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The Role of Aquifer Media in Improving the Quality of Seawater Feed to Desalination Plants

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Abstract This study focuses on the role of the aquifer media as a tool to improve the characteristics of seawater used to supply desalination plants, quantifying this improvement from a considerable number of physicochemical parameters. The evolution of both physicochemical and microbiological characteristics through the aquifer media has been determined by comparing the composition of seawater samples taken via direct intake with those taken over the aquifer. The principal improvements are due to the process of filtration. It includes up to a 95 % reduction in turbidity and up to a 50 % reduction in SDI. Other parameters are also notably reduced (TOC is cut on average by 60 %, and DO by 80 %), due to bacterial activity in the aquifer. It is also important to highlight that only a short distance of water flow through the aquifer is needed to achieve this improvement. If it used the seabed as the filter material, it would be necessary a minimum thickness of a few meters due to biological activity involves a significant increase in the TOC. An understanding of the filtration processes occurring within the aquifer provides a natural analogue on which future improvements in artificial pre-treatment can be based.

Keywords Beach well · Seawater intake · Filtration processes · Aquifer matrix

1 Introduction

The method of seawater capture for supplying reverse osmosis (RO) desalination plants is a key factor in determining the cost of the desalinated water, and a significant factor influencing the useful life of the membranes and the plant as a whole (Kreshman 1985; David et al. 2009). The two abstraction methods most commonly used are *open seawater intake* and *beach well systems*.

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Direct seawater intake is the most widely used technique since it requires relatively simple and cheap infrastructure, and is capable of delivering large seawater flows to the plant. The main drawback of this abstraction method is that water quality is usually poor, due to high concentrations of organic matter and dissolved oxygen, and elevated SDI (*Silt Density Index*), which generally exceed the values recommended by the manufacturers of the RO membranes (Gille 2003; Bonnelye et al. 2004).

An alternative method is to use coastal boreholes (*beach wells*), which offer the possibility of supplying better quality water to the desalination plant: the aquifer formation filters the water before it reaches the plant, so reducing pre-treatment costs (Peters and Pintó 2008; Anderson et al. 2009). The technique consists of sinking a battery of boreholes into a coastal aquifer in order to make abstractions from the seawater wedge that penetrates beneath the fresh water in the aquifer. The disadvantage of this type of intake is the condition that the desalination plant must be sited close to a coastal detritic aquifer with sufficient hydraulic connection to the sea, and the aquifer must possess the features that render it able to be supply the flow demanded by the plant at all times, and at a certain quality. These aquifer features include a minimum transmissivity of 1,000 m^2/day (Voutchkov 2005), and an aquifer depth of at least 50 m below the fresh water-seawater interface. In addition, there must be adequate connection between the aquifer formations, with no lithological or structural barriers (Schwarz 2003). A range of other, much less common, intake techniques also exist, such as horizontal directional-drilled wells (Pintó 2004; Peters et al. 2007; Rodríguez-Estrella and Pulido-Bosch 2009); however, this is a much more expensive undertaking and one that is justified only where an aquifer has insufficient capacity to supply the desalination plant via vertical boreholes, or where a direct seawater intake would not guarantee the minimum specified quality.

Attempts have been made to simulate the improvement in seawater quality provided by the aquifer matrix, by installing pre-filters (sand or cartridge filters) or artificial porous media in an infiltration gallery (Jones 2008). The improvements in water quality that such filters can provide have been the subject of laboratory studies (Wend et al. 2003).

This paper reports a pilot scheme to investigate the behaviour of the aquifer media as a tool for improving seawater quality. The objective of the current study was to quantify the improvement in seawater quality in the experimental plot as it flows through the aquifer matrix from the coastal intake to the desalination plant. Some authors compare the quality of water supply to desalination plants taken directly from seawater or uptaken of aquifers through boreholes (Gille 2003; Jones 2006; Peters and Pintó 2008; Rodríguez-Estrella and Pulido-Bosch 2009). However, none of them quantifies the improvement of quality water controlling a significant number of physicochemical parameters, in both seawater and groundwater. Recognising how this improvement occurs could contribute to improvements in the design of artificial filters, based on the aquifer media as a natural analogue.

The experiment consisted of drilling three boreholes aligned perpendicularly to the coast, the one furthest inland was used as the pumping well to simulate the operation of beach wells that supply desalination plants. The other two boreholes were used as observation piezometers to monitor the changes in the physical, chemical and microbiological characteristics that take place along the flowpath between the sea and the pumping well.

2 Hydrological Setting

The pilot scheme was installed on the left bank of the delta of the river Andarax, in southeastern Spain (Fig. 1a). This region of Spain is one of the most arid in Europe, with

