Characteristics of the fresh water-salt water contact in the Motril-Salobreña aquifer (Southern Spain) using time domain electromagnetic soundings

Duque-Calvache C.[1], Calvache M.L.[1], Pedrera A.[1], Hódar A.[1], López Chicano M.[1], Martín Rosales W.[1], González A.[2], Rubio J.C.[2]

Abstract **The Motril Salobreña coastal aquifer in southern Spain is composed by detritic materials deposited by the Guadalfeo river. The population in this area is rapidly expanding due to tourism related urban development including the construction of various golf courses. Also a dam (presa de Rules) has been constructed (20 km from the coast) in the Guadalfeo river, which is the main source of recharge of the Motril Salobreña aquifer. All these changes are expected to significantly influence the dynamics of the groundwater system. Therefore, studying the position and geometry of the fresh water salt water contact and its future evolution is very important.**

None of the existing boreholes are deep enough to directly locate the fresh water salt water contact from electrical conductivity logs. Furthermore, vertical electrical soundings were made in this zone with no optimal results. Therefore, a time domain electromagnetic soundings (TDEM) campaign has been performed. TDEM soundings are punctual measurements of the response of the aquifer to an artificial magnetic field generated by an electrical loop current. Results are recorded in vertical resistivity logs.

A campaign has been performed with the objective of constructing profiles via correlation of adjacent logs aligned perpendicularly to the coast. Twenty eight TDEM soundings were made distributed along four profiles. Each profile was constructed in zones with different hydrogeologic characteristics. In this paper we only show the preliminary results of one of them. The section showed in this paper is situated along the current Guadalfeo River channel. In the obtained section it is possible to detect the sea water intrusion zone that is related to an important decrease of the resistivity.

The size of the electrical loop current was variable dependent on the expected depth of the saline interface which ranges between 50 and 200 meters. This geophysical method allows to determine changes in depth of the fresh salt water contact with increasing distance from the coast, as we document here for the Motril Salobreña aquifer.

Index Terms **Coastal detritic aquifer, fresh saltwater contact, resitivity, time domain electromagnetic sounding**

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1.Departamento de Geodinámica, Universidad de Granada (email: cduque@ugr es)
2. Instituto Geológico y Minero de España

I. INTRODUCTION

THE Motril-Salobreña aquifer is located in the Southern Andalusian coast, about 60 kilometres to the South of Granada (Fig. 1). It is connected with the Mediterranean Sea in its south side, but also, it is located near Sierra Nevada, a very high mountain range with more than 3000 meters of altitude above sea level. A distance of only 30 Kilometres separates Mulhacen peak (3482 meters above sea level) from the coastline. The Guadalfeo River collects most of its water from the south face of this range, and conducts it to the Motril-Salobreña aquifer. The catchment of the Guadalfeo River has an extension of more than 1200 km2. Therefore, the main recharge of the aquifer proceeds from the river, given the fact that the climate in this zone is semi-arid. The average annual precipitation in the area is about 400 mm, but the precipitation reaches more than 1000 mm in the near ranges. Another important recharge for the system is the groundwater flow that goes in across the sediments of the river alluvial, estimated by Ibáñez, [17] at 14,5 % of the inputs. The precipitation represents a 10 % of the inputs, the river Guadalfeo 34 % and the irrigation return 29.5 %. Other inputs are not very important. The temperature is high along all year (18ºC), so this zone is called the Tropical coast.

The area is located into the Internal Zones of the Betic Cordillera. The geology of this zone is structured in tectonic nappes separated by mechanic contacts. The lithologies that correspond to this zones are carbonates, schists and filites (Alpujarride Complex)[1][12]. These rocks act as a basement for the Motril –Salobreña aquifer. The aquifer is composed by detrital materials showing a wide variety of grain size. So, there are gravels, sands, silts and clays in stratified beds [2][9][10]. These sediments have been carried mainly by the Guadalfeo river and by other secondary streams in a short period of time due to the quick erosion of surrounding mountains. The materials are lightly compacted as cementation and lithification had no time to work. The alluvial sediments build a delta although at present time there is no connection between the river and the deltaplain due to human canalization.

