Geologica Acta, Vol.2, Nº2, 2004, 97-107
Available online at www.geologica-acta.com

geologica acta

Pumping seawater from coastal aquifers for supplying desalination plants

A. PULIDO-BOSCH P. PULIDO-LEBOEUF and J. GISBERT

Department of Hydrogeology, University of Almeria
Crtra. Sacramento, s/n, La Cañada de San Urbano, 04120 Almeria, Spain. E-mail: apulido@ual.es

ABSTRACT

The lack of water in the coastal areas demands an onerous search for an appropriate solution. One solution is that of water transfer from areas of surplus, but this is itself problematical. Technological developments have introduced the possibility of utilizing desalinated seawater as a drinking water source at a competitive price. Abstraction from coastal aquifers that are connected to the sea appears to be the cheapest means of supply. However, pumping poses some problems due to the corrosiveness of seawater. These problems include the difficulties of choosing suitable sites for the abstractions, drilling method, casing, filter pack, as well as the design of a monitoring system to assess aquifer behaviour as a result of the generally high exploitation rate. The 31 boreholes that have been drilled in the Andarax Delta near the city of Almeria are cited as an example of a real application.

KEYWORDS **Coastal aquifers. Desalination. Drilling methods. Drilling muds. Borehole logging. Well casing. Development.**

INTRODUCTION

Several coastal areas enjoy a benign climate, with moderate temperatures and many sunny days. As a result, people are attracted to live there all year round or at least during the summer. Equally, the climate favours the development of highly profitable agriculture. The continued population growth and the enormous summer influx, together with the large agricultural water demand, mean that these coastal areas frequently face serious supply problems, especially if there are no large rivers nearby.

Seawater desalination plants may be one solution. Certainly, they have proved to be so in many places in Spain, particularly in the Canaries and Balearic Islands and they are becoming common practice along the most "arid" parts of the Mediterranean, from Malta to Cyprus, Israel, Libya and Tunisia (Torres, 2001). Saudi Arabia, the Arab Emirates and the countries around, all large oil producers, use desalination techniques. It is estimated that the world current desalination capacity is 20 Mm^3/day.

The problems related to abstraction of saline or brackish waters for desalination require the exploitation systems to be appropriately designed, including drilling, casing, cleaning and development of boreholes. These factors are considered only once the optimum abstraction points have been selected. The importance of selecting the right abstraction points is such that the final location of the desalination plant cannot be determined until after this phase has been completed.

The classic manuals of hydrogeology (or more specifically, the chapters relating to the study of the freshwater-saltwater interface and seawater intrusion processes) describe one way of reducing the risk of marine intrusion as the simultaneous pumping of salt and fresh water in the same well in a ratio of 5:1. Another way is the creation of negative barriers against the advance of the saline wedge by pumping seawater from below the interface so that the wedge is pushed seawards. It therefore appears that the option of tapping seawater from the aquifers along the coastal fringe may provide the optimum means of exploitation because it reduces the risk of marine intrusion.

The specific objectives of this paper are to identify and describe the main problems that can arise at each stage. These are the selection of abstraction points, well-design (including the choice of the appropriate techniques for drilling, widening, logging, selection of well-casing and placement of screens), cleaning and development, as well as a consideration of the monitoring and control systems to be used during the exploitation phase. A variety of solutions are offered and their respective advantages and disadvantages are discussed, using the boreholes that supply the seawater desalination plant in Almería (SE Spain) as an illustration.

HOW TO APPROACH SEAWATER ABSTRACTION SCHEMES

Selection of the abstraction zone

The stratigraphy, sedimentology, tectonics, neotectonics, hydrogeology and hydrogeochemistry are among the principal topics to consider. The information should not be limited to the zone of abstraction, but extended to a much wider area, in order to gain a general understanding of how the system operates.

With respect to the geometry of the system, mechanical boreholes provide the most reliable information, though geophysical prospecting can help solving some uncertainties. Seismic methods, and in particular reflection techniques, are the most suitable though also the most costly. Electrical methods (in the widest sense, including electromagnetic) can be very helpful in determining the freshwater-seawater contact, because of the marked contrast in conductivity between them (Olmo and López Geta, 2000; Himi, 2000). However, they are of little use in sediments saturated by seawater along the coastal fringe, which occurs in almost all the cases we are concerned with.

Of course, we are interested in tapping aquifers that are connected to the sea, which is ultimately the source of water to be exploited. The aquifer materials with intergranular porosity are of particular interest, since these will best filter the water to be extracted. On the other hand, they are prone to deliver fines, which can pass through the filter matrix. Fissured and fractured aquifer materials can deliver high flows, especially through open fractures. The latter also facilitate the passage of organic material. A similar situation is noted for karstic aquifers, which can deliver very high yields, especially where there have been several changes of sea level over the last few hundreds of thousands of years, as is the case for the Mediterranean Sea (Zazo, 1999; Ginés, 2000).

Drilling

Any method that can produce a drilling diameter in excess of 600 mm would serve, though the optimum technique would be fast, clean, and precise in terms of the lithological assignment, and would additionally ensure adequate stability of the walls. Percussion is the most versatile technique, offering very little restriction in terms of diameter or lithology. Nevertheless, this technique can give rise to problems that limit its applicability. In the first place, it is slow. The risk of collapse is also high. Common to nearly all drilling methods is the problem of identifying the provenance of the cuttings precisely; this information is needed to determine the placement of the filter screens. This is normally solved by logging the boreholes once drilling is complete.

Standard rotary drilling using bentonite muds is a very fast technique, though it suffers from the need to remove the layer of mud-cake that forms on the wall of the borehole. Since part of the drilling is through terrains saturated with brackish and saline water with a composition close to that of seawater, conventional drilling muds may not serve, and seawater-specific muds must be used (Driscoll, 1986). The use of degradable muds is another option; this is a more sophisticated technique, which permits greater autonomy and facilitates some of the complementary operations, such as the emplacement of gravel packs and final cleaning.

