DECISIVE INFLUENCE OF NEOTECTONICS ON THE WATER CONNECTION BETWEEN THE MEDITERRANEAN SEA, MAR MENOR AND THE CAMPO DE CARTAGENA AQUIFERS (SOUTH-EAST OF SPAIN).

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Abstract

Due to the existence of the "Coastal Fault", the Upper Miocene and Pliocene aquifers from the Campo de Cartagena are disconnected from the Mediterranean Sea and the Mar Menor. In addition, the Quaternary aquifer shows a difficult connection. However, in the Campo de Cartagena of Alicante, the absence of the above-mentioned fault connects the Pliocene aquifer with the Mediterranean Sea. This tectonic-hydrogeological phenomenon has had repercussion in the drillings made to collect sea water for desalination plants. The fractures which affect the calcarenites of Tyrrenian age constitute preferential water flow features which are wide enough to produce flows greater than 100 L/s.

Keywords: *Continent-sea water connection, neo-tectonics*, *desalination plants, South-East Spain.*

Introduction

The Mediterranean coastal areas in the South East of Spain enjoy a privileged climate, with moderate temperatures and many days of sunshine. Consequently they are places where many people live throughout the entire year or, at least, during the summer period. On the other hand, the climatic conditions favour the development of highly profitable agricultural activities. The continuous increase in population and the high demand of water for agricultural use create recurrent and serious supply problems in these areas.

This is the situation in many areas in the Southeast of Spain and, more specifically, in the provinces of Almería, Murcia and Alicante, where the few existing rivers cannot supply enough water for the existing demand. Many of the riverbeds are frequently used as tracks, such as the typical "ramblas" (dry riverbeds). On the other hand, coastal aquifers that used to supply a well developed agricultural activity, suffer from seawater intrusion and, consequently, many of them have had to be abandoned.

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Within the possible alternatives to this increasing water shortage we can mention, among others: saving water, the reuse of waste water once it has been treated, and importing water from other basins. There is also the desalination of sea water.

In the case of the province of Almería (Spain), after the dramatic drought period that ended in 1995, the decision was taken to use desalinated sea water. The desalination plant that was designed to supply the city of Almería would have an initial capacity of 4000 m^3/h (1100 L/s). Furthermore, the first stage of the Carboneras (Almería) desalination plant is finished and the second is just being started. This second stage has the peculiarity of being the largest in Europe and one of the few that exist in the world for essentially agricultural use, although not exclusively.

Concerning the province of Murcia, the first and only sea water desalination plant was built in this autonomous region in 1996, using vertical boreholes, and is owned by the Comunidad de Regantes de Mazarrón (Mazarrón Irrigation Association). It processes 30 Mm^3/yr of sea water (1000 L/s from 13 boreholes) and obtains 16 Mm^3/yr of product water (Rodríguez Estrella, 2003; Rodríguez Estrella et al., 2003). Currently, the construction of several desalination plants is being planned for irrigation and some to supply water for towns, such as the Nuevo Canal de Cartagena Plant (New Cartagena Canal), which will supply the needs of the city of Murcia and other coastal towns, such as Alicante and Cartagena.

This alternative has a long tradition in other parts of Spain, especially in the Canary and Balearic archipelagos, and is going to become a common practice throughout the most "arid" part of the Mediterranean, from Israel to Libya and Tunisia (Torres, 1996; 1999). Saudi Arabia, the United Arab Emirates and all the countries in that region, which are large oil producers, frequently use these desalination techniques and even, in some cases, have assessed the possibility of using desalinated water for artificial recharge, specifically in Kuwait (Mukhopadhyay, 2002). We must consider that technological investigations concerning desalination methods (Zarza, 1996) are in full production, which will allow, in a very near future, a significant and continuous reduction in price.

It is less costly to extract sea water by means of boreholes than to take it directly from the sea. Coastal boreholes extract water that has already been filtered, practically free from organic matter, which, consequently, requires fewer pre-treatment processes and, therefore, reduces costs. However, not all the points on the coastline provide a hydrological connection between ground waters from continental aquifers and sea water because impermeable materials may appear separating both units, thus preventing this relationship: in some areas, such as in the Segura Basin, the contact between permeable rocks and the sea is only 27.5 % (Rodríguez Estrella, 2002) and, in many cases, this is due to the influence of neotectonics and, specifically, faults, which also condition the geomorphology of the coastline. Therefore, the problems related with the uptaking of salt water for desalination purposes require a prior hydrogeological survey and, at a later stage, the selection of the most ideal collecting sites, the appropriate design of exploitation systems, including borings and termination of boreholes, their cleaning and development. Its importance is such that the final location of the plant will be conditioned by the results of this stage and not the opposite, as many public and private entities have assumed on many occasions, with the consequent technical failure, economic consequences and delays (Rodríguez Estrella, et al. 2003).