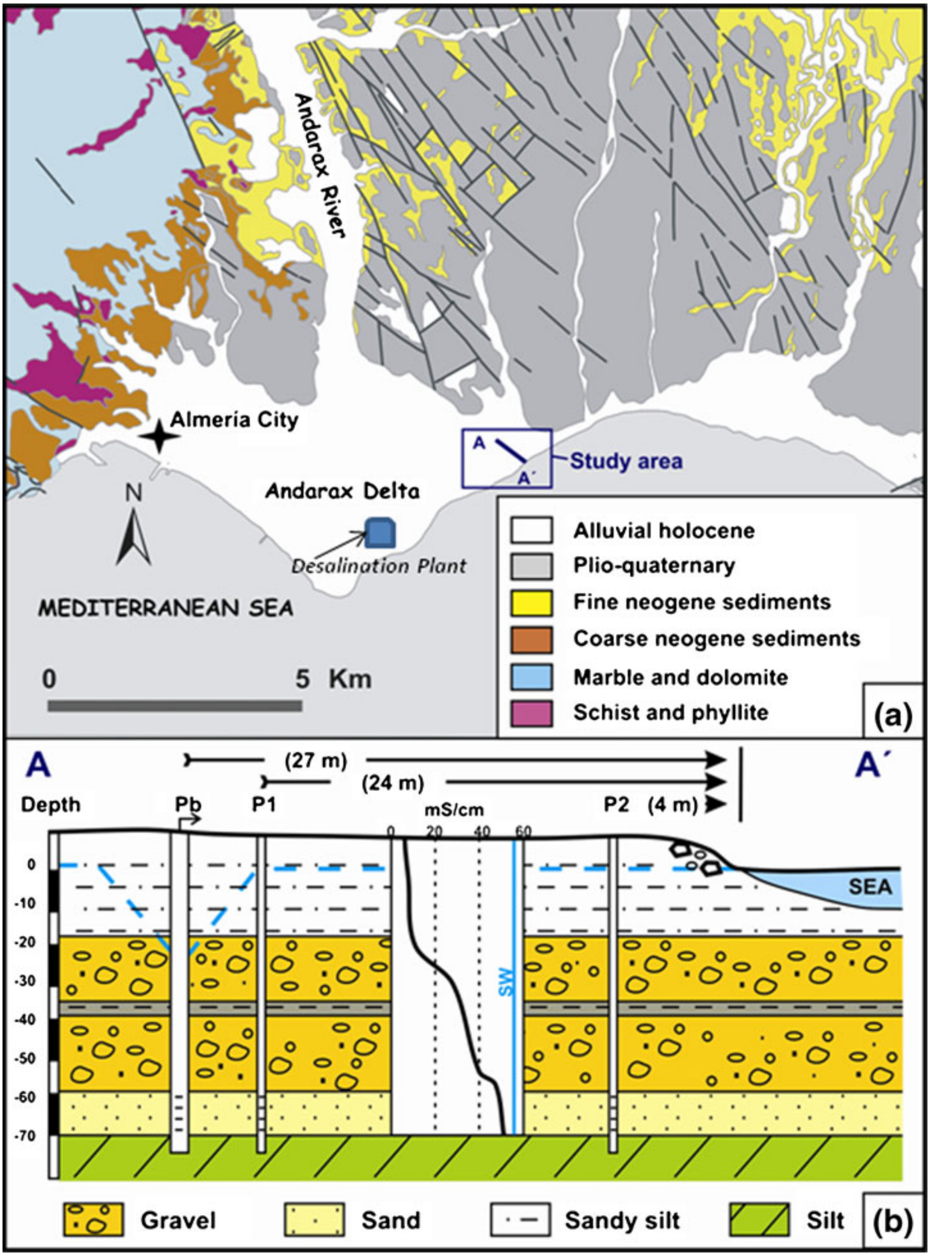

Fig. 1 **a** Hydrogeological map of the Lower Andarax. **b** Hydrogeological scheme of the experimental monitoring system. The *central graph* shows the evolution of salinity (in mS/cm) with depth. *SW:* seawater

mean precipitation of less than 350 mm and mean annual temperatures of 17 °C (Lázaro et al. 2001). Paradoxically, it is also one of the most productive agricultural regions in the Mediterranean catchment, thanks to intensive horticulture in plastic-covered greenhouses, which has been on the increase since the 1960s. Linked to this economic development, population density has also been increasing, especially along the coast. Moreover, in the summer months the coastal fringe accommodates a large tourist influx. Traditionally, water supply was met from aquifer abstractions because surface water is scarce and cannot be guaranteed. This situation has provoked overexploitation of the main aquifers (Pulido-Bosch et al. 1998), and marked saline intrusion in coastal aquifers (Molina et al. 2002; Sánchez-Martos et al. 2002; Daniele et al. 2008). In addition, land subsidence is one possible consequence of the drop in piezometric level (Pulido-Bosch et al. 2012). Attempts to palliate the water deficit have involved the commissioning of desalination plants all along the southeastern coast. The supply of saline water to the plants varies according to the hydrogeological characteristics in each case.

One of the desalination plants is at the tip of the Andarax river delta. This plant is supplied from 18 beach wells situated 30–50 m from the coast, each pumping some 100 Ls^{-1}. The aquifer from which the water is taken—called Lower Andarax Aquifer—extends along the whole valley and delta of the river Andarax and is formed by Pliocene and Quaternary fluvio-deltaic deposits (Fig. 1a). The aquifer has a complex geometry and a very heterogeneous granulometry, which means that there is a wide range in its transmissivity (Sánchez-Martos et al. 1999). Based on information gained from deep boreholes in the area, it is known that the seawater wedge in the central part of the delta penetrates more than 3 km inland.

3 Site Description

A field experimental site was designed to simulate and monitor the main processes affecting the seawater from the time it enters the aquifer until it is abstracted from the beach wells. Accordingly, three boreholes were drilled in a line perpendicular to the coast. The one farthest inland (P-b) was emplaced 27 m from the coastline and used as the extraction well. P-1, situated 23 m from the shore and P-2, only 4 m from the water's edge, were used as observation piezometers (Fig. 1b). P-b was pumped continuously over the 14 months of the experiment. Periodic water samples were taken from the three boreholes to monitor the evolution of physical, chemical and microbiological quality over the stretch of experimental aquifer. All three boreholes were 75 m deep and penetrated the entire aquifer formation. They were lined with PVC tube, incorporating a single slotted length 10 m long, at 60–70 m below sea level, corresponding to the most productive horizon of the aquifer. To avoid influx of vertical flow into the boreholes, the annular space above the slotted length was cemented with expansive clays and sulphur-resistant cement.

