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The role of SWRO Barcelona-Llobregat Plant in the water supply system of Barcelona Area

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ABSTRACT

Barcelona-Llobregat Desalination Plant is actually the largest seawater desalination plant in Europe producing potable water from the seawater of the Mediterranean Sea. The plant is able to supply approximately the 20% of tap water of Barcelona Metropolitan area having a maximum capacity of 200,000 cubic meters per day. This project was developed by Aigües Ter-Llobregat, public company of the Catalonian Government (Generalitat of Catalonian) to face the lack of water resources and to improve the water quality in Barcelona's south area. A Joint Venture of Degrémont, Aigües de Barcelona and Dragados-Drace built the plant during a severe drought period in a extremely tight delivery time of 24 months. The plant was inaugurated on July 2009 and from this date the same JV is operating it. Barcelona-Llobregat SWRO plant won the Global Water Awards 2010 as the Desalination Plant of the year. A pilot plant was operating for two years to help in design and for getting experience with Mediterranean seawater. The facilities are located in El Prat, an industrial area between Barcelona Harbour and Llobregat mouth, just close to one of the waste water treatment plants of Barcelona, DepurBaix. A deep intake located 2 km offshore feed the plant avoiding the Llobregat river impact, especially for heavy rain period, and the harbour leaks. Sea water is pumped for more than three and a half km, crossing the river through an underground pipe. A very strong pre-treatment protect reverse osmosis (RO) membranes: a set of 10 SeaDAF®, high speed floatators, is the first step followed by 20 Mediazur® gravity filters and 20 SeaClean® pressurized dual media filters. The polishing is guaranteed by 18 cartridge filters of 5 microns. The silt density $index_{15}$ of pretreated seawater is always below 3.0%/min, with an average of less than 2.5. Ten RO trains with a unitary production over 20,000 m^3/day are fed by individual HP pumps and the energy recovery is assured by a set of 23 PX220 per train. A partial second pass guarantees a boron concentration in treated water below 1.0 mg/l (two trains of 16,500 m^3/day). Remineralization is made with CO_2 and upflow limestone filters with an innovative design. Potable water is pumped over 12 km to Fontsanta reservoirs to be blended with waters coming from two potable water plants, one with electrodialysis reversal treatment. Brine have an innovative treatment: it is blended with treated water from DepurBaix waste water treatment plant in a ratio lower than 1:1 and discharged through diffusers at 50 m depth to more than 3 km from intake. All effluents are treated before discharge and the plant has sludge treatment. The plant has increased the "green label" adding a wind generator and photovoltaic panels in the building roofs to minimize the electric internal consumption. The operational criteria and managing water production is another important chapter, because it takes into account all available resources. The paper will describe:

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– several innovative details of the plant and the construction;
– the construction and operation feedback;
– the criteria to decide the production of the plant;
– the follow-up of main parameters of seawater and plant;
– the real energy consumption in the different stages;
– results of pre-treatment, RO trains and post-treatment from the first two years of operation;
– and the integration of the plant in the regional water supply system, considering the principal factors:

- Volume storage in the dams.
- The operation of the drinking water plants.
- The pluviometry and the climate predictions.
- The regional water supply planning.The rest of the available resources (ground water, etc.).

Keywords: Seawater desalination; Pretreatment; Flotator; Barcelona; Degrémont; ATLL

1. Introduction

The Barcelona Metropolitan area has an historical lack of water resources to ensure a permanent guarantee of water supply. Additionally there is a quality problem due to the high hardness and salinity, coming from the salt mines in Suria and Cardona. Finally the lack of flexibility in the distribution network has not facilitated the optimization of resources management in Ter and Llobregat basins [1].

Aigües Ter-Llobregat (ATLL), public company of the Catalonian Government, has developed several actions focused on reducing the indicated deficiencies. The most significant action is the Llobregat Seawater Desalination Plant. Besides this one, they have added the extension and improvement of the Drinking Water Treatment Plant (DWTP) Abrera (including an electrodialysis reversal [EDR] plant) and Sant Joan Despí (including and UF and backish water reverse osmosis [BWRO] plant), as well as the interconnection pipe between Fontsanta and Trinidad reservoirs. This allows supply flows from the Ter river to the south of Barcelona or flow from the DWTP Abrera and from the Llobregat Desalination Plant to the north of Barcelona, due to its reversible character. Due to these actions, Barcelona has three plants including the three-membrane technologies to desalt within few kilometres around the Llobregat River (see Fig. 1).

A Joint Venture of Degrémont, Aigues de Barcelona and Dragados-Drace built the plant during a severe drought period in an extremely tight delivery time of 24 months. The plant was inaugurated on July 2009 and from this date the same JV is operating it.

The Barcelona-Llobregat Plant is the main element to ensure the water supply in the area in the case of severe drought. Because of this, being the largest in Europe, its quick commissioning and for the innovations given to the Desalination world, it was awarded the prize of the Plant of the Year at the Global Water Awards 2010.

2. Previous studies and pilot plant

Three specific water studies were done, starting one year before the presentation of the proposals with the last after the client's final decision. The water studies include pilot plant at Lab scale. One study per season evaluating the evolution of the seawater quality, and its influence in the design of the RO Plant (silt density index [SDI], Temperature, total dissolved solids and so on) depending on the source of the seawater. The main objectives of the studies were to: improve knowledge of the raw water quality; validate the pre-treatment process and determine of the optimum chemical regime and design parameters.

ATLL also performed several studies to decide the final intake:

- One year of operation of a pilot sub-seabed drain.
- Preliminary sea studies including online sample collection (turbidity, conductivity and temperature).

Once ATLL selected the JV to build the plant, a pilot plant was installed. This pilot had the same pretreatment elements as the real plant, but designed for 40 m^3/h. A lamellar clarifier (Pulsatube®) and a flotation with SeaDAF® were installed in parallel. Both units were followed by a double stage of Dual Media Filtration, cartridge filter and a RO rack with a pressure vessel with seven membranes of 8 inches, with a capacity to produce about 90 m^3/day. A limestone filter and CO_2 dosing system were also incorporated to make remineralization tests.