In the case of the plant for the public supply of Almería, the collecting area had to be located next to the desalination plant, as this plant was being built near the mouth of the Andarax River, within its delta . Not much information was available on the area, although there was information on the basin of the Andarax River (Pulido Bosch et al. 1992; Sánchez Martos, 1997), where the Hydrogeology Research Group of the University of Almería had been working for years (Sánchez Martos et al. 1999), as well as other agencies from the Administration (Carrasco and Martin 1988). Something similar has happened with the "Nuevo Canal de Cartagena" plant, where the collecting area had to be located next to the desalination plant, which was in an advanced stage of construction, without any previous hydrogeological knowledge of the area.

On the other hand, in classical hydrogeology manuals and, more specifically, in chapters dedicated to the study of fresh water-salt water contact (Davis and De Wiest, 1971) and to processes of marine intrusion (Custodio and Llamas, 1976), one of the techniques mentioned to reduce the risk of marine intrusion is to pump fresh water and salt water simultaneously in the same well (Benítez, 1963) in a 5:1 proportion or the creation of negative boundaries to the advance of the saline wedge by pumping water under the interface to be rejected to the sea. Therefore, it seems that the alternative to collecting sea water from the coastline aquifers may entail an improvement in the exploitation of coastal aquifers by considerably reducing the risk of marine intrusion and, at the same time, extending the life of large numbers of aquifers that are considered over-exploited.

The essential purpose of this paper is to state the importance of taking the neotectonics of the Segura Basin into consideration and, more specifically, in the Campo de Cartagena area, when designing an inverse osmosis desalination plant. Two areas have been analysed: A), which includes the coastline of the Mar Menor in Murcia and the Mediterranean coastline of Alicante as far as Punta de la Horadada (Cape Horadada); and B), from the above-mentioned cape to Torrevieja. In the first case, there is no hydrological connection between the most productive aquifers in the Campo de Cartagena and the sea due to the influence of what we have called “The Coastal Fault”; the Mancomunidad de los Canales del Taibilla (Taibilla Canal Association), after boring several vertical boreholes to be dedicated to collecting water to supply the Nuevo Canal de Cartagena desalination plant, with no results, decided to bore a marine aquifer by controlled horizontal boreholes. In the second case, the absence of the mentioned fault has allowed vertical boreholes near the coastline to extract flows of sea water of over 190 L/s for the future desalination plant of the Sindicato de Regantes del Trasvase Tajo-Segura (Tajo-Segura Transfer Irrigation Association).

General features of the Campo de Cartagena

The Campo de Cartagena district has the particular characteristic of being a geographical, geological, geomorphological, hydrological and hydrogeological unit (Rodríguez Estrella and Lillo Carpio, 1992) and, consequently, one can understand how, in the past, the inhabitants of this district have tried, on several occasions, to create an independent political unit (e.g. the "Cantón de Cartagena", in the XIX century).

Geographically, it is a plain area that spans the provinces of Murcia and Alicante and that extends towards the east to the Mar Menor, with a small island-hill called Cabezo Gordo; the plain is surrounded by hills.

Concerning the hydrological aspects, it is a basin that is not connected with the Segura Basin, where there are only small dry "rivers" that flow into the Mediterranean Sea (such as Seco and Nacimiento) and a number of "ramblas" (dry riverbeds) that lead to the Mar Menor (among which we can mention Albujón and Miranda).

From a geomorphological point of view, the Campo de Cartagena forms a wide basin with hills that, in general, slopes towards the Mar Menor.

