STUDY OF THE SALT WATER – FRESH WATER INTERFACE IN ENVIRONMENTS OF LOW RESISTIVITY: DOÑANA AQUIFER (SPAIN)

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Abstract

During the deposition of the sediments, a part of the Almonte-Marismas (Doñana) aquifer was covered by the seawater, which remained trapped in some layers. The salt water was moved by the recharge water coming from the unconfined portion of the aquifer, giving rise to an interface. Since 1967 several geophysical surveys have been made to determine the position of the interface, mostly based on the use of Vertical Electrical Soundings (VES). New surveys in 1976, 1982 and 1995 used hydrochemical analysis, conductivity logging and VES, giving new versions of the interface. Due to the dimension of the area and the long distance between measuring points, these lines offer a very rough image of the actual interface situation. From 2002, IGME is essaying new geophysical strategies. Electrical imaging is the base method. Seismic reflection was also performed to avoid the interpretation problems caused by the low-resistivity environment. Temperature, conductivity, induction logging, spectral gamma ray and down-hole velocity have also been measured at several wells. The initial conclusion of our work is that the penetration needed in this area is not always reached by the electrical imaging method. Otherwise, the real situation of the interface seems to be rather more complicated than previously deduced from the available information.

Keywords: Doñana, petrophysics, electrical imaging, salt water, induction logging, spectral gamma

Introduction

The Almonte-Marismas aquifer (also called Doñana aquifer) is located in the Guadalquivir river basin, at the south west of Spain. It is limited to the north by the outcropping of a Miocene-Pliocene formation of blue marls, which is believed to be the impervious base of the aquifer, and that follows a line between Huelva and Seville; the eastern limit is the Guadalquivir River, and to the south the aquifer meets the

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Atlantic Ocean (Figure 1). It has an area of about 3400 km^2, working as an unconfined aquifer except in the oriental part, of about 1000 km^2, which is covered by a marsh and where the aquifer is semi-confined to confined: the Marismas area, partially located inside the Doñana National Park. The western domain of the aquifer contains materials of deltaic and eolian nature (Salvany and Custodio, 1995), forming uniform layers with a gentle dipping to the south, where the sediments may reach more than 1000 m of thickness. In the Marismas area, over the deltaic formation a superposition of marsh and alluvial materials produces a rather more complicated sedimentary structure, with sudden and frequent lateral changes of facies. Clay and silt, with some levels of sand and gravel form the marsh unit; it acts as semi-permeable, with electrical resistivity values lower than 5 ohm·m. Gravel and sand form the alluvial unit, with some clay and silt; it has a higher permeability than the marsh unit, and the electrical resistivity is between 5 and 30 ohm·m for the clay rich portions and up to more than 50 ohm·m for the gravels. At the surface there is a clay layer very rich in salt, with electrical resistivity lower than 0.5 ohm·m. The water content and the quality of this water produce great variations in the values of the resistivity, which in general is very low. The maximum thickness of sediments in the marsh area may be 150 m (IGME, 1992).

