley of Hermosillo, vadose zone, resistivity measurements, salinisation of the soil.

## INTRODUCTION

The Valley of Hermosillo is in the desert climate zone of northern Mexico. The Valley is located near the Gulf of California coast of the state of Sonora (Figure 1). The landscape is arid and precipitation is scarce. The rainy season lasts from May to October, but during most of the year, evapotranspiration exceeds precipitation.

The vadose zone and the upper part of the aquifer of the Valley of Hermosillo consist of Miocene and younger alluvial material of the delta of the former Sonora river (Figure 1) (Arreguín *et al.* and Figueroa, 1968; Anonymous, 1993; Andrews, 1981). According to these authors, the vadose zone consists of silt, sand and gravels, present in this order, with increasing depth.

The vadose zone above the aquifer suffered substantial changes in the last three decades due to massive ground water extraction from the aquifer beginning in the 1960s (Anonymous, 1993). This was related to the creation of an extensive irrigation district in the Valley of Hermosillo. Due to the local climatic conditions described above, agriculture is completely dependent on irrigation of ground water from the Valley of Hermosillo aquifer, which converted it into an extremely overexploited aquifer. The results of more than thirty years of ground water extraction have been described by several authors (i.e. Andrews, 1981; Anonymous, 1993; Marín *et al.*, 1996). Significant lowering of the ground water level (Anonymous, 1993) and subsequent sea water intrusion from the Gulf of California has occurred (Andrews, 1981; Marín *et al.*, 1996). In addition, the uppermost part suffered an important change in its infiltration dynamics. While infiltration originally occurred only during the rainy season from May to October, irrigation now occurs practically during the whole year, except for a few weeks in the fall when all wells are turned off for maintenance. This aquifer and its related vadose zone have been negatively impacted by this ground water extraction. In addition to the massive cones of depression that increase the volume of the vadose zone, fertilizers and pesticides are used regularly. The untreated sewage of the City of Her–

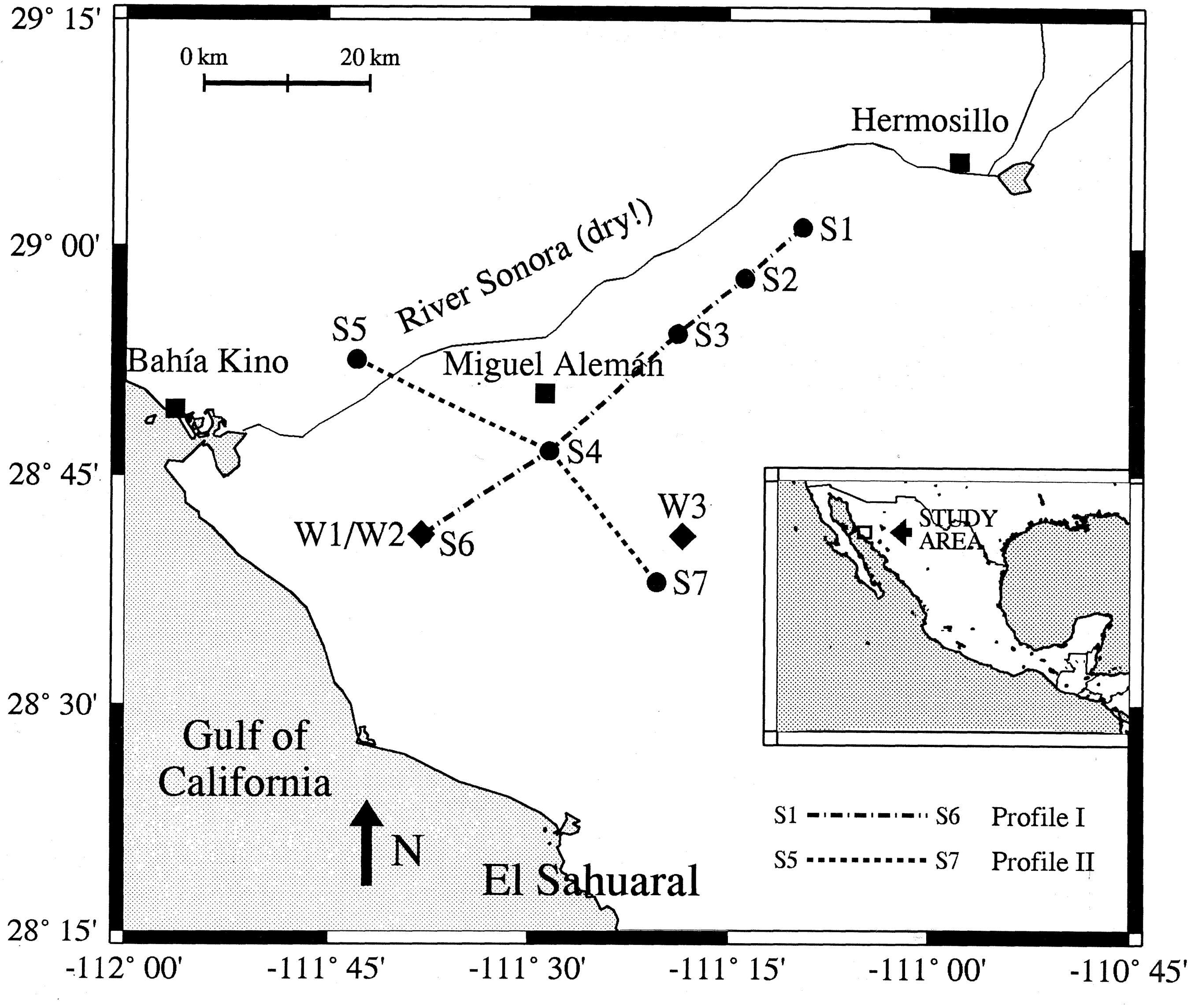

Fig. 1. Overview of the study area. The seven Schlumberger-type vertical electric soundings are marked S1 to S7. The Wenner type azimuthal measurements are labelled W1 to W3. W1 and W2 were made at the same site with different spacings.

mosillo is used for irrigation. Marín *et al.* (1996) have reported a background level of $NO_3^-$ of 4.5 ppm in the aquifer. Due to the absence of surface water, the drinking water supply of the area south of Hermosillo depends entirely on ground water from the Valley of Hermosillo aquifer.