It is geologically located within the Betic Mountain Ranges, on materials of the Betic Area, which crop out in the surrounding hills and are formed by Palaeozoic shales and Triassic carbonate rocks. The Campo de Cartagena, as such, is one of the post-tectonic inland depressions that is occupied by considerable Neogene fillings, mainly marls with a thickness of over 1000 metres. There are alternating Tortonian conglomerates and sandstones (150 m on average), Andalussian or Messinian calcarenites (125 m) and Pliocene sandstones (75 m). The more recent formations belong to the Quaternary with silt, clay, conglomerates, travertine and caliche (continental), and Tyrrenian (marine) oolitic calcarenites, with an average thickness of 50 m Tertiary materials, with synclinal structures discordantly resting and in sub-horizontal positions on a structure of blocks from the Betic period, such as Cabezo Gordo (emerged) or Riquelme (submerged). These blocks have been caused by a series of faults in a predominantly N 140 and N 65 E direction, which have conditioned the deposits from, at least, the Messinian, Pliocene, even the Quaternary times; this would explain the different thicknesses, depending whether they are found in a depressed or an elevated area. We must mention the heights of Cabezo Gordo and the trough of S. Pedro, where the Pliocene sandstone presents 10 and 110 m and the Messinian calcarenites, 80 and 210 m respectively; in the trough area, the Quaternary reaches a thickness of 150 m, a fact that is the consequence of neotectonics linked to the recent movement of certain faults. In the south of this depression, there is Miocene volcanism, mainly of a potassic calc-alkaline nature, with late ultrapotassic, shoshonitic and basaltic manifestations. In the case of the Mar Menor, volcanic rocks are calc-alkaline and, therefore, their appearance must be dated from the late upper Tortonian or early Messinian (6.6 to 7 Myr, according to Bellon et al. 1976). Volcanic emissions took place through weak areas of fractures, in a N 140 E and N 65 E direction and, more specifically, at the intersection of these. The igneous outcrops at the Mar Menor and nearby areas are small and frequently present an ellipsoidal shape with the longer axis in a N-S direction and star shaped with four points.

The Campo de Cartagena forms a hydrogeological unit, in which six aquifers have been defined (IGME-IRYDA, 1975; IGME, 1990, 1992 and 1994), which are the following: Triassic Victorias (over-exploited), Tortonian, Andalussian, Pliocene, Cape Roig (this one with permeable rocks from the Pliocene and over-exploited) and Quaternary (Figure 1).

All these are disconnected (geologically and hydrogeologically) from the Mar Menor by "The Coastal Fault" except the Quaternary aquifer. The Cape Roig Aquifer is hydrologically connected with the Mediterranean Sea. The hydrological connection between superimposed aquifers (Andalussian, Pliocene, Quaternary), which in principle should not take place as they are separated by thick sections of impermeable material from the Neogene, is caused by the boring operations performed over many years in the Campo de Cartagena district without grouting to insulating the different levels (with the intention of obtaining the greatest possible flow). This has caused an inflow (Figure 2) and consequently the progressive contamination from the higher aquifers, with low chemical quality, to the deeper aquifers, which initially had a good quality. With the arrival to the Campo de Cartagena of the water from the Tajo-

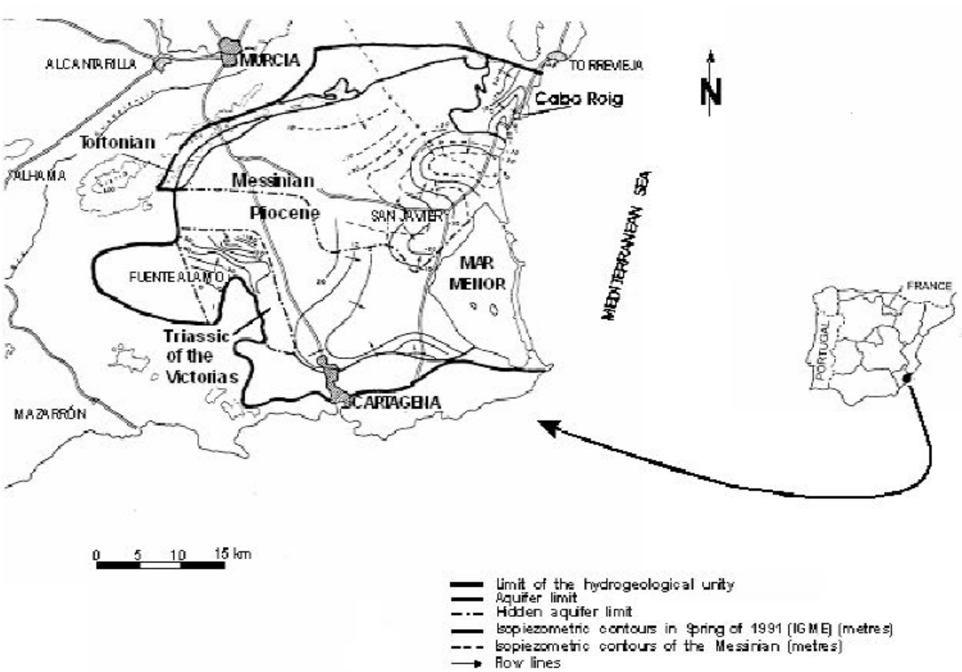

Figure.1. Tertiary and Triassic aquifers.