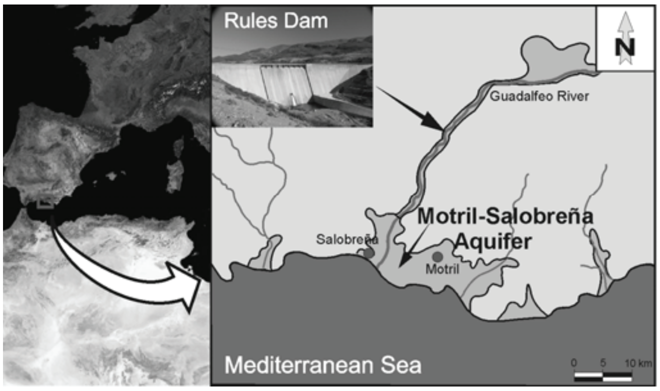

Fig 1. Location of the Motril-Salobreña aquifer and the Rules Dam

The aquifer has an extension of approximately 50 km^2 and two cities are within its area, Motril and Salobreña, which give their names to the aquifer (Fig. 1). The population in this area is rapidly expanding due to tourism related to urban development including the construction of various golf courses. Also a dam (presa de Rules) has been constructed (20 km from the coast) in the Guadalfeo river, which is the main source of recharge of the Motril-Salobreña aquifer [6]. All these changes are expected to significantly influence the dynamics of the groundwater system.

The decrease of the recharge in the aquifer can modify the fresh water-salt water contact. Nowadays, no well in this area extract salinizated water because the aquifer is in a very good state [4][17]. No problems of salinization have been observed, but the changes of the land-use, as well as the decrease in the inputs, can make the interface saltwater-freshwater move inland. The necessity of defining in the most precise way the situation of the sea water wedge is basic to forecast the alteration that could happen in the future. The monitorization of the movements of this surface can avoid the salinization of one of the best preserved coastal aquifer of Andalusia. The quantification of the effects of the dam on the aquifer will make possible the establishment of an adequate management system.

II. METHODOLOGY

A. TDEM soundings

There are some methods to determine the situation of the freshwater-saltwater contact. The direct way is the measure of the water conductivity in boreholes that have enough depth 22]. In t[his aquifer, there are no wells of these characteristics, the utilization of geophysical methods became neccesary. The Vertical Electric Soundings have some problems when there are resistive beds, and with very conductive zones [13][14][15][16][20]. The presence of seawater makes the materials more conductive in a coastal aquifer like this. Therefore it looks like that the best way of identifying the seawater intrusion zone is the Time Domain Electromagnetic Soundings (TDEM).

TDEM soundings are punctual measurements of the response in the underlying materials of the aquifer to an artificial magnetic field generated by an electrical loop current. Results are recorded in vertical resistivity logs. We measure with a PROTEM system of the Geonics trademark. It is composed of: a TEM-37 transmitter, a Protem-D receiver and a low frecuency receiver bobbin as sensor. The process and interpretation of the data have been made with the IX1D commercial program that has been developed by Interpex. This program works by modelization and inversion.The size of the electrical loop current was variable (between 50 and 200 meters), dependent on the characteristics of the terrain and the expected depth of saline interface.

A campaign has been performed with the objective of creating sections via correlation of adjacent logs, aligned perpendicular to the coast. Twenty eight TDEM soundings were made, distributed along four sections. Each section was constructed in zones with different hydrogeologic characteristics. In this paper we only show the preliminary results of one of them. The aim is to establish an adequate work methodology with the data of the TDEM soundings. When we have determined the way of work in one of the profiles, we can proceed faster with the others profiles. Each one of these zones responds in a different way to the changes in the aquifer, so it is important to know the situation in each one. The section showed in this paper is situated along the current Guadalfeo River channel (Fig. 2). In the obtained section it is possible to detect the sea water intrusion zone that is related to an important decrease of the resistivity.