The unsaturated zone may serve as a buffer between anthropogenic activities and the underlying aquifers. Contaminants produced at the surface travel through this zone before entering the aquifers. The nature and hydrogeology of the vadose zone may delay the percolation of contaminants, which may accumulate in the vadose zone. Salt water intrusion contributes indirectly to this accumulation because irrigation water is pumped from local wells and infiltrates the vadose zone without treatment. As a consequence of this practice, the salinity of the soil has increased to a point where extensive areas near the coast have been abandoned.

The upper part of the Valley of Hermosillo aquifer is unconfined. Thus changes in the hydrogeological regime impact on the vadose zone, as does the accumulation of inorganic contaminants due to agricultural activities. A study of the vadose zone may provide information on the ongoing deterioration process of the Valley of Hermosillo aquifer. Numerous monitoring activities have been undertaken, including the analysis of water samples and the application of geoelectrical methods, to better understand this complex hydrogeological regime. Some results from the latter study are presented here. Geoelectrical soundings can be especially useful in the study of processes in the vadose zone, since moisture content and accumulation of inorganic contaminants modify the resistivity of the soil. We study lateral variations in the resistivity of the vadose zone in the aquifer of the Valley of Hermosillo, in order to estimate the porosity and the quality of the pore water of the vadose zone and to determine an eventual resistivity anisotropy in the vadose zone.

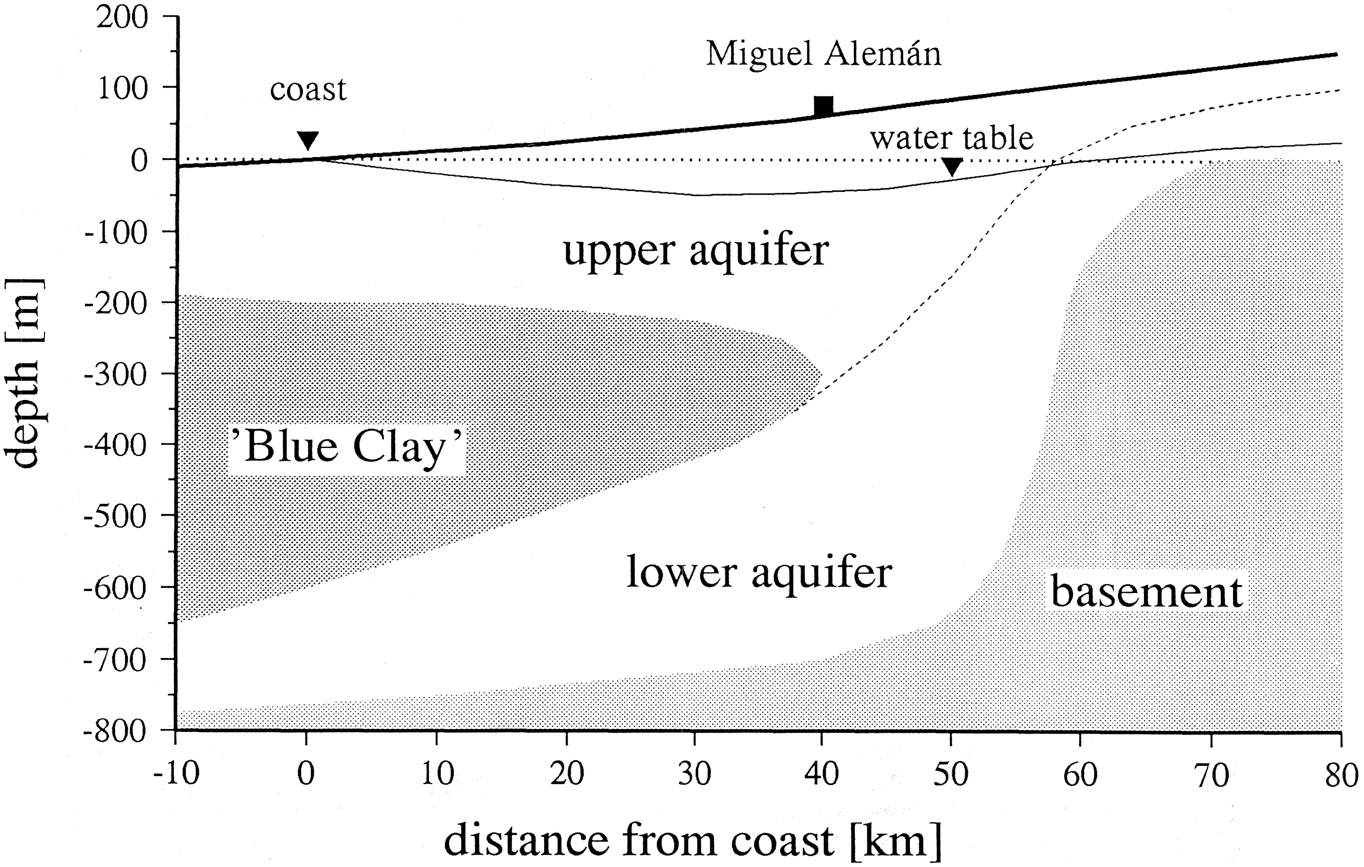

Fig. 2. Hydrogeological profile of the Valley of Hermosillo aquifer. The profile has a northeast-southwest trend (compare Fig. 4). The dashed line represents the limit between the lower and upper aquifer units. Mean sea level is shown as a dotted line. The solid line is the water table. Note the drawdown cone with maximum depth near Miguel Alemán.

## DESCRIPTION OF THE STUDY AREA

The Valley of Hermosillo is located in the state of Sonora, northwestern Mexico (Figure 1). It consists of an area between 110°45' and 112°00' west and 28°15' and 29°15' north. The City of Hermosillo is in the northeastern part of this valley, which terminates at the Gulf of California to the southwest. On the coast line, the area is limited by Bahia Kino on its northwestern section and by 'El Sahuaral' in the southeast (Figure 1). The valley measures about 100 km in length and is only a few kilometers wide near Hermosillo. It fans out to a maximum width of 80 km along the coast. Altitudes range from a few meters above mean sea level (msl) near the coast and rise towards Hermosillo, which is between 200 m and 250 m above msl (Anonymous, 1987).