Segura Transfer in 1980 and as they were supplied by gravity irrigation system, the surplus from irrigation operations penetrated through the boreholes because, as already mentioned, the Quaternary aquifer had not been insulated. The consequence of this latter phenomenon is that the chemical quality of the Andalussian and Pliocene water has improved a bit (as the water from the transfer is less mineralised than the water of the mentioned aquifers), but, moreover, their piezometric levels have increased, as, on the one hand, important amounts of groundwater have been freed as they have been substituted by the surface water from the Transfer and, on the other hand, the deep aquifers have received the extra inflow of the irrigation surplus, through the boreholes (Rodríguez Estrella, 1995 and 2000 and Rodríguez Estrella and López Bermúdez, 1992).

Neotectonic analysis of the eastern coastal area of Murcia and the southern coastal area of Alicante

We have already mentioned that the Campo de Cartagena district, and especially its coastal area, has been affected by a neotectonic compression, the main axis of which is in an approximately N-S direction (Rodríguez Estrella, 1986); this has predominantly caused the appearance of shear faults at N 140 E (to the right) and N 65 E (to the left). These forces have continued until present times (active tectonics) and are displayed in epirogenic movements. This is why the coastal area from Cartagena to Cabo de Palos (Cape Palos) is rising, as well as the section between Punta de la Horadada and Torrevieja, while the area of the Mar Menor and the Manga are sinking by 3.8 mm/yr (Giménez García, 1998).

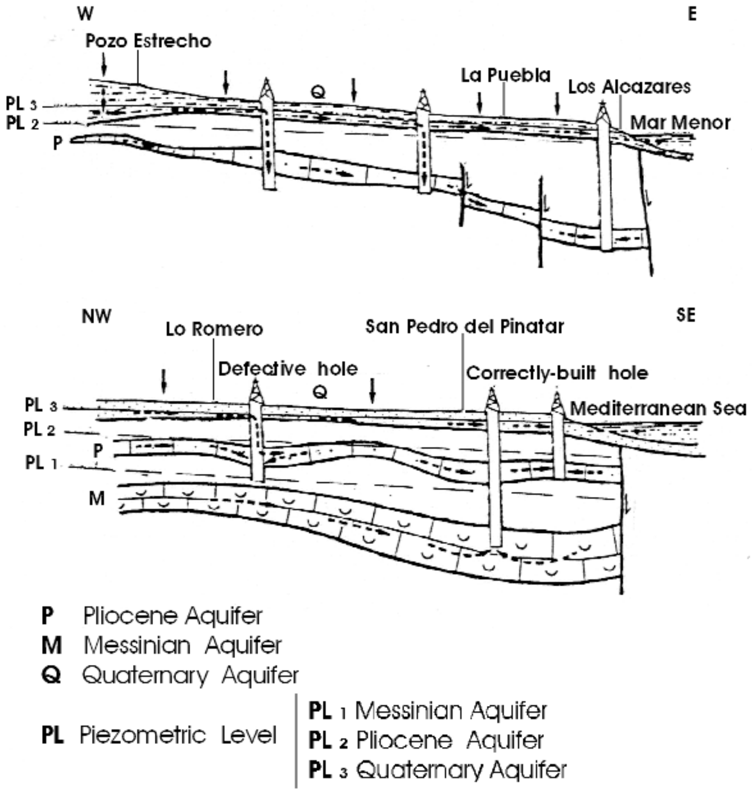

Figure 2. Hydrogeological relationships between the Campo de Cartagena aquifers, Mar Menor and the Mediterranean sea.

The Mar Menor is a hypersaline mass of water, almost closed, and in the shape of a triangle. It covers a surface of 130 km^2 and is between 5 and 8 m deep. It is located next to the Mediterranean Sea and separated from it by a detritic-volcanic sandbar from the Upper Miocene - Quaternary, called La Manga; this rocky cordon is interrupted in four places by channels (known as "golas") that communicate the two seas; two of them have natural origins and the other two are of anthropic origin, especially the El Estacio, which was opened in 1973 to allow the passage of yachts.

La Manga is formed by a coastal sandbar that is 24 km long and between 100 and 800 m wide. It was formed after a number of volcanic eruptions that created a line of several islands, connected by windswept sand. It is necessary to admit a subsidence in the Mar Menor, synchronic with sedimentation, that would explain the paradox of the lack of silting; this fact has been proved by Rodríguez Estrella (1986) in this and in other coastal lagoons located in the south of the province of Alicante, where this author senses, at a small scale, the existence of "micro-geosynclinals" with abnormal N-S and NW-SE directions, quite different from the NE-SW that characterise the Betic Mountain Ranges.