Reverse rotary drilling is the best method of drilling through unconsolidated materials, given the ease of drilling large diameter boreholes, its speed and cleanliness, particularly if water is used as the drilling fluid. However, water is rarely the only drilling fluid and problems can arise because of the drilling muds, but these are usually more easily eliminated than in standard rotary drilling. The autonomy of the drilling equipment allows fast cleaning of the well.

Down-the-hole (DTH) hammer drilling is optimally used in consolidated limestone, dolomite or sandstone strata. It is rapid and clean (Plote, 1985), whilst its most significant limitations are the small drilling diameter (less than 450 mm) and the limited depth (rarely exceeding 250 m). The ODEX system is a variant that includes simultaneous casing of the borehole by means of a pilot drill bit with an excentric jig borer, which enables holes to be drilled with a slightly greater diameter (Detay, 1997). The method has the great advantage that the cuttings obtained derive almost exactly from the drilling depth, since the casing sunk with the drill avoids their mixing with materials from other depths. A problem with this method may be the subsequent withdrawal of the auxiliary drilling tube. A more recent technique is reverse DTH, probably one of the most precise techniques for determination of cuttings depth.

Lengths composed of fine, sorted sands may be difficult to drill, since they tend to be eroded and may enlarge the diameter of the bore to the point of collapse. Use of natural or artificial binding agents reduces this risk. A difficulty common to almost all drilling techniques is the assignment of the cuttings collected to their true depth; the effect of gravity segregation that normally occurs can lead to errors of several metres in drilling columns of less than 100 m.

Due to all of the above factors, when drilling through heterogeneous, non-consolidated material, it becomes necessary to log the borehole. The results from electrical methods in the seawater of the saturated zone lack resolution or else provide results that are difficult to interpret. Gamma ray logs may provide the best information; these are easy to interpret, giving good resolution of clayey layers, which give the highest values.

Using the record of the lithological column obtained from samples taken for each metre depth drilled, together with the geophysical logs, the screened and unscreened lengths of the borehole design can be calculated; bearing in mind —in the case of boreholes that tap seawater— that the greatest precision is required below the mixing zone. In rotary-drilled boreholes (normal or reverse) the connection between the electrodes and the formation is facilitated by the presence of drilling fluid filling the void; the physicochemical characteristics of the drilling muds must be considered when interpreting the logs (Chapellier, 1987; Hilliard, 1997).

Casing and Filters

The casing and filter materials need to be chosen with special care since the sea water has a high ionic strength and a considerable corrosive capacity. Conventional metal casings are rapidly corroded, and even stainless steel may not be immune from corrosion. Cathodic protection guarantees greater durability, though the soldered parts remain fragile. Special plastic casings are the most resistant to corrosion but they tend to have a lower mechanical strength. The fragility of plastic casing may be increased by the cement grout in the annular space between the casing and the wall of the borehole, mainly because of the liberation of heat as the cement sets.

The position and the opening size of the screens must be decided on the basis of the cuttings and well logs. As mentioned above, gamma ray logs usually yield the most useful information and are the easiest to interpret. The opening size must ensure the integrity of the gravel pack and of the aquifer material itself but equally, during the cleaning and development of the well, it must not impede the elimination of fines, so as to leave a well-classified gravel pack.

Gravel Packs

When an unconsolidated aquifer formation is tapped, it is imperative to anticipate the emplacement of an artificial gravel filter material. The methods of selecting an appropriate pack are well-known (Driscoll, 1986; Hilliard, 1997). It is always desirable to have siliceous gravel, due to its greater resistance to corrosion. Calculations may suggest particle sizes that vary widely over the depth of the borehole. Frequently, an optimum grain-size is chosen, based on local knowledge obtained about the area.

Cleaning and development always lead to settling and some restructuring of the grains, leaving a void in the annular space that could collapse and put the casing at risk (Fig. 1). For this reason, when installing the pack, it is recommendable to anticipate a system, which will enable more sorted siliceous gravel to be added. Two pipes are introduced from the wellhead to the bottom of the cemented zone, allowing to add gravel. When reverse rotary drilling is used, there is usually some mud in the borehole when the filter medium is put in place; this mud is partly trapped by the filter and has to be subsequently removed. This mud could otherwise clog the system when the siliceous gravel is injected.

Sealing and isolation of different levels

To tap seawater lying below the mixing zone, the most appropriate approach is to isolate the overlying freshwater layer using cement grout and/or an isolating material in the annular space between the casing and the wall of the borehole. It is advisable to extend the seal several metres into the seawater layer, in case of changes in the geometry of the freshwater-seawater contact during the abstraction period.