We have five punctual measurements. One of the problems is that we need to obtain a continuous section. The way of join must be based in some aspects like the distance between the points, the differences and similarities of resistivities and the knowledge of the zone. Another typical problem that we can find with the TDEM soundings is the interpretation of the obtained results. The changes in the resistivity can be associated with differences in the conductivity of the water because of the presence of saltwater, or because of the contrast in the properties of the sediments that compose the aquifer[13][14][20]. In the Motril-Salobreña aquifer, the schists that form part of the basement can lead to mistakes, because the resistivity of these rocks is very low.

B. Boreholes Information

The information of the boreholes that coincides with the location of the TDEM soundings is limited by the depth as no one is deep enough to reach the basement. Therefore we only obtain information about the minimum depth of the alluvial deposits. The boreholes drilling system and the low degrease of lithification of the alluvial materials, make difficult a good description of the changes in the type of sediments. Therefore we can not describe clear limits in the sedimentary facies.

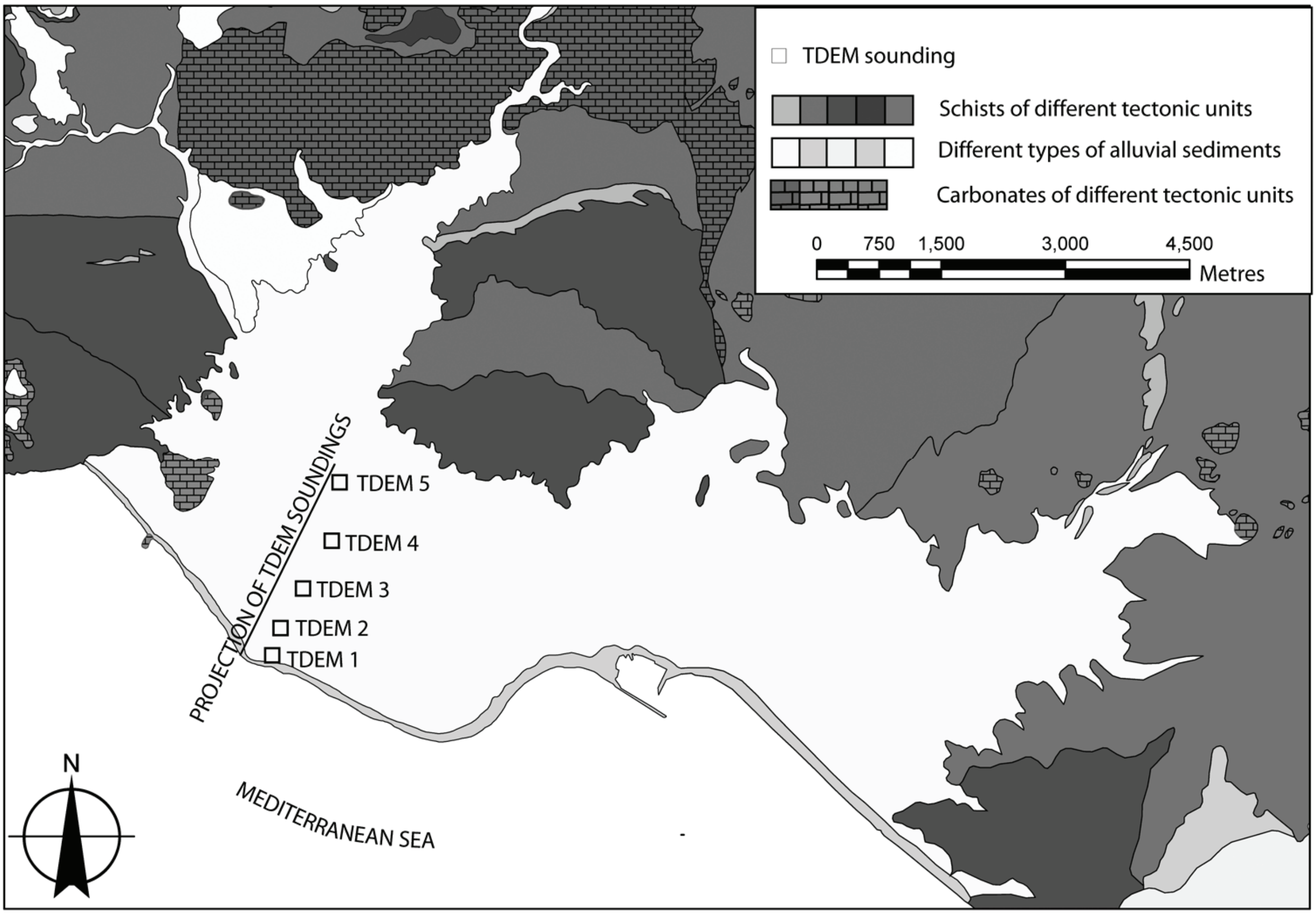

Fig.2. Simplified geology and situation of the TDEM soundings

III. RESULTS

We have made six TDEM soundings in the Western zone of the Motril-Salobreña aquifer. In this area there are some boreholes and wells, but the detailed information deriving from them is not very clear. We try to gather this information to obtain a general result. The electromagnetism section is more than 2200 meters long. Before the dam starts working, the main recharge of the aquifer happens in this zone when the river is under high discharge situation [5].

The curves of apparent resistivity and their respective interpretations can be separated in two groups attending to different characteristics (Fig.3). The first three TDEM soundings are closer to the coastline. They show similar curves of apparent resistivity and so the interpretations have a big similitude. In general, the resistivity of the soundings decreases as we go deeper. We consider that a resistivity below 10 Ωm is probably due to the presence of seawater [3][7][15][16][19]. The distance to the coastline can help us to determine if the low resistivities are associated with rich graphite-schist or with the saltwater. The depth where the resistivity drops to 10 Ωm changes in the different profiles. It is lower close to the coast.

The TDEM soundings more banished from the coastline do not reach as low values as in the closer profiles. At a deeper position the resistivities in this profiles increases to more than 200 Ωm. As this resistive rock is very deep, we conclude is a rock basement. The study of the basement that crops out in the surrounding area makes possible to assign this values to carbonates.

