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SEAWATER INTRUSION IN THE NE OF THE CAMPO DE DALIAS CARBONATE AQUIFER, ALMERÍA, SE SPAIN.

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ABSTRACT

From a hydrogeological point of view the Campo de Dalías is the SE slope of the Sierra de Gádor range and the coastal plain between it and the Mediterranean Sea, in the Almería Province, Spain. It is a semiarid area receiving about 150 mm of average yearly rainfall in the SE part of the plain, but up to more than 600 mm in the highlands to the NW. The Sierra de Gádor is formed by Triassic carbonates resting on Permo-triassic phyllites, which constitute the lower impermeable boundary. These materials progressively sunk towards the plain by means of faults, in a series of grabens and horsts. Generally they become covered by marly and detrital Upper Miocene to Quaternary sediments. Due to the complex lay-out of the materials, up to three overimposed aquifers are found in the plain. The carbonate aquifer is the lower one and the most important. This paper refers mainly to the NE part of it, which is called here AIN. In this semi-arid area, most of the aquifer system recharge is produced in the Sierra de Gádor, which receives isotopically light rainfall from storms coming from the SW, across the Iberian Peninsula. Under undisturbed conditions groundwater flow in the carbonate aquifer discharged into the sea through a small coastal area in the NE known as Aguadulce (freshwater). Although these springs are currently disappeared, the flow pattern is still clearly identifiable by relatively low water temperature in the deep layers and the chemical and isotopic environmental characteristics. The AIN aquifer is intensively developed, with pumping increasing from the 1970's to present. Groundwater heads are kept below sea level. As a result the wells of some areas have been affected by salinity increase. This paper contributes new insights about seawater intrusion and the lower aquifer behaviour by using only existing data from monitoring, logging and sampling in the long-screened wells and boreholes. This means taking into account vertical flows and mixing inside the wells and boreholes.

INTRODUCTION

The Campo de Dalías is in the SW of Almería, the capital of the Province of the same name, in SE Spain (Fig. 1). A traditionally depressed area due to its aridity is currently a rich one due to intensive special crops, mostly under greenhouses, which are irrigated almost exclusively with local groundwater.

The carbonate aquifer of the Campo de Dalías is the most important one in the southern area of the Sierra de Gádor range–Campo de Dalías aquifer system. The aquifer system supplies about 130.10^6 m^3/a for the close to 250.000 inhabitants and irrigated agriculture. About 110.10^6 m^3/a come from the deep carbonate aquifer.

The area has been intensively studied and surveyed by the Geological Survey of Spain (Instituto Tecnológico Geominero de España, ITGE) Project Office at Almería since the early 1970's, mostly from the geological and groundwater development point of view. A series of internal reports and a data/base contain the results, filled for public use.

This paper summarises the results of the doctoral thesis of the first author (Domínguez, 2000) under the guidance of the second one. It concentrates on the deep carbonate aquifer of the NE sector, called the NE lower aquifer (AIN), which supports a large fraction of total groundwater development.

From mid 1980's wells from some areas of the AIN have been affected by salinity increase and some of them have been abandoned. Further degradation is a thread to the socio-economic framework of the area.

GEOLOGICAL AND HYDROGEOLOGICAL FRAMEWORK

The aquifer system is in the eastern Mediterranean sector of the Alpine ranges of the Betic chain. This corresponds to the Sierra de Gádor massif and the coastal plain, called Campo de Dalías (Fig 1).

There is a carbonate series of the Middle to Upper Triassic of about 1000 m thickness, resting on thicker Permo-triassic materials, mostly phyllites that form the core of the antiform of Sierra de Gádor (Jacquin, 1970).