Many multilayer aquifers have been described along

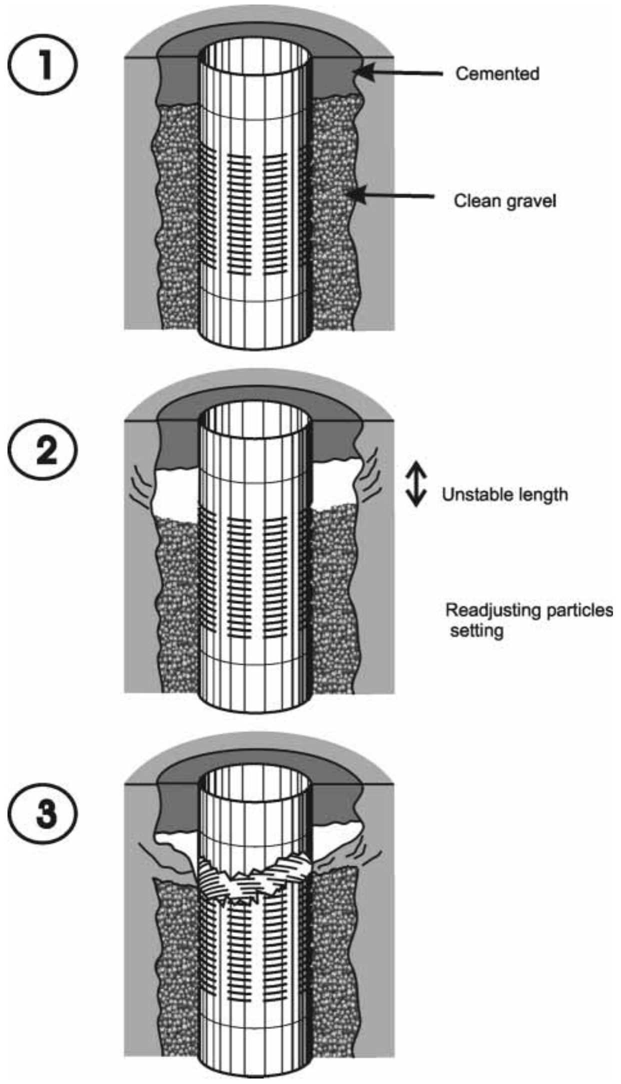

FIGURE 1 **Scheme showing the risk of collapse after settling of the gravel pack.**

the Mediterranean coast, generated by confined or semi-confined intercalations deposited at various times through the geological history of the area. These are related to relative changes in sea level and to the variable nature of the terrestrial inputs. The confining layers are of uneven thickness and usually thin laterally. Sometimes, the deeper layers have the greater hydraulic heads so that, with depth, the base of the interface lies closer to or even in the sea.

Monitoring

The design of a monitoring network must take account of the conceptual model of the system in the abstraction zone and any peculiar features. The simplest model is that of an aquifer within a homogeneous matrix. In this case, monitoring must take account of the fact that there is a vertical gradient of freshwater overlying sea water, with a transition zone of variable thickness in between. The hydrodynamics of the three layers may differ, such that sensors would need to be placed in each of the three layers, previously discretized.

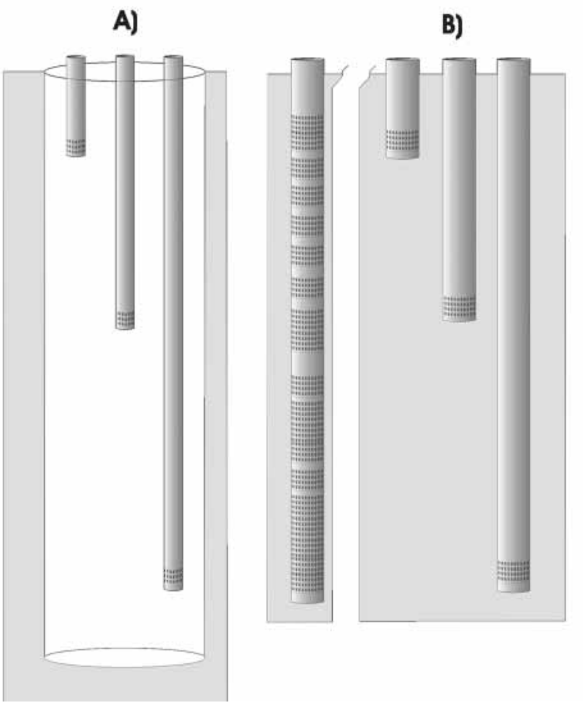

FIGURE 2 **Two types of multiple piezometers. A) Multipoint piezometer in a single borehole. B) Cluster of independent piezometers.**

There are many alternatives for placing the sensors in each of the three levels. The simplest one is using individual point piezometers, i.e., each one driven to just the depth at which observations are required and sealed from separate layers. Another option is to accommodate the whole set into a single, large diameter well. In the latter scheme it is difficult in practice to ensure the piezometers do not influence each other, and so it is not a highly recommended option. A simpler and more practical option is a cluster of piezometers (Fig. 2).

Once the piezometer sets are installed, there is not usually sufficient annular space for taking samples without dislodging the cable in each piezometer tube. For this reason, it is recommendable to have a piezometer that is screened along the entire aquifer column, with no sensor within it. This has to be placed far enough from the point piezometers so as not to disturb the natural state, especially if there are vertical components to the groundwater flow. This complex piezometer also enables conductivity and temperature logging.

Main Impacts

The tapping of seawater from coastal aquifers poses problems as yet not wholly resolved. Although it may be

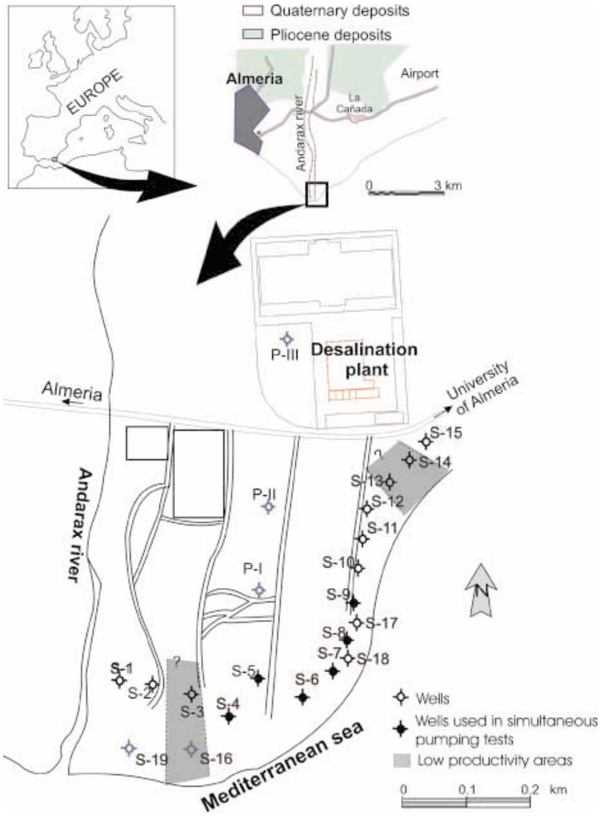

FIGURE 3 **Geological sketch and geographic situation of the boreholes drilled to supply the Almeria desalination plant. P-I, P-II and P-III: Piezometer set.**

used as a means of reducing or eliminating marine intrusion, there is a risk of an opposing "freshwater intrusion", caused by a loss of head in the seawater which leads to the advance of freshwater from the land towards the sea.

