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Al Dur SWRO plant: a double challenge for pre- and post-treatments

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ABSTRACT

The Al Dur Power & Water Company is a 2.1 billion USD gas-fired greenfield power generation and seawater reverse osmosis desalination plant that is located on the southeast coast of Bahrain. The company Degrémont has been selected to design and build the Reverse Osmosis (RO) desalination plant, for a drinking water production capacity of 218,000 m^3/day. The plant design had to answer to particularly challenging requirements, both for the pre-treatment and for the post-treatment steps. The pre-treatment step is one of the key factors for the success of desalination using the reverse osmosis process. Its purpose is to remove the major foulants, which can be found in the seawater to allow for a reliable operation of the reverse osmosis units. It is even more essential within the Gulf area, where the seawater contains high concentrations of organics and is subject to algal blooms. Al Dur RO plant was thus designed with an efficient two-step pre-treatment process: a flotation step, including an enhanced coagulation stage, and a filtration step. In parallel, to assess the seawater variability and demonstrate the performances of the selected pre-treatment line, a pilot study was carried out on-site during one year. Al Dur drinking water objectives were particularly challenging and the design had to incorporate unusual guarantees such as a Silt Density Index below 3.0%/min, a turbidity below 0.2 NTU and a Langelier Saturation Index between 0.1 and 0.3. As a consequence, to comply with both the Bahraini drinking water standards and the tender specifications, the Al Dur mineralization unit design included a high velocity lime water saturator and a lime water filtration unit. The present paper describes the pre- and post-treatment performances based on the initial project design, the pilot study and the on-site results during the commissioning and the first few months of operation.

Keywords: Al Dur seawater RO plant; Pre- and post-treatment; Bahrain; Seawater reverse osmosis desalination; Remineralization

1. Introduction

The long-term and reliable operation of a SWRO plant is depending on the two following key steps:

- the pre-treatment, if designed in conformity with the category of pollutants found into the raw sea water, will allow a safe operation of the Reverse Osmosis (RO) membranes,

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- the post-treatment through the remineralization process, designed in accordance with the tender specifications, will provide water suitable for drinking purpose and free of any aggressiveness to the pipes and networks.

The Addur site, in the south of the Kingdom of Bahrain, has been known since the early 1990s for its desalination plant, submitted to numerous and various operating issues. Most of these issues were related to the poor seawater quality in the area, which is linked to several industrial and residential waste disposals and results in high organic contents and high bioactivity [1–3].

Since its commissioning, the plant has been experiencing severe flux decline on the reverse osmosis step, caused by an important biofouling development. This biofouling was accentuated by a continuous intake chlorination, known to split the large nonassimilated organic compounds into smaller parts, which will ease the microorganism growth [1]. An inadequate pre-treatment, either at the plant start-up or after the two successive rehabilitations, worsened the phenomena [2,3] and the plant never achieved to produce its full design capacity.

Al Dur Power and Water Company (ADWPC) is a 2.1 billion USD gas-fired greenfield power generation and seawater RO desalination plant located just near the Addur site. Degrémont has been selected to design and build the RO desalination plant, for a drinking water production capacity of 218,000 cubic meters per day.

The Addur's difficult background demonstrated the need for a three-step pre-treatment, associated with the possibility of enhanced coagulation, which was designed for the Al Dur desalination plant. As presented in the figure below, a first step of flotation SeaDAF^{TM} was implemented, followed by dual-media filters (SeaCLEAN^{TM}) and polishing cartridge filters. The flotation step allows a dosing up to 25 ppm of mineral coagulant ($FeCl_3$) to significantly reduce the amount of organic matter at the membrane inlet.

Concerning the post-treatment, highly challenging and unusual guarantees were required in the RFP documents, such as a Silt Density Index (SDI) below 3.0%/min, a turbidity below 0.2 NTU associated to a Langelier Saturation Index (LSI) in the range of 0.1–0.3. As a consequence, to comply with both the Bahraini drinking water standards and the tender specifications, it was necessary to produce lime water of a very high quality from the turbidity point of view. To cope with this requirement, a fully innovative water lime production design, including a lime water filtration step has been implemented.

