Desalination and Water Treatment
www.deswater.com

31 (2011) 331–338
July

1944-3994 / 1944-3986
doi: 10.5004/dwt.2011.2380

7 year operation of a BWRO plant with raw water from a coastal aquifer for agricultural irrigation

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Received 13 June 2010: Accepted in revised form 24 March 2011

ABSTRACT

This paper will show the most relevant aspects in the 7 year operation period in the management of the O&M (operation and maintenance) at a BWRO (brackish water reverse osmosis) plant at Cuevas de Almanzora, Almeria, Spain. This plant has a current capacity of water production of 25,000 m^3/d and it was built to supplying agricultural consumers in the proximity of the plant. Cuevas de Almanzora BWRO plant is an exceptional plant in many aspects: 1) It is a plant working with brackish water but it was designed to be able to working with seawater with regards to materials, qualities and pressures (except the high pressure pump), and it could even be converted easily into a seawater plant; 2) Extensive hydrogeological studies have been completed allowing the control of aquifer exploitation and water extraction in the seawater-brackish water interface; 3) Water is distributed to different agricultural users with different water quality requirements (it produces “a la carte” water); 4) RO trains include inter stage energy recovery device to improve the hydraulic equilibrium between stages and reducing the energy consumption. This paper will present the following aspects: BWRO plant description; Results of the aquifer hydrogeological studies for the determination of saline intrusion. Conclusions and operation guidelines; Operation of the plant, results, operational problems arising from increasing salinity and specifically from sulphates; Description of the planned changes at the plant to allowing a possible future conversion into an SWRO plant; O&M costs.

Keywords: Brackish water; Reverse osmosis; Operation; Maintenance; Agriculture; Sulphates; Aquifer

1. Introduction

1.1. Desalination for agriculture in the area

Spain suffers a serious lack of water resources which is aggravated with time and includes cyclical drought periods. In this worrying situation the cases of general water use are prioritized for human supply, leaving other uses of agricultural irrigation, recreational uses as golf courses, irrigation of parks and gardens and urban services in the second place.

For this reason the use of potable water is restricted, therefore it is necessary to look for other non conventional resources (reuse, brackish and seawater desalination). For example, in Spain the use of potable water for irrigation of golf courses is totally forbidden.

Then, in the case of Spain, farmers and other users of this water have assumed in their production costs the price of this new water coming from desalination or reuse installations.

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Presented at EuroMed 2010 — Desalination for Clean Water and Energy: Cooperation among Mediterranean Countries of Europe and MENA Region, 3–7 October 2010, David Intercontinental Hotel, Tel Aviv, Israel. Organized by the European Desalination Society.

From water shortage around 1995, many farmers and agricultural businessmen decided to install desalination plants in the South East of Spain (mainly Mediterranean coastal areas) to solve the problem of available resources. In Spain these technologies were previously used in Canary Island but it was the first time in the mainland. We estimate that between 1995 and 2000 more than 200 desalination plants were installed for this application in this area, with typical sizes ranging between 100 and 5,000 m^3/d, with some plants treating more than 10,000 m^3/d.

Two examples of it are the Mazarron and Cuevas de Almanzora plants, with sizes of 13,500 and 25,000 m^3/d, respectively. Mazarron plant was built following a project from the owner and although it incorporated some technical innovations as energy recovery devices (turbocharger) it was not successful due to the increase of salinity in less than a year from 9,000 ppm of TDS (total dissolved solids) to more than 20,000 ppm of TDS, being finally restored into a seawater desalination plant with larger capacity. The plant at Cuevas de Almanzora (Fig. 1) is described in this paper.

The implementation of 'AGUA' program from the Spanish Environment Ministry could change this situation because large plants installed all over the Mediterranean coast could supply water for human consumption, agriculture and services (although there is a discussion with the farmers about the final price of water), leaving the small facilities built in recent years, some of which were even illegal, unused or abandoned.