In complex coastal aquifers with intergranular porosity, subsidence may be induced as a result of the dewatering. The semi-confined layers with a low storage coefficient may be modified, their grains being restructured causing compaction. In very low-lying coastal areas, these small variations in elevation may cause a change in the position of the coastline.

Either effect can have important socio-economic impacts, especially in areas where both water and land have a high economic value. There may be claims for indemnization and legal proceedings that could paralyze the abstraction.

BOREHOLES OF THE ANDARAX RIVER DELTA

Choice of the seawater source

Almeria province contains few rivers and those that do exist have insufficient flow to meet the water demand. Alternatives for making up the increasing water shortage include water saving and reduction of wastage, reuse of treated wastewaters, and transfer of water from nearby catchments with greater water resources. After the dramatic drought that ended in 1995, Almeria opted for the desalination of seawater. A desalination plant was designed with a capacity of 4.000 m^3/h, equivalent to a continuous demand of more than 1100 l/s.

The plant is being constructed on the delta near the mouth of the river Andarax (Sánchez Martos, 1997; Sánchez Martos et al., 2002). As direct pumping of seawater causes clogging of the membranes due to the turbidity and the organic content of the water, it will be supplied by pumping from below the freshwater-sea water interface in the detritic aquifer that lies on the delta of the Lower Andarax. Nineteen boreholes were drilled at distances of 30 - 150 m from the coast (Fig. 3).

Figure 4 shows a summary of the materials drilled in the boreholes. The top ten metres are composed of a thin soil layer and alternating layers of lutites, medium-fine sands and some gravels; in addition, the boreholes towards the west cross some artificial filling in the first few metres. From 20 to 30 m depth, there is a layer of coarse gravels and sands, over a bed of lutites, with thickness diminishing from west to east. Between 35 – 80 m gravels are more abundant, and the grain size decreases with depth while the proportion of medium-fine sands increases. This bed thins out towards the NE, with increasing distance from the mouth of the river Andarax. Under this layer there are some alternating strata of lutites and sands that tend to disappear towards the east, giving

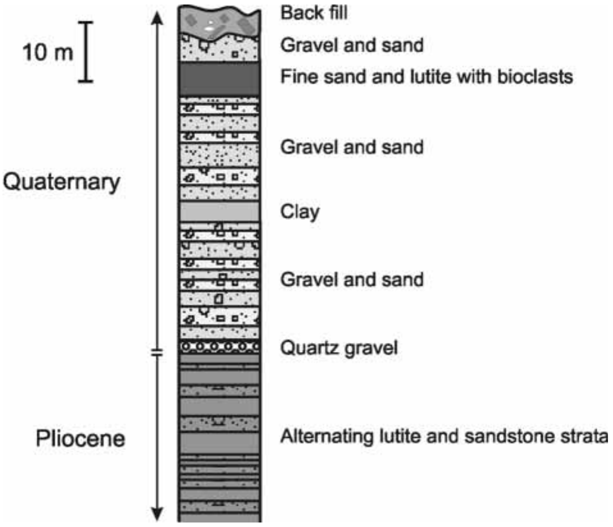

FIGURE 4 **Materials drilled in the boreholes of the delta of the Andarax river.**

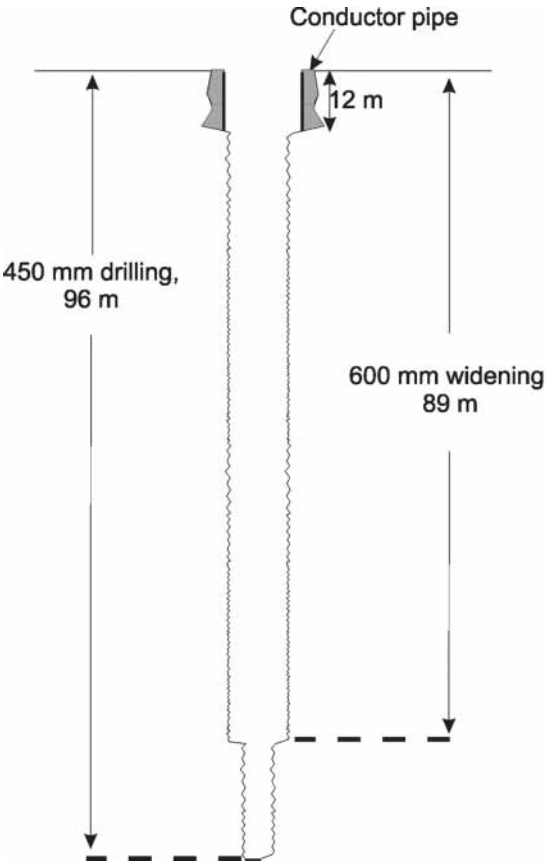

FIGURE 5 **Type-borehole characteristics (showing mean depths).**

way to a bed of bioclastic sandstones, cemented with many marine fossils. Finally, there is a layer of Pliocene gravels and sands between 90 and 100 m.

Drilling

The boreholes were drilled in a line parallel to the coast, at a distance of about 50 m from the coastline. Each well is separated at least 50 m from the others to reduce interactions. The type borehole (Fig. 5) consists of an upper solid casing (conductor pipe), whose function is to give stability to the rig whilst it drills. Its diameter is 700 mm and its depth varies between 9 and 14 m, according to the siting of the borehole. After sealing the conductor pipe, drilling continued at 450 mm diameter, for a depth of between 78 and 154 m. Once the type of casing and the position of the screen had been calculated, the hole was increased in diameter to 600 mm as far as the required depth. This depth was 118 m in borehole 1 and 78 m in boreholes 6, 7 and 8.