The Table 1 summarizes the parameters which need to be respected for the required range of pH (between 7.0 and 8.0) for the produced water.

The present paper presents the pre-treatment and the post-treatment performances based on the initial project design, the pilot study, and the on-site results during the commissioning phase and the first few months of operation.

2. Al Dur plant description

The plant is located on the south east coast of Bahrain, near the sea, as presented in Fig. 1.

2.1. Seawater Intake

The selected seawater source is an offshore open intake that is located at a distance of 1,500 m from the coast at a depth of 6–8 m, according to the tide. Four independent intake lines, equipped with manholes every 200 m for maintenance purposes, feed the sea water intake tank, common to the power and the desalination plants. Each line is equipped with a full chlorination system, which allows the possibility of shock chlorinating the whole line, an important action to prevent the excessive growth of shells inside the intake pipes.

2.2. Pre-treatment

The selected pre-treatment is particularly robust and reliable, including both a clarification and a filtration process, coupled to an enhanced coagulation system that has been designed to face the rough sea water from the Gulf area.

The clarification process is performed by the SeaDAF^{TM} high-rate flotation technology, which is the most suitable and proven technology to face the potential algal blooms and the high fouling potential of the Gulf seawater. The flotation is followed by one stage of dual-media filters and a polishing step of 5-micron cartridge filtration.

Table 1
Tender requirements for the drinking water

Calcium hardness (mg/L as $CaCO_3$ at 25°C)	70–200
Total alkalinity (mg/L as $CaCO_3$ at 25°C)	70–200
Conductivity (μS/cm at 25°C)	250–500
pH (as requested by the client)	7.0–8.0
Langelier Saturation Index (LSI)	+0.1 to +0.3
Silt Density Index (%/min)	<3.0
Turbidity (NTU)	<0.2

Fig. 1. Al Dur site view.

The pre-treatment is divided in two independent lines, each one including the following facilities and equipments:

- *Chemical dosing system* $FeCl_3$, H_2SO_4, Coagulant Aid. Both static mixers and coagulation chambers with flash mixers are placed before the first pre-treatment step.
- *Seven high-rate SeaDAF™ units* (Fig. 2) with hydraulic flocculation, followed by a flotation cell equipped with an AquaDAF patented floor system. It is possible to bypass the floatation process in case of better seawater conditions.
- *Twenty two pressurized dual-media filters* (Fig. 2) with the possibility of dosing $FeCl_3$ and Coagulant Aid to fine-tune the quality of the pre-treated water.
- *Six cartridge filters* with 360 cartridges of 5 microns each.
- *Chemical dosing system* sodium bisulphite, anti-scaling and caustic soda with properly placed static mixers to ensure the mixing before the RO membranes.

2.3. Reverse osmosis

As the maximum boron concentration required in the final drinking water is 1 mg/L, the Reverse

Fig. 2. Al Dur flotation unit (left) and filtration line (right).

Osmosis step (Fig. 3) incorporates a double-pass system as follows:

- 1st pass: 26 trains with a recovery rate of 42%. The Toray Membranes TM820C and Pelton turbines as energy recovery device were selected.
- 2nd pass: 12 two-stage trains and a recovery rate of 90%. The Toray membranes TM720 were selected.
- A pH adjustment before the 2nd pass, with an injection of caustic soda to reach the required pH and increase the boron removal in the 2nd pass.

2.4. Brine and sludge disposal

Concerning the environmental impact, the plant design takes all the local requirements into account. The sludge treatment step includes two Densadeg™ to thicken the sludge from the pre-treatment before a final dewatering. The Densadeg™ is designed to reach total suspended solid concentration in the supernatant below 40 mg/L and an iron concentration below 1 mg/L. As a result, once it is mixed to the brine, the final discharge complies with the local legislation and the Standard for Industrial Effluents from the World Bank 1998 (as specified in the tender).