1.2. Description of the customer and their needs

The 'Comunidad de Regantes'(community irrigation) of Cuevas de Almanzora is an association with agricultural producers who supply water for different clients and end users in the area of Cuevas de Almanzora, Palomares, Villaricos and Vera, in the Almeria province, Spain.

Fig. 1. Cuevas de Almanzora BWRO.

Until recent years water resources of this community came from the dam of Cuevas, which recorded minimum levels in the last years and the contributions of water transfers from other regions (also restricted). These allocations were insufficient meaning many farmers had to reduce land size for their crops. Another additional problem was the increased salinity of aquifers making groundwater useless for agricultural purposes.

In 2002 a new desalination plant began to solve the water problems of this community. The BWRO plant was designed with some common elements for a total flow of 30,000 m^3/d, with the building, intake and other installations ready to treat 60,000 m^3/d. Given the increasing salinity forecasts and even the possibility of exclusive use of seawater, the plant was built with components prepared to treat seawater including 1,200 psi pressure vessels, high pressure piping 904 L stainless steel, etc. This makes it possible to convert existing facilities to treat seawater at a reduced cost. The installation of RO trains (5,000 m^3/d each), train by train, recorded an increase in salinity in the raw water. Construction stopped with 4 trains which was enough for the community needs and maintaining a stable aquifer. In recent years another 5,000 m^3/d were added with the incorporation of another small disused plant from a farm.

2. Description of the project

2.1. Basic data

Location: Road between Villaricos and Palomares, Almería, Spain.
Owner: 'Community Irrigation' Cuevas de Almanzora.
Design, construction and operation: Consortium between SADYT (Valoriza, Sacyr Group) and Talleres y Gruas Gonzalez (local civil works contractor)
Project type: Private installation partially subsidized by local government (Junta de Andalucia), including European Community funds and with an O&M contract for 15 years.
Technology: Reverse osmosis desalination plant.
Purpose of installation: To obtain quality water for agricultural irrigation.
Flow: 30,000 m^3/d in different stages (currently in operation 25,000 m^3/d)
Recovery: 65–70%
Water quality: Brackish water underground from coastal aquifer. Conductivity between 9,000–20,000 μS/cm (with increasing salinity)
Treated water: Contract: < 500 μS/cm

The plant was executed in a record time:
Beginning of the works: September 2002
Term of execution: 8 months (6 months to start-up the first RO train)

2.2. Plant description

Treatment process

1. Water intake
   By wells (6 currently), with an average depth of 20–30 m. Depth of 50 m while maintaining the water level between 8 and 11 m.

2. Raw water tank 1,500 m^3

3. Physical pre-treatment (sand filtration and cartridge filter):
   – 4 low pressure pumps 350 m^3/h
   – 1 backwash filter pump 450 m^3/h
   – 4 units of sand filters 3,000 mm diameter and 11,000 mm length
   – 1 blower for filter backwash
   – 4 units of GRP (glass reinforced polyester) cartridge filters, with 150 cartridges of 40″ length and 5 µ selectivity

4. Chemical pre-treatment: hydrochloric acid, sodium hypochlorite, sodium bisulphite and antiscalant. Currently only antiscalant is added.

5. Reverse osmosis trains
   – 4 high pressure pumps 350 m^3/h, 27.5 bar, with frequency variation with 400 kW electric motor.
   No. of trains: 4
   Unitary flow: 5,000 m^3/d
   Total flow: 20,000 m^3/d
   Additionally in the last years a small 5,000 m^3/d plant was transported and installed into the RO building increasing the total flow to 25,000 m^3/d. This small plant (in 2 trains) was installed with all the required pre-treatment (sand filters, cartridge filters, chemical dosing, etc.)

   Design recovery: 65–70%
   Array: (34:17) × 6

Fig. 2. Cuevas de Almanzora BWRO plant.