The high salinity of the water required atapulgite to be used as the drilling mud, instead of bentonite. Bentonite does not disperse in sea water and behaves as a separate phase, whilst the atapulgite does not flocculate and maintaines the necessary thixotropia (Detay, 1997). To avoid collapses in the fine sand strata, sawdust was added as a binder, with great success. The bed of quartzite gravel at the base of the Quaternary also caused problems, due to its hardness and its highly permeable nature, characteristics to which this type of drilling is not well-suited.

Geophysical logging

Detailed geophysical logging was undertaken before the borehole casing was installed. Measurements were made of spontaneous potential, monoelectrode sonde, gamma ray, normal, short and long resistivity, temperature and conductivity. The logs were interpreted together with the cuttings representative of each metre of the lithological column.

Figure 6 is a plot of the most important results from borehole 2. Based on these data, it was decided to case 104 m of the borehole, of which 27% would be screened (28 m) coinciding with the well-sorted sands and gravels

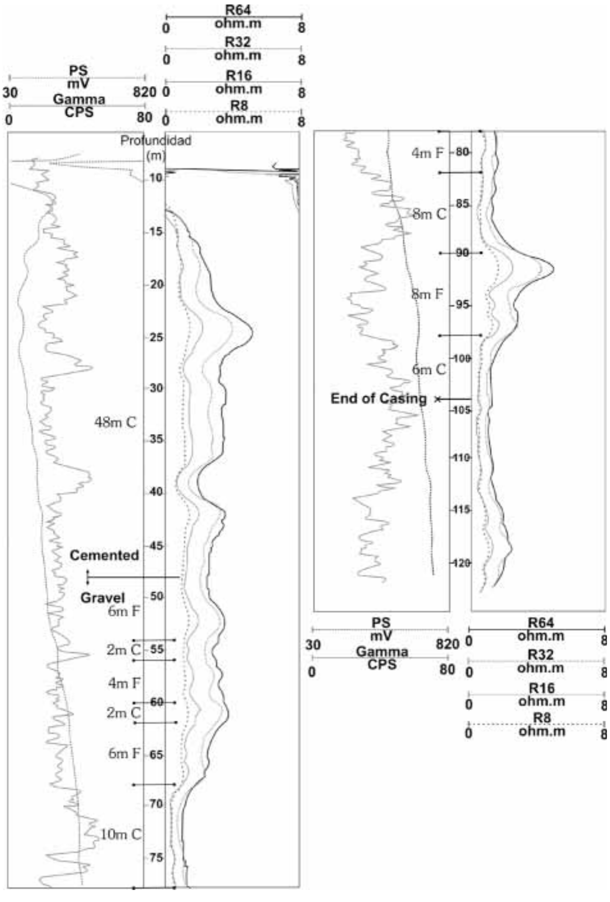

FIGURE 6 **Logs of spontaneous potential, resistivity and gamma in borehole 2. The lengths of screened and unscreened ling are indicated, based on these data. F: screen; C: casing**

below the mixing zone, and the remaining 76 metres, unscreened. The first screened length was placed at 48 m depth, and the last reached 96 m depth.

An interesting and rather surprising fact was the divergence of more than 5 m found between the cuttings obtained from a particular depth and the result of the logs, between the depths of 40 and 90 m.

Casing and filter packs

After a careful analysis of the various well-logs, the well casing was defined. The casing is made of a special plastic, which is resistant to sea water, salts, dilute acids, leachates, etc. The entire column was cased with 450 mm diameter tubing; at this diameter the thickness of the tube is 19 mm. Threaded joints joined the screened and unscreened lengths of tube. The total casing length varied between 116 and 65 m (Table 1), the last few metres of casing are not screened. All the boreholes bottoms are sealed with a wooden plug, which serves to prevent detritic materials from entering the casing (Sánchez Martos et al., 2002).

The screen selected has an aperture of 1 mm. To confirm that this size was adequate, the velocity of water flow into the borehole was calculated. The result was a velocity of between 2.2 and 4 cm/s, for a flow of 100 l/s, depending on the screened length in each case, which had a 10% open area. 20-31% of the screened casing was placed in lengths of at least one metre. The screened portions coincided with the well-sorted sands and gravels. The first screened length was situated between 35 and 53 m depth.

TABLE 1 **Borehole characteristics (values in metres).**

No	DEPTH	CASING	SCREEN LENGTH	CEMENTED	DISTANCE
1	154	116	20	51	150
2	115	104	28	47	150
3	106	100	24	42	150
4	105	99	27	38	100
5	102	100	24	40	73
6	78	65	20	33	64
7	78	65	18	33	60
8	78	72	21	31	60
9	83	75	18	37	52
10	82	76	22	36	51
11	82	76	20	40	51
12	86	80	19	40	52
13	84	80	22	42	50
14	87	81	19	40	50
15	114	79	21	40	50
16	96	79	19	38	50
17	90	76	21	35	50
18	96	85	19	36	40
19	87	79	21	39	50

Artificial gravel pack and grouting-in

All the boreholes incorporated a sorted siliceous gravel pack of clean, well-rounded, smooth and uniformly sized gravel, which extended over the entire productive length. A pack of standard granulometry was chosen, made up of 50% 2 mm-diameter and 50% 4 mm-diameter. Subsequently, the annular space was grouted in. Quick-setting cement was poured into the annular space to join the unscreened casing to the wall of the borehole. The upper part of the aquifer containing fresh and brackish water had to be perfectly isolated. For this, 700 kg of swelling clay (*Compactonit)* were used as a seal, extending upwards from a couple of metres above the first screened length —about 6 to 10 metres— and the remainder was cemented up to the ground surface.