## METHODOLOGY

Ten resistivity measurements were conducted in December, 1995. Seven Schlumberger soundings are shown in Figure 1, marked S1 to S7. Maximum AB/2 spacings ranged between 315 m and 675 m. Three Wenner-type azimuthal measurements were conducted in two locations. Wenner azimuthal surveys W1 and W2 were conducted at the same site as the Schlumberger S6 sounding. The Wenner spacings were a = 40 m (W1), a = 20 m (W2), and a = 40 m (W3). All measurements were made with a SYSCAL R1 resistivity meter. Locations were determined with a GPS Garmin 50. Schlumberger soundings were interpreted using a FORTRAN code written by the senior author, based on digital linear filter theory (Koefoed, 1979). Figures 1, 2, 4 and 5 were generated with the Generic Mapping Tool (GMT) version 3 (Wessel and Smith, 1995).

## HYDROGEOLOGICAL SETTINGS

The coastal aquifer system of the Valley of Hermosillo consists of two interconnected aquifers (Figure 2). The upper aquifer contains silt, sand and gravel from Miocene to Recent and is approximately 200 m thick. Silt is predominant in the upper 100 m and sand and gravel in the lower part (Andrews, 1981; Anonymous, 1993). The upper aquifer has been classified as unconfined.

A thick marine clay, the so-called blue clay (Arreguín *et al.*, 1968), underlies this aquifer with a thickness of 400 m near the coast; it pinches out towards the northeast. About 40 km from the coast, e.g. near the town of Miguel Alemán (Figures 1 and 2), the blue clay layer disappears.

The blue clay layer acts as an aquitard which separates the upper aquifer from the lower one (Arreguín *et al.*, 1968). The lower aquifer contains Late Mesozoic clastics and volcanics, and Early Tertiary intrusives and rhyolite flows (Anonymous, 1993; Andrews, 1981; Arreguín *et al.*, 1968). Both aquifers merge where the blue clay aquitard disappears, forming a single unconfined aquifer in the northeastern part of the study area (Figure 2).

The study area has an arid climate which is characterized by the lack of water. Agriculture in the study area is only possible based on irrigation of water extracted from the upper aquifer (Anonymous, 1993). The lower aquifer is unsuitable for irrigation because of its high contents of sulfur and its hydrothermal characteristics (Arreguin and Figueroa, 1968). There has been practically no surface water in the area since the construction of the 'Abelardo L. Rodríguez' dam in 1948, east of Hermosillo. The water of the Sonora River is now dammed up in the reservoir which is used as a water supply source to the City of Hermosillo.

The recharge of the aquifer system is by horizontal flow entering the aquifer north and northeast of Hermosillo, and by vertical flow rising from the lower into the upper aquifer (Arreguín *et al.*, 1968). There is no contribution from runoff of the Sonora River since the construction of the dam. The vertical recharge from the lower aquifer across the blue clay layer was estimated at approximately 271 million $m^3$ per year (Arreguín *et al.*, 1968). The total recharge for the Valley of Hermosillo aquifer can be quantified at 350 million $m^3$ per year (Arreguín *et al.*, 1968; Anonymous, 1993).

The Valley of Hermosillo has an area of 2833 $km^2$; it contains 498 water supply wells which extract 566 million $m^3$ of water per year, over 90% of which is used for irrigation (Anonymous, 1993). Pumping exceeds recharge by 216 million $m^3$. The water table has dropped up to 40 m in the last four decades (Anonymous, 1993).

## GEOPHYSICAL RESULTS AND DISCUSSION

The vadose zone above the aquifer of the Valley of Hermosillo contains two different units. The first unit consists of the same material as the upper aquifer and is present throughout the whole study area. Its thickness decays with distance from the coast (Figure 2). The vadose zone consists entirely of this material between the coast and up to approximately 55 km inland. Between 55 km and 80 km inland the vadose zone is composed of two units. The upper unit is the upper aquifer material described above. The lower unit consists of Late Mesozoic clastics and volcanics and Early Tertiary intrusives and rhyolites as in the lower aquifer. While the upper part can be considered as a granular medium, the lower part may be described as a fractured medium. The thickness of the vadose zone increases with distance from the coast; yet the aquifer thickness in the northeastern part is reduced significantly due to the granitic basement, which is found less than 150 m below the surface. Recharge of the aquifer by lateral flow is through this thin saturated zone.

The vadose zone has suffered significant changes in the last three decades due to over-exploitation of the aquifer. Anonymous (1993) described the rate of lowering of the water table in the two decades between 1965 and 1987. The drop was as large as 40 m southeast of Miguel Alemán. Figure 2 shows a profile of the drawdown cone, with maximum depth near Miguel Alemán. The increase in volume of the vadose zone is mainly in the first unit; i.e. it affects the granular part of the vadose zone.

### Lateral changes in resistivity

Lateral changes in resistivity of the vadose zone of the Valley of Hermosillo aquifer may be due to changes in lithology and/or to changes in quantity and quality of the pore water. The latter may be a result of the concentration of solids related to evaporation and/or to the accumulation of secondary materials such as inorganic contaminants, from infiltration by irrigation water. The former may be assumed to occur nearly uniformly over the whole study area, while the latter may depend on local irrigation practices and on the quality of irrigation water from local wells.

Figure 3 shows the data and the respective resistivity models for two sites. The models of all soundings are presented as Profiles I and II (Figures 4 and 5, respectively). Figure 4 shows the NE-SW resistivity Profile I, made up of five resistivity soundings (S1 to S4, S6). Sounding S6 traverses the upper aquifer into the 'Blue Clay' lens, while S1 and S2 reach the basement. Resistivities interpreted from the five soundings of Profile I suggest that a value of approximately 100 Ωm may be representative for the vadose zone. The model of the sounding S3 shows highly conductive layer, which may be interpreted as a small clay lens. Note that there is no evidence of this layer in the neighboring survey S2.

A comparison of surveys S1 to S3 shows resistivity values of 100 Ωm for S3 and S2, except for the local resistivity minimum interpreted as a small clay lens. The resistivity in survey S1 is significantly lower, having a value of 50 Ωm. The same feature can be observed in the second unit of the vadose zone, related to the lower aquifer. The interpreted resistivity values are 70 Ωm in survey S2 and 8 Ωm in survey S1. Resistivity values for the saturated zone follow the same trend, being 20 Ωm in the case of S2 and 1.2 Ωm in the case of S1.