It is not possible to establish the exact moment when the Mar Menor was formed and, even less so, when the Manga became an almost continuous sandbar; but it is possible to present some considerations, in line with Rodríguez Estrella and Lillo Carpio (1992):

During the Tortonian period a compressive stage took place, in a N-S direction, followed (during the Messinian and Pliocene periods) by another stretching phase related to the volcanic activity in the area.

At the beginning of the Pliocene (5.2 Myr), the sea practically flooded the entire Campo de Cartagena district (except Cabezo Gordo island and Cape Victorias).

Towards the end of the Pliocene (1.6 Myr), the sea level fell and only some isolated lagoons remained, near the coast, with occasional communication with the sea (Plio-Quaternary continentalisation process). This is the period when the Mar Menor must have become a gulf, although of larger dimensions than its current size and with a non-linear perimeter. The Manga must have also commenced its formation in that period (or even a little earlier) related to the pre-existing volcanic relief and probably conditioned by the normal faults that formed a narrow tectonic horst.

At the beginning of the Quaternary, there was a compression period in a N-S direction where older faults were affected, mainly those in a N 140 E and N 65 E direction. These two groups of fractures would be the ones that have conditioned the current "pointed" shape of the Mar Menor and the coastline from the Tyrrenian.

The existence of current neotectonics, at least in the Manga, is proved by the location of seismic epicentres in the Mediterranean Sea, near this area.

The existence of vertical movements after the installation of fossil beaches is clear, both in the case of Caleta and at The Manga, where, at Seco Grande, a robust specimen of Strombus was obtained at a depth of almost five metres; this sinking continues today.

The geomorphology of the coastal area of Alicante, between Punta de la Horadada and Torrevieja, is greatly conditioned by predominant compressive neotectonics in a N-S direction, which have generated structures with directions in an approximate W-E direction, among which we can include anticlinals and synclinals and faults in a N 110 E direction with a right-hand and normal tearing component, among which we can mention the Fault of S. Miguel de Salinas (the sunken northern block of which presents a 300 m jump) and, to a lesser extent, those of Punta Prima, Cape Roig and Punta de la Horadada, which condition their respective capes; the Nacimiento and Seco Rivers adapt to NW-SE faults.

When the “Coastal Fault", which affects the coastline of Murcia and the coastline of Mojón in Alicante, reaches the Pilar de la Horadada fault, it is interrupted and disappears, a fact that has an obvious effect on hydrogeology and on the collection of sea water from the continent (Figure 3).