Development

Having put the filter pack in place, development of the borehole begun using compressed air produced at the drilling rig. Starting at greatest depth, the outflowing water was very dirty at first, but became clear after the first few minutes. The whole operation took twelve hours. The pumping equipment was then installed at a depth of between 35 to 40 m, the precise depth depending on the situation of the screening.

Various clearance tests were done, repeating the flow rates of the exploitation phase in increasing order. In the first test various flow rates were tried, each for various periods of time, until the water ran completely clear.

During the test, a pause was made between each repetition or increase in flow rate so that the static level could recover. During the second clearance, decreasing yields were pumped, stopping the pump in between each phase. Altogether, these operations took 24 hours, since some flow rates had to be repeated up to three times.

After development, the drawdown for each pumped yield had decreased. The results were highly variable, ranging from cases in some boreholes where development was not effective, to others that produced drawdowns of 4 to 5 metres for flow rates of 100 to 130 l/s.

In four of the wells, it was not possible to increase the flow above 50 l/s, even though the water was running clear, since the water level rapidly dropped as far as the level of aspiration (30 m). It is difficult to explain this deficiency, though the proximity of the wells affected (nº. 3 and 16 were only just 50 m apart, and nº. 13 and 14, the same distance) leads one to think that the local features of the aquifer have probably an influence (Fig. 3). The boreholes with the greatest yield (Table 2) in the multiple rate pumping test (100

TABLE 2 | **Characteristics of the boreholes with the greatest yield. The specific flow corresponds to that obtained in a stepped pump test for a flow of 100 l/s.**

No	Depth (m)	Casing (m)	Screen (m)	Efficiency (%)	Specific Flow (l/s/m)	Reduction in drawdown (m)
4	105	99	27	76% (115 l/s)	22.5	0.5 – 1.5
6	78	65	20	63% (125 l/s)	20.5	0.5 – 2
8	78	72	21	67% (140 l/s)	48.8	0.2 – 1
10	82	76	22	44% (147 l/s)	28.4	0.4 – 0.6
11	82	76	20	64% (130 l/s)	17.7	2 –0.5
17	90	79	21	46 % (100 l/s)	26.11	3 – 0.5
18	96	85	19	29 % (130 l/s)	23.9	1 – 3
9	83	75	18	59% (130 l/s)	16.9	1.5 – 4

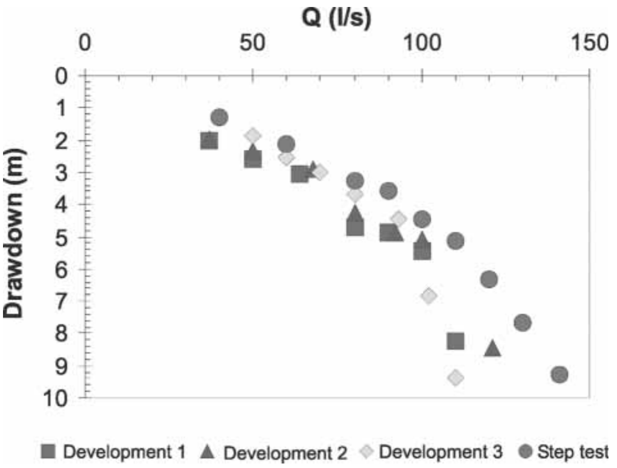

FIGURE 7 | **Yield-drawdown relationship for borehole 4, corresponding to development and multiple rate test.**

l/s) exceeded 20 l/s/m and borehole 4 reached 48 l/s/m. Figure 7 shows the results for borehole 4 during the development, in which very small increases in yield were made, repeating each flow rate up to three times. The results of the multiple rate test, done after the 24 hours development, are also shown.

As it has been explained above, each borehole was subject to individual pumping tests, using existing boreholes to act as piezometers. To gain some idea of the interference between boreholes when abstractions are made to supply the desalination plant, simultaneous pumping was tried at six boreholes (4, 5, 6, 7, 8 and 9 –representing those boreholes most easily accessed for monitoring–, Fig. 3). Four separate tests were made at combined flow rates of between 530 and 690 l/s.

Logically, well interference meant that the drawdowns for the combined pumping were greater than those recorded for individual pumping tests. The biggest difference was in borehole 7 and exceeded 5 m, whilst in boreholes 4 and 5 it was less than 2 m, even at the highest yields. Figure 8 shows a comparison of the individual and simultaneous drawdowns in various wells.

Figure 9 shows the spatial distribution of the drawdown at the end of the tests. A flow rate increase brings a marked increase of the drawdown; drawdowns of 6 m or more are shaded in grey.