   Membrane: TORAY SU-720 F (1st stage)/SU-820 FA (2nd stage)

6. Energy recovery system
   There are energy recovery devices (Turbocharger) installed to recover some of the residual energy from brine, increasing the pressure between the first and second RO stages.

7. CIP system
   With cleaning and flushing pumps 270 m^3/h, cartridge filter and 2 tanks with 20 and 50 m^3, respectively equipped with agitation and heat resistance.

8. Electrical installation
   The plant has 3 transformers with 750 KVA each, CCM, and SCADA system for control.

9. Product water pond
   Works included an open pond with 23,000 m^3 capacity to store product water

10. Product water pumps
    Plant includes 2 pumping stations:
    – Pumping station to Cuevas de Almanzora containing 4 pumps with 290 m^3/h at 18.5 bar, which sends product water to the water pipes net for distribution of community varying the flow and pressure depending on the needs of end users.
    – A second group of pumps to send water to Palomares village, with 3 additional pumps

11. Brine discharge
    The facilities include a submerged pipe for discharge of brine that joins to another brine pipe in Pulpi (another desalination plant) and ends at 350 m of shoreline and 6.5 m deep at the mouth of the Almanzora River.
    The outflow pipe is 650 mm in diameter with horizontal injection diffuser nozzles at the point of discharge. The point of discharge, which derived from the environmental impact study, was decided due to the characteristics of the river Almanzora with flooding periods and without sensitive species, not forgetting that this is a discharge of water with lower salinity than seawater at the mouth of a river, which is an area degraded by sediment transport.
    For optimization of operation management the plant is fed from different wells with different flows and salinities, depending on behaviour of each well (those are medium values);
    – Well 1: between 17.00 mS/cm and 18.00 mS/cm (practically not used)
    – Well 2: between 9.00 mS/cm and 15.00 mS/cm
    – Well 3: between 9.00 mS/cm and 15.80 mS/cm
    – Well 4: between 7.00 mS/cm and 8.60 mS/cm
    – Well 5: between 7.00 mS/cm and 8.80 mS/cm
    – Well 6: between 8.00 mS/cm and 10.00 mS/cm

2.3. Innovations

2.3.1. Plant ready to treat different water qualities

The plant was designed knowing the problem of increasing salinity in raw water, and then the concept of it was in 2 stages:

- 1st stage: recovery of water from the river mouth (although the intake is from wells) avoiding the seawater. Designed to treat water with conductivity between 7,600–30,000 µS/cm
- 2nd stage: Progressive incorporation of seawater treatment

In the last few years the equilibrium of the system has been maintained with growing salinity although stable, and then the transformation into a seawater RO plant was not necessary.

Solutions to operate with growing salinity

- RO plant designed to work with salinity 25,000–30,000 µS/cm
- High pressure pumps designed in a very conservative way and with frequency variation
- For correct hydraulic balance between stages an energy recovery turbine (Turbocharger) was included and membranes are different at each stage:
  - Membrane 1st stage: SU 720 F (brackish water)
  - Membrane 2nd stage: SU 820 FA (seawater)

But if it fails, we will go to the plan B. The plant is easy to transform into a seawater plant due to the following facts:

- 1,200 psi pressure vessels
- 904 SS pipes, Sch 80 in high pressure
- GRP and materials resistant to seawater corrosion in pre-treatment
- Carbon steel filters with rubber lining
- High pressure pump has a longer shaft that can attach to a Pelton turbine. Another option would be changing the pumps and incorporating other energy recovery devices
- Other materials (valves, pipes, fitting, instruments, etc.) were also designed for seawater treatment

2.3.2. Production of "a la carte" water

Quality of water supplied is different depending on the requirements of each end-user. The quality requirements are also different depending of the irrigated crops e.g. tomatoes, lettuce, potatoes, melon, etc. or the type of user e.g. agriculture irrigation, golf course, sometimes even drinking water for surrounding districts.

