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THEMATIC ISSUE

Methods to supply seawater to desalination plants along the Spanish mediterranean coast and their associated issues

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Abstract

Many coastal areas of our planet receive only scarce precipitation, and have limited or often non-existent surface water resources. Over the last four decades, the intensive agriculture and tourism along the Spanish mediterranean coast have led to a large increase in water demand. The economic development of this, the most arid stretch of the Mediterranean coast has been dependent on the availability of good quality groundwater. Desalination in Spain has contributed to the progress and development of these areas, being considered as the solution to this increased demand. Along the Spanish mediterranean coast, around 30 desalination plants of medium–high capacity, between 20,000 and 125,000 m^3/day, have been built over the last 25 years, and there are several plants in the planning stage, to be constructed in the near future. In addition, 100 small plants desalinate brackish water. Desalination plants are usually supplied from coastal boreholes if there is a coastal aquifer with hydraulic connection to the sea. Nevertheless, the water to desalinate in other cases comes from evaporitic aquifers or even fossil water. Regarding the water intake systems, horizontal directional drilling can give good results, not to mention a number of other sophisticated and curious designs, each with their particular advantages and drawbacks. This paper describes the main problems and also the benefits concerning water intake systems to some desalination plants along the Spanish mediterranean coast.

Keywords Coastal aquifers · Desalination plants · Seawater · Brackish water · Water intake systems

Introduction

A considerable proportion of the planet's coastlines support dense populations, either because large megalopoli have grown from established coastal settlements or due to more recent reasons of tourism. Coastal zones and adjacent land areas support 60% of the human population, as well as eight of the top ten largest cities in the world (González-Baheza and Arizpe 2018). This implies fierce pressure on natural resources, especially water resources. Frequently, these coastal areas enjoy a climate favourable to agriculture, which means that a large seasonal demand for irrigation water has to be added to the demand for urban water supply and to the summer tourist demand. All these aspects are aggravated, where the coastline is subject to a semi-arid or Mediterranean climate with their characteristic dry season—as occurs in the case of the Mediterranean Basin (Kopsiaftis et al. 2017; Mazi et al. 2016). Furthermore, rainfall has decreased throughout the Mediterranean region, southern Africa and the Sahel, the Aral Sea basin, and Australia over the past century (Ragab and Prudhomme 2002). Over the coming years, this downward trend will become more widespread, which will make these coastal lands even more vulnerable (Colombani et al. 2016; Ferguson and Gleeson 2012; Iyalomhe et al. 2015).

Faced with the constantly growing demand for water resources and the gradual depletion of surface water resources, the pressure on groundwater resources is becoming ever greater (Wada et al. 2010). In the case of coastal aquifers, their overexploitation implies the advance of the saline wedge further inland and the consequent salinisation of groundwater resources. The presence of just 5% seawater in a mixture with fresh water renders it unsuitable both

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for human consumption and for the majority of agricultural activities (Custodio and Bruggeman 1987). The majority of aquifers along the Spanish mediterranean coast show indications of marine intrusion (Custodio 2017; Leduc et al. 2017) as a consequence of the marked increase in water demand over recent decades.

One solution to this issue has been the construction of desalination plants (Baltanás 2006), which take water directly from the sea and/or from coastal boreholes (Shahabi et al. 2015) that tap the water below the freshwater–saltwater mixing zone (Pulido-Bosch et al. 2004). The decision to construct the first large plant on the Iberian Peninsula, in Marbella (Málaga), was taken following a period of severe drought that ended in 1995 (Rico-Amorós 2004).

In the year 2000, the production capacity for desalinated water in Spain reached approximately 1.2 mm^3/day, supplied from 750 desalination plants. By 2005, the capacity reached 1.5 mm^3/day from approximately 950 plants (Palomar and Losada 2008). By 2010, capacity exceeded 2.8 mm^3/day, making Spain the fourth country worldwide in terms of its production capacity for desalinated water (Palomar and Losada 2010; García-Rubio and Guardiola 2012). This increase in capacity to produce desalinated water is related on one hand to the increased demand and on the other to the fall in the costs of production (Proskynitopoulou and Katsoyiannis 2018). The expansion in the desalination market has attracted many organisations and companies to improve desalination technologies to reduce costs. Tremendous decreases in desalination costs have been continuously achieved in recent decades causing the price of water to fall to 0.50 US$/$m^3$ (Ghaffour et al. 2013).