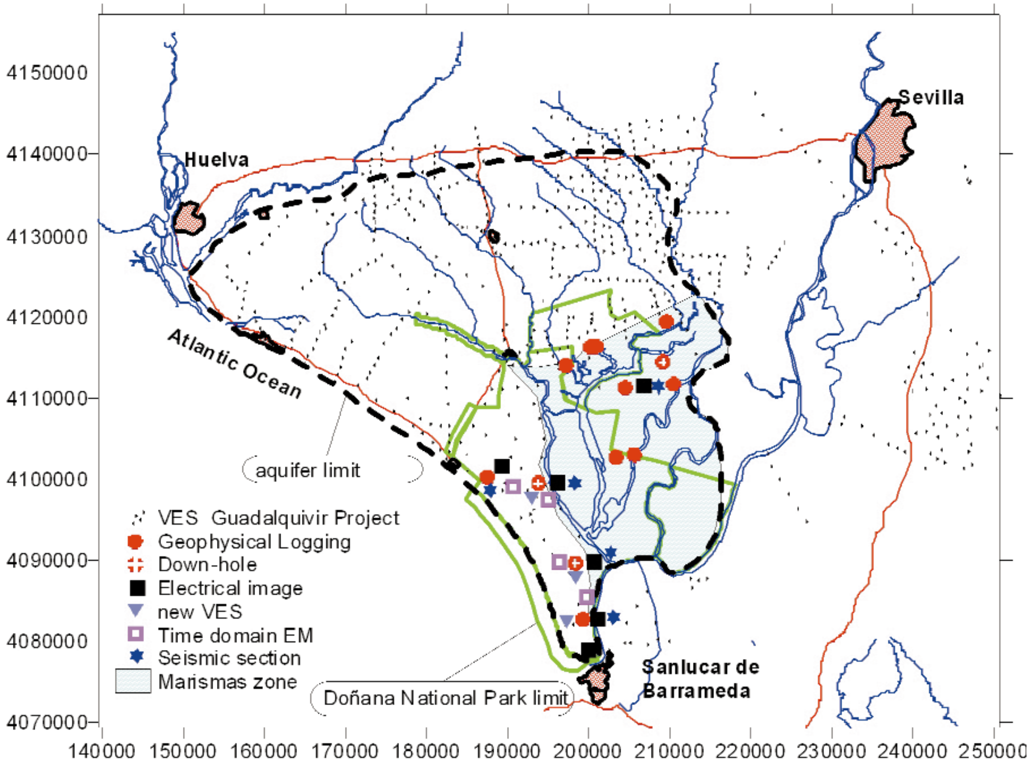

Figure 1. Situation and limits of the Almonte-Marismas aquifer. The position of the new geophysical surveys undertaken by IGME since 2002 are also indicated.

The Marismas are then formed by continental sediments and by marine sediments, which during the process of sedimentation retained the sea water. Due to the recharge water coming from the unconfined portion of the aquifer, and also to the water extraction from pumping wells for irrigation, the sea water imbedded in the marine layers was displaced to the south, giving rise to the existence of two areas with different quality of groundwater. In the unconfined aquifer and in part of the semi-confined one, groundwater is of good quality (with electrical conductivity lower than 1 mS/cm). In the south and southeast, where the thickness of the sediments is more important, groundwater becomes richer in NaCl (with more than 20 mS/cm). So, an interface with NE-SW direction is supposed to exist limiting these two areas.

Historical Geophysical determinations of the interface

The aquifer has been studied from the sixties of the last century, and the problem of defining the situation on the salt water- fresh water interface has been always considered. From a geophysical point of view, the only petrophysical parameter that is able to characterize the presence of salt water in a rock is electrical resistivity. Nevertheless, there are some geological situations where the contrast of resistivity due to the presence of salt water in a permeable layer may be masked by the low resistivity of the limiting impermeable ones. This is the case in Doñana, where the apparent resistivity measured in a VES may be the same for a clay layer and for sands with salt water. The existence of a very conductive surface layer, with less than 1 ohm·m, puts still more difficulties to the use of the geoelectrical methods, because below this layer, everything has a resistive behaviour: sands with fresh water, sand with salt water or a clay layer. Otherwise, the contact resistance of the electrodes presents in this area a very great variation, going from 0.5 ohm·m for the salty clay to more than 1 000 ohm·m for the dry sand dunes that at some places are over the marsh formation. This variation may affect to a large extent the interpretation of the field data of Vertical Electrical Soundings, mostly with the interpretation tools available a few decades ago.

Trying to avoid the difficulty for a correct interpretation of the VES in these conditions, different approaches have been used through the years in order to define the situation of the interface at Doñana. At a first instance, the transversal resistance T was used instead of the apparent resistivity. With a few VES and the knowledge of the salinity in two wells, a first "interface" was traced in 1967 (Astier, 1967) as a line separating points where the transversal resistance was higher than 5000 ohm·m·m. As the exploration of the aquifer went on, new wells were made providing new data about water salinity, and modifications to the interface position were needed. In 1969 more VES were measured, and the limit value of T was modified to 3000 ohm·m·m. The drawing of this interface line covers distances greater than 50 km, with two or three tying points along it. A new methodology was applied in 1970 (Astier, 1970): chemical water analysis from ten wells were correlated with the T values from the VES closest to each well, giving an equivalence of 1.5 g/L of NaCl for 3000 ohm·m·m. Assuming a thickness of 100 m for the aquifer and a porosity of 20%, this value was translated to all the VES made until this year, and a new interface line, modifying at some places the previous one, was drawn.

Between 1971 and 1976 more than 460 wells forming a grid of less than one kilometre of side were made in an area of about 30 x 15 km^2, which allowed the improvement of the studies. Only ten wells were logged with geophysics, getting information of the formation resistivity, gamma ray, spontaneous potential and water conductivity. More than 1180 water samples were taken from 206 wells and analysed for salinity, establishing the equivalence of 1 g/L for 1.7 mS/cm. Using an equation probably based on hydrostatic equilibrium, a map of the depth of the interface was drawn (IRYDA, 1976) covering not only the region occupied by the wells, but extrapolating it rather far away, and even over the part where the calculated interface resulted to be below the impermeable bottom layer (Figure 2). This map offers a three dimensional vision of the interface as a surface, and not as a line. If the crossing of this surface with the impermeable bottom layer is taken as a "line" interface, a displacement of the former line of the order of five km to the west and for a length of about 20 km is needed. Due to the extrapolation used, we think that the drawing of this new line is only valid in its southern portion of about 10 km. It shows a surface with a trend dipping to the south, at a depth of 100 m in the north and at more than 200 m in the south. This describes a situation of a very high concentration of salt (more than 100 g/L) in the superficial silt layer, due to concentration of groundwater arriving to the surface by capillary upwards movement, followed by a terrain with fresh water of about 0.6 g/L down to the deeper part of the aquifer, where there is saltwater reaching 35-40 g/L. Zones with high gradients and some curious irregularities can be observed in the drawing of this interface, which for some unknown reasons, have never more been considered.