3. Pre-treatment performance

Designing a reverse osmosis pre-treatment step is highly dependent on the sea water quality and the site-specific characteristics. During the Al Dur tender phase, in 2008, two water studies were performed in order to evaluate the quality of sea water and assess the best pre-treatment line. During the execution phase, a complete pilot study was then carried out, from October 2009 to October 2010, to demonstrate the efficiency of the selected pre-treatment line and to optimize the chemical dosing rates in regard to the variation in sea water quality. This piloting approach has been an essential factor to issue operating recommendations in regard to seawater characteristics before the commissioning of the main plant.

3.1. Sea water characterization

During the 1-year pilot plant study, the quality of sea water in Al Dur has been highly variable and of very poor quality, even if no algal bloom were encountered during the entire period. Several parameters, such as salinity, temperature, turbidity, $SDI_{75\%}$, suspended solids, algae concentration, and organic matter concentration were sampled and reviewed while undertaking the study. The seawater SDI was measured according to the 75% plugging method developed by Degrémont, which allows measuring the SDIs up to 80% plugging/minute [4].

The main parameters that were recorded during the pilot study are summarized in the Table 2. Among the parameters affecting the quality of seawater and impacting the performances of the pre-treatment line, the $SDI_{75\%}$ and the turbidity were the most variables.

The $SDI_{75\%}$ profile measured during the pilot study showed variations between 5 and 80%/min, with several peaks (above 40%/min) in May, July, October and December. The high values recorded in

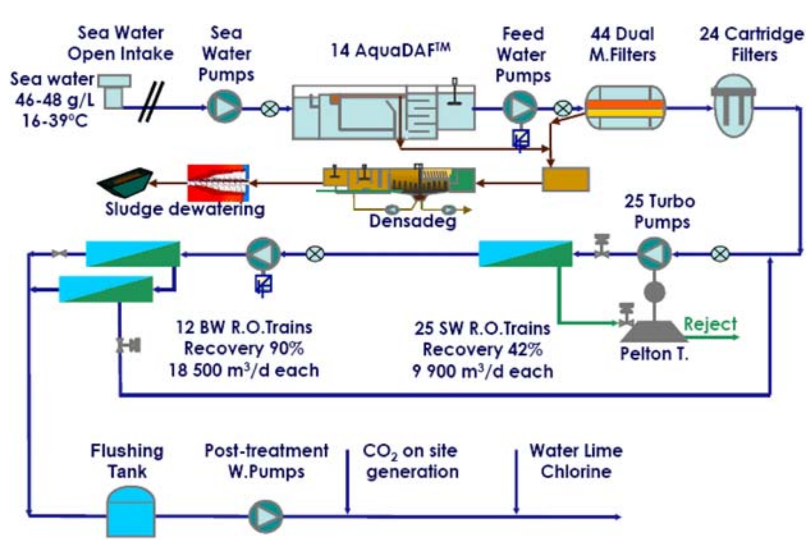

Fig. 3. Al Dur plant flow sheet diagram.

Table 2
Sea water quality parameters

	$SDI_{75\%}$ (% plugging/min)	Turbidity (NTU)	Temperature (℃)	Conductivity (mS/cm)	Boron (mg/L)
Minimum value	5	0.15	16.5	65	5.7
Maximum value	80	10	35.5	69	6.3

May were attributed mainly to the strong winds blowing across the area at this period of the year, whereas the peaks observed in October and December were caused by rainy events. During the commissioning of the plant, similar peaks due to winds were recorded for the April and June months; except for these events, no other peaks with $SDI_{75\%}$ values above 40%/min were noticed. The $SDI_{75\%}$ was oscillating mainly between 20 and 30%/min from July until the end of December. Fig. 4 below illustrates the $SDI_{75\%}$ evolution during both periods.

The temperature profile, monitored during the pilot study, with variations from 16 ℃ in winter time (January, February) to 35 ℃ in summer time (July, August), was similar during the commissioning of the plant, with even higher temperatures during the summer, up to 39 ℃ (cf. Fig. 4).