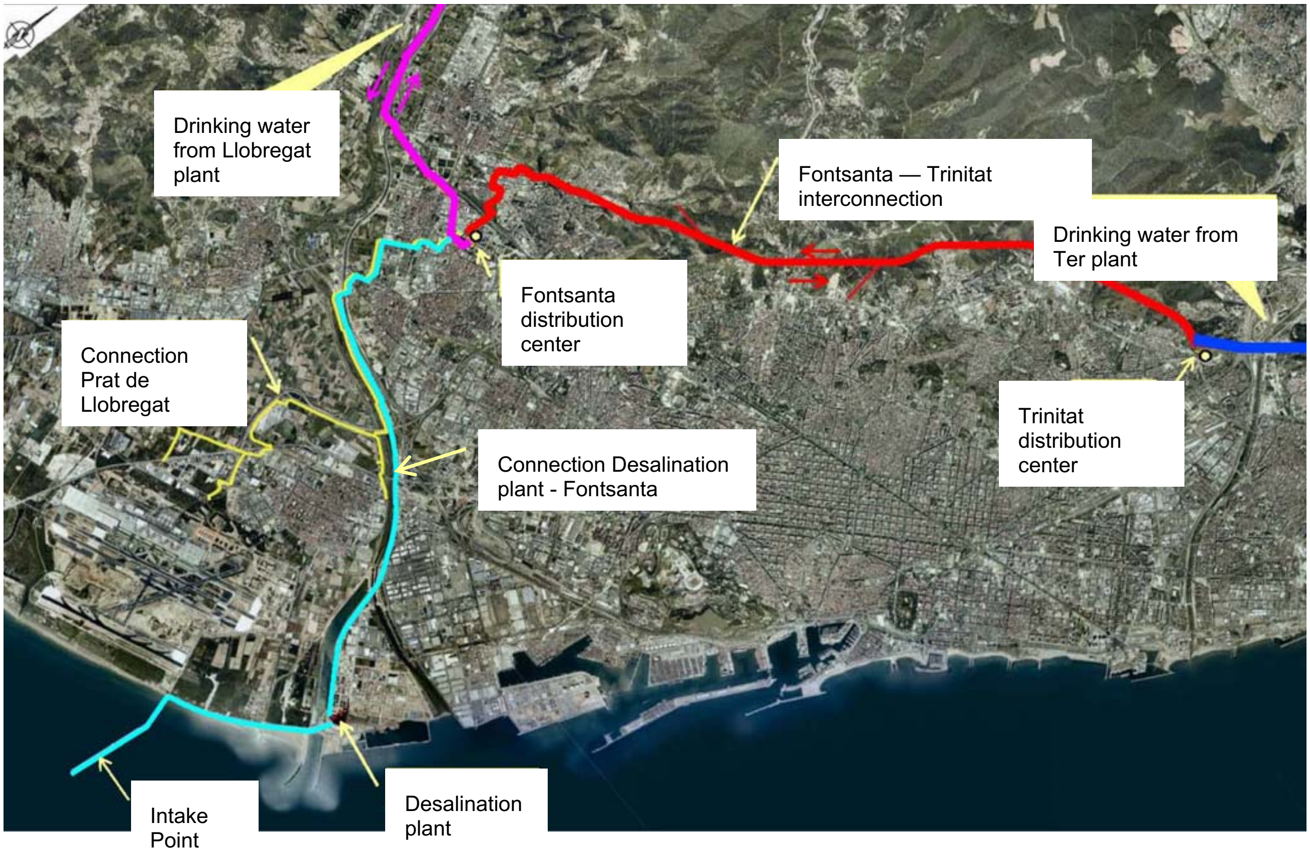

Fig. 1. Situation of works of Barcelona Plan.

A specific open intake was built for this pilot at 1.075 m from the coast to take the seawater at 10 m. depth. This means worse quality conditions than in the definitive intake (25 m depth at 2.200 m from the coast).

All tests proved that the planned treatment line was suitable. The SeaDAF® flotation was definitely selected as the best solution, with a non-mechanic and piston flocculation, as the same as the definitive design of the rest of the components of its operating parameters. The performance of the RO membranes was also evaluated for a long time confirming the selected hybrid design.

In parallel to this pilot plant and taking profit from the sea water excess supplied by this intake, other Degrémont Research pilots have been installed in the same area, with different objectives, making easier the synergy between the different platforms to create a Research Platform for Seawater treatment. The pilot has been working until 2010.

3. Plant description

The sea water intake is located at 2,200 m from the coast, at about 30 m depth using a double polyethylene conduit of 1,800 mm diameter, with 2 intake towers that allow to capture sea water at about 25 m in depth. This intake avoids any influence of particle discharge from the Llobregat river, even with the worst storms. This double conception ensures the operation of the plant, at great flow and also with one of the intakes under maintenance.

The intake pipes were built in Norway and transported floating to Barcelona in stretches of 500 m length. In the port of Barcelona, the concrete ballasts were installed and were transported to its location at the dug marine bottom [1] (see Fig. 2).

The solution of the sub-seabed drains was ruled out because of the space needed to install the drains interconnection and the pump station, as well as the doubts of clogging in the future.

Sea water pump station is located close to the beach of Prat of Llobregat. After screening six pumps with frequency converters, to minimize electrical consumption, the seawater is sent to the plant through a pipe, crossing the river along its course.

After fine screening, the water goes to the coagulation chambers and the piston flocculation areas of 10 SeaDAF® flotators, five per line. The SeaDAF®s allow

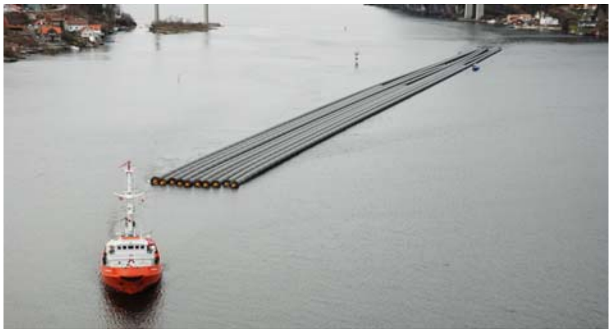

Fig. 2. Transporting intake pipes from Oslo.

to eliminate at a speed superior to 30 m/h without using the polymer, suspended solids and mainly the seaweed in the sea water, using only mineral coagulant, typically ferric salts.

Another coagulation chamber precedes the first filtration stage composed of two lines in parallel with 10 Mediazur® filters of 155 m^2 each. These filters have got numerous references worldwide and its effectiveness has been proved in large desalination plants such as Fujairah (EAU) or Wadi Ma'In (Jordan) [3].

The filtrated water is stored in an intermediate tank, of 3,500 m^3, where it will be pumped to the second stage of filtration, made with two pumping groups, one per line, each with six pumps, one on standby. This second phase has 20 SeaClean® dual media pressurized filters, divided in two lines. The unitary surface is 66 m^2, one of the largest in the world for pressurized filters. SeaClean® filters have a lot of experience in desalination plants such as Minera Escondida, San Pedro del Pinatar, Perth or Barkha II. They have been designed to have large filtration cycles, ensuring an excellent quality of filtrated water, also when they work as the only phase of pre-treatment [2].

SeaDAF® Floatation and Mediazur® filters can be by-passed allowing to make the plant run with one, two or three pre-treatment phases depending on the sea water quality.

The last security phase in the pre-treatment is the 18 cartridge filters of 5 microns, divided also in two lines (see Fig. 3).

The RO is divided into two production lines of 100,000 m^3/day each. The first pass has 10 racks of 230 pressure vessels mega side port with seven membranes inside, with 20,000 m^3/day of unitary