In 1982 new determinations of the interface were made (IGME, 1982). Four VES profiles perpendicular to the former (1970) trace of the interface were carried out with AB/2 = 1,500 m and a total of 25 measurements, covering a distance longer than 40 km. In this case, and in contrast with the previous experience on the restrictive value for the use of the apparent resistivity deduced from VES, as a good discriminator for the presence of saltwater, the results were presented as maps of apparent isoresistivity for fixed values of AB. Resistivity values smaller than 5 ohm·m were assimilated to the existence of water with more than 1.5 g/L. Surprisingly, the interface line drawn in this way was coincident with the older one.

As the knowledge of the aquifer has continuously being improved through the years, problems of incongruence with the position of the interface has always been present, because its supposed situation could not explain the new findings. The last study made at a large scale took place in 1995 (IGME, 1995). In this case 31 wells were logged for water conductivity and temperature, and 34 chemical analysis of water were made. In this case, instead of drawing a "line" to indicate the presence of the interface, or a map of the depth of the contact surface, a map of lines of isoconductivity was drawn (Figure 3), which presents a rather smoother surface than the one deduced in 1976. The authors of this survey found quite difficulties to establish a comparison among the data, because of the influence of the positioning of the filters in the different wells.

New geophysical strategy

So far, from the initial studies of the Marismas aquifer in 1967 until nowadays, quite a few geophysical determinations of the fresh water- salt water interface have been carried out. The methodology used in each case was different: the value of the transversal resistance of the aquifer layer calculated from VES surveys; the use of the apparent resistivity; the correlation of the mentioned geoelectrical parameters with chemical water analysis; and lastly the logging of the well water conductivity and/or its translation to salt content in g/L through correlation with water analysis. Some singularities can be found in the way these data have been used to represent the interface, as well as some contradictions, even in the hydrogeological

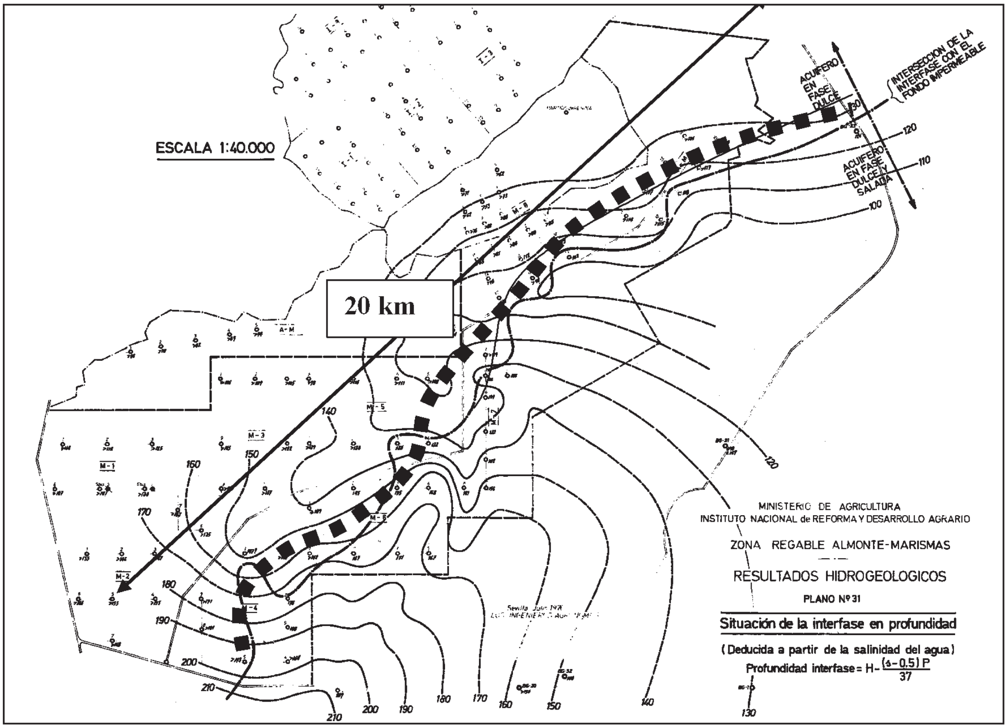

Figure 2. Map of the depth of the surface separating fresh and salt water drawn in 1976 based on data from chemical analysis of groundwater collected in more than 200 boreholes. A line indicating the limit of the interface as the intersection of the surface with the bottom impermeable layer has been drawn. (Modified from IRYDA, 1976).