Untreated sewage water is used for irrigation near the City of Hermosillo, which may result in an increased concentration of dissolved solids accumulated in the soil. This interpretation agrees with the observation of an increasing resistivity of the soil with increasing distance from Hermosillo.

Comparing soundings S2 to S4, a parallel decrease in resistivity of the vadose zone can be observed. With the

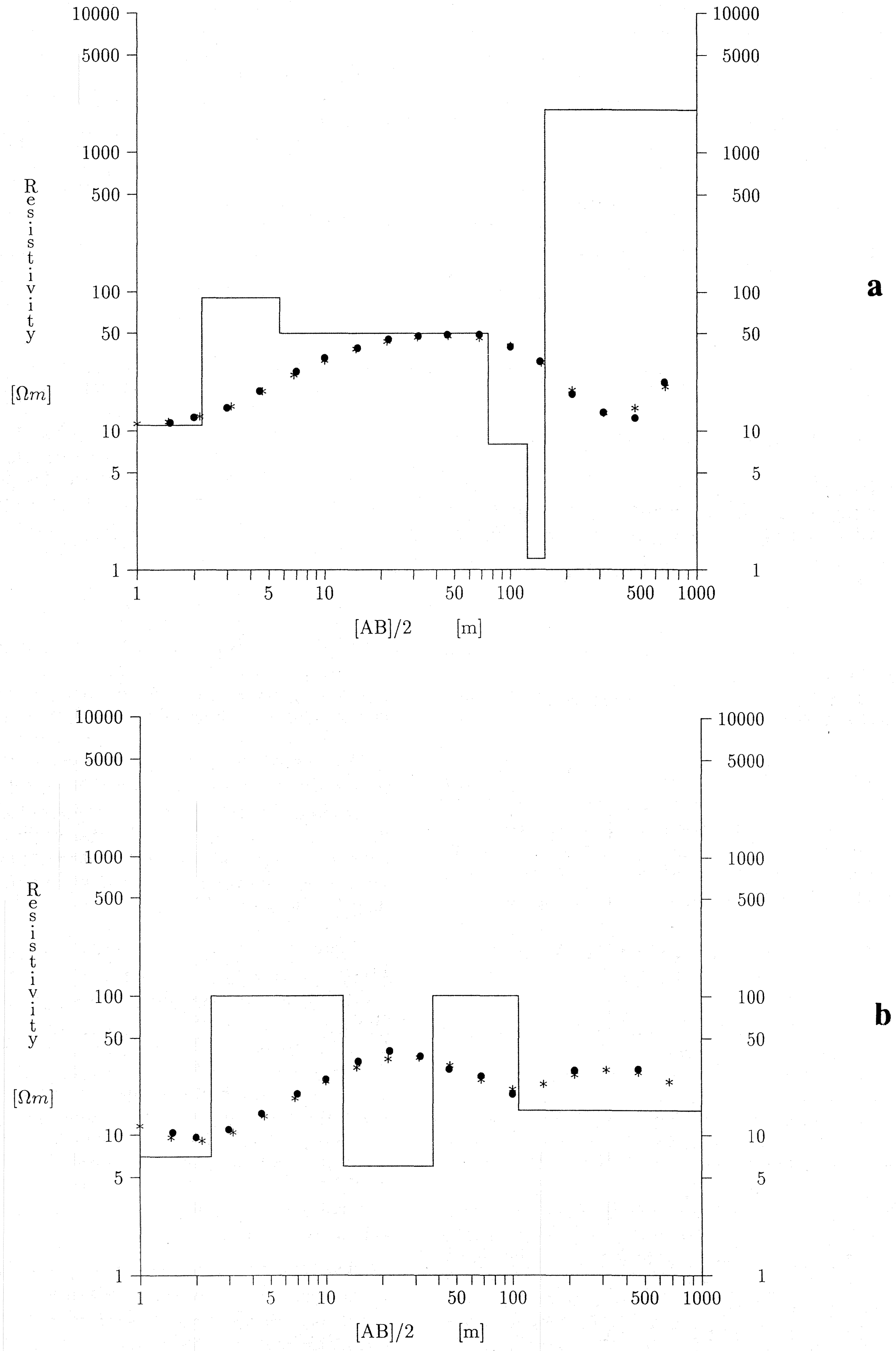

Fig. 3. Data and resistivity models of two soundings S1 (Fig. 3a) and S3 (Fig. 3b). Field data is represented as solid circles (•) and apparent resistivities of the model curve as asterisks (*). The solid line represents the resistivity model.