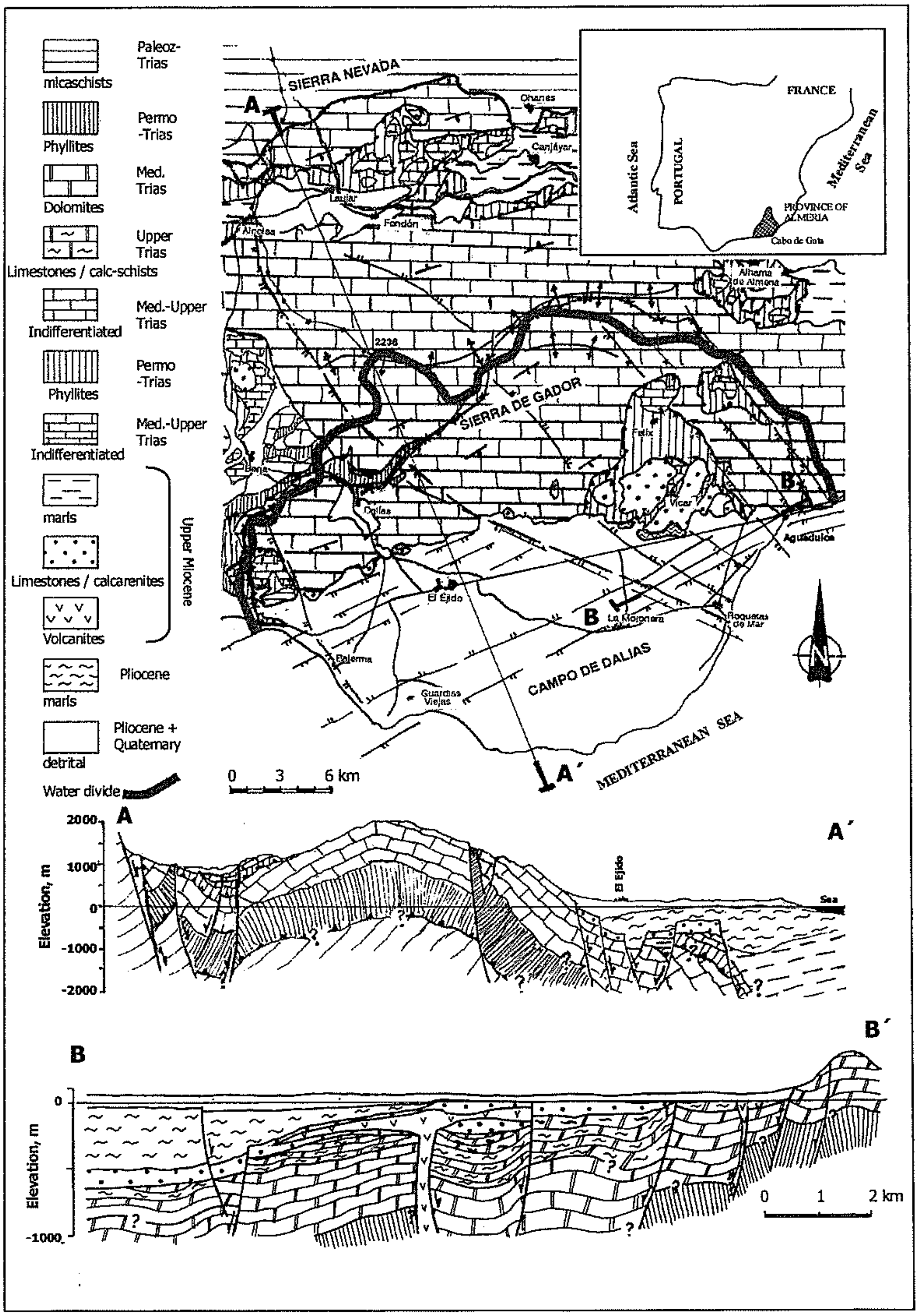

Figure 1: Situation and simplified geological map of the Sierra de Gádor range and surrounding areas. Two representative cross-sections are indicated. After ITGE internal documents.

This corresponds to the Alpujarride Tectonic Unit called Manto de Gádor. Inside this carbonate series there is a lower unit, mostly calc-schists, that is highly fractured and which is often the sliding surface of the thrusted upper formations. The Middle unit is the most continuous and massive, of mostly dolomites, and is the main outcrop at Sierra de Gádor. The Upper unit, of limited areal existence, is formed principally by limestones with frequent clayish interlayerings. The Post-orogenic materials filling the Neogenic basins that bound the Sierra de Gádor are Upper Miocene to Quaternary in age. They have a highly variable lithology, especially the Miocene sediments of continental shelf and interior basins. They include sands, sandstones, conglomerates, limestone, calcarenites, gypsum, marls, andesitic volcanites, etc. Near the coast, thick marly units are found, except at the NE and SW corner. Tectonics produce different blocks and consequently the aquifers are broken into more or less linked compartments.