Spain now boasts 30 or so desalination plants with a capacity of between 20,000 and 125,000 m^3/day, though practically, none operate at their full capacity. Here, we aim to review the most important issues associated with the systems employed for water intake to desalination plants, supported by the experience gained over years of operation.

Principal water intake systems to desalination plants

Approaches

The most intuitive means of supply is an 'open' or direct intake of seawater. This approach requires that suspended and entrained particulates are eliminated, along with organic material and any organisms. For large plants—with production capacities of more than 200,000 m^3/day—this is practically the only viable option from an economic point of view (Voutchkov 2004). In other situations, the most suitable intake solution is by means of a water intake works in the coastal aquifer, and this is the least costly solution in the medium–long term, provided of course, that there is an aquifer along the coastal strip that possesses the necessary characteristics (Gille 2003). There is always a hybrid option, namely, for part of the water to be abstracted via headworks in the coastal aquifer, supplemented with a direct seawater intake in times of higher demand.

Plants with a direct seawater intake require a series of pre-treatments to remove sediments in suspension, algae, bacteria, and other organic matter that would foul the membranes (Fig. 1). Pre-treatment technology is divided into conventional pre-treatment, which includes disinfection, coagulation/flocculation and filtration process, and non-conventional, such as microfiltration and ultrafiltration (Prihasto et al. 2009). Water supplied via an aquifer matrix has undergone natural filtration, which markedly reduces these concentrations (Dehawh et al. 2015), involving up to 95% reduction in turbidity and up to 50% reduction in SDI (Silt Density Index). Other parameters are also notably reduced (TOC is cut on average by 60%, and DO by 80%), due to bacterial activity in the aquifer (Sola et al. 2013; Stein et al. 2016). This improvement in water quality reduces the final desalination costs significantly (by 5–30%) (Missimer et al. 2013).

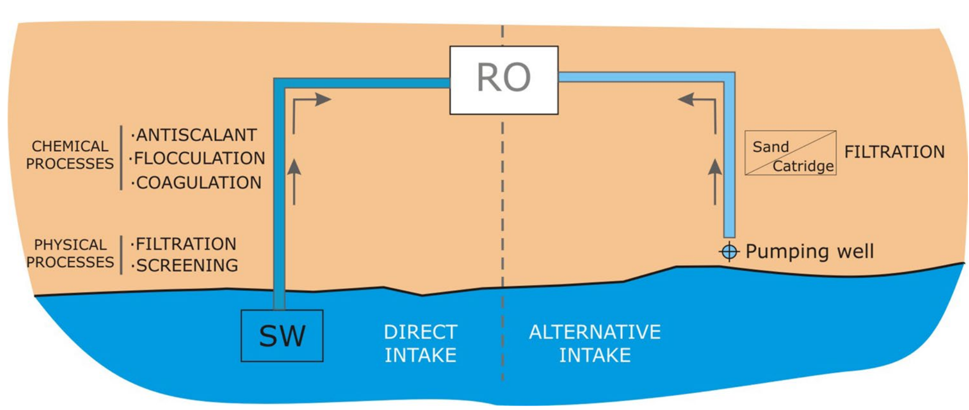

Fig. 1 Scheme showing typical pre-treatment processes for an SWRO plant using direct or subsurface intake (*SW* seawater, *RO* reverse osmosis)

Small- and medium-sized desalination plants (< 200,000 m^3/year) are fed from collection wells tapping coastal aquifers, below the fresh water–seawater contact (Gille 2003; Pulido-Bosch et al. 2002; Rodríguez-Estrella and Pulido-Bosch 2009). The various phases of work need to be carefully designed to avoid seasonal operational problems.