In parallel of such high water temperature, analyses were performed on the biopolymers and associated transparent exo polymers (TEPs), which are believed to play an important part in membrane clogging by biofouling. The results are presented in Table 3.

The analyses performed show that the concentration of Biopolymers in Al Dur is particularly high comparatively with other sites in the world (Oman Gulf, Mediterranean Sea or Atlantic Ocean). The results also seem to confirm a correlation between the temperature and the biopolymers' content.

Table 3
Sea water concentration in Biopolymers and TEPs

	Biopolymers (ppb)	TEPs (ppb)
Spring time	130	15
Summer time	296	94
Autumn time	234	46

As a conclusion, the results obtained during this period (pilot and commissioning of the plant) fully confirmed the previous conclusions of the studies made in Addur about the complexity of the sea water matrix, which makes the Al Dur sea water one of the most difficult sea waters to treat in the world.

3.2. Flotation and enhanced coagulation results

During the 1-year pilot study, the flotation performance, through the application of Degrémont's SeaDAF^{TM} process, was tested in several conditions of chemical dosing rates, to face various sea water conditions.

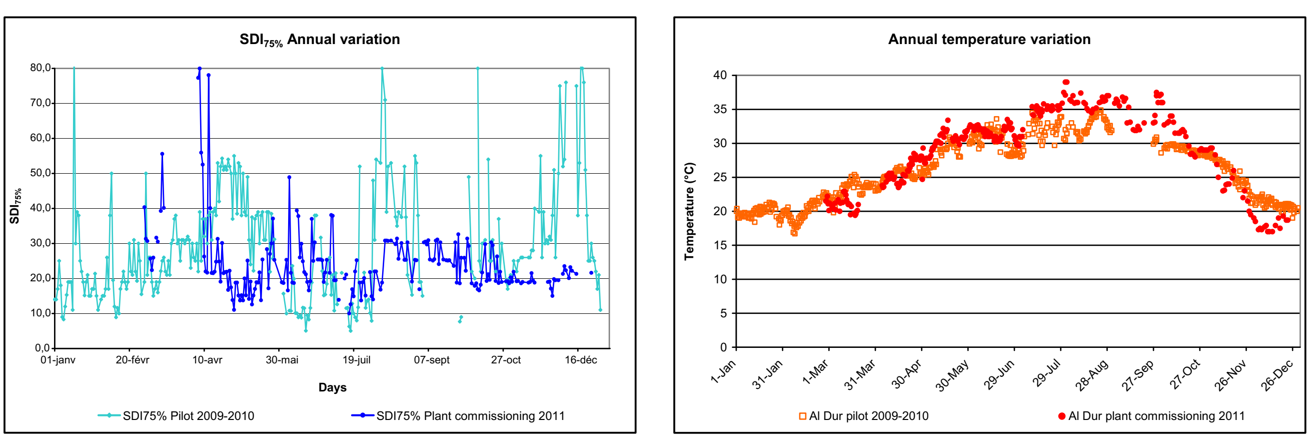

Fig. 4. Annual $SDI_{75\%}$ variation and Annual temperature variation at the Al Dur site.

3.2.1. Turbidity removal

It was observed during the pilot study that the turbidity removal in the flotation unit depends mainly on two parameters: the inlet sea water turbidity and the coagulant ($FeCl_3$) dosing rate.

The SeaDAF^{TM} unit was operated with a dosing rate of ferric chloride between 12 and 20 ppm as $FeCl_3$ at the inlet. Turbidity up to 10 NTU was recorded and in those conditions, the turbidity removal of the SeaDAF^{TM} was:

- for inlet turbidity < 2 NTU: maximum 50–60%,
- for inlet turbidity between 2–5 NTU: 65–75%,
- for inlet turbidity between 5 and 10 NTU: 80–95%.