Monitoring the freshwater-sea water contact

Since abstraction will be made from an aquifer

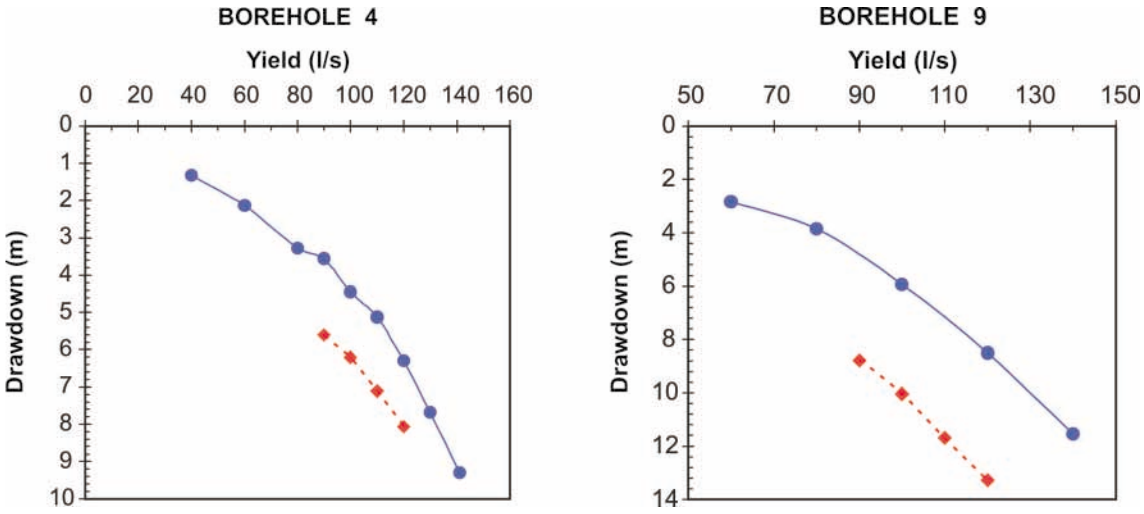

FIGURE 8 | **Yield-drawdown curves for two boreholes in the combined test. The solid line represents the individual pump test; the discontinuous line, the simultaneous test.**

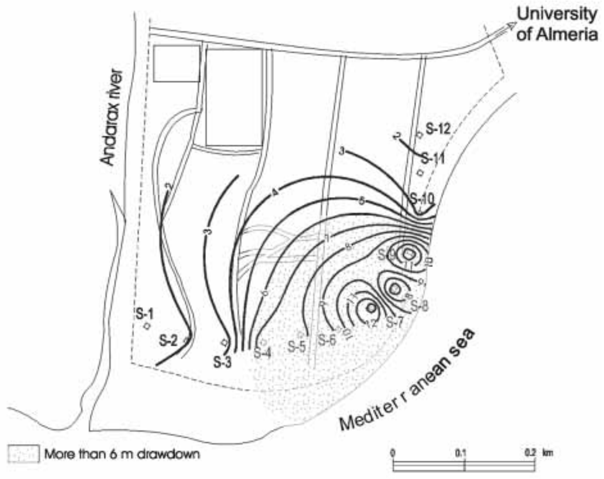

FIGURE 9 **Drawdown lines (m) for the 690 l/s combined yield pumping test.**

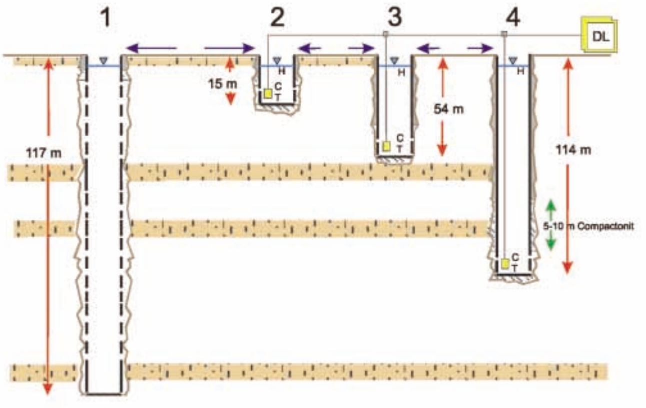

FIGURE 10 **Scheme showing the third piezometer set.**

where there already are users with rights acquired many years ago, there is an obligation to provide the installations with a monitoring network in the freshwater, the mixing zone and in the saline water, in order to record the response of the aquifer system to such a large extraction. Accordingly, three piezometer sets were designed (Fig. 3). The set consists of four observation points. The first passes through the freshwater layer, the transition layer, and penetrates the saline water; it is screened along its entire length, with large-grain-size gravel and coarse sand. The aim is to have a monitoring point at which conductivity and temperature logs can be made over the entire water column, and which allows samples to be taken from different depths, if necessary.

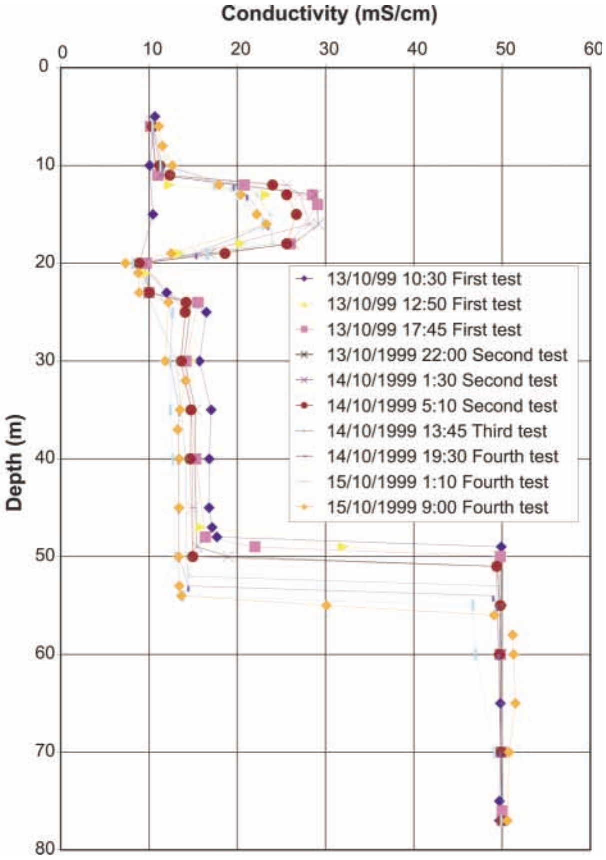

FIGURE 11 **Conductivity logs in piezometer 1 during the combined pumping test.**

The second one only penetrates the freshwater zone and is a point piezometer, i.e. it has only a 1 or 2 m screen; the third one is deeper and is screened only within the transition zone. The fourth and final point piezometer has a 1 or 2 m screen in the saline layer. The last three points will be equipped with water level sensors to measure fluctuations in each of the layers, and with conductivity and temperature sensors, so that the origin of water in each of the bands can be determined (Fig. 10).