Many locations worldwide enjoy hydrogeological conditions that allow one or more types of subsurface intakes to be developed, while other locations do not have this subsurface intake feasibility. A key issue is the pre-design technical assessment of the hydrogeological conditions before the facility design and bidding process begin (Voutchkov 2005; Missimer et al. 2013). The first stage is the selection of suitable abstraction sites, which requires a good understanding of the hydrogeological context. Drilling of a test borehole allows potential difficulties to be identified. Logging of the test borehole must deliver the lithological column penetrated, including a complete cross section of the aquifer granulometry. Geophysical borehole logging is a supplementary technique, which—sing gamma ray logging, for example—can differentiate between more conductive and more impermeable layers. Cross sections of salinity in the saturated zone are necessary to determine the thickness of the seawater column within the aquifer, as well as the position of the freshwater interface. A pumping test is also required to estimate the transmissivity and storage coefficient of the aquifer and to quantify the maximum pumping rate the well can supply. Water samples from the test pumping should be taken and analysed for chemical composition, DOC, SDI, and turbidity.

Abstraction from a littoral aquifer

If the terrain to be penetrated consists of gravels and sands with variable proportions of lutite, the optimal technique of drilling a vertical borehole is by reverse circulation rotation. This terrain corresponds to a typical coastal detritic aquifer in Spain. Attapulgite should be used as the drilling mud, since at high salinities, it maintains its flocculating character, so that the desired mud density can be achieved. Up to 50–60 m/day can be drilled using this technique in large diameter boreholes. The output in coastal areas is usually very high, between 80 and 140 L/s for a works at 100 m depth. In consolidated formations, this system is rejected on economic grounds, and instead, percussion or rotopercussion drilling are the most suitable techniques. Given that these boreholes are sunk to tap seawater, it is recommendable that the band of the aquifer occupied by fresh water, as well as part of the transition layer, remains isolated from the well screen (Fig. 2). This is achieved by cementing a seal over this stretch—which is normally 40–50 m long, and/or by adding expansive clays, which avoid the inconvenience of the process of cement curing—an exothermic process that can damage the plastic well casing or well screen (Pulido-Bosch et al. 2004). In addition to the advantage of the natural filtration that occurs using this water intake method, the ensemble of boreholes intercepts inflowing seawater and so acts as a barrier against seawater intrusion (Todd 1980; Pool and Carrera 2010; Mogheir 2016). Abstraction of water from below the interface generates a drawdown cone in the piezometric level of the saline wedge, and for this reason, these kinds of arrays are known as negative hydraulic barriers (Pool and Carrera 2010). The disadvantage of this technique is that, with the passage of time, the wells begin to extract a certain proportion of fresh water (Pool and Carrera 2010; Otero et al. 2011).

In order that the good quality of water taken from these boreholes is preserved, with low concentrations of bacteria and DOC, the water must be directed as quickly as possible into the desalination plant. Moreover, it is advisable to undertake periodic maintenance of the boreholes to avoid biofouling or mineral precipitation on the well screens.