description of the nature and origin of the interface. Anyway, it seams that none of measurements and theories constructed about this interface is still good enough to explain the observations made in the recent research works. One of the explanations for this situation, we think, derives from the problem of the lack of real information in many sectors of the aquifer, where the interface data used are extrapolated from observation points rather far apart. Another reason for the lack of fitness may come from the fact that a line separating points with different values of any parameter can never be considered as representative of a two-three dimensional phenomenon. At some studies the interface is defined as a sharp surface, while at others a more diffused solution is given. The complex geometry of the aquifer inside the Marismas area may contribute in an important manner to the difficulty for a correct delimitation of the interface. Technical problems in the construction of the pumping and piezometric wells may also be in the base of some of the disappointments. Also the possibility of the inexistence of just one "interface" has to be considered, because of the mechanism by which the seawater was trapped in the geological layers.

For all these reasons, IGME has undertaken a new Project to make a revision of the geophysical surveys made at Doñana aquifer (Plata *et al.*, 2002). Among the objectives of this Project is the development of a geophysical methodology able to help in the solution of some stratigraphic problems, and to investigate once more the interface. Several places at the aquifer were selected in order to carry out geophysical tests;

in the case of the salt-fresh water interface we are going to refer here just to the works done inside the Marismas area. A relatively small area was selected inside the zone covered by the last works conducted in 1995 (Figure 3), and a battery of methods employed (Plata and Rubio, 2003). Vertical Electrical Soundings and Time Domain Electromagnetic, which have been used in other areas of the aquifer for other purposes, were disregarded because a more continuos sampling was needed in this case. To verify the petrophysical behaviour of the different lithologies, geophysical logging has been chosen as the most efficient tool (Plata and Rubio, 2004). With the natural gamma ray we expect to be able to differentiate between clay and gravel layers, and is also good for correlation among borehole information. To get a more precise knowledge of the composition of the silt and clay layers, spectral gamma data have been measured, recording the K, Th and U channels with a calibrated probe. This provides more information about the mineralogy of clay and allows a good differentiation between clay rich sand layers and sand rich clay layers.

Fluid temperature and conductivity are standard measurements in this kind of surveys. These logs are supposed to provide information about the inputs and intakes of water, as well as of the salt content, whose evolution inside the casing is a result of the equilibrium established by the piezometric level and groundwater flow. Nevertheless these measurements may be distorted because of the borehole construction system and the positioning of the filters, which produce variations on the properties of groundwater not related to the hydrogeological situation. It is also necessary to bear in mind that the water column inside the borehole may not be representing the situation of the formation water at the same depth. The fluid conductivity does not provide information about the nature of the fluid inside the layers, which modifies its resistivity and the contrast of this parameter between adjacent layers. Conductivity has been reduced to 25 °C.

Formation resistivity has been logged by electromagnetic induction at several wells on both sides of the interface, in boreholes with PVC casing. With this parameter we try to determine the formation resistivity of the different layers, as well as the influence of the water quality on it, as a fundamental tool for the design and interpretation of the electrical surface methods.

The surface base method has been the electrical imaging, making a profile of 3,300 m on the aforementioned area (Figure 3). The distance between stations has been established in 15 m, with an electrode arrangement of 1,200 m. Several electrode configurations have been used: Wenner, dipole-dipole and Schlumberger. Along the same profile a seismic reflection section was measured with the idea of reducing the ambiguity in the interpretation of the geoelectrical data with the help of a correct geometry supplied by the seismic section. Down-hole seismic velocity has also been measured at some selected boreholes to improve the processing of data and the time-depth conversion.

Before interpreting the geoelectrical section it is necessary to calibrate the resistivity values found in the logs. As an example, in the case of the well shown in Figure 4, made inside the Marismas formation, there is a sequence of 190 m of clay with some gravel and sands intercalation. The fluid conductivity is of about 15 mS/cm in the first 24 m, and more than 20 mS/cm from a depth of 50 m to the end. The gamma ray log shows a sand intercalation not previously detected between 10 and 25 m, clearly identified not only by the total counts of the gamma ray, but by the complete absence of U in the spectral gamma and the higher resistivity in the induction log, which reaches 8 ohm·m. Therefore, a contrast of all these parameters