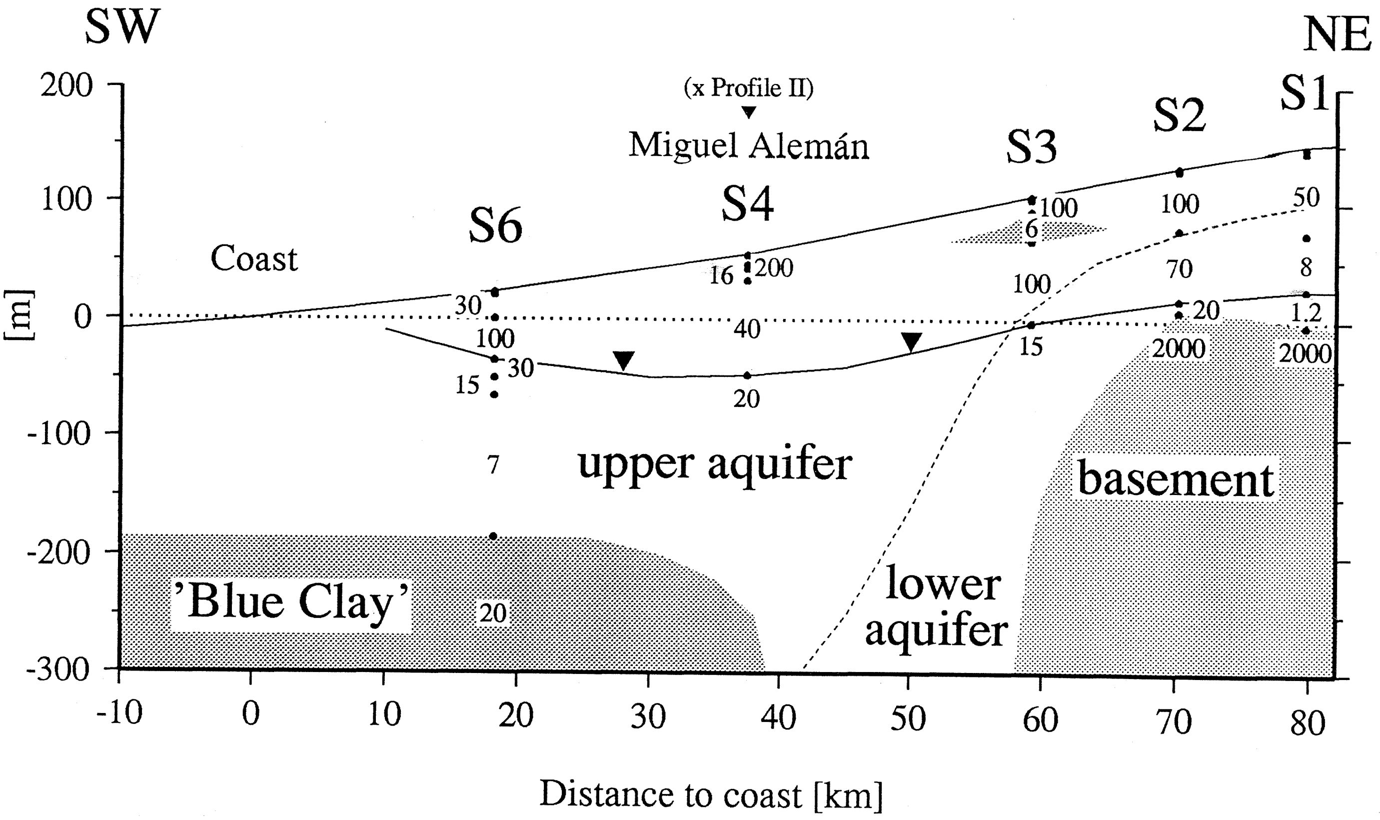

Fig. 4. Profile I: northeast-southwest resistivity profile, showing five resistivity models for S1 to S4 and S6. Resistivities are in [Ωm]. The dashed line represents the limit between the lower and upper aquifer units. Mean sea level is shown as a dotted line.

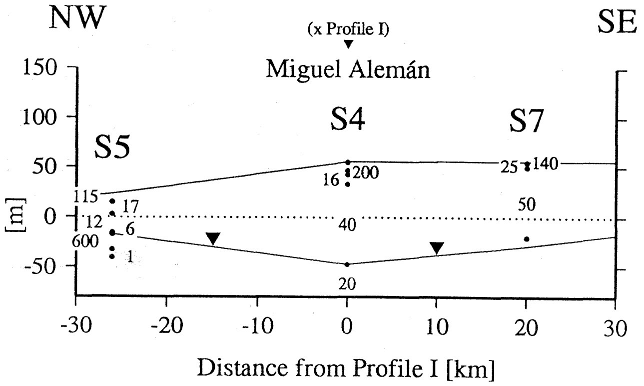

Fig. 5. Profile II: northwest-southeast resistivity profile, showing the three resistivity models S4, S5 and S7. Resistivities in [Ωm]. Mean sea level is shown as a dotted line.

exception of a small layer with a resistivity of 200 Ωm, the rest of the vadose zone has resistivity values of 16 and 40 Ωm. The town of Miguel Alemán is the major industrial area between Hermosillo and the coast; it has a high population density. Domestic and industrial sewage enters the vadose zone without treatment. The depression cone is centered beneath Miguel Alemán and the related hydraulic gradients may contribute to the accumulation of inorganic contaminants in this zone. Both phenomena may contribute to the low resistivity values observed in survey S4.

The model of survey S6 shows a low resistivity value of 30 Ωm followed by the 'background' value of 100 Ωm. The ground water from local wells is affected by sea water intrusion in this area (Marín *et al.*, 1996), and irrigation with this water enhances the salinisation of the soil. We propose that the low resistivity of the upper part of the vadose zone may reflect these features.

Figure 5 shows the NW-SE Profile II, which intersects Profile I at point S4 (Figure 1). Resistivity values for the vadose zone of the three soundings S5, S4, and S7 are generally low in comparison with those in the northern part of the study area (S2 and S3 of Profile I, Figure 4). They are as low as 6 to 17 Ωm under S5 and 25 to 40 Ωm under S7. We suggest that these relatively low values are due to irrigation with brackish ground water from local wells, as in the case of S6. The Bahía Kino segment as well as El Sahuaral are both affected by sea water intrusion (Andrews, 1981), and the ground water from local wells is used for irrigation and has high contents of total dissolved solids (Marín *et al.*, 1996).

The NE-SW profile (Figure 4) shows that resistivities in the same hydrogeological unit of the vadose zone decrease beneath the major population centers (Hermosillo and Miguel Alemán) and toward the coast. The lowering of the resistivity of the soil may be related to the accumulation of ions from secondary materials such as inorganic contaminants and sea water. This interpretation will be taken into account when estimating the porosity and the quality of the pore water of the vadose zone in the next section.

## Estimation of the porosity and the quality of the pore water of the vadose zone

Archie's law can be used to estimate the porosity of porous and saturated media. As the degree of saturation decreases, the formation factor and the porosity will increase. Pore space formerly containing water will be replaced by air decreasing the area of water available to transport electrical current (Gorman and Kelly, 1990). Keller and Frischknecht (1966) propose that the variation of formation factor with respect to saturation is described by the equation

$$F = \frac{\rho_s}{\rho_p} = a \cdot \Phi^{-m} \cdot S^{-l} \quad , \qquad (1)$$

where F is the formation factor, $\rho_s$ and $\rho_p$ are the resistivities of the soil and the pore water, respectively, $\Phi$ is the porosity and S is the saturation index. The other coefficients in the equation are constants which depend on the media: *a* depends on the internal geometry of the porous medium (Pérez-Rosales, 1983), Asquith and Gibson (1982) related it to the tortuosity of the medium. Gorman and Kelly (1990) presented values of *a* as a function of these characteristics. The value $a$=2.15 was chosen in this study.

Gorman and Kelly (1990) calculated values of $l$ for different sands and found values ranging between 1.42 and 1.58, the latter being representative for finer sands. We chose $l$ = 1.58 value in the following estimation.