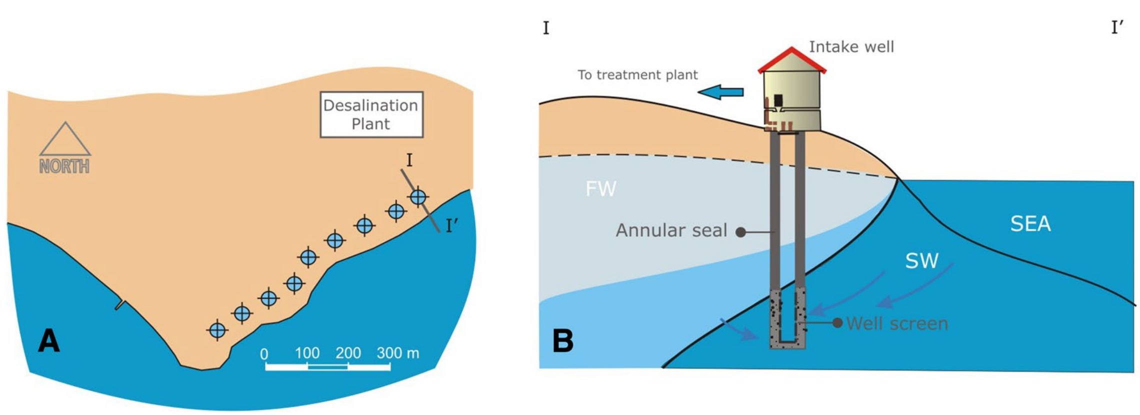

Fig. 2 **a** Scheme and **b** section of subsurface intake by means of vertical beach wells (*SW* seawater, *FW* freshwater)

Another means of benefitting from the filtration offered by the aquifer matrix is through the use of Horizontal Directional Drilling (HDD). This is a more sophisticated technique that aims to take seawater from an aquifer beneath the seabed, so inducing a vertical flow, whereby the seawater flows into the drain across the natural filter provided by the aquifer matrix. HDD involved drilling an inclined, small–medium diameter borehole from a pit or trench situated on the beach and directed into the marine substratum. Three-dimensional geolocation allows the position and direction of the drill head to be continuously monitored (Peters et al. 2007). The output of each borehole is between 100 and 150 L/s for lengths of more than 600 m and diameters of up to 710 mm. The technique is optimal for consolidated terrains. One of its main advantages over the previous technique described is there can be no entrainment of fresh water from the aquifer system. These horizontal or inclined drains can be applied to different variants of intake system.

It is also possible to use wells with radial Ranney- or Felhman-type collectors (or any variant of their principle, Fig. 3). These are expensive works, but they deliver higher efficiency. Collector laterals could be installed only on the seaward side of the well to avoid impacting the fresh groundwater resources inland and to elimination the potential for extracting polluted water or water with high concentrations of undesirable metals, such as iron and manganese, into the wellfield (Missimer et al. 2013).

There have also been attempts to capture water using shallow ditches in the intertidal zone, into which slotted tubes are fitted that are compatible with the granulometry of the beach sands. These ditches are connected to a lateral system that is hermetic with its corresponding well, and from there, the water is pumped to the plant. The biggest drawback with this system is that it is vulnerable to storm damage if the pipe is not anchored properly.

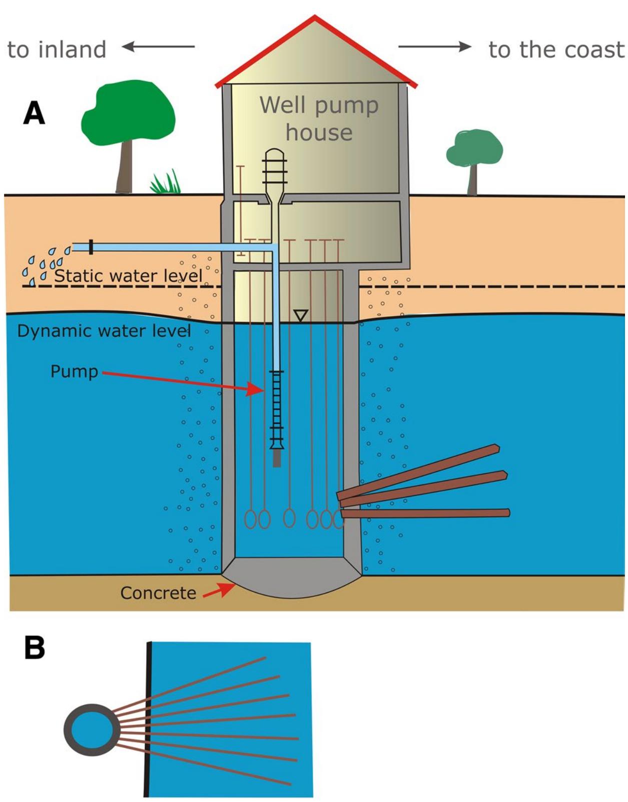

Fig. 3 **a** Section and **b** scheme of subsurface intake by means of radial intake well