Seawater samples were taken at the same time as samples from the boreholes, so as to compare their properties. A fresh water sample was also taken from a borehole 670 m from the coast, aligned with the other boreholes, to provide the extreme value for the fresh water-seawater mixing process.

To better understand the processes that occur at the seabed and to study any changes in the composition of the seawater, three sediment samples were taken at 20, 30, 40 m below sea level. The chemistry of the interstitial water was analysed together with the concentration of organic matter in the sediment. The results were compared with seawater samples taken one metre above the seabed directly over the sediment cores.

4 Methods

In total, 30 weekly or fortnightly surveys were undertaken in the three boreholes over the period March 2009 to April 2010. Over this period, P-b was pumped continuously, first at

23 L s^{-1} and later, due to problems with the stability of the well, at a reduced flow of 12 L s^{-1}. In addition, seawater samples were taken just opposite the boreholes, and fresh water samples from a borehole 670 m from the coast, also aligned with the three test boreholes. Temperature, electrical conductivity and pH were determined in situ. Alkalinity (as HCO_3^-) was determined by titration at the time of sampling. Samples were taken in duplicate, filtered using a 0.45 μm Millipore filter and stored in polyethylene bottles at 4 °C. For metals analysis, samples were acidified to pH<2 with environmental grade (ultra pure) nitric acid to avoid problems of sorption or precipitation. Sample composition was determined by means of ICP-Mass Spectrometer at Lab of the Spanish Geological Survey (IGME).

Samples for microbiological analysis were filtered and estimated by counting the number of colony-forming units (CFU) per millilitre of sample. Differentiation was made between anaerobic and aerobic bacteria. Of the aerobic bacteria, distinction was made between colonies growing at an ambient temperature of 22 °C, and those capable of surviving at up to 37 °C.

Cores of sea sediment were taken by a diver using a corer 60 cm long and 4.5 cm in diameter, which was hammered into the sediment using a mallet. The corer was extracted vertically, closing both ends to seal the sample and prevent the interstitial water from moving around. Once at the surface, 10 cm sub-samples were extracted and the interstitial water was separated using a vacuum pump. Seawater samples taken one metre above the sediment core using a Niskin sampler, which snaps shut at both ends to capture a water sample.

We used a GGUN-FL30 field fluorometer (Schnegg 2003) to take continuous measurements of the dye tracer, uranine. An optical cell measures fluorescent tracer concentrations of the water passing through at sampling chamber set in the centre of the probe. The probe is capable of detecting uranine down to concentrations of 0.02 ppb.

5 Results and Discussion

The effect of the aquifer media on the spatial evolution of water quality over the reach of experimental aquifer was recorded and compared to water quality of samples taken using direct seawater intake. Physical, chemical and microbiological processes were monitored. Lastly, and in order to understand the timeframe over which these changes occur, it has been studied the transit time for seawater from its entry into the aquifer until its capture in the pumping well.

5.1 Physical Processes

The parameters generally monitored in water fed to reverse osmosis membranes are turbidity and SDI (Silt Density Index). Turbidity measures the amount of particles or solids in suspension, but gives no information about the resistance they offer to the passage of water when these solids are deposited on the membrane. Silt Density Index is a measurement or "relative index" of the amount of particulates in water. The test is based on measuring the rate of plugging a 45 micron (μm) filter using a constant 30 psig feed pressure for a specified period of time. The SDI is a more sensitive value of the quality of the water supplied to a desalination plant, especially for low turbidity waters (Mosset et al. 2008). To avoid colloidal clogging, the commercial membrane suppliers recommend a turbidity of less than 0.2 FTU and an SDI of between 2 and 4. The seawater turbidity measurements carried out in the study area showed wide variation as function atmospheric conditions, always exceeding 1 FTU, and reaching 9 FTU in some cases. Turbidity values in borehole samples ranged between 0 and 1 FTU, decreasing as the experiment progressed due to the cleaning action of pumping in the boreholes (Fig. 2a). $SDI_{(15)}$ values (a silt density index test which was run for 15 min) obtained in the boreholes ranged between 0.5 and 6, compared to values of nearly 6 recorded in seawater (Fig. 2b).

Other physical parameters used to characterize the quality of the water feed to desalination plants include temperature, electrical conductivity (EC), pH and dissolved oxygen (Table 1). All these parameters were analyzed in situ. Temperature is an important variable in determining the performance of the desalination process (Frenkel 2010). The groundwater usually approximates to the average outside temperature, while seawater temperature tends to vary over the year, especially in the mid-latitudes. Water temperature in the boreholes was between 21 and 22 °C over the duration of the experiment (Fig. 3a). Seawater temperature showed annual variations of up to 12 °C, with an average temperature of 19 °C, slightly lower than in the borehole water.