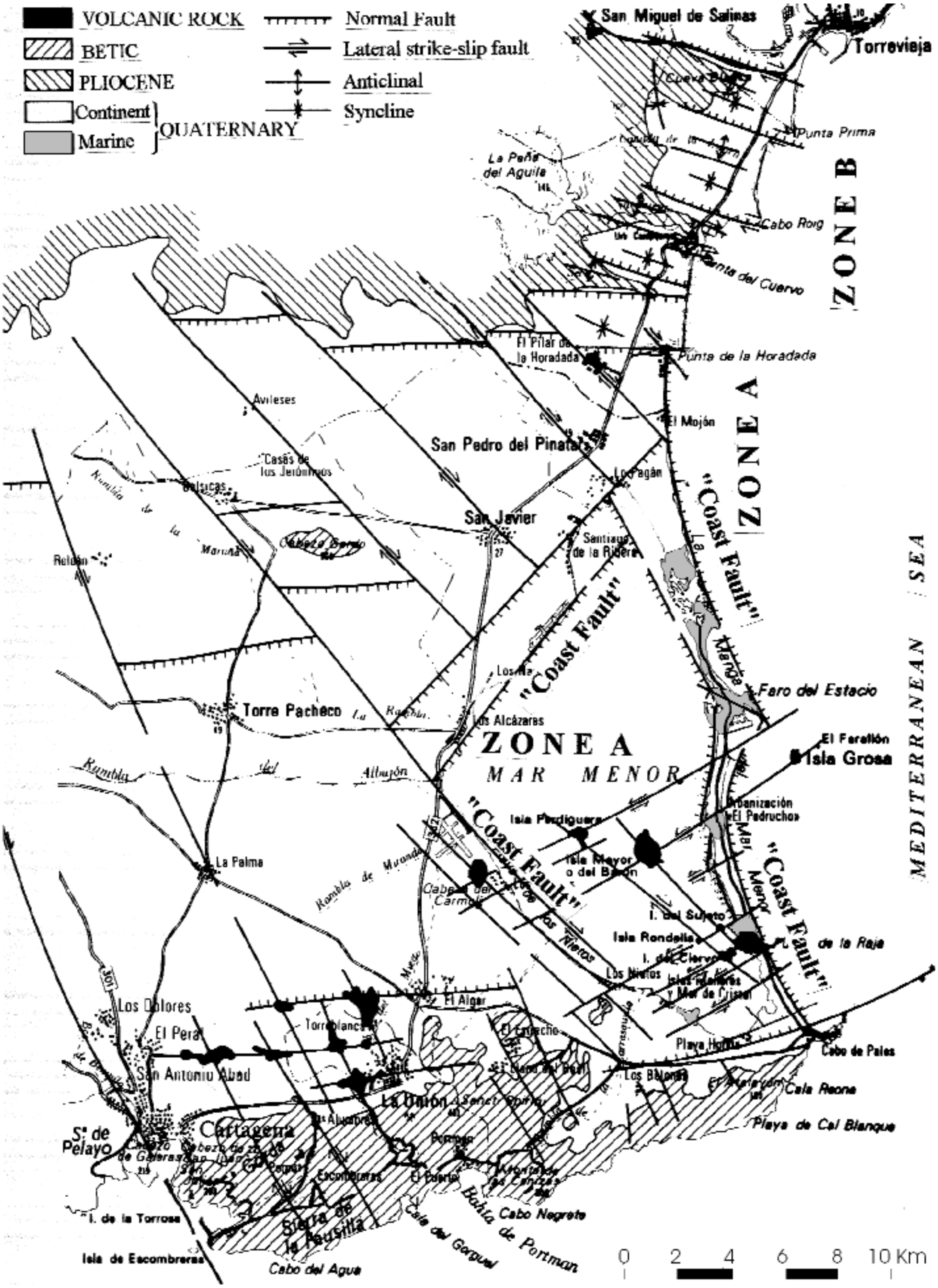

Figure 3. Neotectonic map.

Zone A: Nuevo canal de Cartagena desalination plant

The Mancomunidad de los Canales del Taibilla (MCT) has just built a reverse osmosis desalination plant near the town of El Mojón, which presents a certain peculiarity, as it treats sea water collected from marine aquifers by means of Controlled Horizontal Boring (CHB).

This desalination plant, known as the Nuevo Canal de Cartagena (NCC) plant, will provide a volume of desalinated water of 23.7 Mm^3/yr (65,000 m^3/day) and, in order to achieve this, it has to extract a maximum of 2,000 L/s of sea water from 20 boreholes. Its cost amounts 53 M € (43 M €, the plant and 10 M €, the collection works).

As vertical borings were initiated after the selection of the plant site, even when construction work was quite advanced, the location of the boreholes had to adapt to this situation and the only two permeable rock formations in the area had to be investigated even though, a priori, their scarce hydrological potential was foreseen: the oolitic calcarenites from the Tyrrenian (represented only in the sea) and the travertines from the Pleistocene (represented in the sea and on land), both of which only presented permeability due to fissures and belong to the Quaternary aquifer of the Campo de Cartagena district (Pulido et al. 2003).

As, on the one hand, the "Coastal Fault" conditioned the geomorphology of this area and hydrologically disconnects it from the productive aquifers of the Upper Miocene and Pliocene of the Campo de Cartagena district (Rodríguez Estrella, 1995), even hampering access through the Quaternary aquifer and, on the other hand, the interface is located approximately on the coastline; after boring five vertical boreholes to capture the travertines with discouraging results it was decided to perform controlled horizontal boring operations up to a length of 550 m and a depth of 10 m, in order to reach the permeable rocks under the sea, more specifically the oolitic calcarenites from the Tyrrenian and the Pleistocene travertines.

The *oolitic calcarenites* surface in the sea form an interrupted bar of isles (at least four), known as the "Reef del Mojón". The bar is in a N 170 E direction and intersects the coastline, as this is practically in a N-S direction; it even intrudes in the continent for a distance. The horizontal borings went through more than 300 m of marls in the direction the perpendicular to the bar.

The aquifer linked to these materials presents a limited extension; specifically a length of 1500 m with an average width of about 300 m and a variable thickness that can reach up to 5 metres in the centre of the bar (Figure 4).

It is an unconfined aquifer (there is direct contact at its upper part with the sea), which has been affected by neotectonics and where we can observe outcrops (apart from the boreholes) with metrically spaced orthogonal joints, in an almost N-S and almost W-E direction, in the cracks of which water circulates. As these are stretching fractures, there is a greater level of circulation to the top of the calcarenite than towards the wall and karstification has also become more developed (although to a lesser extent than in the mix zone). The average flow measured in the borehole is 100 L/s, obtaining a conductivity of 52 mS/cm, which proves the unequivocal connection with the sea.