The coefficient *m* might depend on the fractality of the pore space and can therefore be related to the fractal dimension D as follows (Katz and Thompson, 1985; Korvin, 1992; Wong *et al.*, 1984):

$$m \approx (D-1)/(2*(3-D)) \quad . \qquad (2)$$

On the other hand, Krohn (1988) studied fractal distributions of different sands. He proposed a value of 2.75 for the fractal dimension D of an Arizona sand. This value was used here to estimate the coefficient *m*, which is approximately 3.5.

For the purposes of the estimation of the porosity in this study, we assumed that the vadose zone was free of clay minerals and that the size and shape of the fine quartz silica sand grains were fairly homogeneous throughout the study area. Since untreated ground water from local wells is used for irrigation in most of the study area, the resistivity of the pore filling water was taken from Marín *et al.* (1996) who obtained resistivity values of water samples from 70 water supply wells in the study area. A value of 100 Ωm may be assumed to be representative of the resistivity of the soil. For the two soundings S2 and S3, porosity was estimated using this value. Three different values for saturation were used: 10%, 15% and 20%. Table 1 (upper section) shows the results of this estimation. Estimated values of porosity are printed in boldface as are the values of estimated water resistivity. The estimated porosity varies between 20.9% and 29.8%, depending on the saturation and the resistivity of the pore water.

### Table 1

Estimation of the porosity and pore water resistivity

| VES | Resistivity (rock) [Ωm] | Resistivity (water) [Ωm] | Saturation [%] | Porosity [%] |
|---|---|---|---|---|
| S2 | 100 | 21.9 | 10 | **28.5** |
| S2 | 100 | 21.9 | 15 | **23.7** |
| S2 | 100 | 21.9 | 20 | **20.9** |
| S3 | 100 | 25.5 | 10 | **29.8** |
| S3 | 100 | 25.5 | 15 | **24.8** |
| S3 | 100 | 25.5 | 20 | **21.8** |
| S1 | 50 | **11.9** | 15 | 24.3 |
| S4 | 16 | **3.8** | 15 | 24.3 |
| S4 | 40 | **9.5** | 15 | 24.3 |
| S5 | 6 | **1.4** | 15 | 24.3 |
| S5 | 17 | **4.0** | 15 | 24.3 |
| S6 | 30 | **7.1** | 15 | 24.3 |
| S7 | 25 | **5.9** | 15 | 24.3 |
| S7 | 50 | **11.9** | 15 | 24.3 |

We proposed above that low resistivity values in the upper part of the vadose zone could be due to irrigation with ground water mixed with sea water. An estimation of the pore water resistivity was made for S6, using a saturation of 15% and a porosity of 24.3%, averaged from the respective values of the S2 and S3 porosity estimation. The lower part of Table 1 shows that a value of 7.1 Ωm resulted from this estimates. Comparing this result with the resistivity model of S6 (Figure 4) it is found that this value is of the same order of the resistivity of the saturated part of the aquifer from where the irrigation water was taken. Pore water resistivity values for S5 are between 1.4 and 4.0 Ωm, and between 5.9 and 11.9 Ωm for S7. A similar estimation of pore water resistivity was made for the two other cases discussed above, S1 and S4. The estimations for the pore water resistivity have values between 3.8 and 11.9 Ωm.

In conclusion, local lowering of the resistivity of the soil in the vadose zone may be related to abnormally low pore water resistivity due to the presence of low-quality water (high TDS) in the pores. Such low-quality pore water may originate from contamination by irrigation with untreated sewage (as in Hermosillo and Miguel Alemán), or by irrigation with ground water mixed with brackish ground water from sea water intrusions as in the coastal area.

## Anisotropy of the vadose zone

Figure 6 shows the resistivity curves of the three azimuthal measurements. W1 and W2 are shown in the same