The EC of water taken from vertical boreholes is usually different to that of direct water intake. This could be because pumped abstraction can remobilize deep brines or fossil seawater that have higher ECs (Daniele et al. 2011; Vinson et al. 2011) or, conversely, because pumping allows in some fresh water, so reducing EC (Voutchkov 2006; Jorreto et al. 2009). The EC value influences the pressure that must be applied for desalination of the water (Maliva and Missimer 2011). In our experimental plot, EC of the borehole water

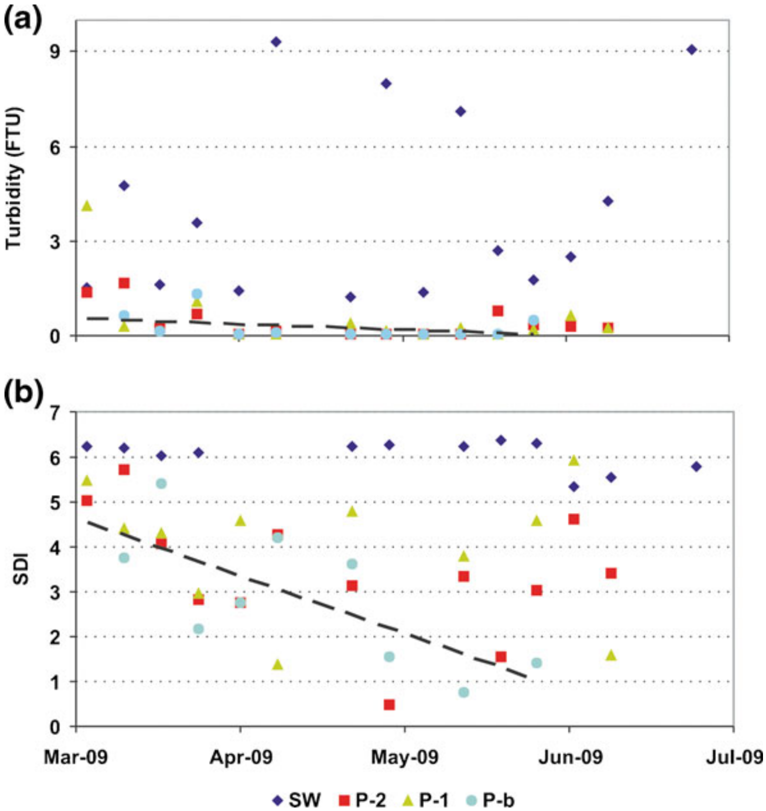

Fig. 2 **a** Turbidity and **b** SDI: *silt density index*, during the first months of sampling in the three boreholes monitored and direct seawater intake (SW). The *broken line* shows the trend for values of P-b

Table 1 Summary of analytical results of the main physicochemical parameters of the samples analyzed

	P-2 (n=22)			P-1 (n=24)			P-b (n=30)			SW (n=31)		
	Mean	Range	StdDev	Mean	Range	StdDev	Mean	Range	StdDev	Mean	Range	StdDev
T (°C)	21.7	20.9–22.1	0.3	21.4	20.7–22.1	0.35	21.5	20.8–22.4	0.88	18.7	13.3–26.4	4.1
EC (mS/cm)	45.8	42.9–47.4	1.41	40	38.7–42.1	0.91	42.8	41.5–44.8	0.91	55	54–58.6	0.91
pH	7	6.73–7.19	0.13	6.85	6.54–7.16	0.19	7.02	6.8–7.34	0.11	8.2	7.93–8.47	0.16
DO (mgL^{-1})	0.65	0.25–1.25	0.30	0.54	0.35–1	0.17	0.4	0.1–1.5	0.31	1.5	0.5–6	0.9
Alkalinity (mgL^{-1})	218	185–237	13.2	220	195–243	10.13	208	162–227	13.31	131	104–149	9.68
Na	10,982	9,768–11,973	462.9	8,641	6,902–10,051	1243.6	9,943	7,080–10,934	841	13,268	12,380–14,757	604
K	295.3	219–346	33.8	186.5	163–212	10.8	240.8	196–295	28.6	491	452–534	20.4
Ca	733.6	580–840	55	839.2	680–900	55.2	825.7	650–960	65.5	469	350–540	31.8
Mg	1,088	1,000–1,190	51	1,122	1,020–1,280	89.6	1,084	1,020–1,260	56	1,415	1,220–1,620	103.2
Cl	18,335	16,800–19,200	631.8	15,983	13,700–17,400	1,074	17,210	15,200–18,200	634.3	22,389	21,400–23,900	583.9
SO_4	2,874	2,670–3,060	89.4	2375.8	2,000–2,740	201.4	2645.7	2,200–2,890	135	2,956	2,700–3,260	119.7
HCO_3	184.4	176–208	7.4	181.4	128–196	12	182.6	164–206	7.3	112.8	91–140	10.1
B	3.2	2.3–4.0	0.49	<2	<2–2.5		2.5	2.2–3.2	0.36	5.07	4.1–6.0	0.49
Br	58.2	54.3–60.9	2	50.7	47–53.7	1.7	53.9	50.7–57.6	1.9	71.7	68.3–74.8	2

n: number of samples analyzed. Ionic values in mgL^{-1} (*P-2*: piezometer 2; *P-1*: piezometer 1; *P-b*: pumping well; *SW:* seawater; *FW:* freshwater)