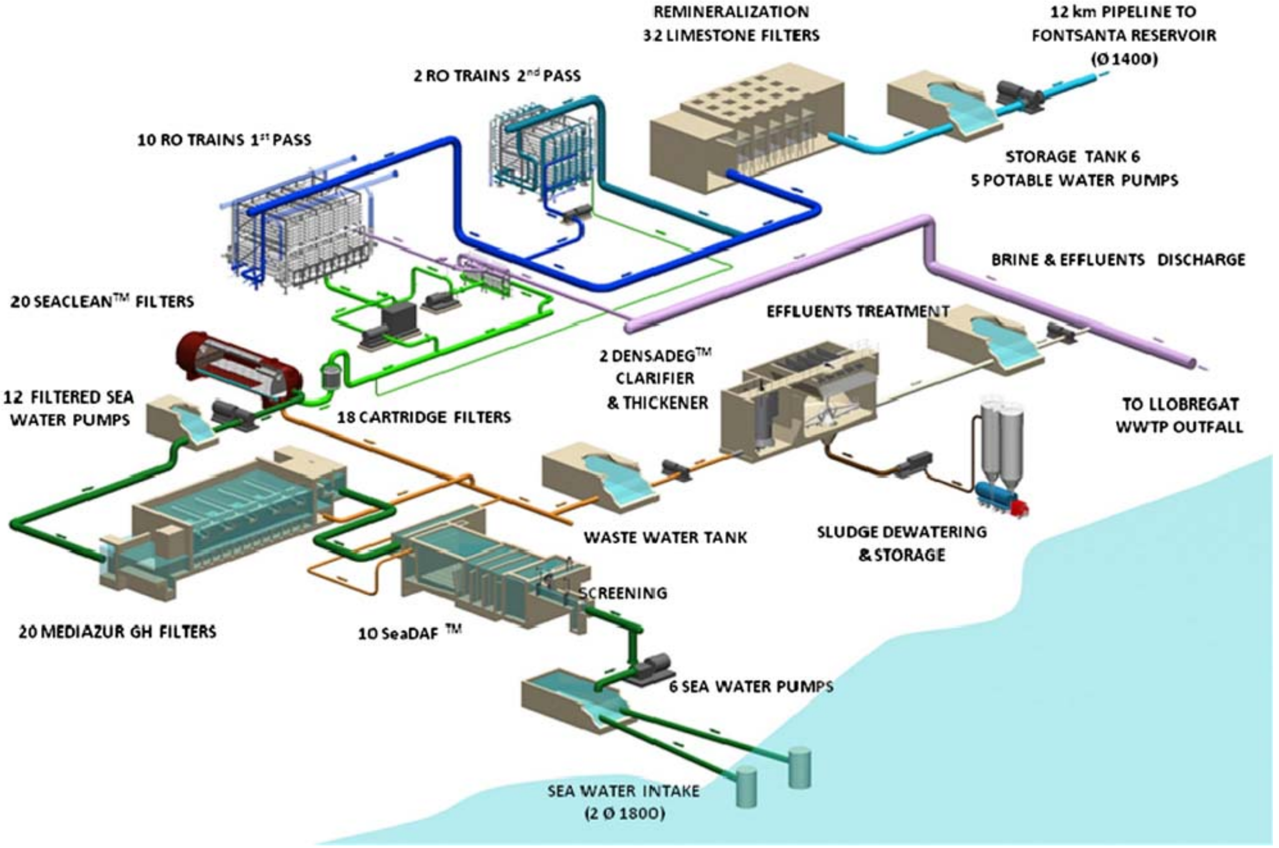

Fig. 3. Plant flow sheet.

production. The racks have a hybrid design combining two types of membranes, SWC4 + and SWC5 of Hydranautics. The C4 is placed in the first places of PV because of the higher salt rejection and C5 in the last places due to the high permeability. This system tested successfully in other plants (Minera Escondida, Wadi Ma'In or San Pedro del Pinatar); it allows to optimize the design, reduce the fouling risk and minimize the energy consumption. Pass recovery rate is 45%.

There is a HP split case pump, a control valve and a booster pump for each rack, as well as 23 pressure exchangers PX-220® from Energy Recovery to minimize the energy consumption [4].

A partial second pass ensures the Boron guarantee (1 mg/l) during the periods of highest temperature in sea water. It has two 16,500 m^3/day racks designed at 85% recovery in two stages. There is 78 PV with seven membranes inside. Each rack is fed by a MP pump, existing one additional on standby.

The water produced by these steps is stored in a tank able to ensure the flushing of all the RO racks. Post-treatment includes the remineralization, the disinfection and the pH adjustment.

A solution of CO_2 and limestone filters was selected for remineralization, for the purpose of optimum operational cost. Carbon dioxide is injected online, though static mixer. It reacts with the calcite of two batteries of 16 upflow filters with constant bed height. Unitary surface is 21 m^2. The loading system of granular limestone is made through the upper cones, which allow a continuous load and adapted to the consumption avoiding the stopping of filters to load it. The filters have floors with filter nozzles and a backwash system to remove the fines. Remineralizated water is stored in the treated water tank of 4,500 m^3. This tank is divided into two chambers to allow the maintenance without stopping the plant.

A caustic soda dosing ensures the necessary pH adjustment for the langelier saturation index required. The disinfection is made by sodium hypochlorite.

The 4 + 1 pumps send potable water through a pipeline of 12 km to the Fontsanta distribution tank, delivery point of all the desalted water to the supplying network of Barcelona.

One of the problems to solve in each desalination plant is discharging the concentrated water from membranes rejection, having a quick dispersion and a strong dilution to produce the minimum impact in the marine environment.

This case has been solved in an original way: blending the brine with the treated effluent from the Baix Llobregat waste water treatment plant, located close to the desalination plant. The Mixing point is the equilibrium tower of the existing submarine emissary. Brine arrives directly pressurized from the outlet of PX. The rest of the effluents are pumped to the same point.

This system allows in the worse case (maximum flow) a mixing ratio of 1:1 between brine and treated waste water. This implies that the salinity of the global discharge is less or the same as that of the sea water minimizing its impact. The discharge point is at 60 in depth and about 3 km from intake, avoiding any interference between both points due to the predominant sea currents.

Other important point taken into account under the point of view of environment is the treatment of all the effluents.

Sludge from SeaDAF®, membranes cleaning and all backwash waters from the two filtration phases are collected and homogenized in a large tank of 3,500 m^3. Two pumps send the waste at a laminated flow to its treatment.

The core of this treatment is two Lamellar Clarifier-thickeners, Densadeg®. This device allows clarifying the effluents (<5 mg/l of SS) and, at the same time, thickens the produced sludge in a way that it can be directly dewatered. When the effluents are mixed with the brine, its concentration will reduce even more, to less than 1 mg/l. This is another additional positive point to its mixing with the effluent of the treatment plant. Sludge produced in Densadeg® is stored in a buffer tank, where is pumped to two centrifuges to be dewatered, with a minimum dryness of 22%. Two silos of 60 m^3, allow storage to be evacuated though lorries, by an authorized waste agent.

Additionally and also by the point of view of environment and specially in renewable energies, it is necessary to underline that the desalination plant has a wind generator and all the building roofs are covered by photovoltaic panels (1,300 kW in 20,372 m^2) able to save 850 ton of CO_2 per year (see Fig. 4).

4. Management criteria for the production of the desalination plant

Llobregat Desalination Plant is integrated in the supply system of Barcelona area, more than 100 municipalities and more than 4.5 millions of inhabitants, together with mainly three drinking water plants: Cardedeu (Ter River), Abrera (Llobregat River), both managed by ATLL and Sant Joan Despí (Llobregat River and aquifer), managed by Aigües de Barcelona.

The majority of available water resources of ATLL come from the six dams of the Ter and Llobregat basins. The desalination plant has been taken as a new dam, with a maximum flow of 180.000 m^3/day (20.000 m^3/day are on spare); It will be a complement

Fig. 4. Renewable energies in Llobregat plan.

to the rest of the dams. To have a reference level the annual production of Llobregat plant, established in 60 hm^3/year (giga liters year), is equivalent to the capacity of one the dams (Boadella, located in Girona).