GROUNDWATER MONITORING NETWORK

The economic relevance of groundwater to the area prompted the ITGE to settle a Project office in Almería to carry out monitoring surveys to help authorities and study the aquifers. Most of the monitoring boreholes are long-screened exploitation wells in which regularly the ITGE has measured water head, water abstraction, and salinity and temperature of water, and has taken samples for chemical analysis of major ion. Samples taken by means of pumping are mixtures from different depths. In some unequipped wells near the NE coast (Aguadulce), repeated downhole logs are available, as well as samples taken by means of a thief sampler at selected depths. Monitoring and sampling long-screened and multiscreened boreholes present problems of possible mixing of waters from different depths and the existence of vertical flows along the borehole due to differences in water head. But still they may be a source of knowledge if carefully interpreted. This topic has been analysed by several authors, such as Church and Granato (1996), Collar and Mock (1997), Custodio (1995, 1999) and Reilly and LeBlanc (1998). In Aguadulce area there is some information from deep exploratory boreholes, down to 550 m. In the Campo de Dalías, temperature and electrical conductivity (salinity) logs show important vertical flows inside the boreholes, which have been also studied by means of flowmeter logs. Repeated logs between 1989 and 1995 show the same pattern in each well. Borehole A-10, the deepest one of Aguadulce, that penetrates the lower tract of AIN, can be used to show the different tracts (Fig. 2). Between 150 and 200 m bsl (below sea level) there is the lowest temperature, 18ºC, which is even less than local surface temperature (20 to 23º C). As commented in Domínguez and Custodio (1992) this tract is very permeable and most groundwater abstraction comes from it. The permeable formations above leak relatively warmer and lower salinity water into the well, that moves downwards to the main tract, where it mixes with the cooler groundwater, of the main aquifer. The less permeable, undeveloped formations below have higher water heads. Thus they also leak water to the well, that moves upwards to the main tract; this water is saline, and relatively warm due to the geothermal gradient. Thus, a sample from the main tract, and also a pumped water sample, is a mixture of mostly water from the main aquifer water with some inflow from the upper aquifers and from the deep formations containing mostly saline water. For pumping wells the mixture is variable

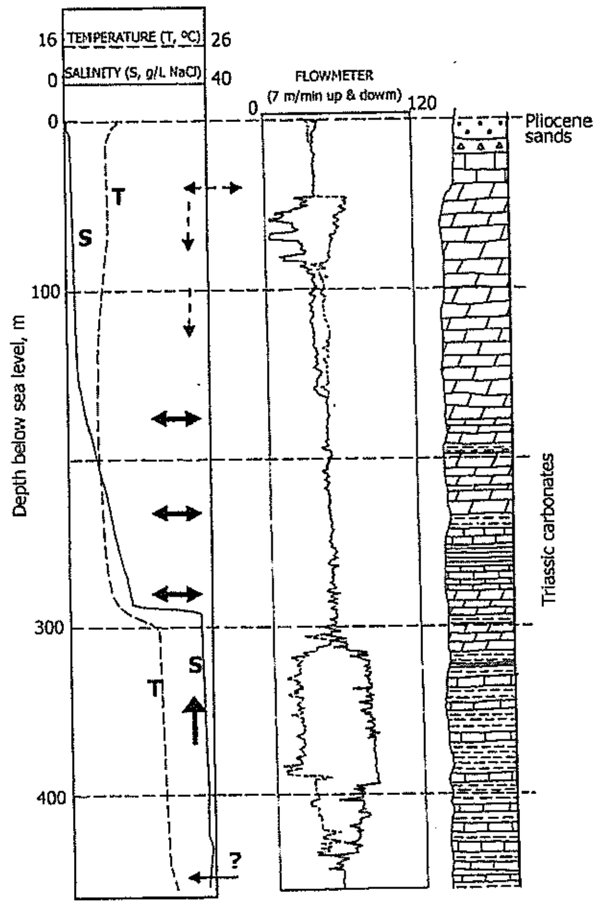

Figure 2: Temperature and salinity log of borehole A.10 (the deepest in the Aguadulce area) in July 1994. It is fully screened. The arrows indicate water flow inside the borehole, the greater the thicker, after interpretation of these logs. Flowmeter log results are in agreement. After Domínguez (2000)

according to the relative heads, discharge value, and duration of pumping. Water from the main aquifer undeveloped formations below have has a variable salinity and temperature (up to changes of 3.5ºC), according to location, as the mixing pattern is modified due to water head fluctuations in the aquifer system.