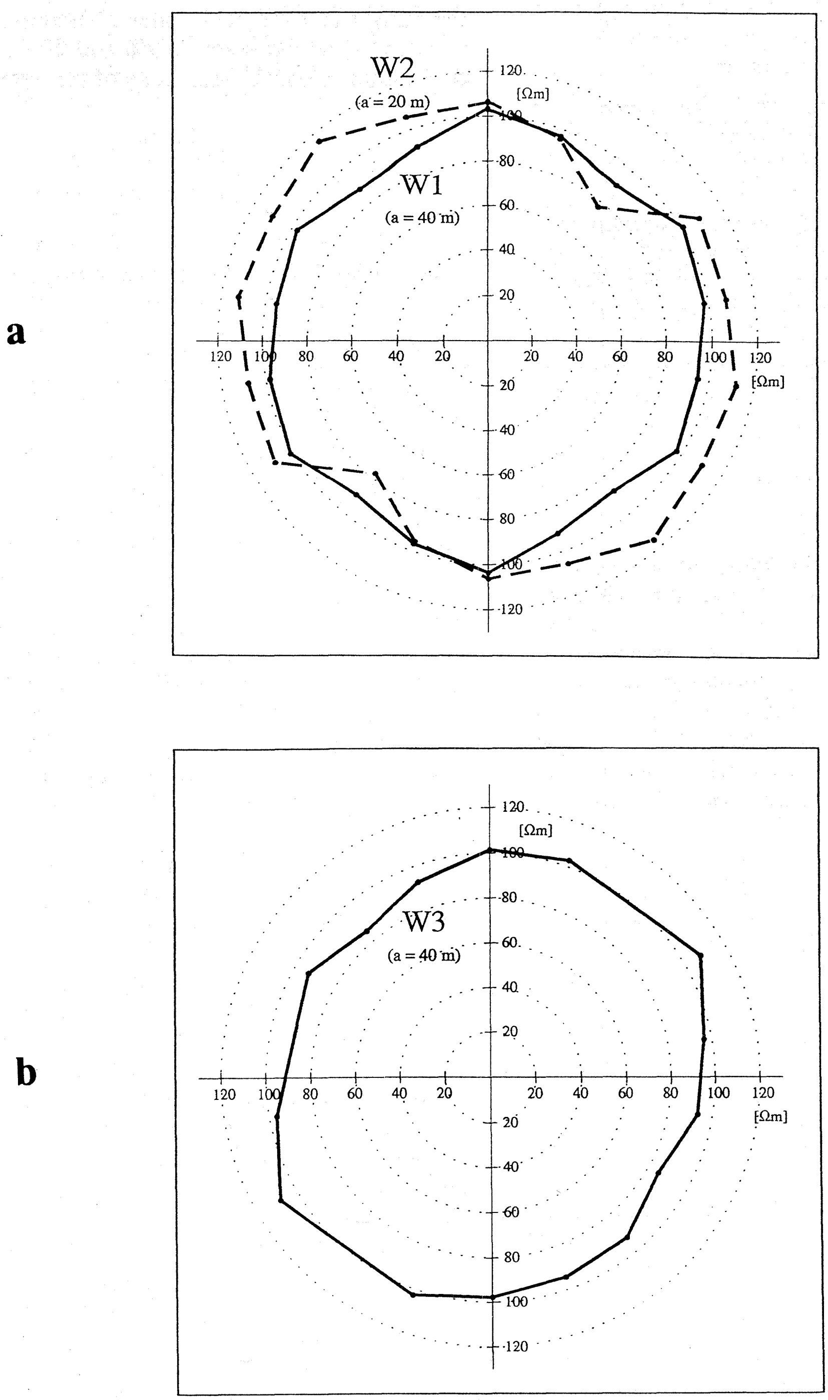

Fig. 6. Anisotropy curves of three azimuthal measurements. (a) Curves of W1 (solid line) and W2 (dashed line) are shown in the same plot since they were conducted in the same site with different spacings. (b) Curve of azimuthal measurement W3.

plot (Figure 6a), since they were obtained at the same site with different spacings, while W3 is shown in Figure 6b. A comparison of W1 and W2 shows that some electrical anisotropy can be detected in the smaller-spaced azimuthal measurement W2, while the wider-spaced measurement at W1 shows less anisotropy. Let $\lambda$ be the ratio between the largest and smallest apparent resistivity measured for each survey:

$$\lambda = \frac{\rho_a(max)}{\rho_a(min)} \quad . \tag{3}$$

Thus $\lambda$ is an index characterizing the eccentricity of the curve with respect to a circle, which would be expected for an isotropic medium and for which the value of $\lambda$ would be unity.

For W1 and W2 the values of λ are 1.18 and 1.49, respectively. Since the spacing *a* = *AB*/3 is representative of the depth of investigation, this data suggests that anisotropy is present in the upper part of the vadose zone and that it decreases with depth. The media where these measurements where conducted are poorly consolidated sands which, in principle, show no preferential direction. We suggest that observed superficial anisotropy may be due to rearrangement by infiltrated irrigation water. This implies that the vadose zone above the aquifer in this area may be described as isotropic with respect to its hydraulic conductivity except for superficial anomalies as a consequence of infiltration of irrigation water. This is reflected in the values of λ mentioned above. Azimuthal measurement W3 has a λ of 1.27 showing a somewhat higher eccentricity with respect to W1, which used the same spacing of 40 m. Other studies (Steinich and Marín, in press) show that the electrical anisotropy of the medium may be related to the local hydraulic gradient. At azimuthal survey site W1/W2, the depth to the water table is approximately 60m, while at site W3 it is 85m (Anonymous, 1987). Figure 7 shows synthetic resistivity curves for a Wenner array with the same resistivity model interpreted from S6 (filled circles and solid line), and with the same model truncated above the water table (open diamonds and dashed line). Comparison with these synthetic resistivity curves show that for a spacing of up to *a* = *AB*/3=40m, the same apparent resistivity would be measured with a Wenner array. In other words, the depth of penetration of W1 and W2 is less than the depth to the water table. A similar result can be obtained for the case of W3, if compared with the model of the nearby sounding S7.This seems to reject a possible relationship between the local hydraulic gradient and the orientation of electrical anisotropy in this case.

## CONCLUSIONS

The upper part of the coastal aquifer system of the Valley of Hermosillo and its vadose zone consist of alluvial material. This part of the aquifer is considered unconfined. Due to the intensive farming and the related over-exploitation of the aquifer, the vadose zone has suffered a substantial increase in its volume and considerable inorganic contamination over the last three decades.

Seven vertical resistivity soundings and three azimuthal resistivity surveys were conducted in the Valley of Hermosillo. Resistivity models showed that 100 Ωm may be regarded as a 'background' value of the resistivity of the vadose zone. Lower resistivity values are found for soundings near the coast and near the population centers of Hermosillo and Miguel Alemán. Thus lateral changes of resistivity values with respect to the background value may be related to deterioration of the quality of the pore water as a result of concentration of secondary material such as inorganic contaminants or sea salt. The former enter the vadose zone as domestic and/or industrial sewage from the major population centers and the latter by irrigation with