According to that the Agència Catalana de l'Aigua (ACA) (Catalonian Agency of Water), ATLL and EMA (Environment Company of Barcelona Metropolitan Area) have established an exploitation criterion for the new infrastructures in the ATLL environment, including the Llobregat Desalination Plant:

- Optimize the reservoirs use and aquifer of Llobregat basin and reducing the contribution of them from Ter basin (to supply Girona region).
- Incorporate the water from the Llobregat Desal Plant to generate a preventive saving of the dam flows.
- Introduce the new treatments (EDR and RO) from the PWT Plants of Llobregat (Abrera and Sant Joan Despí) and from Llobregat Desalination Plant to improve the quality of the supplied water.

In the practice for the PWTP is a quality criterion according to the raw water characteristics, to establish the number of trains of EDR or BWRO being in service in those plants.

For the desalination plant, it is a quantity criterion depending on the average level of Ter and Llobregat dams:

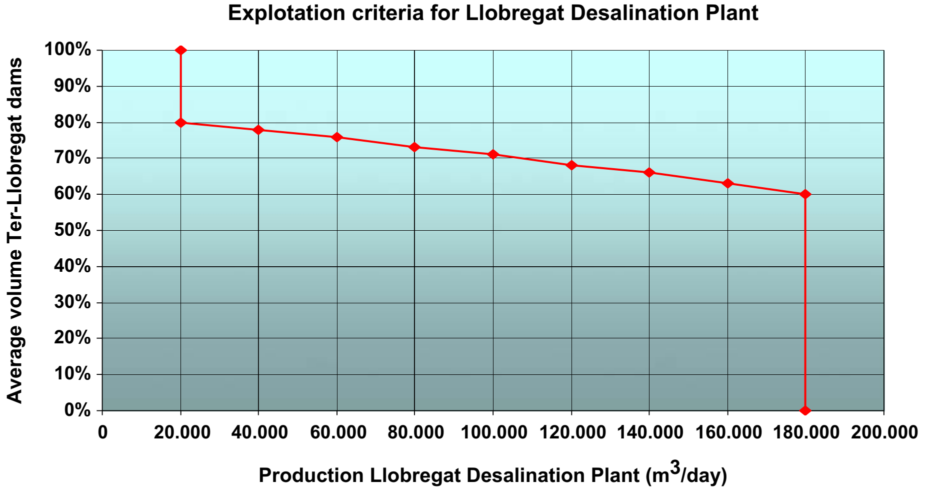

Fig. 5. Curve for Desalination Plant operation.

- Dams level ⩾80%; desalination plant at minimum production: one train, 20.000 m^3/day.
- Dams level ⩽60%; desalination plant at maximum production: nine trains, 180.000 m^3/day.
- Level between 60 and 80%; number of running trains according to the curve of Fig. 5.
- The remaining 10th train will be on standby to be used when other train is on cleaning or maintenance. It also would be used in case of minimum levels of the dams.

These instructions are given by ACA every two weeks in accordance with the average dam levels on the revision day. From November 2009 the plant has been running with these criteria, in the first months it was running from 10 to 50%, but from April 2010 the plant is running at minimum production. The year 2010 and the beginning of 2011 were very rainy, as you can see in the Fig. 6 where the level of the dam Sau is indicated, one of the more important in the basin.

From the data of the averages of the reservoirs levels during the last 10 years it is possible to simulate the "average year", but it will be not the most probable. This is due to the large variability in the pluviometry of the Mediterranean climate, being the filling of the reservoirs normally to catastrophic episodes of rains (high intensity and short duration), given in dif-

Fig. 6. Level of Sau Dam and average of 10 years.

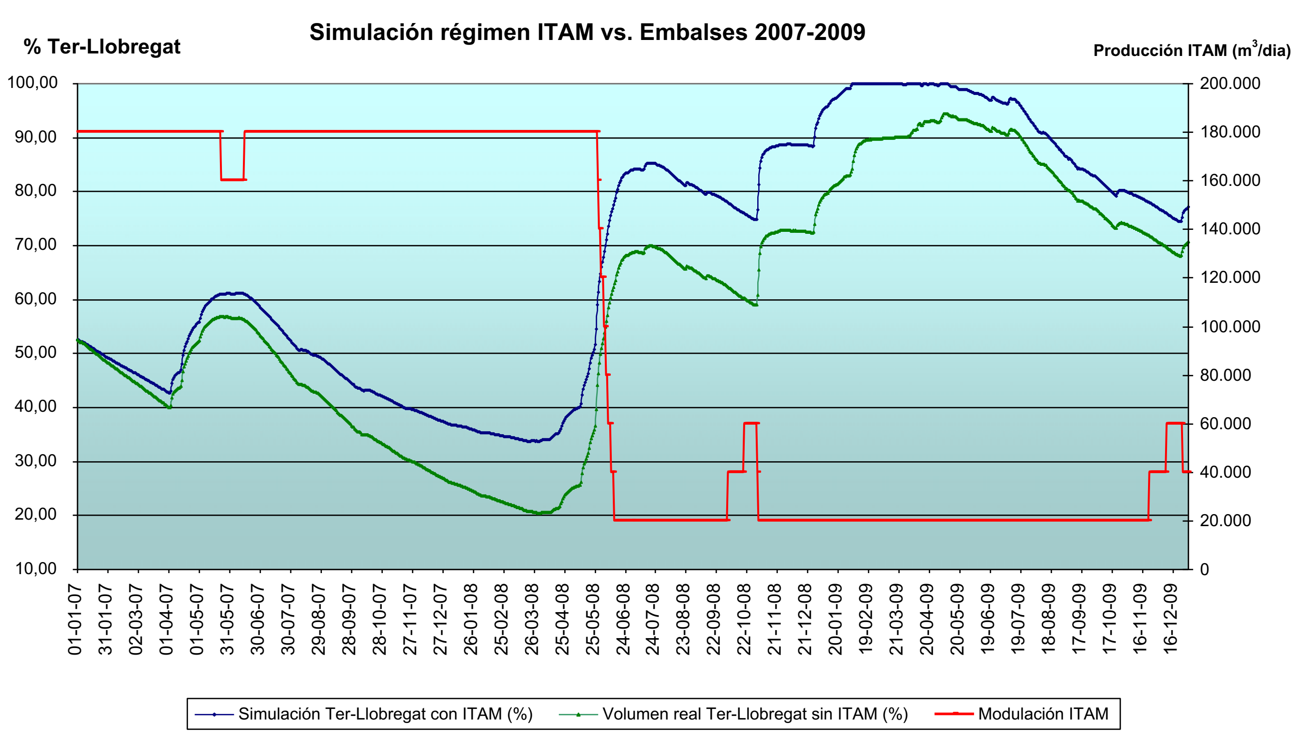

Fig. 7. Simulation of Plant operation in the years 2007–2009.

ferent times of the year (with a bigger variation in the last years). All this makes it practically impossible to predict the desalination operation in medium term; but the operation regimen can be established in dried times, because the emptying of the reservoirs can be determined with elevated grade of accuracy depending on the available statistical parameters.

As an example of Mediterranean climate you can see in Fig. 7 what could have been the desalination production in the years 2007–2009 where Barcelona area passed from a severe drought to a heavy rainy period. The green line is the real volume of the dams, the red line the desalination production. The blue line simulates the volume of water in the dams if the desalination plant was operating in these conditions.

The reality in the last two years can be shown in the Fig. 8.

5. Operational results

The quality of sea water is quite stable throughout the time, confirming and overcoming the established forecasts in the previous studies which determined the location of intake point [5].