This aquifer can be considered a marine aquifer, as it hardly outcrops on the continent. Due to its reef nature, below and next to it there is silt and reddish clay with a permeability level of 10^{-6} m/d, so we can

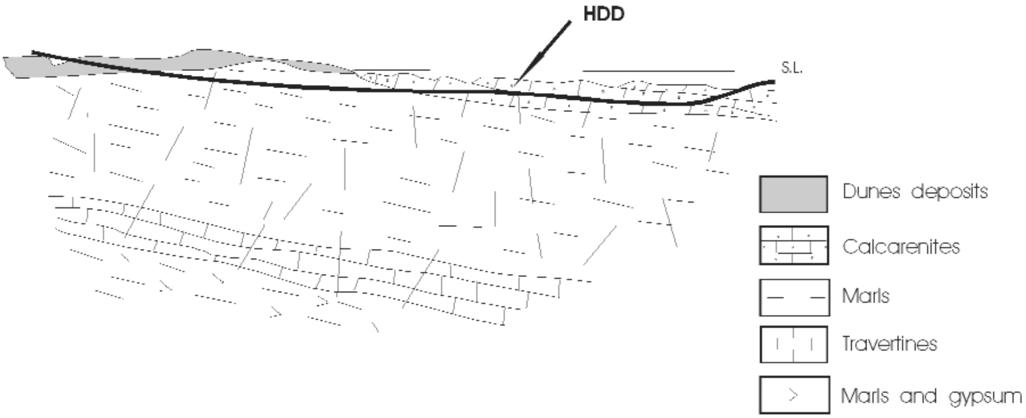

Figure 4. Horizontal Directional Drilling (HDD).

consider that it is isolated from the continent. Therefore, the extraction of groundwater from the calcarenites will not affect continental aquifers.

The other permeable rock formation is formed by about 20 m of white cavernous travertines from the Pleistocene. The aquifer linked to these materials presents a limited extension; it enters the continent for approximately 1.5 km but under the sea it reaches 6 km.

It is a confined aquifer, as it has an aquitard on the top and an impermeable wall (marl from the upper Pliocene). It has also been affected by neotectonics, as has been proved on the continent.

This aquifer has been found to be less productive during the boring surveys (CHB) than the calcarenites aquifer and, therefore, exploitation will be exclusively centred on the latter.

Zone B: Sindicato Central de Regantes del Acueducto Tajo Segura (SCRATS) desalination plant

The SCRATS wishes to build a desalination plant for agricultural purposes, which will produce at least 30 Mm^3/yr of water. For this, they need to perform, at least, 20 boreholes that will pump a total of about 2,000 L/s. From the beginning and being aware of the existence of the "Coastal Fault", that ceases to exercise its influence from Punta de la Horadada to the North, they selected this area and, more specifically, the Cape Roig aquifer to collect water from the sea through it.

The Cape Roig aquifer covers an area of 61 km^2 and the permeable rock is formed by 30-60 m of sandstone and calcarenites from the lower Pliocene, where the impermeable base is marl from the upper Miocene.

The aquifer is confined and plunges to the south, as the strata sink in that direction. Until 1992, due to the over-exploitation of 6 Mm^3/yr, the level was descending and reached, in some areas, levels of 20 m