This profile runs along the Guadalfeo river, from the mouth to 2200 meters inland. The projection of the electromagnetic data of all the soundings allows us to detect important contrast in some points. There are thick beds of a resistive material inside the alluvial deposits, and near the coast, the resistivity decreases suddenly at a specific depth. The lowest values are located at very deep far away from the coast. This can be observed in three of the measuring points. The measuring points that are located deeper and more inland depict really high values of resitivity (Fig 4).

The interpretation related to the marine intrusion is as follows: in the points located close to the coast line and deep enough, the decrease of the resistivity is associated with the saltwater saturation of the alluvial sediments. In the areas where the sea is too far, the presence of low resistivity units is due to the existence of graphite-rich schist in the basement underlying the alluvial ensemble [14]. The high values under the schist are related to the allowance of carbonate units. In the alluvial deposits, the presence of gravels with a low proportion of matrix forms a body with high resitivity[11]. According to this interpretation, the saline wedge is only 700 meters long and starts 150 meters deep under the coastline.

IV. DISCUSSION

The aquifer is composed of sediments with a high variability in its resistivity values. The places where the freshwater saturates the pores, the resistivity ranges from 10-15 Ωm to 400 Ωm. In the zones where the seawater is present the resistivity drops below 10 Ωm. The aquifer has no problems of marine intrusion, it has a good state of conservation due to the high volume of inputs that received. The zone with saltwater do not advance more than 700 meters inland anyway.

The resistivity values for the basement are of two ranks. Somewhere there are very low values, under 10 Ωm. This happens where the basement is composed of rich graphite schist, and the electrical properties of the graphite makes possible the decrease of the resistivity. The high values of resitivity under the schist in the profile is probably associated with carbonates, common lithology in the basement. The carbonate that normally outcrops in the near zones (dolostone, limestone and marbles) is heavely fracturated. We indicate the possibility that, in the zones where the basement is made up this rock, the presence of sea water can change the electromagnetic properties of it.

In the western sector, the recharge of the aquifer is higher due to the presence of the river, and so the marine intrusion is restricted to deeper zones.