Desalination plants on the Spanish mediterranean coast

Figure 4 shows the main seawater and brackish water desalination plants along the Mediterranean coast of the Iberian Peninsula. All of these employ reverse osmosis as the means of desalination, due to its lower energy costs. Energy consumption is much reduced in brackish water desalination plants, since the saline content is less. Two large plants have been built on the Spanish mediterranean coast, at provinces of Málaga and Almería (Fig. 4, Table 1). The Atabal brackish water plant was built to improve the quality of water supply to the city of Malaga from the three Guadalhorce reservoirs, whose salinity can reach up to 16 g/L (Alaminos, et al. 2006). The salt water comes from the gypsum–saline materials, which salinize to the reservoirs. El Atabal produces 165,000 m^3/day of desalinated water (60 hm^3/year)

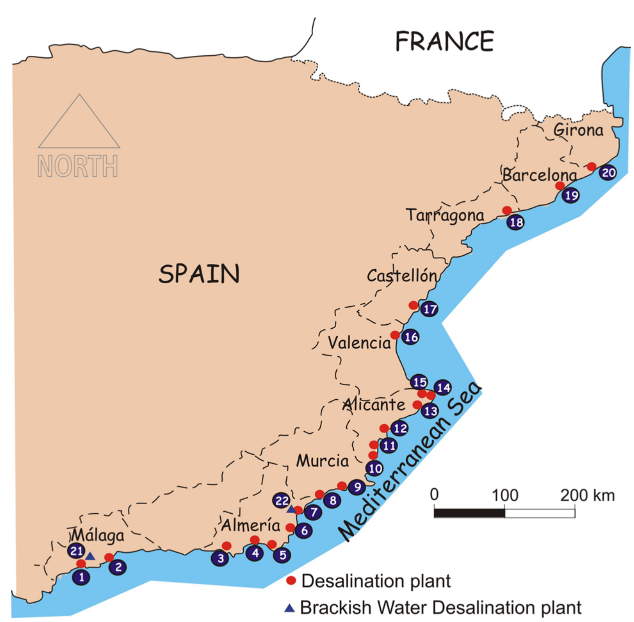

Fig. 4 Location of the main desalination plants (circles) and brackish water desalination plants (triangles) in the Spanish mediterranean coast

Table 1 Desalination plants in the Spanish mediterranean coast and their capacity

	Plant	Province	SW intake system	Capacity (hm^3/year)
Desalination plants				
1	Marbella	Málaga	Open intake	20
2	Mijas	Málaga	Open intake	20
3	Campo de Dalías	Almería	Open intake	30
4	Almería	Almería	Vertical beach wells	20
5	Rambla Morales	Almería	Vertical beach wells	15
6	Carboneras	Almería	Open intake	42
7	Bajo Almanzora	Almería	Open and subsurface intake	15
8	Águilas/Guadalentín	Murcia	Open intake	70
9	Valdelentisco	Murcia	Open intake	70
10	San Pedro Pinatar I	Alicante	HDD wells	24
11	San Pedro Pinatar II	Alicante	Open intake	24
12	Torrevieja	Alicante	Open intake	80
13	Alicante I	Alicante	Vertical beach wells	18
14	Alicante II	Alicante	HDD wells	24
15	Marina Baja	Alicante	Open intake	18
16	Sagunto	Valencia	Open intake	8
17	Moncofar	Castellón	Open intake	10
18	Cunit	Tarragona	Open intake	60
19	El Prat	Barcelona	Open intake	60
20	Tordera	Girona	Open and subsurface intake	20
Brackish water desalination plants				
21	Atabal	Málaga	Reservoir and vertical wells	60
22	Palomares	Almería	Vertical wells	10

and its energy consumption between 0.75 and 1.30 kWh/m^3 depending on the salinity of the raw water. Meanwhile, the Palomares brackish water plant (Almería) that sits on the alluvial deposits of the river Almanzora, one km from the coast, is supplied from various boreholes belonging to an 'irrigation association', whose abstractions had become more and more brackish as time went on. It has a capacity of around 10 hm^3/year. There are numerous other small desalination plants along the south-eastern coast of the Iberian Peninsula, which are supplied from boreholes yielding poor quality water and which are mainly used for greenhouse irrigation.