During the plant commissioning, however, the sea water turbidity remained quite low and varied between 0.5 and 2.5 NTU. As a result, the floated water turbidity oscillated around 1 NTU as an average, for ferric chloride dosing rates between 8 and 20 ppm as $FeCl_3$.

3.2.2. Algae removal

Algae removal was one of the main parameters to follow on the SeaDAF^{TM} unit, especially in the case of algal bloom. However, such an event was not recorded and the maximum algae concentration recorded was around 200 cells/mL. From January to October 2010, the SeaDAF^{TM} was operated continuously and the algae count was recorded on a regular weekly basis. For the entire period, regardless of the chemical dosing rates applied, the algae removal achieved was always above 98%, and for 95% of the time, it was higher than 99%.

3.2.3. Organic matter removal

The organic matter concentration in the sea water and its removal through the pre-treatment line were closely recorded during the pilot study and the commissioning of the plant, through the Total Organic Carbon analyses and the UV absorbency.

During the pilot study, it was observed that the organic matter removal was dependent on the coagulation conditions, confirming the need for an enhanced and optimized coagulation. It was demonstrated that a pH adjustment and a minimum mineral coagulant dosing rate were necessary to achieve a good removal of the organic compounds. During both the pilot study and the commissioning phase, the removal of TOC (through the measurement of UV absorbency) was between 15 and 40%.

3.2.4. Overall flotation performance conclusions

During the pilot study, the flotation technology SeaDAF^{TM} demonstrated an excellent efficiency in terms of pollution removal in difficult sea water conditions, and particularly for the algae, even with very low concentrations. The removal efficiency on the turbidity and on the organic matter was highly dependent on the coagulation–flocculation conditions and in particular on the coagulant dosing (see Table 4).

During the commissioning of the plant, despite a different sea water quality (lower turbidity, presence of organic matter), the performances were similar to the pilot results, confirming the selected technology's suitability and demonstrating the large-scale unit efficiency.

3.3. Filtration results

3.3.1. Biopolymers and TEPs removal

The Biopolymers and Transparent Exo Polymers concentrations were closely followed, as these parameters were suspected to be one of the main causes for the Addur plant's failure. The removal of those compounds was respectively 40 and 70% during the pilot study versus 60 and 85% during the plant commissioning phase.

Fig. 5 shows an example of the excellent removal in terms of biopolymers and TEPs during the commissioning of the plant. In this particular case, 57% of the Biopolymers and 84% of the TEPs were removed (see Fig. 5).

Table 4
Summary of DAF performance during the study

Coagulant dosing as $FeCl_3$	Turbidity removal according to the inlet range			Organic compounds' removal	Algae removal
	<2 NTU	2–5 NTU	5–10 NTU	UV absorbance	
12–20 ppm	50–60%	65–75%	80–95%	15–40%	>98%

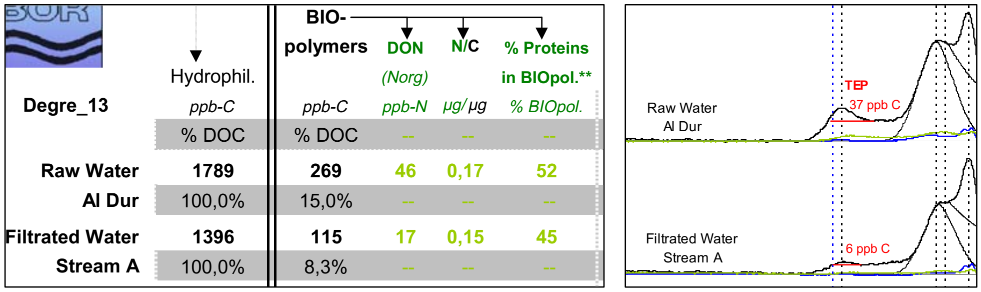

Fig. 5. Removal of biopolymers and TEPs along the Al Dur pretreatment line.