Data used here is mostly from the 1985-1995 period. The aquifer was close to natural conditions in the 1960's. Groundwater development was well established in 1980, mostly in the coastal area.

GROUNDWATER FLOW

The main aquifer (AIN) is recharged at the Sierra de Gádor range, at a high altitude. The aridity of the plain makes recharge at low altitudes not significant but for water mains distribution losses and return irrigation flows; they recharge the upper aquifers and in some areas may be transferred to the AIN. The AIN is covered along the coast by thick marly formations except at the NE corner. So, the flow is towards this area, where freshwater springs were known in the past and gave the name to the locality (Aguadulce = Freshwater). The oldest well data shows a head of about 4 to 5 m above sea level in the 1960's. Water chemistry and temperature agree with this pattern. Relatively cold water is due to the high elevation of recharge in the mountain highlands, which goes in parallel with the light isotopic composition of water respect springs fed locally in the slopes of the Campo de Dalías (Fig. 3).

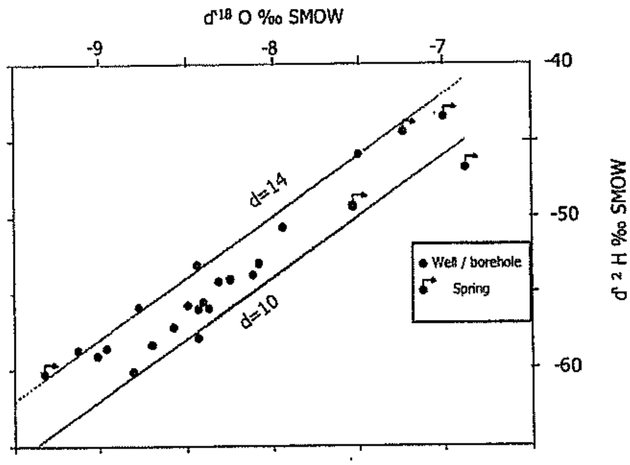

Figure 3: δ^2H vs. $\delta^{18}O$ for springs and boreholes in the Dalías aquifer system after different sources (see Domínguez and Custodio, 1994). For brackish and saline water the freshwater component is shown, which has been calculated after the chloride content. The meteoric water lines are included for excess deuterium of 10‰ (World) and 14‰ (assumed it is the local value for Mediterranean originated rainfall).

Also silica content is very low, about 3 to 4 mg L^{-1} SiO_2, whilst there is 10 to 12 mg L^{-1} and higher in the upper part of AIN and sedimentary cover aquifers. This means a short turnover time in the carbonate aquifer, which main zones should by highly fractured and/or karstified. In fact in this part it is occasionally difficult to get cores in exploratory drilling. It is still unclear how wide was the fast flow strip.

The characteristics given above refer mainly to the AIN aquifer near Aguadulce. Most data from other areas of the aquifer, corresponding to samples from pumping wells, shows similar water characteristics, but with higher temperature and silica content. This may be interpreted as having a longer turnover time due to structural and hydraulic conditions which may be modified by development. They probably correspond to tectonic blocks with restricted hydraulic connection to the strip to the NE where flow is faster, at least in some cases. The patchy development of the aquifer, which leaves areas with scarce or none information down to the AIN does not allow at present a detailed areal description of groundwater characteristics. Intensive development of the carbonate aquifer of the Campo de Dalías since the late 1970's is reflected in a regional head drawdown with heads almost permanently below sea level in the AIN, at least until the end of the observation period here considered. This is not the case of the upper aquifers (Fig. 4). Negative heads in the AIN prevail since 1991 to 1995 in Aguadulce and from 1992 to 1995 in inner areas.