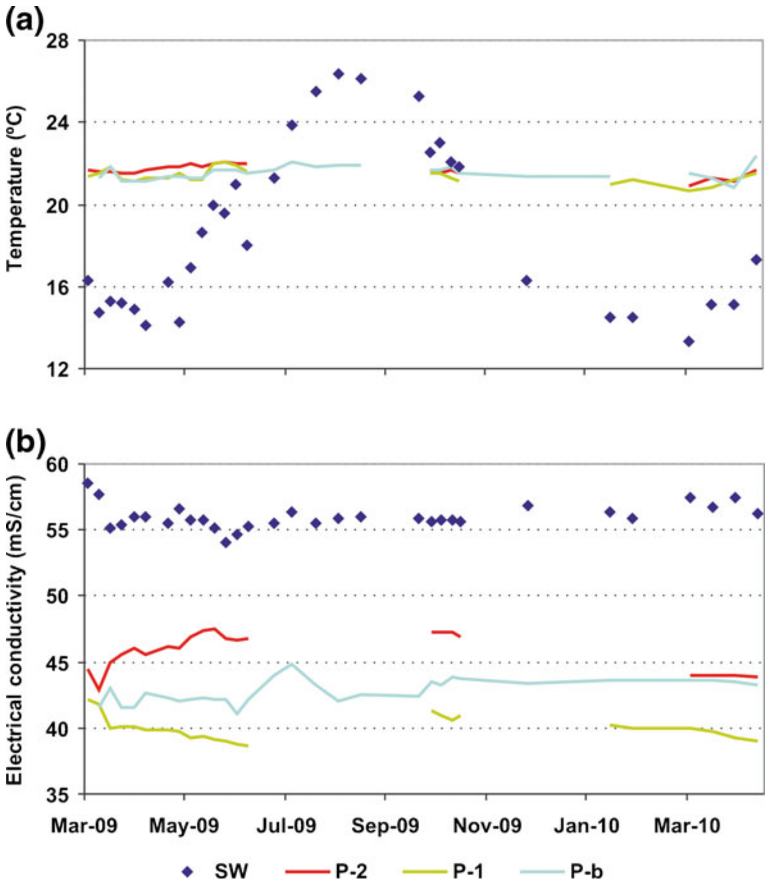

Fig. 3 **a** Temperature and **b** Electrical conductivity in the three boreholes monitored and direct seawater intake (SW)

oscillated between 39 and 47 mS/cm, compared to a mean of 55 mS/cm for seawater (Fig. 3b). The pH of borehole samples was much lower than seawater: between 6.5 and 7.3, compared to between 8 and 8.5 for seawater. Dissolved oxygen (DO) is another important parameter: the higher DO, the greater the potential for biofouling of the membranes (Abdul Azis et al. 2001). DO vary widely in the experiment, from 0.5 to 6 $mg L^{-1}$ O_2 in seawater, with a mean of 1.5. In virtually every survey, the DO of the seawater was higher than in the water pumped from the boreholes, which registered means of 0.65 in P-2, 0.54 in P-1 and 0.4 in P-b. There is a notable drop in mean dissolved oxygen through the aquifer between the different boreholes, with greatest reductions occurring furthest from the coast. This could be due to aerobic bacteria consuming the oxygen, which means that the transit time is also important.

Figure 4 shows the percentage reduction of the main physical parameters controlled in function of the distance to the sea. The reduction in SDI in the two boreholes was 30–50 % compared to the direct intake (Fig. 4). Turbidity fell by 80–95 % compared to the direct intake. However, in the boreholes furthest from the coast (P-1 and P-b) turbidity is slightly higher than in P-2 (Fig. 4), situated only 4 m from the shore. This could be due to

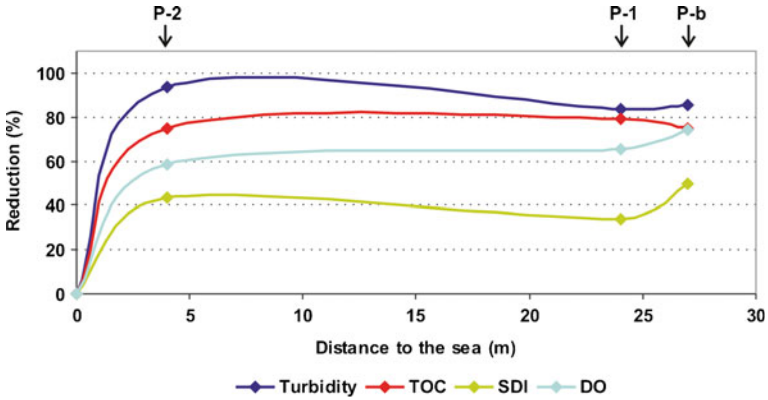

Fig. 4 Reduction (as percentage) in turbidity, TOC, SDI and DO through the aquifer media

mobilization of fine particles around the pumping well, which could affect samples taken in the nearby P-1 (Fig. 1b). The drop in piezometric level in P-b as a consequence of pumping (Q= 12–23 Ls^{-1}) was up to 40 m, due to the low transmissivity of the aquifer: 110 m^{2}d^{-1}. To maximize the effectiveness of the aquifer media as a natural filter of material in suspension, it is necessary that the pump installed does not create much turbulence. To achieve this, the pumping rate needs to reflect the transmissivity of the aquifer in order to avoid significant drops on the piezometric level.

5.2 Chemical Processes

The chemistry of groundwater in coastal environments is heavily influenced by the percentage of fresh water and seawater in the mixture (Kim et al. 2003; Gattacceca et al. 2009). Desalination plants supplied from this type of aquifer usually show a decrease in EC over time as the percentage of fresh water incorporated into the mixture increases (Jorreto et al. 2009; Otero et al. 2011; Alhama Manteca et al. 2012). In the study plot, no such reduction in salinity was recorded; instead the salinity of water pumped from the boreholes, especially P-2, increased over time as the saltwater wedge penetrated further inland. The percentage of seawater in the samples was calculated from the concentration of the Cl ion, which behaves conservatively in water mixing processes (Pulido-Leboeuf 2004; de Montety et al. 2008). The percentage of seawater was 75–85 % in P-2, 65–75 % in P-1 and 70–80 % in P-b. Despite being further inland, values for P-b were intermediate between the two observation boreholes, due to the upconing effect caused by pumping.