The evolution in a year and a half of three important parameters can be seen in Fig. 9. Together with the seawater pH we can follow the temperature and the turbidity, both very important due to the impact in Boron rejection and the pre-treatment.

The pH values and sea water conductivity are very stable through time, as expected. In the year 2010, the statistic values of these two parameters are:

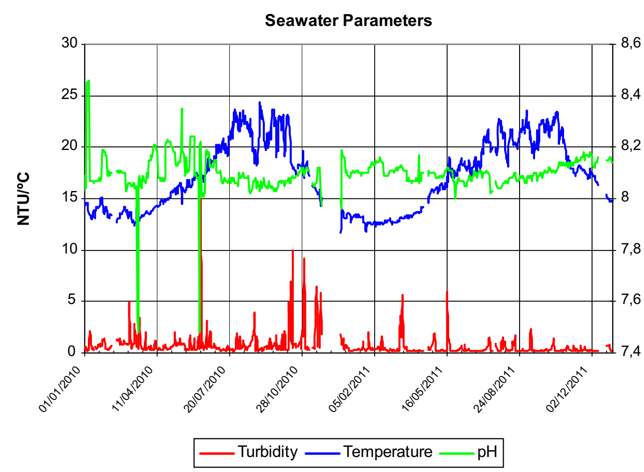

Fig. 9. Seawater parameters: turbidity, temperature and pH.

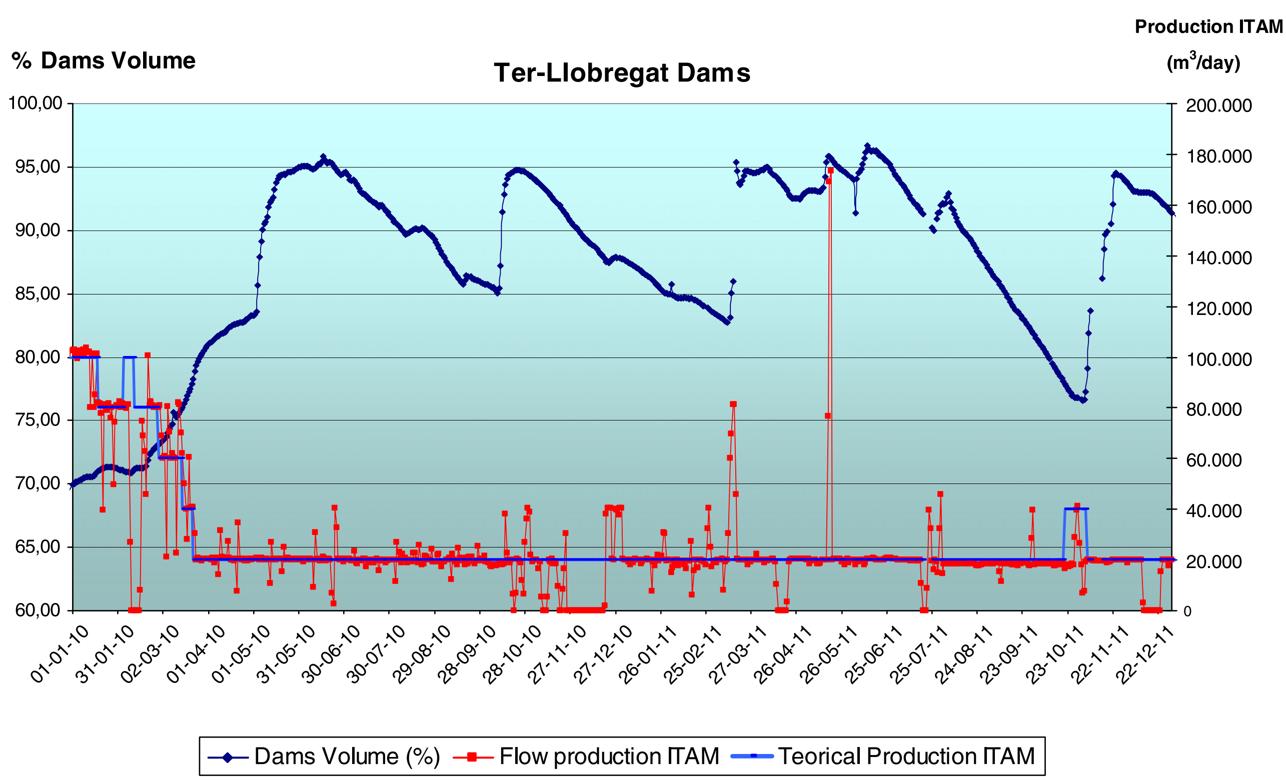

Fig. 8. Evolution of dams and plant production in the years 2010–2011.

	pH	Conductivity (μs/cm at 25˚C)
Medium	8.11	56.390
Stand. Dev.	0.109	831.5

Other parameters of sea water quality are conductivity, chlorine, sodium and boron. Their evolution in the last two years can be seen in Fig. 10.

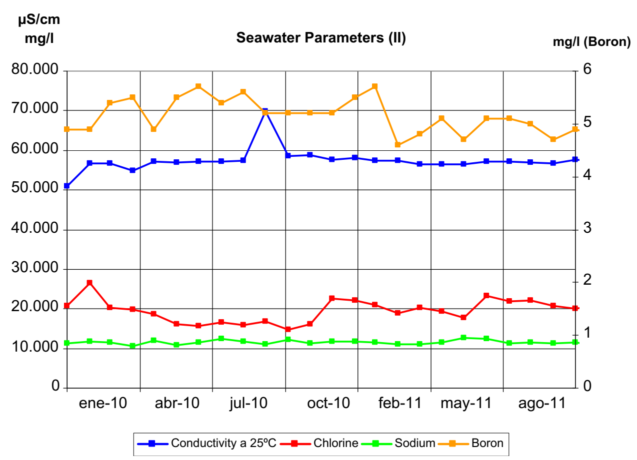

Fig. 10. Sea water parameters: conductivity, chlorine, sodium and boron.

The results in pre-treatment were excellent as it is probed in SDI records for the period of the last two years, having an average of 2.0 after pre-treatment and more than 90% of the time under 3.0:

SDI75%	Seawater	After cartridge filters
Centile 90	19.1	2.9
Centile 75	8.1	2.3
Centile 50	4.6	2.0
Average	11.2	2.0

The SDI evolution through the pre-treatment, in the year 2010 and 2011, is shown in Fig. 11.

Despite part of the time the use of SeaDAF® or the first stage of dual media filters has not been necessary, the results of pre-treatment have been very good, better than those we had during the three years of piloting. Most of the time, the SDI incoming to RO is less than 2.3%/min. Also the turbidity after cartridge filters is very low being less than 0.1 NTU most of the time.