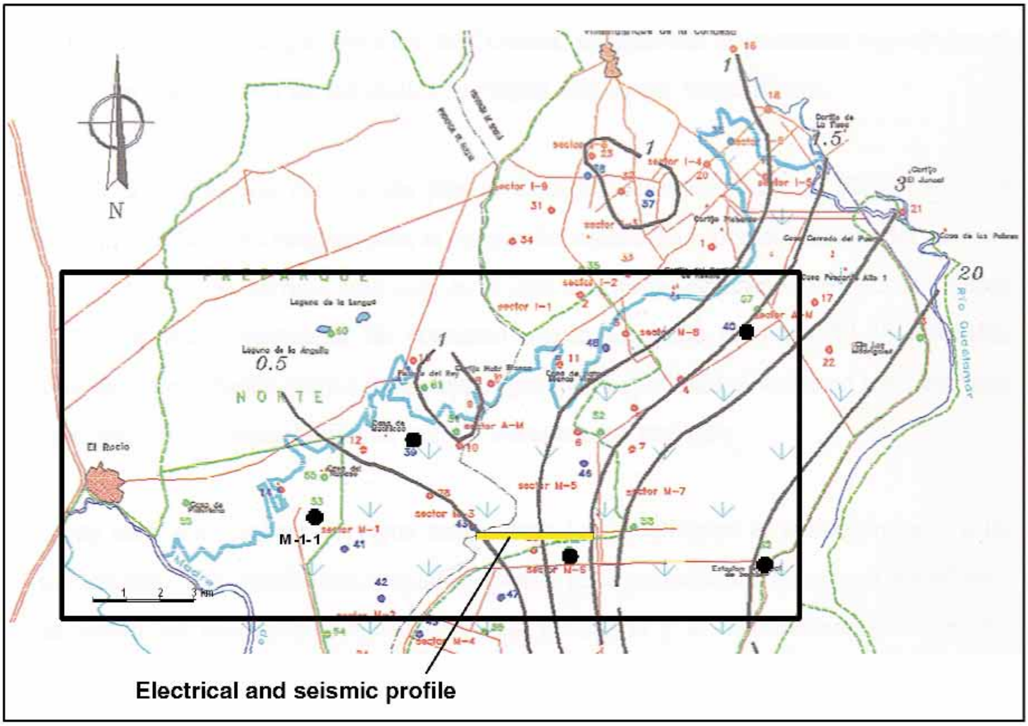

Figure 3. New map of the interface, drawn in 1995, expressed in lines of the same value of water conductivity after logging of 31 boreholes and 34 chemical analyses. The line for 1 mS/cm approximately coincides with the limit of the interface drawn in Figure 2. The area chosen to conduct new geophysical measurements in 2002 is marked. Wells at both sides of the interface have been logged (big black dots). The position of the seismic and electrical image profile is also indicated. (Modified from IGME, 1995).

is present when a change in lithology not affected by the presence of groundwater takes place. Below this layer, the clay layer shows a resistivity of about 1 ohm·m down to a gravel layer at a depth of about 65 m, detected by a raise in resistivity to 3 ohm·m and a low in gamma ray total counts; the U content helps also to identify the nature of this layer, with some clay intercalation. Below 110 m the gamma ray measurements are clearly indicating the presence of additional sand layers than those indicated by the geological column, but no variation in resistivity is appreciable, which remains between 1 and 2 ohm·m. Both the bottom sand layer, where the aquifer filter is set, and the clear intercalation of clay inside it, are not detected by the formation resistivity log. Our interpretation in this regard is that the first gravel layer does not contain water or contains fresher groundwater than the one detected by the conductivity, but the deeper permeable layers bears saltwater, which modifies the resistivity giving no contrast with the impermeable clay layers. The fluid conductivity is indicating the salinity of the water column inside the well, which is not related to the formation water. In these situations, the use of geoelectrical methods from the surface will be useless for lithological discrimination. Comparing this kind of analysis at several wells, we have verified that the resistivity contrast of a sand layer with the surrounding clay layer may be as high as 200 ohm·m when the sand is dry; if the conductivity of groundwater is in the order of 15 mS/cm, the resistivity may be as low as 20 ohm·m for the sand layer, reaching 5 ohm·m when groundwater has a salinity equivalent to 20 mS/cm. With higher values of the electrical conductivity of water, no resistivity contrast at all is present. The clay or silt content in the sand matrix also modifies the resistivity of the sand layer, in such a way that its resistivity contrast with other formations, covers such a wide range of values that it may discourage any attempt to make use of the geoelectrical methods to recognise its presence.