As well as the variation in water chemistry in the pumped abstractions, caused by fresh water-seawater mixing, other modifying processes intervene (Fidelibus et al. 1993; Andersen et al. 2005). The most frequent phenomenon is the precipitation and dissolution of mineral phases and cation exchange between the water and the aquifer, linked to the movement of the mixing zone over time (Appelo 1994; Appelo and Postma 2005). Ionic deltas (Δ) have been calculated for the principal chemical species in groundwater (Andersen et al. 2005). These show how close the content of each ion is to the value expected from a pure mixture where no modifying processes operate. Positive Δ values indicate enrichment, while negative ones point to impoverishment. The results are shown as percentage enrichment/impoverishment compared to the expected value (Fig. 5).

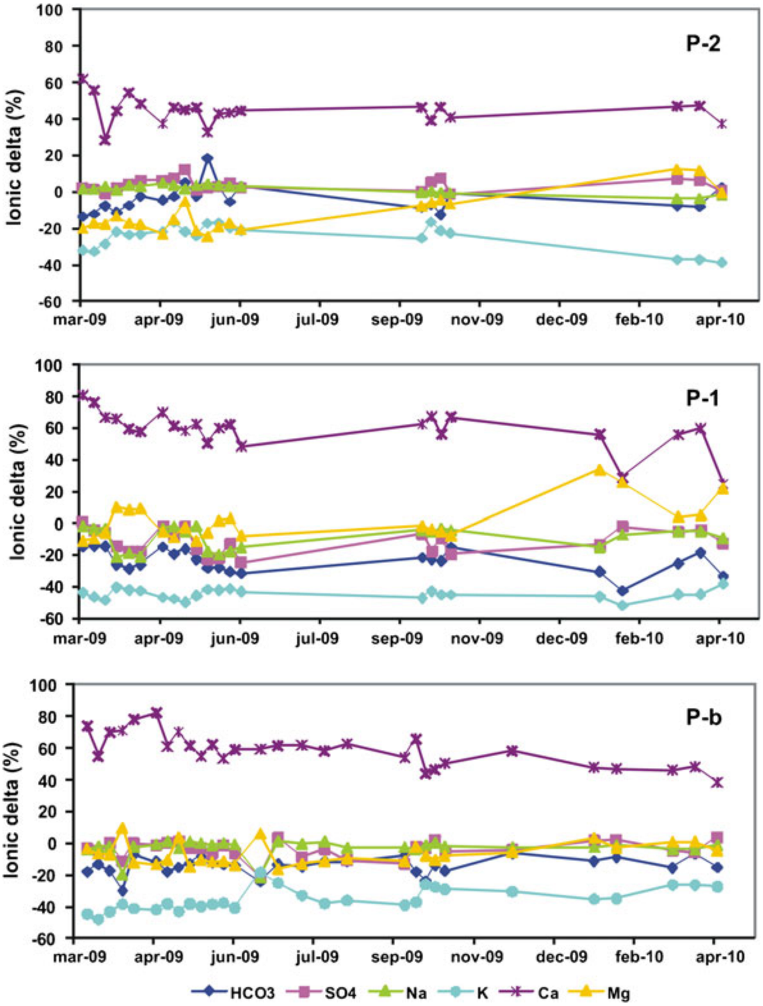

Fig. 5 Evolution of ionic deltas (expressed as percentage) of the major ions

Ca^{+2} shows the greatest percentage variation, with enrichment of 60–80 % in P-b and P-1 and between 40 and 60 % in P-2. The trend for SO_4^{-2} and Na^+ shows they are more conservative, with slight impoverishment in P-1. Mg^{+2} and HCO_3^- varied in time and space by between −20 and 40 %. Lastly, K^+ was clearly impoverished in all samples analysed, by 40 % on average (Fig. 5). The causes of these modifications in the different samples may be related to ion exchange, dissolution and precipitation of mineral phases like gypsum and dolomite, and/or to bacterial reduction of sulphates. In general, the modifying processes tended to reduce the ionic load, especially in samples from P-b (Fig. 5), except for Ca^{+2}. The evolution of %Ca-Δ, spite of being enriched, shows a clear trend towards equilibrium, which could be related with a certain depletion of the exchange sites. The continuous pumping in P-b means that no direct ionic exchange has taken place. It is significant the decrease in the other major ions, which is translated to a lower pressure required on the membranes in the desalination plant.

Other modifying processes in detrital aquifers are linked to the microbial community within the aquifer, which fixes nutrient species along the flowpath, so reducing the concentration of elements like nitrogen, phosphorus and organic carbon (Jones 2008). Water with a lower nutrient content represents an improvement in terms of the quality required to supply desalination plants because the potential for biofilms on the RO membranes is reduced. Nitrogen and phosphorus in the seawater and borehole samples taken were below the limit of detection. Concentration of total organic carbon (TOC) is a common parameter in this type of investigation. The mean TOC in seawater samples was 0.76 mgL^{-1}, 0.19 mgL^{-1} in P-2 and P-b and 0.16 mgL^{-1} in P-1.

As it is showed in Fig. 4, the values in TOC, with mean reductions between 75 and 80 % respect to seawater, show a slight reduction in the amount of organic carbon between P-2 and P-1, but increased again in P-b. The increase could be linked to the presence of a bacterial biofilm around the extraction borehole, which contributes organic carbon to the samples (Fig. 4). Laboratory experiments indicate that the pre-treatment filters made of a mixture of siliceous sand and anthracite, 80 cm thick, can reduce turbidity of direct intake water by 15–70 %, depending on factors such as temperature and rate of filtration (Johir et al. 2009a; Mitrouli et al. 2009). Nevertheless, the effectiveness of this type of filter is much lower for TOC, removing only 30 to 45 % (Johir et al. 2009b), compared to 75 to 80 % recorded in the boreholes in this study.