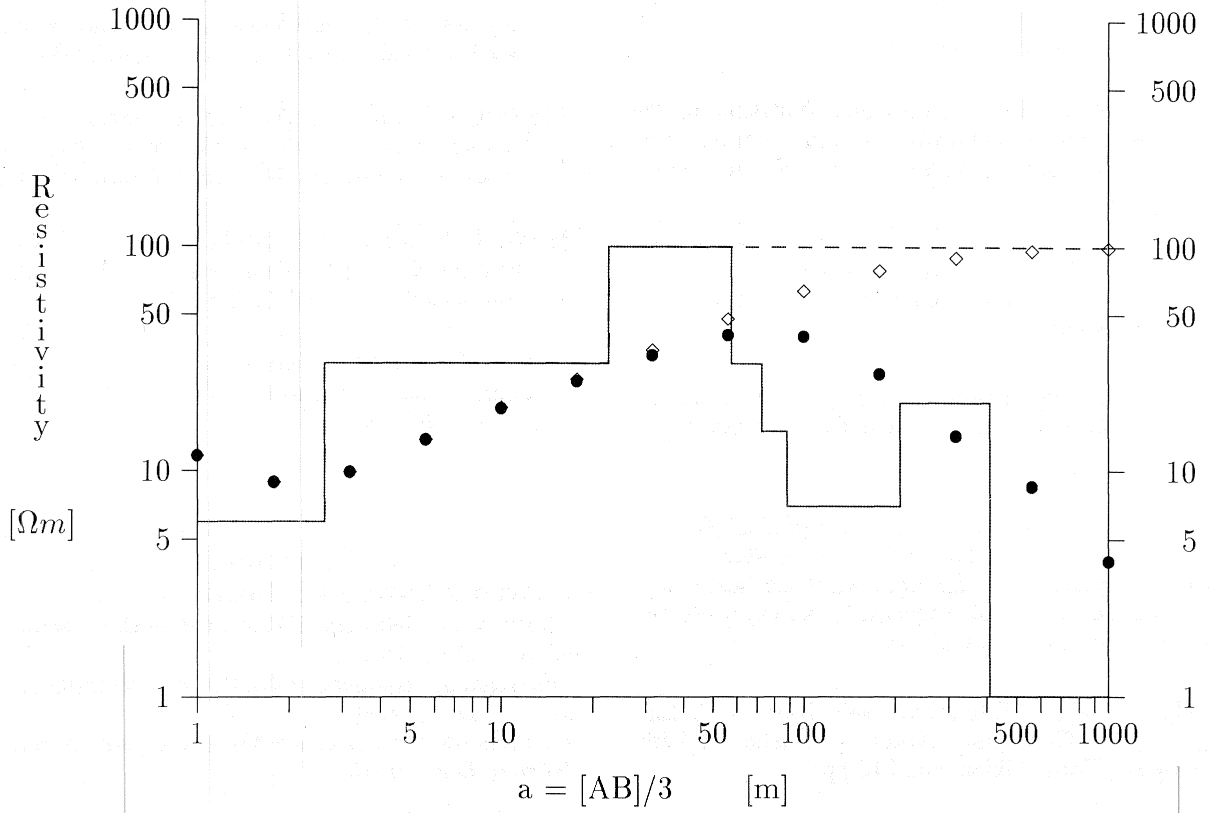

Fig. 7. Apparent resistivity model curves of a Wenner array for two different models. The solid line is the resistivity model interpreted from sounding S6 (Fig. 1, Fig. 4) and its apparent resistivity model curve is shown with solid circles (•). The model represented with the dashed line produces the curve shown with open diamonds (B). See text for explanation.

ground water polluted by sea water intrusion near the coast line.

Archie's law was used to estimate the porosity of the vadose zone. The estimation resulted in a porosity in the order of 25%. Based on this estimation, the resistivity of the pore water calculated from five soundings lies between 1.4 and 11.9 Ωm. These values suggest that the content of total dissolved solids (TDS) may be high. The present study shows that resistivity measurements may help to identify zones where the salinisation process of the soil may be critical in the vadose zone.

Azimuthal resistivity surveys suggested that resistivity anisotropy is weak and decreases with depth. This superficial resistivity anisotropy may be related to the anisotropic patterns of moisture or water chemistry due to infiltration of irrigation water, but not to the local hydraulic gradient.

## ACKNOWLEDGMENTS

The authors thank the Comisión Nacional del Agua (CNA) of Mexico for funding this investigation. B. Steinich and I. Simón were supported by a graduate fellowship through L. Marín, of the Dirección General de Asuntos del Personal Académico (DGAPA, Proyect IN107595) of the Universidad Nacional Autónoma de México. José Luis Escajeda from the Instituto Tecnológico de Sonora (ITSON) assisted with the field work.

## BIBLIOGRAPHY

ANDREWS, R.W., 1981. Salt-Water Intrusion in the Costa de Hermosillo, Mexico: A Numerical Analysis of Water Management Proposals. *Ground Water, 19*, 6, 635-647

ANONYMOUS, 1987. Carta topográfica 1:250 000. Instituto Nacional de Estadística, Geografía e Informática (INEGI), México.

ANONYMOUS, 1993. Estudio Hidrológico del Estado de Sonora. Instituto Nacional de Estadística, Geografía e Informática, México, 185 pp.

ARREGUIN, J., G. FIGUEROA and S. PEÑA, 1968. Estudio hidrogeológico completo de los acuíferos de la Costa de Hermosillo, Sonora. Ariel Consultores y Dirección de Aguas Subterráneas. Secretaría de Recursos Hidráulicos, México, 220 pp.

ASQUITH, G. and C. GIBSON, 1982. Basic Well Log Analysis for Geologists. American Assoc. of Petr. Geologists, Tulsa, Oklahoma, 216 pp.

GORMAN, T. and W. E. Kelly, 1990. Electrical-Hydraulic Properties of Unsaturated Ottawa Sands. *J. Hydrology, 118*, 1-18.

KATZ, A. J. and A. H. THOMPSON, 1985. Fractal Sandstone Pores: Implications for Conductivity and Pore Formation. *Phys. Review Letters, 54*, 12, 1325-1328.

KELLER, G.V. and F. C. FRISCHKNECHT, 1966. Electrical Methods in Geophysical Prospecting Pergamon Press. New York. 519 pp.

KOEFOED, O. 1979. Geosounding Principles, 1: Resistivity Sounding Measurements. Elsevier. Amsterdam. 276 pp.

KORVIN, G., 1992. Fractal Models in the Earth Sciences. Elsevier, Amsterdam, 396 pp.

KROHN, C. E., 1988. Sandstone Fractal and Euclidean Pore Volume Distributions. *JGR, 93*, B4, 3286-3296.

MARIN, L. E., B. STEINICH, G. VELAZQUEZ, I. SIMON and R. GONZALEZ, 1996. Caracterización geoquímica de los sistemas de flujo del Valle de Hermosillo, Sonora. Informe Final, Instituto de Geofísica, UNAM, 74 pp.

PEREZ-ROSALES, C., 1983. Teoría sobre la relación entre factor de resistividad y porosidad. *Revista del Instituto Mexicano del Petróleo, 15*, 4, 26-33.

STEINICH, B. and L. E. MARIN. Determination of Flow Characteristics in the Aquifer of the Northwestern Peninsula of Yucatán, Mexico. *J. Hydrology*, in press.

WESSEL, P. and W. H. F. SMITH, 1995. New version of the Generic Mapping Tool released. EOS Transactions, American Geophysical Union, 76, 329.

WONG, P., J. KOPLIK and J. P. TOMANIC, 1984. Conductivity and Permeability of Rocks. *Phys. Review B, 30*, 11, 6606-6614.

---

Birgit Steinich[1], Isabel Simón[1], J. Andrés Chavarría[2] and Luis E. Marín[3]
[1] *Instituto de Geología, UNAM, Cd. Universitaria, 04510 México, D.F., México.*
[2] *Facultad de Ingeniería, UNAM, Cd. Universitaria, 04510 México, D.F., México.*
[3] *Instituto de Geofísica, UNAM, Cd. Universitaria, 04510 México, D.F., México.*