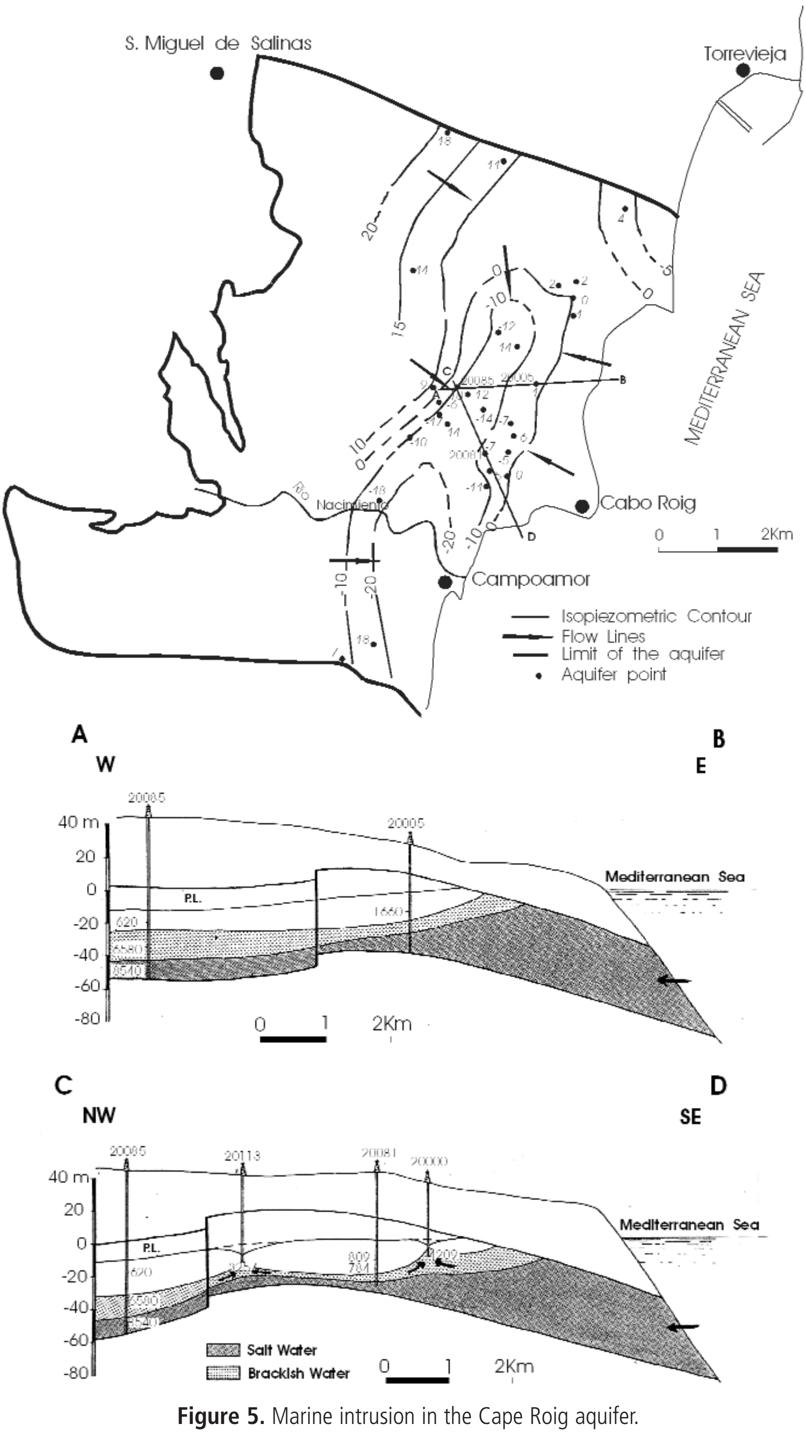

Figure 5. Marine intrusion in the Cape Roig aquifer.

below sea level (Figure 5). However, since that year, the aquifer has been subject to a situation of over-exploitation of 1.6 Mm^3/yr with increases of 0.5 to 0.75 m/yr due to: a) the abandonment of wells, due to the bad quality of the water extracted and b) to the arrival in the area, via the Pedrera Reservoir, of the TTS (Tajo Segura Transfer) water, with the resulting freeing of the underground flow, for irrigation.

Groundwater has an average saline content of 3000 to 5000 mg/L (of which 1000 to 2000 mg/L correspond to chloride) and belongs to a chloride-sulphate sodium-magnesium facies. The most important hydrochemical relations are: rMg/rCa = 1-2; rCl/rCO_3H = 6-14 ; rSO_4/rCl = <1. There is an evident connection with the sea.

Four investigation boreholes have been drilled and two pre-exploitation wells in the Cape Roig aquifer. The hydrogeological objective pursued is the sandstone and calcarenites from the Pliocene that have an average thickness of 50 m and, in all cases, are located in faults that are perpendicular to the coastline (Nacimiento and Seco rivers) in order to reach the more karstified areas and where the strata is more sub-horizontal. Furthermore, three pumping test operations have been performed, some of which have lasted for over a week, with their relevant chemical analyses. The transmissivity values obtained are between 250 and 750 m^2/d and the porosity obtained at the Nacimiento river was of 0.8 %.

The results obtained have been highly positive, as flows of up to 190 L/s have been measured as well as a saline level of 30,450 mg/L at about 100 m from the coast.

Conclusions

1) The knowledge and the awareness of neotectonics in the Campo de Cartagena district, when programming the collection of seawater by means of boreholes for treatment in desalination plants has been decisive, as the coastal aquifers in this district that are in contact with the sea belong to the Pliocene and Quaternary.
2) The "Coastal Fault" has conditioned the hydrological connection between the sea and the continent, disappearing at the Pliocene level or providing a difficult connection at the Quaternary Level, on the coast of the Mar Menor. On the other hand, on the southern coast of Alicante, the connection is very good, because the fracture does not exist.
3) The location of boreholes (last sector) in areas where faults are perpendicular to the coast has provided excellent results, with approximate flows of 200 L/s.

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