Quality of water supplied is controlled by means of an automatic blending of permeate and raw water with the control of conductivity of each flow. The price is different too and is calculated by the different registered qualities or demand.

2.3.3. R&D Centre

Recently the plant has become a research centre for Sadyt, having installed some pilot plants to research brine dilution, ZLD of brine by means of evaporation-crystallization, etc., operating on the plant.

2.3.4. Trasar 3-D

Due to problems in the past with increasing concentration of salinity in raw water (and especially sulphates) and the need to control the adequate dosage of antiscalant, Nalco agreed to the installation of a Trasar 3-D system (Fig. 3), to control accurately this dosage.

Fig. 3. Nalco Trasar 3-D device.

2.4. Hydrogeological studies

To predict the behaviour of the aquifer regarding time and the extraction of well water for the plant, a series of hydrogeologic studies were conducted:

- Infiltration and flow calculation (rainfall studies)
- Geologic and hydraulic environment
- Piezometric levels of groundwater, water quality and evolution with time
- List of water intakes
- Evaluation of resources
- Crops maps and water uses
- Pumping tests

These studies were completed with a campaign of geophysical exploration by means of Electrical tomography (technology based in the analysis of electrical resistance of ground materials). 16 profiles of electrical tomography grouped in 5 lines with direction NW-SE, perpendicular to the coast line. Each profile was 355 m length.

There were 3 different stripes observed in the direction NE-SW parallel to the coast.

- High conductivity (close to the sea). Conductive materials. Very salty water.

- Materials predominantly conductive. Salty water
- Moderate salinity. Thick materials with brackish water in the pores, brackish water.

This study determined:

- The most adequate area for well water intake and possible evolution of aquifer
- The most adequate area for future seawater intake
- The possibility to inject brine in the salty water area (this solution was discarded finally with the construction of the brine pipe).

2.5. Costs

2.5.1. Investment cost

The investment of the works was as follows:

- Investment for the 1st stage of the plant: 12,182,727 €
- Subsidy of 'Junta de Andalucía' (local Government): 6,091,363 €

2.5.2. O&M costs

Water costs are different depending on raw water quality and product water quality required for each user. The typical distribution of costs is shown in Table 1. Normally the costs are below 0.3 €/m^3.

Personnel costs are very reduced in this case (as usual in desalination plants for agriculture irrigation) because the plant is managed with only 4 people and night or weekend staffing is avoided by means of alarms being sent to the mobile phones of O&M personnel.

Table 1
O&M costs for 17,000 μS/cm conductivity in raw water

Concept	€/year	€/m^3
Variable costs		
Chemicals		0.048
Membrane replacement		0.020
Cartrigde filters and others		0,.004
Energy		0.127
Maintenance		0.01
Total variable cost		0.211
Fixed costs		
Personnel	148,750	0.030
Fixed maintenance	16,227	0.003
Other fixed costs	19,833	0.004
Total fixed costs	184,811	0.048
Total cost		0.248

3. Results

3.1. General data

The graphs below (Figs. 4–6) show some characteristics of raw water in the last 4 years, e.g. conductivity, chlorides and sulphates.

As shown, the conductivity and chlorides in the last 4 years seem quite stable, but the sulphates are showing different tendencies. Due to the peak of sulphates

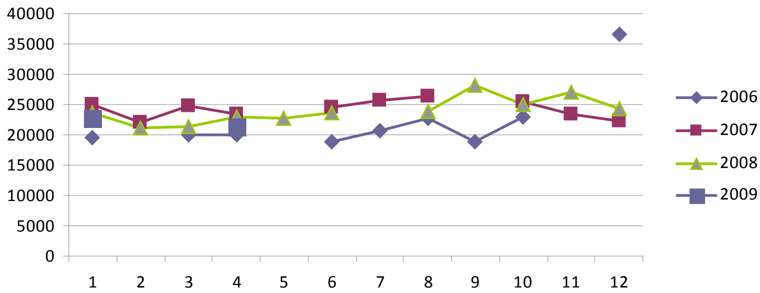

Fig. 4. Conductivity (μs/cm) of raw water.