The high values of resistivity of some of the sediments that compound the aquifer indicate a great porosity. It will be an important problem for the protection of the aquifer from the saltwater intrusion if the inputs are reduced.

V. CONCLUSION

The zones of the aquifer that we detect as affected by seawater are more than 150 meters deep. This fact is associated with the recharge sources, the porosity of the sediments in each zone and the morphology of the basement.

For the determination of the basement morphology we propose a gravimetry survey. This geophysical method allows us to establish with more accuracy the electromagnetic difference between basement and sediments. The results can be extrapolated to the other profiles.

The high values of resistivity of some of the sediments that compound the aquifer indicate a great porosity. It will be an important problem for the protection of the aquifer from the saltwater intrusion, if the inputs are reduced.

The volume of seawater in this zone is important due to the great porosity of sediments that provides an important storage capability.

We have outlined the size of the zone saturated with seawater. Knowing the shape of the aquifer allows us to predict where this process will continue to evolve. The Rules Dam started working 18 months ago. The quantification of the effects of the dam on the aquifer will make possible to establish an adequate system to manage it.

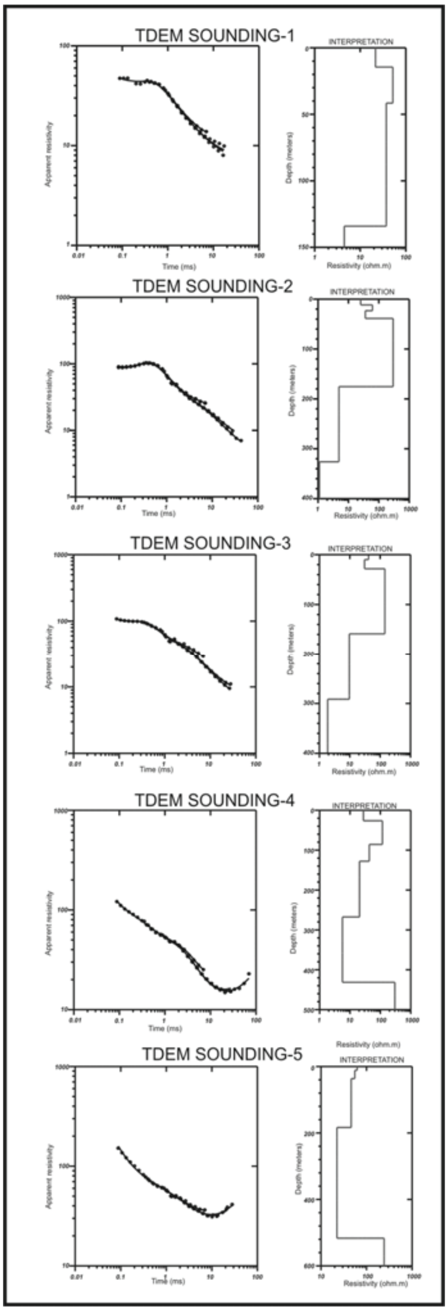

Fig 3. Apparent resistivity curves and interpretation associated

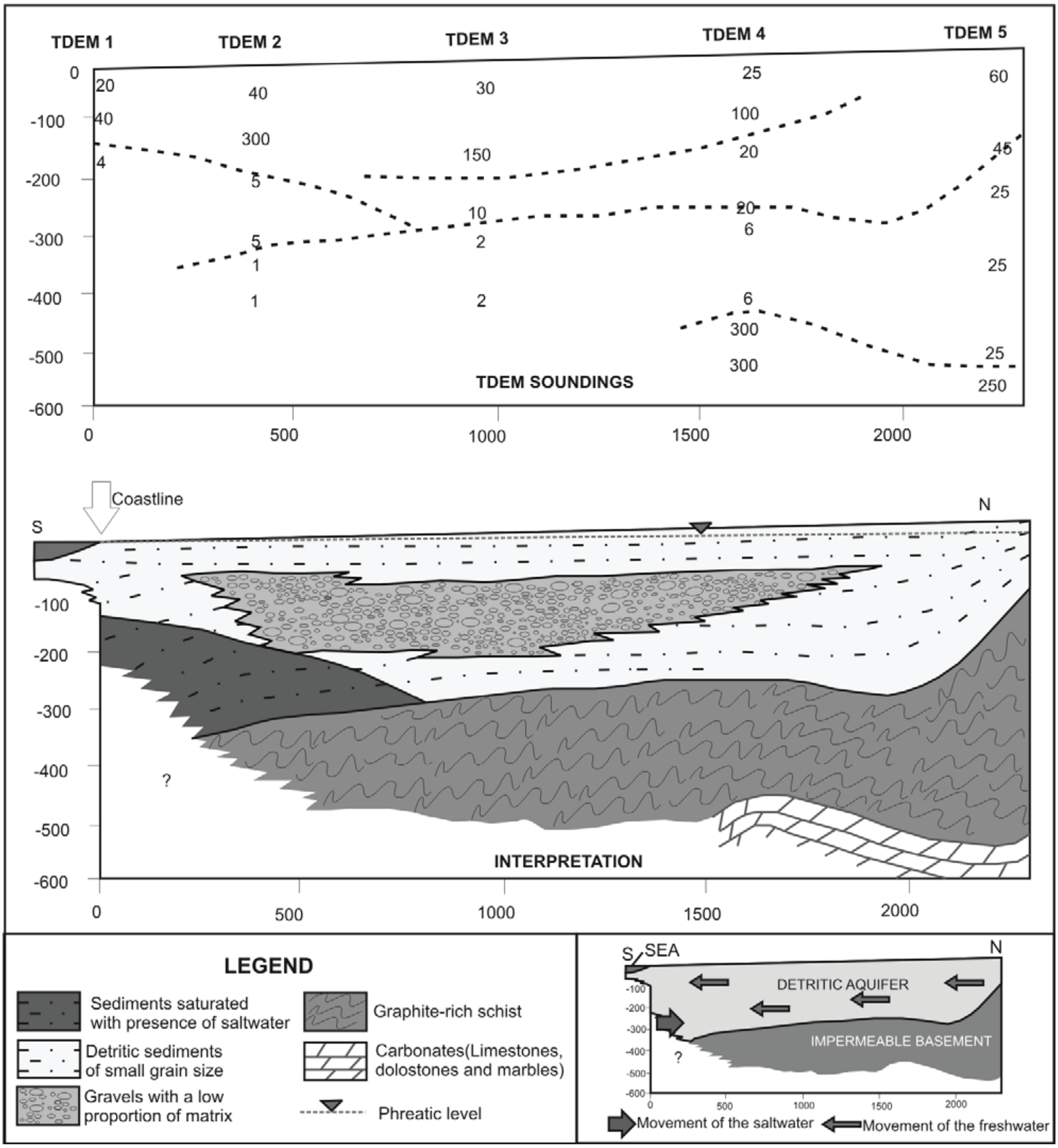

Fig. 4. Section with the electromagnetic data projected and main changes. For the interpretation we have assigned to the units the lithological characteristics of the rocks or sediments that outcrops nearby

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REFERENCES

[1] Aldaya, F. 1981. *Hoja nº 1056 (Albuñol del Mapa Geológico de España a escala 1 50000)*. IGME. Madrid.

[2] Benavente, J. 1982. *Las aguas subterráneas en la Costa del Sol de Granada.* Universidad de Granada. 336 p.

[3] Barbieri G., Barrocu G., and Ranieri G.,1986, Hydrogeological and geophysical investigations for evaluating salt intrusion phenomena in Sardinia. 9th SWIM. Delft

[4] Calvache, M.L., Rubio, J.C., López-Chicano, M., González-Ramón, A., Ibáñez, S., Martín-Rosales, W., Soler, R. and Diaz Losada, E. 2003. *Estado actual del acuífero costero de Motril-Salobreña previo a la puesta en funcionamiento de la presa de Rules.* Tecnología de la intrusión de agua de mar en acuíferos costeros: países mediterráneos. Tomo I: 77-86.