The most widespread intake method used along the Spanish mediterranean is the direct seawater intake. It is the recommended method for the large-capacity desalination plants. Thus, Carboneras (42 hm^3/year), Águilas (70 hm^3/year), Valdelentisco (70 hm^3/year), Torrevieja (80 hm^3/year), and El Prat (60 hm^3/year) (Fig. 4, Table 1) are supplied directly from the sea. Smaller capacity plants are supplied from boreholes into coastal aquifers or with a combination of both, as in the case of the Bajo Almanzora plant (15 hm^3/year).

The desalination plant at Almería city (Fig. 1, Table 1), situated on the delta of the river Andarax, has a design capacity of 50,000 m^3/day, though it has never operated at this flow rate. Its intake is by means of 19 boreholes, and although they do not all operate at the same time, each can abstract up to 100 L/s. The theoretical energy consumption is 4205 kWh/m^3. The desalinated water is mostly destined for urban water supply, though in recent years, it has also been used for greenhouse irrigation. The Rambla Morales plant (Fig. 1, Table 1), situated inside the Cabo de Gata Natural Park in the so-called 'Campo de Níjar', is fed from three coastal boreholes situated 300 m from the seashore. Despite the proximity of the production boreholes to the sea, recent studies have shown that the water abstracted was fossil water, with a salinity that was 10–20% higher than seawater (Sola et al. 2014; Vallejos et al. 2018). After several years in operation, this plant has fallen into disuse. Another plant that is supplied from beach wells is Tordera (Fig. 1, Table 1), which takes water from ten boreholes that are up to 180 m deep, situated just a few metres from the seashore. The salinity of the intake water has gradually decreased over time, indicating that a proportion of the abstraction is fresh water (Otero et al. 2011).

Of the remaining desalination plants, the most innovative means of seawater intake are those used in the San Pedro del Pinatar I and Alicante II plants. Thus, the Alicante II

Desalination Plant (Fig. 1, Table 1) boasts an innovative seawater intake system, consisting of a 1 km-long tunnel that runs parallel to and 50 m from the coast, 3.14 m in diameter (Fig. 5). Inside the tunnel, seawater enters through 103 inclined drains drilled 9.6 m apart, 130 mm in diameter and fitted with well screen over their last 18 m. (Rodríguez-Estrella and Pulido-Bosch 2009). The flow rate in each drain is 25–30 L/s. There are two 35 m-diameter cylindrical cisterns in both ends of the tunnel, from where the seawater is pumped to the desalination plant. The elevation of the base of this cistern is − 14.75 m and it lies − 12.5 m below the base of the tunnel. This design was chosen to avoid the predicted impacts that vertical boreholes would have created on the protected wetland close to this area.

Elsewhere, in the San Pedro del Pinatar I plant (Fig. 1, Table 1), another innovative design consists of 24 HDD that radiate from a central tank excavated on the shoreline and fan out into the seabed (Fariñas and López, 2007). These yield between 100 and 140 L/s. Each borehole was drilled in four stages. The first stage was a pilot borehole, 250 mm in diameter. Having removed the drill head, it was replaced by a backreamer, which increased the diameter of the bore to up to 500 mm. The third stage saw the installation of the piping into the borehole from the seaward end. The piping is connected to a backreamer that goes over the last stretch, so that when the drilling machine pulls it in, the backreamer cleans the tunnel that has previously been opened, while at the same time, positioning the piping inside the borehole. Finally, the boreholes are cleaned, stabilised, and sealed (Malfeito and Ortega, 2006).

Dilemmas

Following several years in operation of many of these desalination plants, we are in a position to understand the various problems encountered, which we summarise below.