Table 5
SDI_{15min} results during the pilot study

	12–24 ppm $FeCl_3$	Al Dur treated water objectives
Average SDI	3.1%/min	No value
<3.5–4.0%/min	86% ile	85% ile
<5%/min	100% ile	100% ile

3.3.2. *SDI_{15min} of the pretreated water*

Concerning the quality of the treated water, the pre-treatment pilot line had demonstrated that with a correct dose of coagulant, the average SDI_{15min} oscillated between 3.0 and 3.1%/min and ranged between 3.5 and 5.0%/min for 14% of the time only (see Table 5).

The Al Dur plant was in commissioning phase from March to September 2011. From October 2011, the plant operation was stabilized and it was then possible to evaluate accurately the process performance of the plant, until January 2012, date of the performance tests. From October 2011 to January 2012, the $SDI_{15\,min}$ at the outlet of the pre-treatment oscillated around 3.0%/min (cf. Fig. 6). At the beginning of October, some peaks around 4.0%/min have been recorded, due to the stabilization process of the plant operation.

4. Post-treatment performance

4.1. *A fully innovative design*

Degrémont has developed a fully innovative design to comply with the tender's specifications. The post-treatment step is divided in two independent lines, each one being composed of one hydrated lime silo, one lime milk preparation tank and a transfer

Fig. 6. Pre-treated water SDI_{15min} during the first months of the plant operation.

line to the saturator. From the saturator, the lime water is stored, and finally filtrated on dual-media filters before being dosed into the permeate so as to reach the correct level of remineralization (see Fig. 7).

To achieve the remineralization targets of alkalinity and total hardness in the range of 70–200 mg/L as $CaCO_3$, as well as a conductivity between 250 and 500 μS/cm, a high dosing rate of lime is required. Consequently, the flow of lime water to be dosed into the permeate represents 10–15% of the total drinking water's delivered flow rate. To comply with the required turbidity of less than 0.2 NTU, it is thus necessary to dose the lime water with a turbidity below 2 NTU.

To face this issue, 2 lines of 4 vertical dual-media filters were installed between the lime water storage tanks and the dosing point. The filters were filled with a first layer of anthracite, which stops the large flocs coming from the lime water, and a second layer of sand, which will achieve the final polishing. Due to this additional filtration step, the turbidity of the lime water before the mixing is kept below 1 NTU and the final water turbidity is within the guarantees.

Along the permeate line, the lime water is injected first, according to the permeate flow rate and the mineralization degree required, then the dose of CO_2 injected is regulated through the pH set point, within a range of 7.5–8.0. From this point, the water is in accordance with the drinking water standards and the tender guarantees, and a sodium hypochlorite dosing ensures its final disinfection. A few hundred meters further, a complete analyzer set including the pH, temperature, conductivity, alkalinity, total hardness, and total organic carbon, controls the final water quality and is used to continuously calculate and monitor the Langelier Saturation Index.

4.2. Large-scale plant results

The plant final performance and reception tests were carried out in January 2012. The plant was operated at full capacity during 15 days with a sea water temperature between 16 ℃ and 18 ℃, the most restrictive case for the remineralization step as it requires the highest lime dosing rate. During this period, the pH set point was 7.8 and all the water quality parameters were recorded online.

4.2.1. Lime water filters performances

The lime water filters were designed for a feed water peak turbidity up to 30 NTU. During the whole period of tests, the outlet filter turbidity was always