This means not only halting the flow of coastal springs as early as 1982, but encroaching sea water through the coastal AIN outcops in the NE and through the nearby overlying detritical cover when it has some permeability and is thin. Wells near Aguadulce, the firsts that were developed, were soon affected by salinity due to the mixing of fresh and saltwater. This promoted their abandonment and replacement by other new wells further inland and in new areas. Many of them continue to extract fresh water after series of years, but the risk of salinization is a serious local concern, since this may seriously

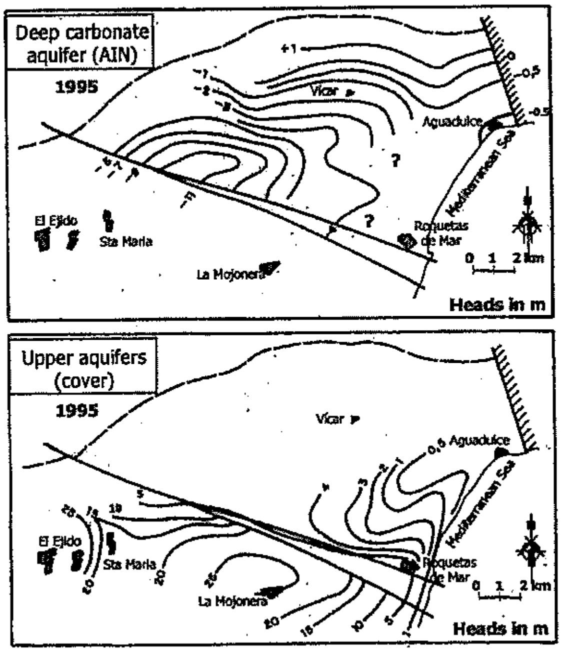

Figure 4: Approximate piezometric maps of the situation in 1995. The upper one shows the AIN carbonate aquifer where there is data. The lower one refers to the cover of detrital aquifers (Miocene to Quaternary). After Dominguez (2000).

jeopardize and disrupt the booming local economy. But this concern is not reflected as yet in funds and support for research, studies and action. A main exception is the continued ITGE surveys, but they have not fully used by the local water authority and economic agents. This explains that most information has to be derived by an inadequate monitoring network.

CHEMICAL CHARACTERISTICS AND SALINE WATER INTRUSION

In general terms salinity has been increasing in the Aguadulce wells of AIN since 1983. Figure 5 shows the increasing trend in an already salinized borehole in the Aguadulce area. Pumped water was increasingly saline. Cationic composition was changed from a simple mixture of fresh and marine water, showing an excess of Ca and a deficit of Na and K (Fig. 6). This is what could be expected as cation exchange when water salinity increases in a medium which formerly contained freshwater. The same characteristics appear in water from the main tract in some observation boreholes.

Apparently, this reactivity does not fit with the fast flow above commented, which means little contact between groundwater and the rock. To solve this it is necessary to take into account the lithologic variability of the AIN in its different structural blocks, and the water mixtures produced by pumping of fast flow ground water and others flows from lower permeability materials, including detrital Miocene and Triassic marls.

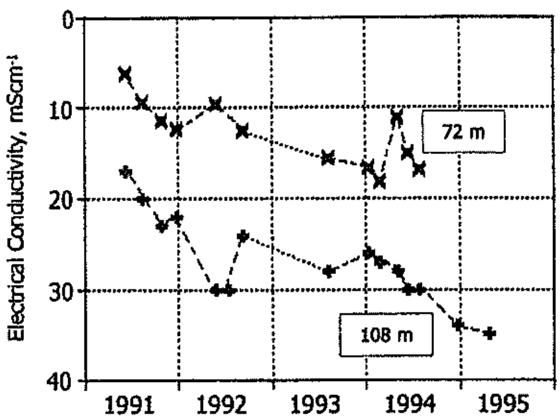

Figure 5: Evolution of electrical conductivity in borehole 224RM at depths below sea level of 72 m (inside the main flow tract) and 108 m (inside the saline water flowing upwards from below). After Domínguez (2000).

One alternative explanation is that saline ground water inflow is through the sedimentary cover or the lower layers of the deep aquifer. This is something to be investigated. This may imply that the coastal springs could be mostly an overflow than an open discharge into the sea.

Samples from the upper part of AIN show excess HCO_3, Na, Ca, and SO_4 with respect the simple mixing of AIN freshwater and marine water. This is the water contribution from upper levels, downward along the borehole. This water is locally recharged.