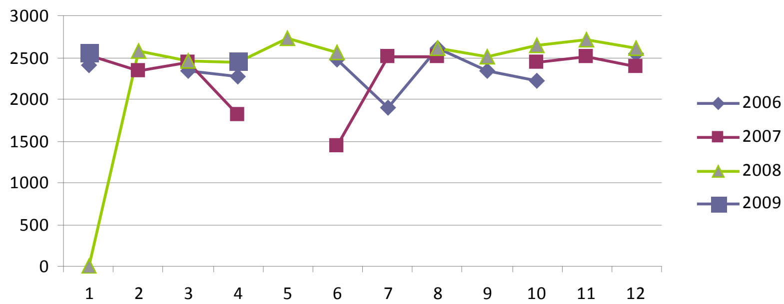

Fig. 5. Sulphates (ppm) in raw water.

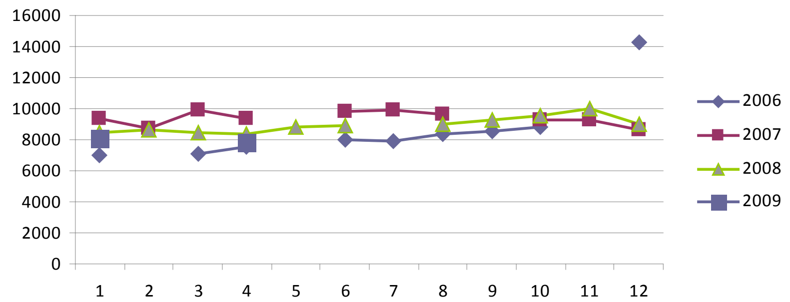

Fig. 6. Chlorides (ppm) in raw water.

obtained in the first years of operation was forced the temporary reduction of recovery and the change of antiscalant type.

3.2. Problems at startup and within the first years

The plant started up in late May 2003 with salinity values in raw water of 9,200–9,400 µS/cm and a sulphate concentration of 2,800 ppm. Recovery was fixed at 63% using the antiscalant 'PermaTreat 191'.

But a progressive increase in conductivity in the raw water was found, reaching values of 10,000–10,200 µS/cm in only one month, with a period of maximum conductivity of 12,000 µS/cm in July 2003, although this trend was stabilizing. The concentration of sulphate at this time was at values between 3,000–3,300 ppm, which forced to a reduce recovery between 55–56%. Given the low economic viability of this recovery, a change of dosage was decided, from the antiscalant PermaTreat 191 to a more specific product such as PermaTreat 504, which allowed the system to raise the conversion to values of 70%.

It also shows the evolution of sulfate with time, which reflects the rapid increase between the months of May and August of 2003, which was moderated over time to remain stable, in the last few months settling to 2,600 ppm.

Curiously, the levels of sulphates were sometimes above the levels of sulphates in seawater and the Chloride concentration was relatively stable. The interpretation of this problem was that perhaps it was due to the aquifer material solution.

The graph (Fig. 7) is for the purpose of showing the trend of parameters, but it can not be interpreted rigorously because it represents blended water values from individual wells (which have different characteristics and location), and the operation has not always worked with all the wells and sometimes alternating wells. Some other water parameters (pH, temperature and conductivity) can be seen in Tables 2 and 3"

3.3. O&M data

Points about the main process parameters:

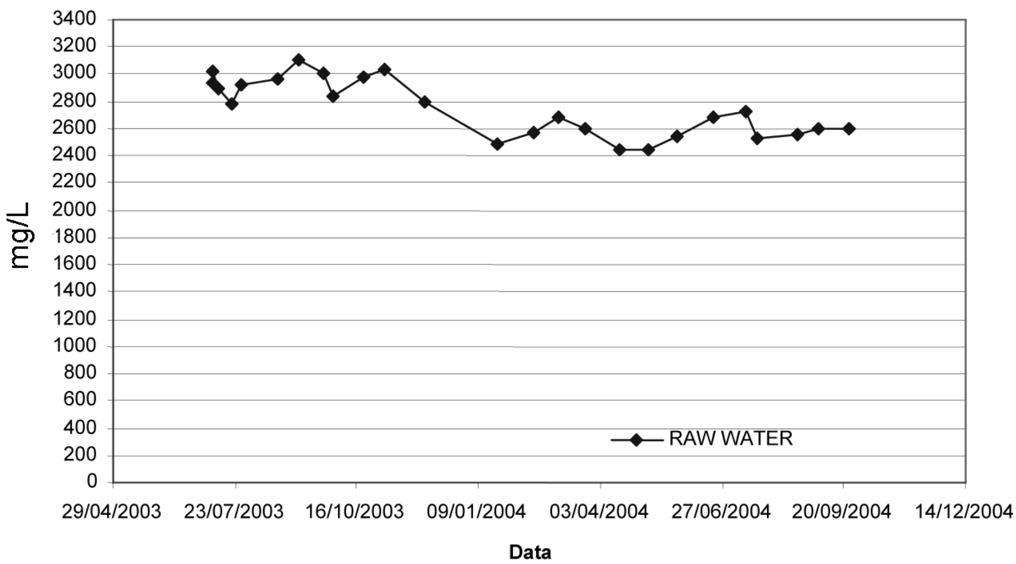

Fig. 7. Sulphates in raw water, 2003–2004.

Table 2
Some water parameters in 2009 (values obtained from 2 data per day)

	pH of raw water	$pH_{prod.}$	Temperature (°C)
Minimum value	5.6	5.4	19
Maximum value	7.6	5.9	23
Average value	7.1	5.6	21

- Temperatures are very stable all over the year with values around 20°C
- No membranes have been replaced from the start of the project (7 years)
- Cartridge filters have been changed usually once a year
- Only antiscalant is added as chemical treatment (Permatreat 191 and Permatreat 504 in the peak periods with high sulphate concentration)
- 1 chemical membrane clean is completed per year
- No membrane replacement has been necessary during all this time

Typical operating values can be seen in Table 4.

3.4. Energy consumption and energy tariffs

Energy recovery due to the rurbochargers is over 30%, with a specific electrical consumption in high pressure pumping of 0.9 kWh/m^3 and 1.9 kWh/m^3 in the whole plant including permeate pumping.

Table 4
Typical operating values in the year 2009

Pressure	
1st stage, bar	19.7
Outlet 1st stage, bar	19.1
Inlet 2nd stage, bar	31.3
Outlet 2nd stage, bar	30.7
Outlet 2nd stage, bar	0.6
Backpressure, bar	2.0

Shown below (Table 5) is typical table of results, for energy recovery for a raw water conductivity of 15,000 μS/cm.

Another very important issue in this plant is the use of special energy tariffs also with a discontinuous operation. The plant stops automatically in peak and high-peak hours reducing the energy costs. Unfortunately, sometimes the peak water demand is in months with more energy peak hours so it is more difficult to manage this situation.