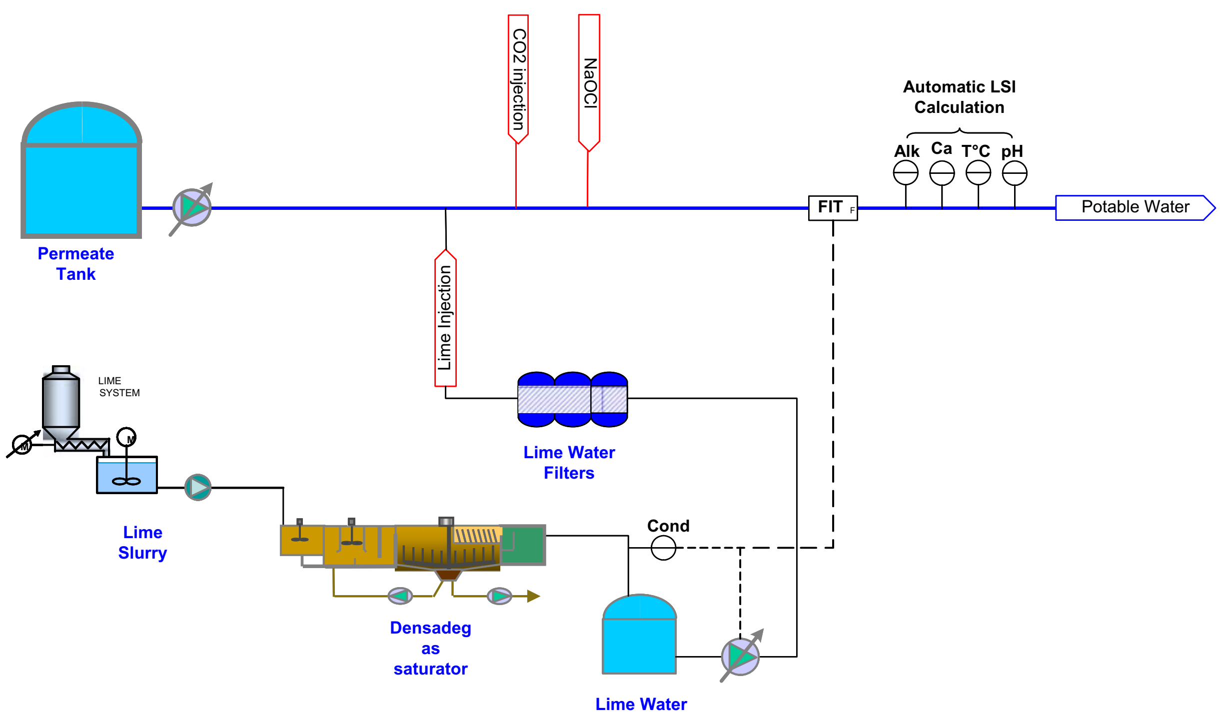

Fig. 7. Al Dur post-treatment step flow sheet diagram.