[5] Calvache, M.L., Cerón, J.C ,Rubio, J.C., Martín-Rosales, W, López-Chicano, M., González-Ramón, A., Ibáñez, S., and Duque-Calvache, C. 2004 *Caracterización de las relaciones río-acuífero en el sistema Motril-Salobreña (Granada).* VIII Simposio de Hidrogeología, 433-442. Zaragoza

[6] Calvache M L., Martín-Rosales W., López-Chicano M., Rubio-Campos J.C.,González-Ramón A., Duque, C. and Cerón, J.C, 2006. Repercusión de la presa de Rules sobre el acuífero detr´tico costero Motril-Salobreña (Granada) in El agua subterránea en los países mediterráneos. Guía de las excursiones. AquainMed-06

[7] Cantos Figuerola J., *Tratado de Geofísica Aplicada*, 1974

[8] Cardenal, J., Benavente, J , Cruz Sanjulián, J.J. and Fernández Gutiérrez, R. 1991. *Estimación de parámetros hidráulicos en el acuífero aluvial del río Guadalfeo (provincia de Granada).* II SIAGA, 313-324. Córdoba.

[9] Castillo, E. 1975. *Hidrogeología de la Vega de Motril-Salobreña y sus bordes*. Tesis de Licenciatura. Universidad de Granada. 184 p.

[10] Castillo, E. and Fernández Rubio, R. 1978. *Hidrogeología del acuífero de la Vega de Motril-Salobreña*. Bol. IGME, LXXXIX, 39-48. Madrid.

[11] Duque, C., Calvache, M.L., Rubio, J.C., López-Chicano, M., González-Ramón, A., Martín-Rosales, W. and Cerón, J.C. 2005. *Influencia de las litologías en los procesos de recarga del río Guadalfeo al acuífero de Motril-Salobreña*. VI SIAGA, 343-355. Sevilla

[12] García-Dueñas V. and Avidad J., 1972. *Hoja nº 1055 (Motril del Mapa Geológico de España a escala 1 50000)*. IGME. Madrid.

[13] Geirnaert, W , Pulido Bosch, A., Castillo, E. and Fernández Rubio, R. 1981. *Estudio de la geometría del acuífero detrítico de la vega de Motril-Salobreña mediante SEV.* I SIAGA, 291-302.

[14] Goldman M.,1988, Métodos de prospección eléctrica en el control de la intrusión marina. TIAC´88, Almuñecar.

[15] Granda A.,1988. Aplicación de los métodos geofísicos al estudio de la intrusión en acuíferos costeros. Experiencia española. TIAC´88, Almuñecar.

[16] Granda Sanz A. and Cambero Calzada J., 2000. Reflexiones sobre la experiencia de más de diez años de utilización del método de los sondeos electromagnéticos de dominio de tiempos (SEDT) en España, pag 175-183, in Actualidad de las técnicas geofísicas aplicadas en hidrogeología, IGME.

[17] Ibáñez S. 2005. Comparación de la aplicación de distintos modelos matemáticos sobre acuíferos costeros detríticos. PhD Thesis. Universidad de Granada. 304 p.

[18] I.T.G.E. 1991. *Investigación hidrogeológica para apoyo a la gestión hidrogeológica en la Cuenca del río Guadalfeo (Granada).* Technical Report (unpublished).

[19] Orellana E., 1972. *Prospección geoeléctrica en corriente continua*

[20] Pulido Bosch, A. and Cañada, P. 1983. *Estudio de acuíferos costeros mediante prospección geofísica eléctrica. Aplicación a los Llanos de Carchuna*. Hidrog. y Rec. Hirául. IX, 363-374.

[21] Pulido Bosch, A. and Rubio, J.C. 1988. *Los acuíferos costeros de Motril-Salobreña*. TIAC'88. 209-238. Almuñécar.

[22] Reeve C., Finch J., Butler A., Wheater H., 1986. The development and use of a resitivity probe to investigate saline intrusion in a coastal aquifer. 9th SWIM, Delft

[23] Soto, J.M. 1998. *Aportaciones al conocimiento del acuífero detrítico de Motril-Salobreña (Granada)*. BsCh Thesis. Universidad de Granada. 135 p.