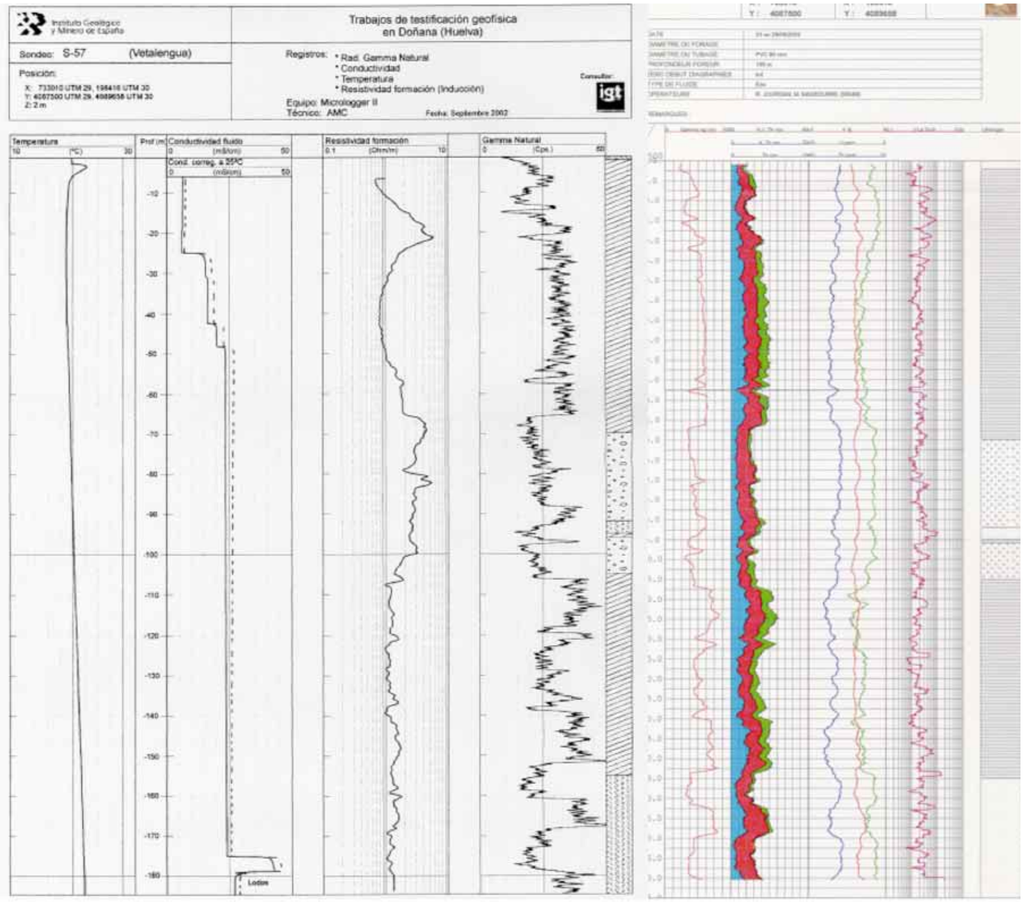

Figure 4. Interpretation of a set of logs using temperature and fluid conductivity, formation resistivity, total counts gamma ray and spectral gamma ray. See description in the text.

Regarding to the differences between using VES or TDEM methodology and electrical imaging, the most significant is the sample interval of the surface measurements and its influence on the vertical, and mainly, in the horizontal resolution achieved. When a very high conductivity surface layer is present, it acts for the electromagnetic method as a screen to the current penetration; using VES, after this layer, anything has a response as a resistive layer, making also rather difficult the interpretation of the results. Nevertheless, the use of electrical logging is a good help to assign the correct depth to the VES interpretation, improving the determination of the apparent resistivity values. All these features apply to the electrical image method, whose interpretation in these environments needs also the use of logging and of seismic sections. In our experience in the Doñana aquifer using all these electrical methods of geophysical exploration, there is one more difficulty to add: the geometry of the bodies is rarely two dimensional and a great heterogeneity is nearly always present due to a rather fast change of the sedimentary facies and chemical nature of the water content. Anyway, the use of electrical images is expected to allow a better definition of these changes.

Preliminary interpretation

Preliminary results obtained in the above-mentioned zone to verify the presence of the salt-fresh water interface shows all the general conditionings and limitations found in the calibration analysis of the data. Until the seismic section was available, we have been using to interpret the electrical image (Figure 5) a geological section deduced from the correlation of four boreholes along the profile.

The first layer in the geologic data is the clay of the Marismas formation, about 40 m thick to the west and dipping east, where it reaches 80 m. This layer has an intercalation of alluvial materials with sand and gravel of variable thickness and continuity. The geoelectrical image reflects rather well the presence of this first layer, with a resistivity lower than 1 ohm·m at the surface and clearly showing the high degree of discontinuity of the sand deposits. The second geological unit is formed by a 100 m thick sand formation, but multiple clay intercalations are present. The resistivity of this unit, upon the previous analysis, can be as high as 200 ohm·m or as low as 5 ohm·m and even lower, depending on the kind of water contained, if any. The probability of differentiating the interbedded clay layers depends also on the salinity of water in the permeable rock. The result of the image is rather surprising. Where the "interface" should be placed it can be seen a clear resistivity contact: in the fresh-water side the resistivity is higher than 30 ohm·m, reaching up to more than 100 ohm·m, but it is interrupted by a very clear conductive body with less than