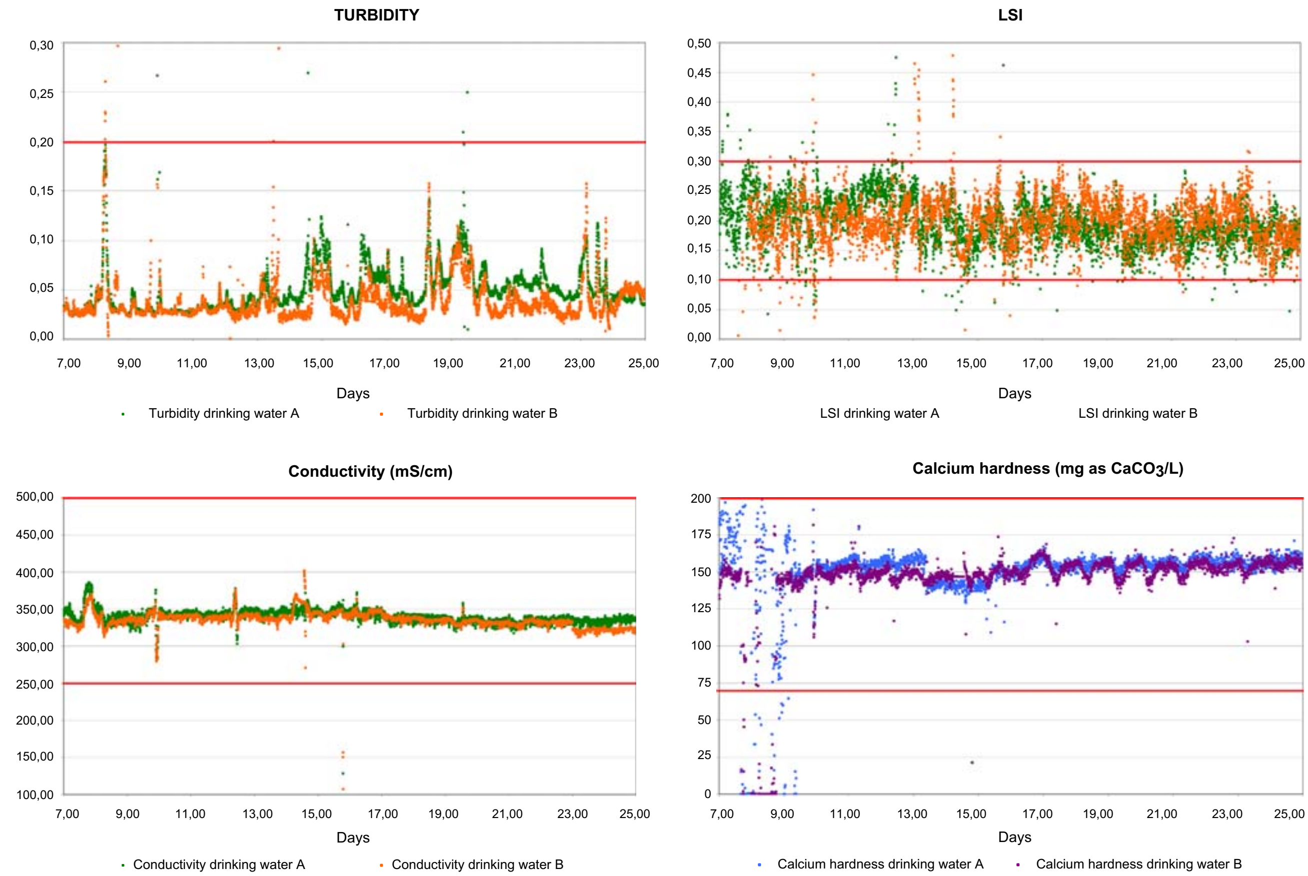

Fig. 8. Al Dur plant drinking water quality during the reception tests.

below 1 NTU, ensuring that the final mixed turbidity did not exceed 0.2 NTU.

4.2.2. Final drinking water quality

During the entire period of the tests, the plant produced water in accordance with the international drinking water standards and within the guarantees specified in the RFP.

It was demonstrated during the commissioning phase that when turbidity of the final water was below 0.2 NTU, the SDI_{15min} was below 3.0%/min. During the tests, the turbidity remained below 0.2 NTU, the LSI oscillated between + 0.1 and + 0.3, the conductivity were around 350 µS/cm and the alkalinity and the hardness around 150 mg/l as $CaCO_3$ (see Fig. 8).

5. Conclusion

Al Dur 1-year pilot study allowed Degrémont to proceed to a complete and detailed characterization of the sea water, and to reveal the large variations in some of the quality parameters such as turbidity and the $SDI_{75\%}$. The data obtained were in accordance with the data available for previous years and were corroborated during the first few months of the full-scale plant operation.

During 1 year, the pre-treatment line has demonstrated that the selected process was adapted to the quality of sea water and that the objectives of the filtered water quality were met. The efficiency and the key role of the SeaDAF™ have to be underlined as well as the importance of enhanced coagulation, to remove the various pollutants (organic matter, algae) and achieve a suitable pre-treated water quality. The performances obtained at the industrial plant have been very stable since October 2011 and the quality of the pre-treated water is in accordance with the design, the pilot study and the guarantees.

As for the post-treatment, the design was specifically adapted to meet the challenging objectives and the drinking water guarantees of the project. The design was particularly innovative and a specific automation system was included in the plant scada so as to make the post-treatment step fully automatic, even in case of temperature variations.

The plant performance tests have underlined the accuracy of the selected design as a drinking water of excellent quality was produced and all the objectives fulfilled.

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