The optimized criteria to operate the pre-treatment are related to sea water quality, mainly SDI, turbidity and OM. The SeaClean® dual media pressurized filters should be always running, the second to enter in operation should be the Floatation SeaDAF® and

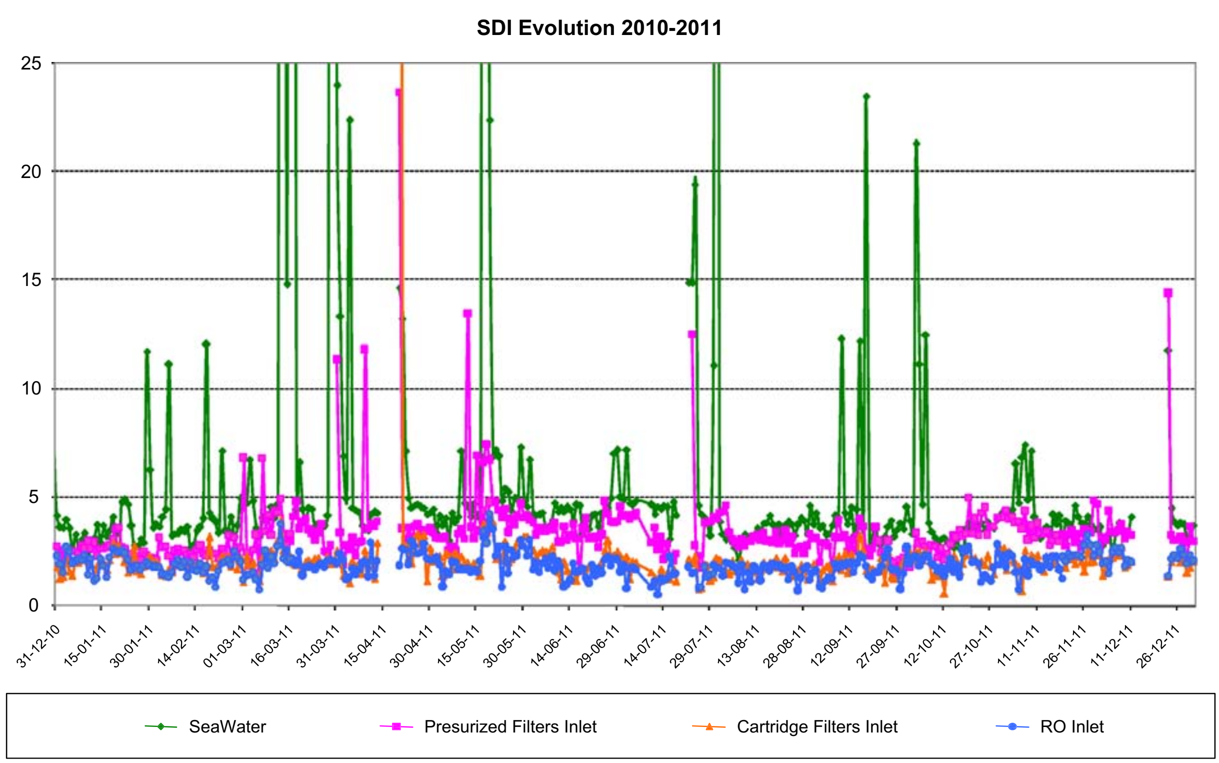

Fig. 11. 2010 and 2011 SDI evolution in pre-treatment.

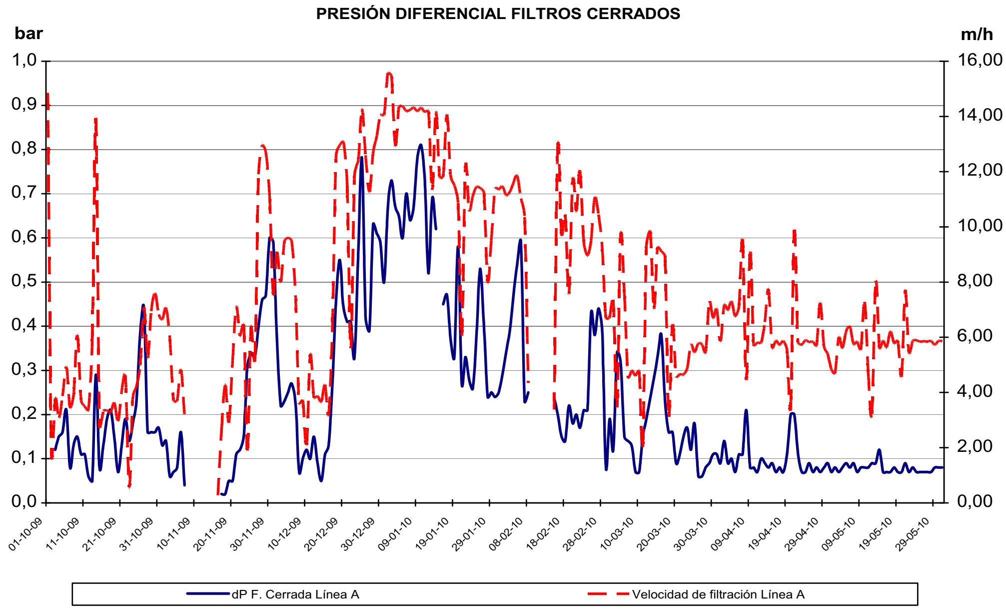

Fig. 12. SeaClean® Filters: operating conditions.

the third the Mediazur® gravity filtration. But the flexibility of design allows also to keep running two or three stages using fewer chemicals; it is a decision of the operators. Both systems have demonstrated good results. Until today, the worse design case has not been arrived.

Different operational modes have been tested in the operation of SeaClean® pressurized Filters to decide what is the optimum way to operate at lower flows; in all cases the quality of filtered water remains stable and very good. Different running times and head losses are shown in Fig. 12 operating at different velocities.

The actual criteria imply the use of four filters running per RO train in operation till all the filters are running (five RO trains in service) as more economical for operation.

The control of process includes the microbiological parameters, determined in each step of pretreatment, and also in the outlet of the racks and the outlet of product water, as demanded in the RD140/2003. Although the microbiology values in the sea water contain a high dispersion, caused by the variability of the conditions of the sea, just to give a general idea, Fig. 13 presents the average values of the different parameters in each step of pre-

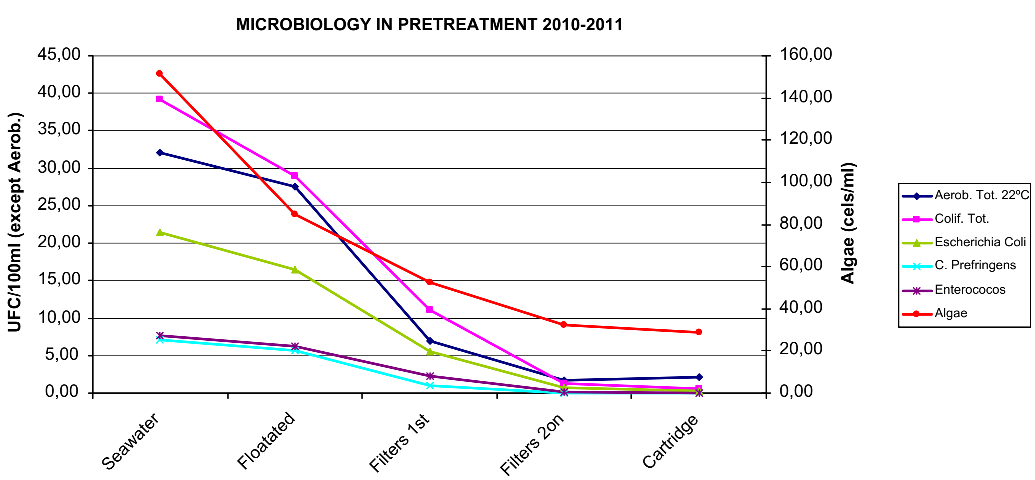

Fig. 13. Microbiology in pre-treatment.