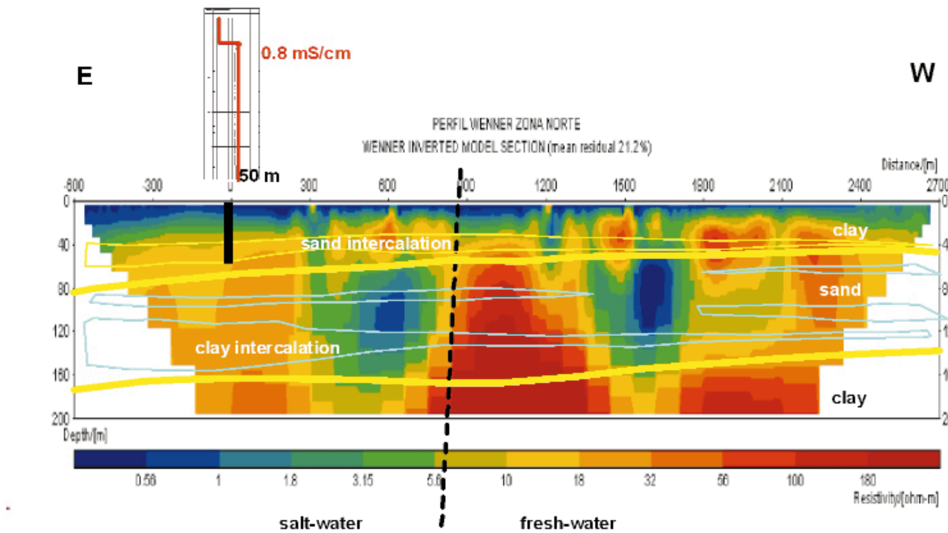

Figure 5. Geoelectrical image taken at the point crossing the trace of the salt-fresh water interface. The geological information deduced from four boreholes along the profile has been used in the interpretation. Explanation is given in the text.

0.5 ohm·m, whose meaning is unknown. No correlation with the clay intercalation is appreciated. At the salt-water side, the resistivity is below 30 ohm·m, and a very conductive body with less than 5 ohm·m is also present; some correlation of this body with the clay intercalations could be interpreted. This geoelectrical situation is also visible in the dipole-dipole and Schlumberger sections, with the inherent differences that are due to the electrode configuration.

The third layer is the blue marl, which is the impermeable substratum of the aquifer, and appears at a depth of 140 m, reaching 170 m to the east. It is rather evident that the current has not reached this penetration, and that the information derived from the electrical image may be probably valid only down to 100 m.

From the point of view of the interface, the results could be interpreted as the existence of a rather complex surface. The conductivity log of the well M-6-6, situated in the salt-water side and rather close to the more resistive portion of this side of the profile, shows that at least the first 50 m of the water column is fresh water. Unfortunately the casing of this well is made of iron and no electrical measurements can be made.

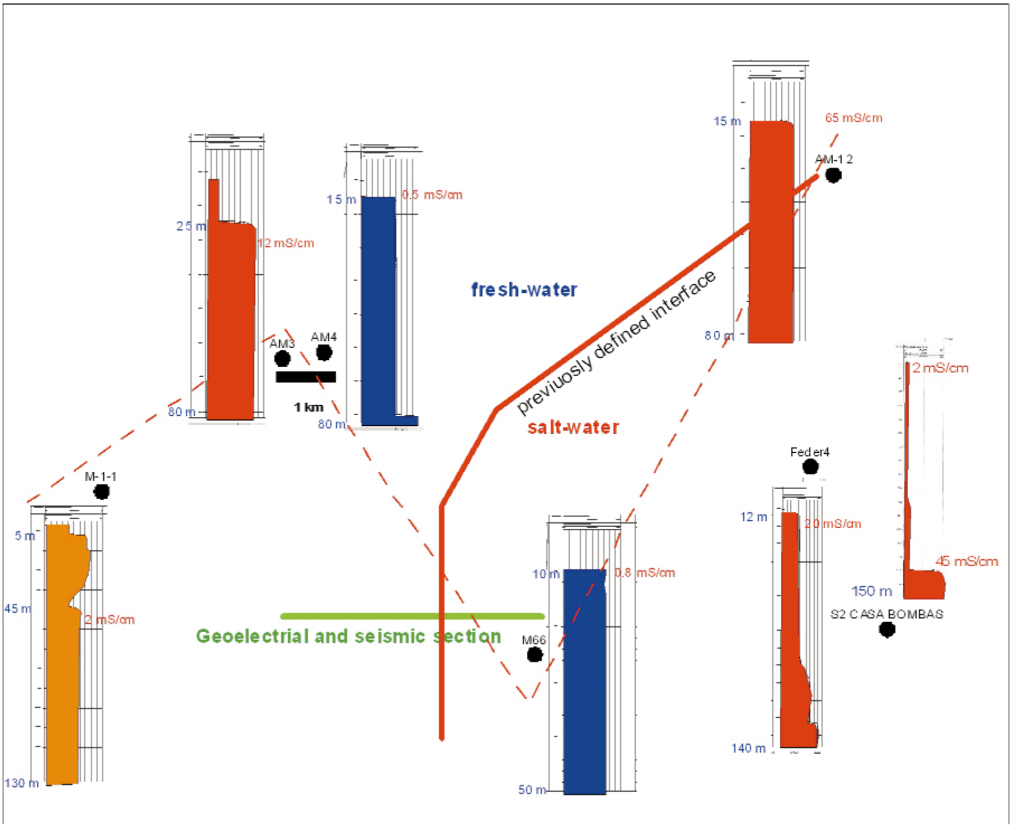

Figure 6. Scale scheme showing the fluid conductivity results attained in boreholes at both sides of the interface. The wells used are those indicated in Figure 3.

