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One-year operational experience with ultrafiltration as pretreatment of seawater reverse osmosis desalination system (Maspalomas-I Plant)

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ABSTRACT

The selection of a proper pretreatment for reverse osmosis (RO) systems is essential to produce a high-quality feed water in order to ensure a more sustainable and reliable operation. Traditionally, seawater RO installations have been operated with conventional pretreatments based on single- or two-staged media filtration, and occasionally preceded by coagulation/flocculation processes. In recent years, however, hollow fiber ultrafiltration (UF) technology has increasingly gained acceptance as a viable pretreatment alternative for seawater desalination, due to advantages such as greater capability to cope with fluctuations and high solid loads in raw waters (typical of open intakes), smaller footprint, higher and more consistent filtrate water quality, and higher environmental sustainability, ultimately demonstrating lower total water cost in the long-term operation. In this article, design and operational aspects of the country's largest integrated UF and RO system to treat seawater in a remote island of Spain will be provided. Special emphasis will be given on the benefits that the UF technology has brought to the operator compared to the conventional pretreatment it replaced.

Keywords: Ultrafiltration; Reverse osmosis pretreatment; Integrated membrane systems; Desalination; Seawater

1. Introduction

Bordered by seawater on all sides and experiencing low levels of annual rainfall, freshwater is a scarce resource in the island of Gran Canaria (Spain). In order to meet the needs of local and tourist populations, the historically dry island has established desalination plants to support the production of potable water.

"Maspalomas-I" belongs to the group of desalination plants built during the decade of the 80s in the Canary Islands to solve the scarcity of water in the middle of an increasing demand due to the growing tourism and the agriculture. Originally, Maspalomas-I was built using electrodialysis reversal technology to

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treat the brackish waters which were collected from wells in the south of the island of Gran Canaria. This water, once treated, served as the drinking water supply to the popular touristic areas of Playa del Ingles and Maspalomas. The start up of this plant took place in 1986 with a capacity of 20,000 m^3/d, which was a huge challenge for those years. Two years later, it was expanded by 2,000 m^3/d being the final capacity of 22,000 m^3/d.

The moment of renewing Maspalomas-I Plant came together with a decreasing availability of brackish water and the maturity of the seawater desalination so it was decided to retrofit this plant into a seawater reverse osmosis (RO) plant. This took place in 2006 with the installation of two RO trains producing 1,250 m^3/d each. A further module producing 6,000 m^3/d was started up in 2010 and another 6,000 m^3/d module was started up in 2013.

The modern seawater Maspalomas-I Desalination Plant has been built and is operated by Elmasa Tecnología del Agua, S.A. The RO plant, with a current total capacity of 14,500 m^3/d was originally designed and run with conventional pretreatment (i.e. pressurized multimedia filters). The plant supplies water to the country's largest touristic area, and biggest municipality of the island, San Bartolomé de Tirajana.

In 2012, due to the increased water demand in the area, it was decided to expand the plant capacity, and a new open intake was constructed. With this, the decision of replacing the existing conventional pretreatment by an advanced one using Ultrafiltration (UF) technology was taken.

In the last few years, hollow fiber UF technology has gained increased acceptance in the seawater treatment field as RO pretreatment. The benefits of the UF vs. conventional technologies are already amply known and documented, such as better and more consistent filtrate quality in terms of e.g. turbidity, SDI, pathogens, particles or colloidal matter, smaller footprint, higher reliability for the RO system operation, or lower environmental impact, and process higher simplicity when no coagulant is used.

However, without a proper optimization of the process, UF is not free from operational challenges, such as excessive consumption of chemical products used for cleaning, risk of oxidation of the chlorine-sensitive RO membranes due to the use of chlorine in the UF process, or biofouling issues in the filtrate tank, and/or RO membranes installed downstream.

This paper will describe the drivers to adopt the UF technology, as well as provide an evaluation of the first-year performance and challenges of the integrated UF/RO system "EDAM Maspalomas-I", located in the island of Gran Canaria (Spain).

2. Drivers to adopt UF in Maspalomas-I Plant

With over 12 million visitors per year, the island's local water demand has steadily risen, requiring Maspalomas-I Plant to extend its water processing capacity. However, the plant's existing intake system based on beach wells did not have the capability to provide the new required feed water flow to accommodate for the plant's expansion; therefore, a new open intake had to be constructed.