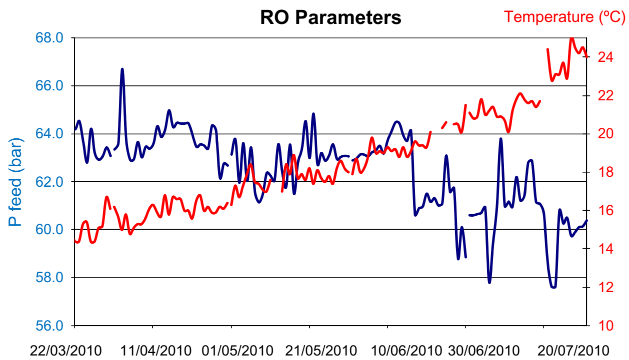

Fig. 14. RO feed pressure and permeate.

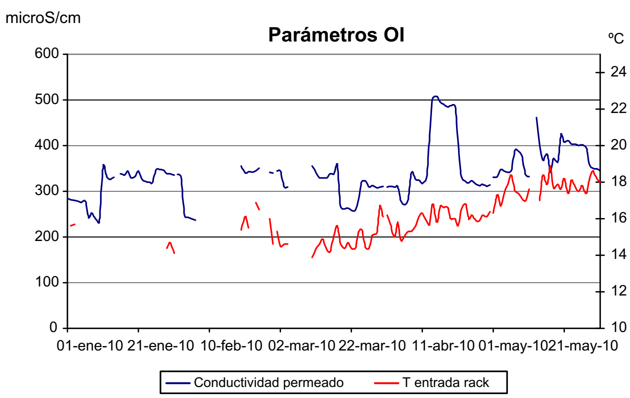

Fig. 15. Conductivity vs. water temperature.

treatment. As it can be appreciated, in the outlet of the second step filters and cartridge filters, the presence is null or very small, in the order of less than 0.5 UFC/ml.

The efficiency in algae removal is being studied now.

From the commissioning, due to operating conditions indicated by ACA, the plant has been operated with a variable number of trains, from 1 up to 5, with rotation between the racks on service. Due to that the data shown below have a large dispersion, because there are linked results between one rack and the results of other racks. Figs. 14 and 15 show the evolution of Feed Pressure and Permeate Conductivity vs. sea water temperature.

Typical operational parameters of a first pass train are presented in Fig. 16. The data are from the rack number 10. We can also see the parameters of Energy Recovery: conductivities at inlets and outlets and head losses; all ERI parameters are under the guaranteed figures. It is also important to underline the elevated back pressure of PX due to the direct reject of brine to the waste water treatment plant equilibrium tower where it is blended with the treated effluent.

The average efficient of Pressure Exchanges, PX-220, has been 96.5%, calculated under the formula established by ERI.

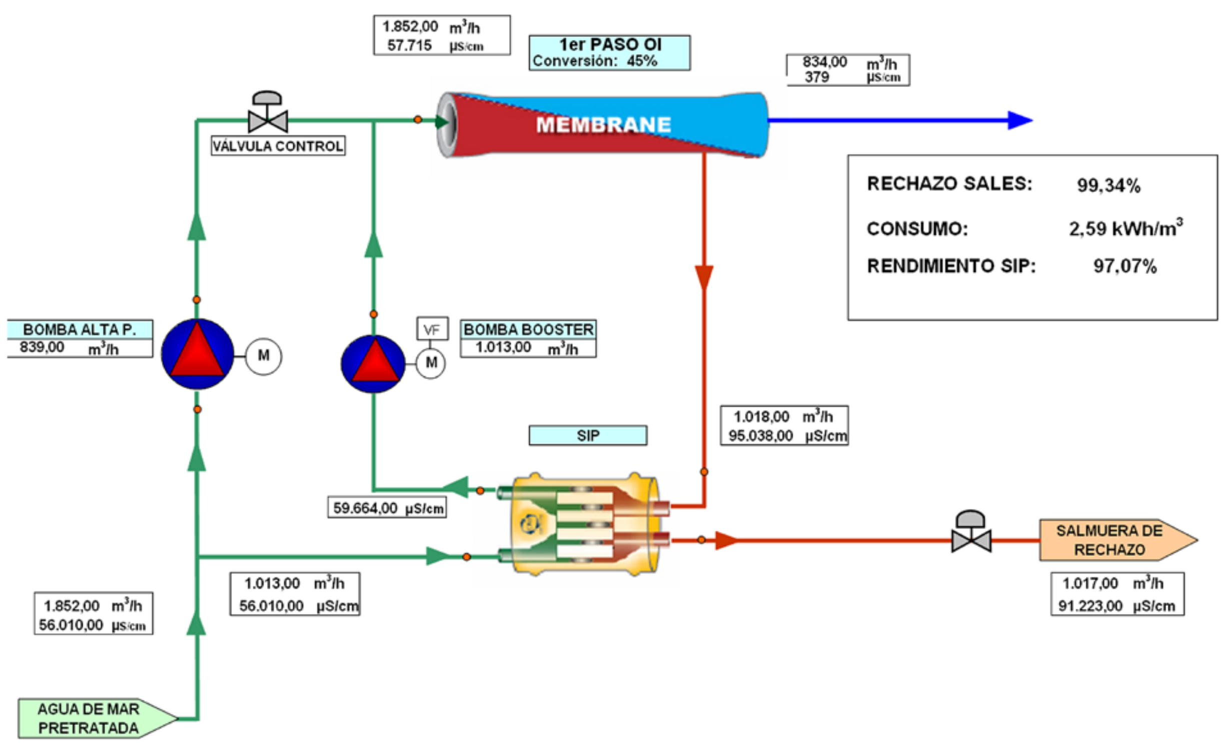

Fig. 16. Tenth RO train typical parameters, May 2010.

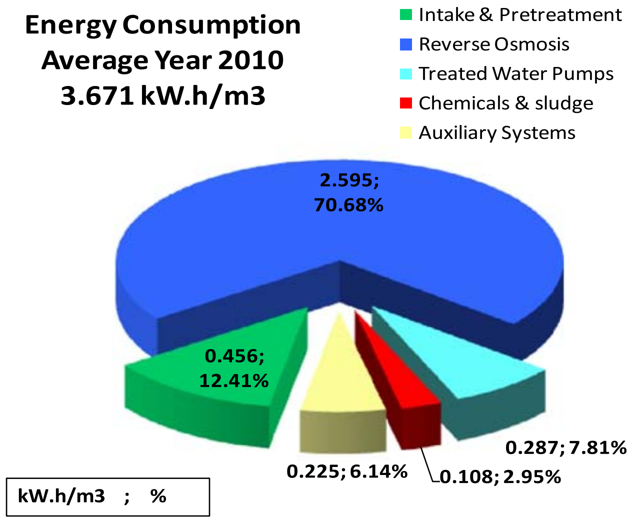

Fig. 17. Energy consumption in 2010.