Looking now at the conductivity logs of the wells surrounding the electrical profile (Figure 6) other anomalies are found. Toward the salty side, wells AM-12, S-2 and Feder-4 are filled with salt water (more than 20 mS/cm), though it is interesting to see the huge gradient identified between Feder-4 and S-2 wells. The already mentioned M-6-6 borehole does not present high salinity in the first 50 m. To the fresh-water side, the well M-1-1 is in the limit of 2 mS/cm from the surface, and wells AM-3 and AM-4, just a few hundreds of meters apart, show a very different situation: in the first 80 m water is saline in one of them and fresh in the other one. If the same criterion that has been used in the older studies for drawing the interface is used with these new data, an important and strange modification of the interface "line" should be made.

Conclusions

In the former studies of the Doñana aquifer the methodology for the determination of the interface was based on the resistivity measured in Vertical Electrical Soundings (VES), taking as discrimination parameter just the apparent resistivity or the transversal resistance. Correlation of the VES apparent resistivity with the water chemical analysis and water conductivity from logging was the next step in the system used to draw a line separating points where the value of one of these parameters was different. The results of none of these surveys are enough to explain the new discoveries about the distribution of salt water in this aquifer. The only way to draw a two- or three-dimensional surface is the use of two or three dimensional sampling, which is only possible if a tied grid of wells is at our disposal or if a geophysical method is used with such a sampling rate, as Electrical Image. For the right interpretation of the field measurements, the resistivity values need to be calibrated with the aid of geophysical logging, lithological information and chemical analysis of water. At the Doñana aquifer the use of geoelectrical methods is specially difficult, because the distortion produced by salt water in the resistive layers and the presence of a very conductive layer at surface does not always allow the distinction between the different geoelectrical situations. The penetration of the current is also limited using the short interval between electrodes imposed by the instrumentation available for electrical imaging. With all these limitations, and as a result of a first interpretation of some of the new data taken, our feeling is that the interface at Doñana is rather more complicated than previously believed.

References

ASTIER (1967). Etude hidrogeologique du bassin du Guadalquivir. Rapport sur les résultats de la prospection géophysique. Centro de documentación del IGME S/R. (Unpublished).

ASTIER (1970). Interprétation d´ensemble de sondages électriques des zones d´Almonte et des Marismas. Centro de documentación del IGME. S/R. (Unpublished).

IGME (1982). Estudio hidrogeológico del acuífero Almonte-Marismas. Estudio geofísico de la interfase agua dulce - agua salada. Geological Institute of Spain, IGME, Ref. 35.655. (Unpublished).

IGME (1992). Hidrogeología del Parque Nacional de Doñana y su entorno. Colección Informe. Geological Institute of Spain, IGME, Madrid.

IGME (1995). Estudio sobre la evolución de la calidad fisico-química de las aguas subterráneas en el sector oriental de la unidad hidrogeológica de Almonte-Marismas. Geological Institute of Spain, IGME. Ref. 35.963. (Unpublished).

IRYDA (1976). Informe final de los sondeos de la zona regable de Almonte-Marismas y síntesis hidrogeológica. Spanish Institute of Rural Development. (Unpublished).

PLATA, J.L.; RUBIO, F.M.; MANZANO, M.; MEDIAVILLA, C. and ARIAS, M. (2002). Proyecto para la revisión de la información geofísica existente sobre el acuífero Almonte- Marismas (Doñana). *Proceedings III Asamblea Hispano Portuguesa de Geodesia y Geofísica*. Valencia. España: 1916-1919.

PLATA, J.L. and RUBIO, F.M. (2003). Avance de los trabajos geofísicos últimamente realizados en el acuífero Almonte-Marismas (Doñana). Geological Institute of Spain, IGME; Serie Hidrogeología y Aguas Subterráneas nº 8; *TIAC03,* I: 169-176.

PLATA, J.L. and RUBIO, F.M. (2004). Nuevas testificaciones geofísicas en el acuífero Almonte-Marismas. *Proceedings IV Asamblea Hispano Portuguesa de Geodesia y Geofísica*. Figueira da Foz. Portugal: 367-368.

SALVANY, J.M. and CUSTODIO, E. (1995). Características litoestratigráficas de los depósitos plio-cuaternarios del bajo Guadalquivir en el área de Doñana: implicaciones hidrogeológicas. *Rev. Soc. Geo. España,* (1-2): 21-31.

Topic 5.

Hydrochemical and isotopic aspects of saline water intrusion