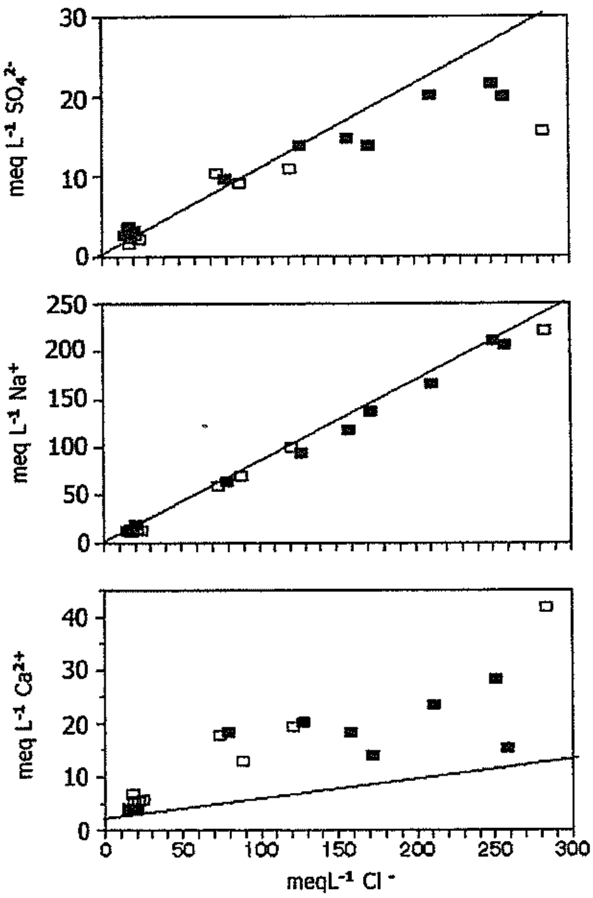

Figura 6: $SO_4{}^{2-}$, Na^+ and Ca^{2+} versus Cl^- samples taken at depth in the boreholes in the central part of Aguadulce area. The line indicates simple mixing of fresh and marine water. After Domínguez (2000).

The structural sinking of the main aquifer (AIN) towards the W conditions aquifer-sea relationships since it becomes progressively confined below low permeability Miocene volcanics and/or Pliocene marls. In the Aguadulce area, from E to W seawater is progressively found at a deeper depth: from 0 to 100 m (below sea level) in the E, from 100 to 200 in the centre, and down to about 300 m in the W, for 1994.

CONCLUSIONS

The monitoring data from long-screened observation boreholes are useful to know the salinity pattern and evolution of the main aquifer (AIN) once the existence and characteristics of along-the-hole vertical flows are known. Temperature logs are important in this respect.

In the Manto de Gádor Triassic carbonates (AIN aquifer) there are at least three subaquifers in Aguadulce area, of which the central one is the most continuous and yielding. This one is in contact with the sea at the NE corner, but becomes confined to the W. It is not clear if the contact with the sea is direct or through the sedimentary cover, and if the old springs were overflows or discharges into the sea.

It is necessary to know in detail the materials in contact with the sea and the effects of abstraction on aquifer water characteristics. Pumping may produce a mixture of different groundwaters, which render difficult the study of subaquifers and the different groundwater transfers among them.

Groundwater heads in the coastal area of the AIN were below sea level from 1991 to 1995, and this explains the salinity increase after 1985, and the abandonment of several wells.

From 1992 to 1995 (end of the observation period) groundwater head in inner areas of the AIN aquifer, which are actually the most developed, are lower than in Aguadulce. Then there is a water head gradient favourable to flow from Aguadulce, and there is the possibility of being affected by saline water. Until 1998 salinization of abstraction water has not been produced except in one area, but the risk is a real one. Aquifer management for a sustainable groundwater development needs additional studies and a new monitoring network with point boreholes. For an adequate groundwater management the relationship between the different blocks has to clarified and monitored and salt water heads have to be known besides freshwater heads. Saline upconing is probably an important process, currently poorly known. Chemical and environmental isotope studies are important to define many of current unknowns.

ACKNOWLEDGEMENTS

Studies have been carried out with the permission of the Geological Survey of Spain (ITGE), which has provided means, time and data. The support of Geol. Angel González Asensio, head of the ITGE's Project Office in Almería is specially acknowledged. The guidance and scientific support has been provided by the Department of Geotechnical Engineering, Mapping and Mining of the Technical University of Catalonia, Barcelona. The ideas are the authors' and do not have to be shared by the institutions in which they work.

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