Vertical boreholes

These are boreholes that are predominantly bored into recent detritic deposits which, if they are subject to intensive abstraction, may eventually cause subsidence over the terrain at a rate that is greater than under natural regime (Pulido-Bosch et al. 2012). This subsidence can affect local infrastructure. There is also the risk in this type of terrain that part of the well pipe unthreads and becomes loose as a result of the continuous stopping and starting of the pumps. To avoid this difficulty, it is advisable to install a system that prevents the pipes from unscrewing. Given that this is salt water, the pipes cannot be made of metal, since they would soon suffer from corrosion, and therefore, PVC pipes are the most suitable for this type of borehole. There is also the potential for settlement of gravel pack, which could collapse the borehole. This settlement would lead to the ingress of fine particulates into the borehole, silting it up rendering it unserviceable. Another documented problem is the possible incorporation of fresh water into the pumped abstraction, with the consequent drop in salinity of water delivered to the membranes (Pulido-Bosch et al. 2002). Likewise, part of the reject brine can get incorporated into the intake water, producing the opposite effect.

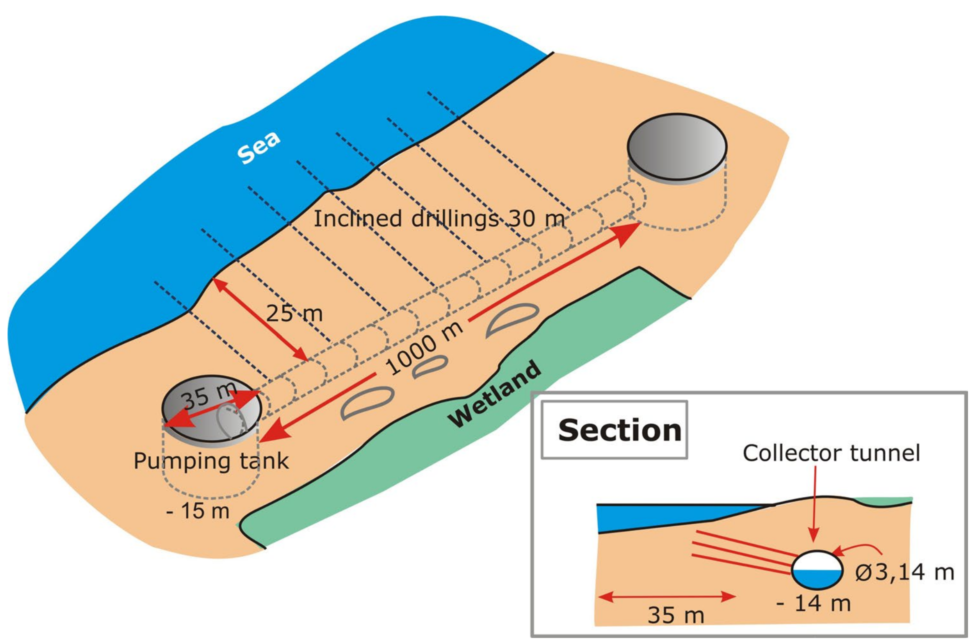

Fig. 5 Schematic plan and section of seawater intake system in Alicante II Desalination Plant

Incorporation of fresh water into the abstraction boreholes can cause problems, where it reduces the volume of fresh water available to other users. Nevertheless, this anomaly can significantly reduce the costs of desalination, and it is especially useful, where the fresh water tapped is very high in nitrates and, therefore, unsuitable for other uses (Hezi et al. 2018). A fall of up to 15% in the salinity of the water collected in boreholes has been recorded in the supply boreholes to plants including Tordera (Otero et al. 2011) and Almería (Jorreto et al. 2009). In contrast, the Rambla Morales desalination plant was pumping fossil water, whose salinity was up to 15% higher than seawater (Daniele et al. 2011; Sola et al. 2014; Vallejos et al. 2018).

HDD

It is relevant to note that the HDD technique has improved significantly in recent years. Systems that are more than a decade old bear the insurmountable limitation of having been executed in unconsolidated deposits. Moreover, the method of drilling the borehole used to allow sand and microorganisms to pass through. Since these works can exceed 500 m in length, the flow abstracted is small in comparison with vertical boreholes. These difficulties mean that, at a certain moment, some drains behave like direct seawater intakes, i.e., they become pipes taking water from the seabed without any kind of filtration.