In an attempt to recognize the processes occurring in the first few metres of the seawater ingress into the aquifer (which is the stretch where variations in the measured parameters are detected), three seabed sediment samples were taken, from different depths, perpendicular to the coastline and in line with the three inland boreholes. Samples were collected from 10, 20 and 40 m b.s.l. In addition, samples of seawater were taken directly above the sediment cores in order to compare the readings taken in the sediment samples with the seawater directly above. The parameters analysed were percentage organic matter, total organic carbon (TOC) and major ions.

The amount of organic matter present in the seabed sediments contained a mean percentage of 1.2 % by weight, whilst the percentage in the sediment cores extracted from the boreholes during drilling was 0.2 %. The seabed sediments show some variability; so those taken at −10 m depth contain more organic matter than deeper samplers (Table 2) because a certain amount of light penetrates to −10 m depth allowing the seagrass, *Posidonia oceanica*, to grow, while at greater depths, light penetration is limited.

Organic compounds found in natural waters usually comprise humic compounds at concentrations between 0.5 and 20 mgL^{-1} TOC. When TOC exceeds 3 mgL^{-1}, pre-treatment is likely to be needed to eliminate it. Humic substances can be removed using coagulation, ultrafiltration or absorption using active carbon. TOC in seawater taken via direct intake to supply desalination plants is usually between 1 and 2 mgL^{-1}. The seawater samples taken in the pilot study gave slightly lower TOCs (0.8–0.9 mgL^{-1}). Meanwhile, the results

Table 2 Mean TOC concentration in mgL^{-1} in samples from boreholes, seabed sediment cores and seawater

Boreholes	P-2	P-1	P-b
	0,19	0,16	0,19
Core	10 m b.s.l	20 m b.s.l	40 m b.s.l
0–10cm	0,7	0,1	0,3
10–20cm	0,8	0,1	0,4
20–30cm	0,5	0,3	0,4
30–40 cm	–	0,3	–
40–50 cm	–	0,6	–
SW	0,76		

from the investigation boreholes were between 0.1 and 0.2 mgL^{-1}. Hydrogeological studies in recharge areas associated with infiltration lagoons reveal reductions of 25–30 % in the first few metres of transit of the surface water into the aquifer matrix (Massmann et al. 2004). However, interstitial water in the seabed sediment samples give much higher mean TOCs of 20 mgL^{-1}. No fall in TOC is detected over the 50 cm of the sediment core studied (Table 2). Therefore, the reduction observed in TOC between the seawater and the investigation boreholes must occur along the flowpath inside the aquifer, below the band of biological activity (the first metre or so of the aquifer), which is clearly enriched in organic carbon.

5.3 Microbiological Processes

The microbial population of groundwater tends to be scarce, given the lack of nutrients, the limited or zero energy input and the intense filtration that occurs over the unsaturated zone (Cullimore 2008). The origin of most of the microorganisms present in groundwater is related to human activity, leading to infiltration of wastewater, animal slurry and agriculture (Sen 2011). Under natural conditions, the most commonly encountered microorganisms in aquifers arise due to connection between the aquifer and surface water bodies like rivers, lakes or the sea.

The seawater samples taken contain a community of aerobic bacteria of between 100 and 10,000 CFU/mL. The anaerobic bacteria showed a parallel evolution to the aerobic, but at a lower order of magnitude. The number of bacterial colonies that survived heating the samples to 37 °C was zero in most cases, but 100 CFU/mL were recorded in some samplings (Fig. 6). The efficiency of the aquifer media as a means of filtering out microorganisms can be judged by comparing the values for seawater with those for the borehole samples. In the boreholes, the aerobic count was also between 100 and 10,000 CFU/mL. However, no anaerobic bacteria were recorded, nor any of the aerobic bacteria that can survive at 37 °C (with the exception of very localized cases).

5.4 Transit Time

Few studies have examined the residence time of seawater in a coastal aquifer. This residence time is usually calculated from the radioisotope content of ^{3}H, ^{14}C or $^{226}Ra/^{228}Ra$

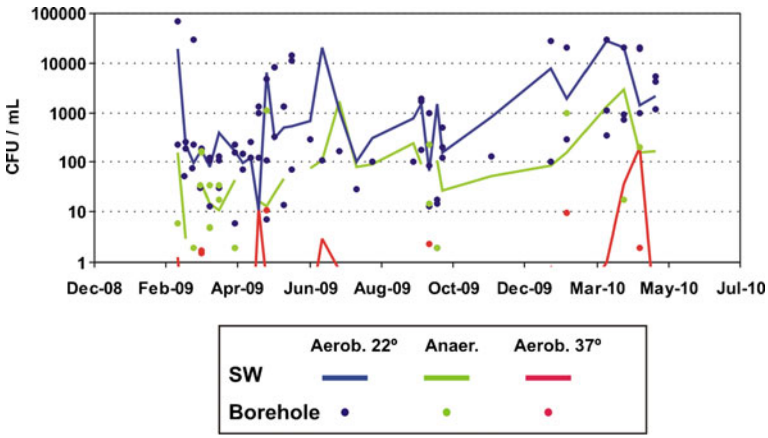

Fig. 6 Bacterial colonies from the direct seawater intake and boreholes. Anaerobic bacteria, aerobic bacteria at 22 °C and aerobic bacteria at 37 °C have been differentiated