Since the beginning of free market in the electricity sector in Spain the cost of energy have changed both in terms of power and energy increasing 59% in power cost and 35% in consumption cost. The rate 6.1 corresponds to our facility; the costs set out in the regulated part of the electricity tariff for access to the free market are listed in Table 6. Fixed energy costs are part of the regulated tariff because of this we must increase the marketing and distribution costs with a formula such as:

Table 3
Some water parameters in 2009 (values obtained from 2 data per day)

	Conductivity of raw water (μS/cm)	Conductivity of product (μS/cm)	Conductivity of reject 1st stage (μS/cm)	Conductivity 1st stage (μS/cm)	Conductivity 2nd stage (μS/cm)	Conductivity brine (μS/cm)
Minimum value	14,400	335	20,200	143	249	23,265
Maximum value	20,800	551	34,900	578	651	60,020
Average value	17,369	431	30,933	399	441	44,135

Table 5
Energy recovery

	Pressure (bar)	Raw water conductivity (mS/cm)	Product water conductivity (μS/cm)	Recovered pressure (bar)
Train 1	19.0	15.00	150	9.5
Train 2	18.5	15.00	145	8.5
Train 3	19.0	15.00	155	8.5
Train 4	18.2	15.00	180	8.0

Table 6
Tariff 6.1

	P1	P2	P3	P4	P5	P6	Increase (%)
Power (€/kW y)							
2008	10,092230	5,050488	3,696118	3,696118	3,696618	1,686408	
2009-January	10,092230	5,050488	3,696118	3,696118	3,696618	1,686408	0
2009-July	13,119911	6,565634	4,804953	4,804953	4,804953	2,192330	30
2010 January	16,268690	8,141386	5,958142	5,958142	5,958142	2,718489	24
(Proposed) 2010 July	17,082124	8,548455	6,256049	6,256049	6,256049	2,854414	5
Consumption (€/kWh)							
2008	1,930500	1,693400	1,287000	0,730700	0,471900	0,429000	
2009-January	3,571400	2,963500	1,698800	0,964500	0,622900	0,429000	0
2009-July	4,642800	3,852600	2,208400	1,253900	0,809800	0,557700	30
2010 January	6,964200	5,201000	2,771500	1,379300	0,890800	0,557700	0
(Proposed) 2010 July	7,312410	5,461050	2,910075	1,448265	0,935340	0,585585	5

Final cost =

Fixed cost + (Market cost) × Passage coefficient

Fixed cost = cost of the regulated rate indicated in Table 6; Market cost = in the energy cost published daily; a day in advance; Passage coefficient = is a variable rate set by the trader; it includes the benefit and cost of toll distribution.

With this formula, there are two contract possibilities:

- The first option is through a flat rate for each period and it is renewed annually, in which the trading company after their market forecasts set a price that is unchangeable during the contracted period.
- The second option is a type of Pool. In our case, it consists of the price varying by the monthly average for each period to which using the above formula. Therefore we are not subject to a fixed price with the advantages and disadvantages that it implies.

Advantages: due to the situation of the current suffering market, due to lower consumer demand for the fall of national productivity it makes energy more affordable now and below average prices that companies offer.

Disadvantages: it is possible that market prices may rise sharply and there is no possibility of changing the contact detail until it has ended.

Since the free market in Spain came into force we had two forms of contracts. At first our method was tied to a fixed rate contract with an average cost of 0.07–0.08 € per kWh. After analyzing the market trends the decision to change the type of contract to the second option provided the project with a commitment with our client that allows us to share the benefit. Since then the cost per kWh is below 0.06 €.

4. Conclusions

The main conclusions obtained during this experience are indicated below:

- Desalination plants treating underground brackish water require rigorous studies of the aquifer to test their possible temporal evolution and the impact on water extraction and exploitation.
- Aquifer studies can also determine the most appropriate for deposits, the optimal operating system and the location of the discharge.
- The design of a facility of this type, and more so, in coastal aquifers, must be flexible and able to respond to different situations of water quality an expected worsening.
- The desalination plant in Almeria Cuevas de Almanzora is a unique facility in many ways.
- It is a plant that is currently working with brackish water, but is ready to work with sea water, in terms of materials, qualities and pressures (except pumps).
- Rigorous hydrogeological studies were undertaken which controlled the exploitation of the aquifer and the extraction of water to be desalinated brackish water interface of seawater–water distributed to different users with different requirements (produced water "on demand").