The technique is based on a previous understanding of the nature of the terrain to be drilled. This knowledge comes from shallow marine seismic profiling, which can deliver high-resolution results. Work begins with the excavation of a ditch some 3–4 m deep, next to which the drilling rig is installed that allows three-dimensional inclined drilling, by means of high-pressure mud jets (*Neodren Drilling Fluid*—organic and degradable ; Peters and Pintó 2008, Peters and Pintó 2010; Peters et al. 2007). The first stage is to drill a pilot bore, which is subsequently widened to 600 mm. Then, the pipes are introduced from the seaward end. It is necessary to cement the 20 m closest to land to prevent fresh water being entrained, and this cement must be resistant to sulphur.

Tunnel with drains

This is a very costly procedure. The difficulty of appropriately sizing the screens means that the ingress of particulates can be high. As in any borehole array, the interaction between drains means that the flow of a drain (25–35 L/s) is reduced considerably when all the drains are open (5–6 L/s). In the Alicante II desalination plant, 103 drains discharge some 600 L/s. In addition, in this particular case, the aim was to avoid any impact on a nearby wetland. This was unsuccessful, since in the end, the drains led to a fall in its surface area of water, and as a result, a flow of salt water had to be supplied to the wetland to mitigate this environmental impact (Alhama et al. 2012).

Brackish water desalination plants

The main difficulty in supplying water to these plants is maintaining a constant salinity of the pumped water, avoiding gradual increases during the dry season and possible sharp falls after rainy periods. If, in addition, the reject brine is not disposed of properly, the salinity will continually rise. The experience with this type of plant in The Netherlands has led to the ability to keep the salinity fairly constant by means of complex mixing of waters with widely differing salinities (Stuyfzand and Raat 2010), taken from different depths and distances, using vertical and horizontal works (Zuurbier et al. 2015).

There are cases where the water intake infrastructure is salinized by saline rise, containing the brackish water extracted a part of fresh water. In other cases, fresh water and saline water are collected separately from two boreholes, to enable precise control of the abstractions to keep the salinity of the feed water relatively constant. Other systems capture brackish water through a deep well and add a small fraction of fresh water (Custodio 2017).

Given that the proper operation of the desalination system requires that the composition of the intake water remains as constant as possible over time, the seasons of the year when demineralisation can occur can lead to problems of a varying salt constant over time, sometimes doubling the salinity of the intake water (Valdés-Abellán et al. 2013). The solution to this problem is to have various nearby wells that are continuously monitored and which take water from different depths (Anderson et al. 2009) and of different salinities, blending the intake water, so that its salinity varies only very slightly (Schwarz 2003).

The reject brine can be injected into a deep aquifer if conditions allow. This injection can be a complicated and costly process and, over the long term, can lead to a degradation in water quality of the phreatic layer and, in the short term, cause damage due to errors or malfunction. The discharge of the reject brine into ramblas (dry river beds or ephemeral streams), near the point of use, is even more problematic, since it ends up salinising the system.

Final considerations

Spain has long experience in the construction and commissioning of seawater and brackish water desalination plants, starting on the Canary Islands in 1965 (Sadhwani and Veza 2008) and consolidated in the AGUA Programme (MMA 2005). The most common intake works are direct seawater intakes, particularly for large-capacity treatment works.

However, it is increasingly common for plants to take seawater from coastal wells or using horizontal directional drilling, and other novel systems also exist, such as tunnels excavated using tunnelling machines, and from which numerous bores are drilled beneath the seabed that collect water that flows towards two large cylinders at the end of the tunnel.

Each system has its advantages and drawbacks and pose environmental and socioeconomic challenges, though it seems that for small- and medium-sized works, there is unanimous agreement that coastal boreholes carry most advantages, provided that they are adequately designed. One very important aspect that has to be considered is that construction of the seawater intake and pre-treatment has to be adapted to the specific conditions of each plant.

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