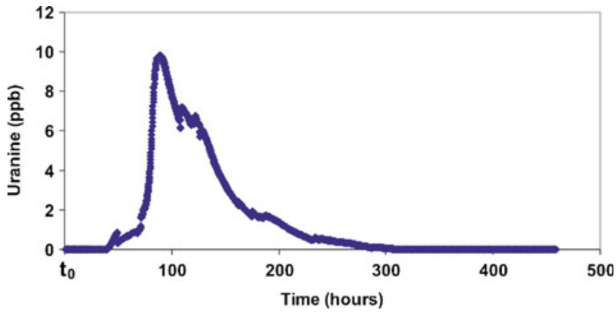

Fig. 7 The uranine breakthrough curve for tracer test

(Araguás 2003). Occasionally, the seawater in the aquifer derives from marine intrusion that took place hundreds or thousands of years ago (Kennedy and Genereux 2007; Hiroshiro et al. 2006). Other studies of uninfluenced aquifers found that seawater took decades to penetrate 100 m inland, although this depends on whether the aquifer is free or confined (Sivan et al. 2005). In pumped aquifers, this time is enormously reduced, with seawater being picked up within 1 year (Otero et al. 2011).

To determine the residence time of seawater in the experimental plot, a tracer study was designed, whereby 100 g uranine was injected into piezometer P-2 (4 m from the shore), and measured in P-b. The distance between the two points is 23 m. The tracer solution was allowed to fall by gravity to a depth of 65 m, halfway up the slotted length. The pumping rate throughout the tracer test was 6.8±0.2 Ls^{-1}. The tracer was first detected in P-b after 40 h (Fig. 7). Then its concentration increased, peaking after 89.6 h at 9.8 ppb. After this, the tracer concentration gradually tailed off and disappeared after 308 h. During the tail-off, small short-lived peaks could be detected.

Thus, a period of 3 to 4 days was required for the water to travel the distance from P-2 to P-b. What it is really needed to know is the time taken for water from its entry point into the aquifer to its capture in P-b. Injecting artificial tracer into the sea is not a viable option, and so natural tracers—physicochemical parameters—are monitored in the seawater and in P-b (Fig. 8). These parameters vary over time according to samples from direct seawater intakes. EC and alkalinity show the same trend through time, sometimes with a slight delay. Given

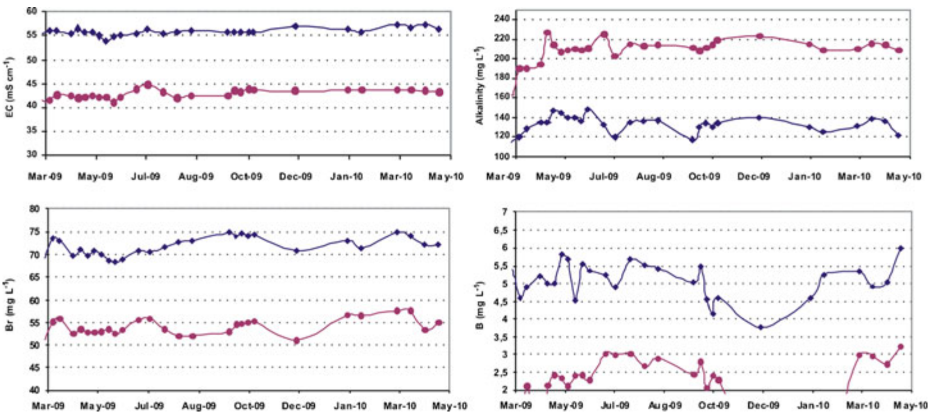

Fig. 8 Evolution of physicochemical parameters

the sampling frequency (weekly), it is not possible to have control of this lag, but based on the results obtained (Fig. 8) it can be considered approximately 1 week. Br and B show the same trend through time. Concentration of boron in Mediterranean seawater is around 4.5–5 mgL^{-1} (Dotsika et al. 2006). Up to 6 mgL^{-1} have been found in May 2009, but only 2–2.5 mgL^{-1} in pumped water. If the percentage of seawater is 70–80 % in P-b, probably the boron suffers some interaction, i.e. adsorption.

6 Conclusions

Intakes of saline water by abstracting from coastal boreholes provides clear improvement in water quality compared to direct seawater intakes, in terms of the water quality parameters relevant for supplying desalination plants. Analysis of certain physical, chemical and microbiological parameters allows this improvement in quality, due to filtration through the aquifer media, to be identified. It includes up to a 95 % reduction in turbidity and up to a 50 % reduction in SDI. Other parameters are also notably reduced (TOC is cut on average by 60 %, and DO by 80 %), due to bacterial activity in the aquifer. The aquifer is also a good filter of bacteria, especially of anaerobic bacteria and those aerobic bacteria that can survive at temperatures of 37 °C, which are the most difficult to remove and, therefore, potentially the most dangerous. The efficacy of the filtration and ion exchange will depend, in large degree, on the characteristics of the aquifer media from which the desalination plant is supplied. In general, a sandy aquifer containing a certain fraction of fine particles and organic material would be more useful than a clean sand aquifer. Nevertheless, high amounts of fines and organic matter will reduce aquifer transmissivity and so the proportion of TOC and the turbidity of the water will be greater.

The reductions that are known to take place in borehole abstractions occur in the first few metres of the aquifer transit. However, data obtained from seabed sediment cores indicate that the uppermost metre or so of the seabed incorporates large amounts of TOC, due to its greater biological activity. Therefore, the reach of aquifer between the sea and the plant must be of a certain length if the “improvement” in the seawater is to be effective.

Understanding the filtration processes that occur within the aquifer matrix and the concomitant improvement in the quality of the seawater intake will enable its application as a natural analogue for designing artificial pre-treatment systems.

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