These piezometers are set at depths of between 120 and 15 m, the deepest ones lying furthest from the sea. All of them were drilled with a diameter of 400 mm and screened at 180 mm. Isolation of the different water layers was done using the same sealant as in the abstraction boreholes, backfilling them afterwards with a sorted siliceous gravel-pack. All the piezometers were carefully cleaned with compressed air from the drilling rig, for a variable time of between 9.5 and 26 hours. Then they were cleaned using a small pump with a maximum output capacity of 10 l/s.

During the combined pumping test, and to take advantage of the fact that piezometers 1 and 2 were already constructed, a series of conductivity and temperature logs were made in these piezometers (Fig. 11). It is noticeable is that the transition zone was reduced to a minimum, whilst the upper layer showed a marked increase in conductivity over the course of the pumping test. These changes were sharper in piezometer 1 then in piezometer 2, and may be attributable to the greater salinity of the aquifer closer to the sea.

CONCLUDING REMARKS

The drilling of boreholes for the abstraction of brackish and saline waters presents a series of unique problems in comparison to more conventional boreholes. These arise from the fact that the medium is more hostile, in terms of aggressivity and corrosive potential. Various measures are therefore required to prevent problems at a later date. With respect to siting of the boreholes, conventional geophysical methods are not reliable for the water below the interface. Once a site has been determined, a suitable drilling method must be chosen. Reverse rotary drilling gives satisfactory results in aquifers with intergranular porosity, with a variable granulometry, though percussion drilling may be a useful adjunct in the first few metres.

Where drilling muds are required during borehole construction, it should be kept in mind that bentonite may not mix properly. Thus, muds that disperse correctly in brackish and saline waters have to be used. Emplacement of open screen within the casing column must be based on the results of a detailed study of the borehole column, derived from cuttings and geophysical logs. With respect to the latter, gamma rays provide the most sensitive method below the interface. Differences in level of more than 4 metres between the cuttings and the logs were recorded at depths of between 40 and 100 metres.

The well casing has to be specially prepared to tolerate the highly aggressive water. Not even stainless steel tubing offers a total guarantee against corrosion, though cathodic protection reduces the risk. Special plastic tubing may give the best results, though its mechanical strength is significantly less than metal.

An adequate monitoring system is desirable, particularly where the behaviour of the system must be known because of the existence of other aquifer users with acquired rights. Monitoring should include the freshwater, interface and seawater heads. These parameters can be complemented by records of the electrical conductivity of the water, this being the parameter that most easily identifies the processes of freshwater-seawater mixing. All the measurements can be made by constructing piezometer sets.

The application of conventional logs proved highly useful, together with the lithological log, in providing information about the formations penetrated by the borehole, in designing the well-casing. The use of the ideal, high-quality materials will guarantee the success of the installation and extend the useful life of the wells against incrustation, corrosion and clogging of the filter packs and screens.

ACKNOWLEDGEMENTS

This study was undertaken as part of a contract between the companies building the desalination plant and the University of Almeria. The work has made use of certain aspects of the HID99-0597-C02 project funded by the CICYT (Spanish Interministerial Commission for Science and Technology). We are grateful to Drs. Sánchez-Martos and Vallejos for their collaboration during the contract. This paper was presented as a keynote at the Meeting Computational Methods for Porous Media held in Fez (Morocco, May 2001).

REFERENCES

Chapellier, D., 1987. Diagraphies Appliquées à l'Hydrologie. Paris, ed. Tecdoc, 165 pp.

Detay, M., 1997. Water Wells, Implementation, Maintenance and Restoration. Chichester, John Wiley and Sons, 379 pp.

Driscoll, F.G., 1986. Groundwater and Wells. Saint Paul, Minnesota, Johnson Division, 1089 pp.

Ginés, J., 2000. El karst litoral en el Levante de Mallorca: aproximación al conocimiento de su morfogénesis y cronología. Doctoral thesis. Universidad de Baleares, 595 pp.

Hilliard, V., 1997. Drilling. Australian Drilling Industry Training Committee Limited. Boca Ratón, ed. Lewis Publication, 615 pp.

Himi, M., 2000. Delimitación de la intrusión marina en los acuíferos costeros por métodos geofísicos. Doctoral thesis. Universidad de Barcelona. 342 pp.

Olmo, M., López Geta, J.A. (eds.), 2000. Actualidad de las técnicas geofísicas aplicadas en Hidrogeología. Madrid, Instituto Tecnológico Geominero de España-Diputación de Granada, 375 pp.

Plote, H., 1985. Sondage de reconnaissance hydrogéologique. Méthode du marteau fond-de-trou. Orleans, ed. Bureau de Recherches Géologiques et Minières, série Manuels et méthodes, 12, 150 pp.

Sánchez Martos, F., 1997. Estudio hidrogeoquímico del Bajo Andarax (Almería). Doctoral thesis. Universidad de Granada, 278 pp.

Sánchez Martos, F., Pulido Bosch, A., Calaforra, J.M., 1999. Hydrogeochemical processes in an arid region of Europe (Almeria, SE Spain). Applied Geochemistry, 14, 735-745.

Sánchez Martos, F, Pulido-Bosch, A., Pulido-Leboeuf, P., Vallejos, A., Gisbert, J., 2002. Los sondeos de abastecimiento a la planta desaladora de agua de mar de Almeria. In: Pulido Bosch, A., Vallejos Izquierdo, A., Pulido Leboeuf, P.A. (eds.). Acuiferos costeros y Desaladoras. Almeria, ed. Club del Agua Subterránea, 169-184.

Torres, M., 2001. La desalación de agua de mar ¿recurso hídrico alternativo?. In: Pulido Bosch, A., Calaforra Chordi, J.M., Pulido Leboeuf, P.A. (eds.). Problemática de la gestión del agua en regiones semiáridas. Almería, ed. Instituto de Estudios Almerienses, IEA, 81-96.

Zazo, C., 1999. Interglacial sea levels. Quaternary International, 55, 101-113.

Manuscript received March 2003;
revision accepted November 2003.