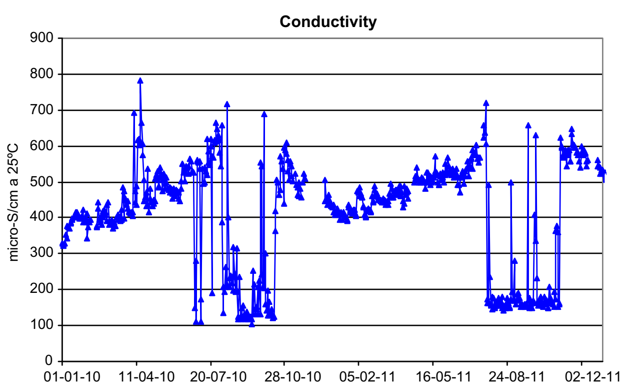

Fig. 18. Potable water conductivity.

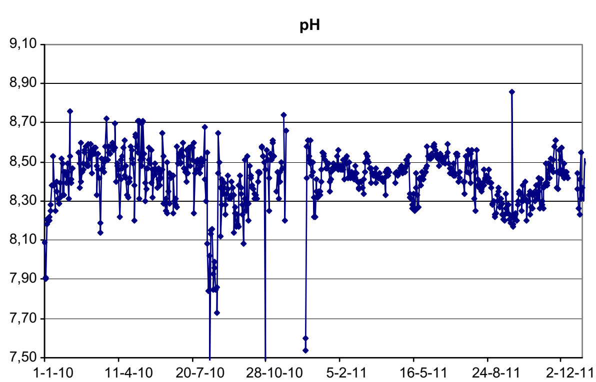

Fig. 19. Potable water pH.

The specific energy consumption is under the guaranteed values. The average of the year 2010 splitted by Pretreatment, RO, Treated Water Pumping, Chemicals and Sludge Treatment and Auxiliary Systems is presented in Fig. 17. It is the total energy used to put the water in Fonsanta Reservoir, 3.67 kWh/m^3.

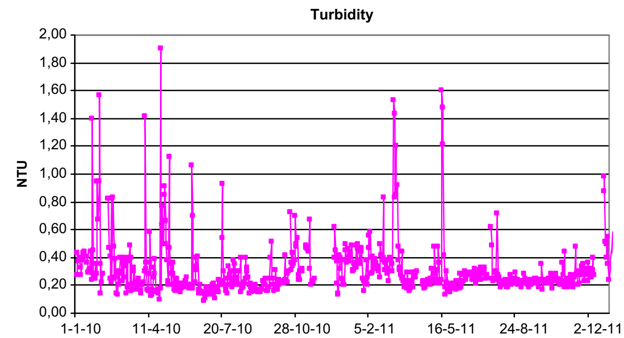

Fig. 20. Potable water turbidity.

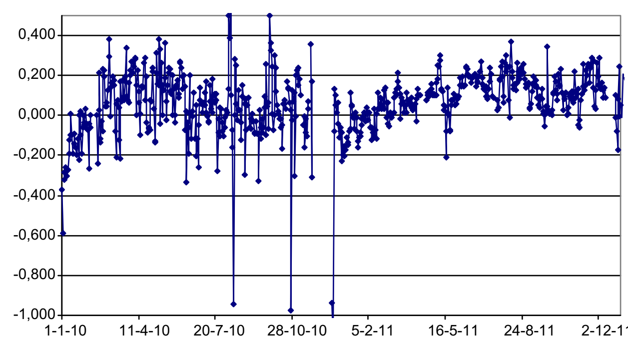

Fig. 21. Potable water LSI.

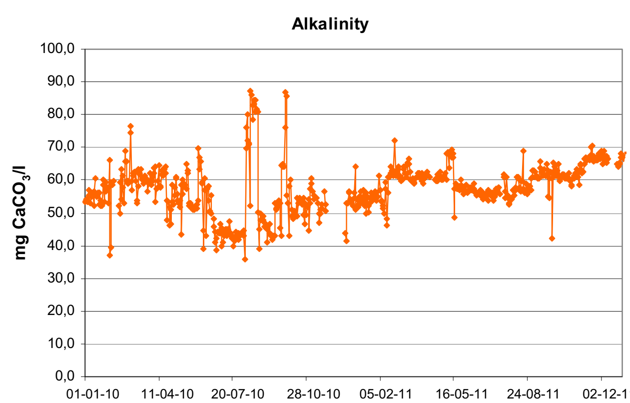

Fig. 22. Potable water alkalinity.

The parameters of treated water are also under expectations and guaranteed values as it can be seen in Figs. 18–24.

The conductivity shows the expected values for the remineralized desalted water. As for the boron, the outlet concentration has kept below 1 mg/l most of the time, due to NaOH dosing in the feeding to the

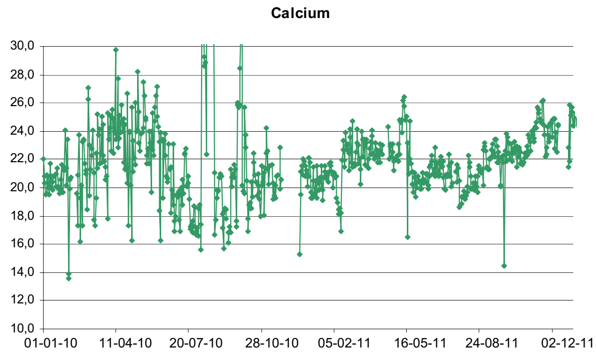

Fig. 23. Calcium in potable water.

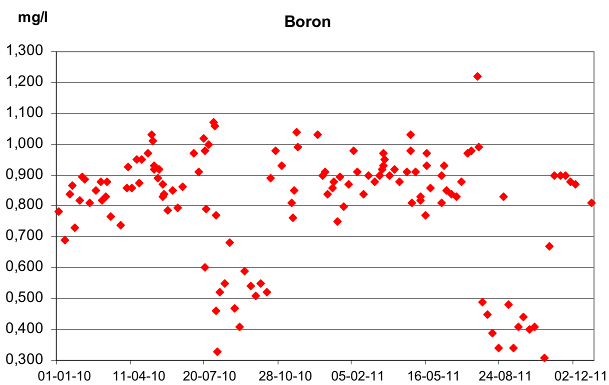

Fig. 24. Boron in potable water.

first pass racks over 17°C, and in August starting a second pass train.

The LSI has been progressively adjusting to locate it in positive values, to get it the NaOH has been dosed in the outlet of product water, once all parameters of upflow remineralizing filters has been optimized. The same effect can be observed in pH, alkalinity and calcium results. The alkalinity shows very acceptable values, over 60 mg $CaCO_3$/l.

Generally speaking, the upflow filters present good results. The turbidity at plant outlet remains stable below 1 NTU, with the exception of some sporadic episodes, with no ordinary manoeuvres carried out in the remineralization installation.

The product water of the Llobregat Desalination Plant is getting the expected quality, and also excellent organoleptic characteristics.

6. Conclusions

The Llobregat Desalination Plant is the largest sea water plant in operation in Europe for human supply and one of the largest in the world.

Together with all works taken by ATLL it has become the key element to ensure the water supply in the area of Barcelona in the most severe droughts and its design has been made to work in the most unfavourable conditions.

The tight construction and its innovations have made it to receive the prize the *Desalination Plant of the Year* at the *Global Water Awards 2010*, being classified as the flagship of the desalination in Spain. And Degrémont also won the prize of *Desalination Company of the Year* at the same Awards.

Barcelona-Llobregat Desalination Plant has fulfilled the expected objectives of operation and quality of treated water since the inauguration in July 2009, despite the reduced regime of operation due to the high level of the dams in this period.

The desalination facilities have also been very respectful with the environment and have also reduced the carbon footprint with renewable energies.

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