A conventional two-stage pressurized sand filtration was initially studied for the new open intake pretreatment; however, this option was finally discarded in favor of the UF technology due mainly to the following reasons in order of importance:

(1) Needs of land acquisition and therefore longer lead times associated to conventional treatment (i.e. due to the layout of the conventional treatment scheme, it would have required acquisition of further land at a high cost, obtain related permits, etc.).
(2) Higher transportation costs of vessels and media filter to the island.
(3) Lower plant footprint needed for the UF (35–40% lower, including prefilters and UF chemical systems).
(4) Higher capability of the UF to cope with variable feed water quality and tidal changes, especially for an open intake.
(5) Superior and more consistent filtrate water quality provided by the UF.

3. UF pilot trial

A ten-month pilot trial (from September 2012 to June 2013) preceded the execution of the full-scale plant and allowed to define the maximum stable flux as well as the rest of operating parameters (e.g. frequency of backwashes and requirements for chemical cleanings). The UF trial was carried out in EDAM Las Palmas III desalination plant, few kilometers away from Maspalomas; however, this was considered a conservative approach as the UF pilot unit feed water quality was worse than that expected for Maspalomas-I full-scale plant.

The pilot unit runs at a gross flux of 80 L/m^2/h (LMH) with a transmembrane pressure (TMP) in the range of 0.45–0.70 bar through the testing period (at 25°C temperature). The UF module was regularly subjected to maintenance cleanings with sodium hypochlorite (i.e. every 24 h) and hydrochloric acid (i.e. every 72 h).

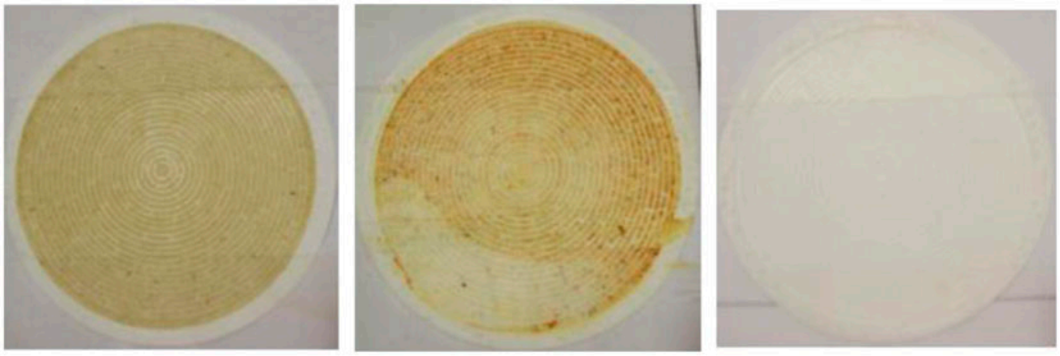

Fig. 1. SDI_{15} filter for raw water, conventional treatment outlet, and UF unit filtrate.

Fig. 1 shows a comparative of the silt density index (SDI_{15}) filter for the raw water, the existing conventional treatment outlet and UF unit filtrate, where it can be observed the significant higher removal of suspended and colloidal matter achieved by the UF technology.

4. Full-scale plant description

Maspalomas-I Desalination Plant is located in the island of Gran Canaria, Spain, and has been built and is operated by Elmasa Tecnología del Agua, S.A. The RO plant, with a current capacity of 14,500 m^3/d and originally designed with conventional pretreatment (i.e. pressurized multimedia filters), was started up back in 2006. The plant supplies water to the country's largest touristic area, and biggest municipality of the island, San Bartolomé de Tirajana.

In 2012, due to the increased water demand in the area, it was decided to expand the plant capacity, and a new open intake was constructed. Besides, the existing conventional pretreatment was substituted by DOW™ UF technology, for the reasons mentioned in the previous section. The DOW™ UF plant was commissioned in April 2013 and is currently the country's largest municipal UF system designed with pressurized modules for seawater desalination pretreatment.

Fig. 2 shows the whole process scheme of the plant.

The seawater from the open intake (at approximately 450 m from the shore, 5.5 m depth, and 4.5 m above seabed) is initially pumped to a sand removal basin, where it removes sand and settling particles above a size of approximately 200 μm, and then fills the feed water tank. Previous to the UF system, a battery of 100 μm self-cleaning strainers acts as a safety barrier for particles and debris susceptible to damage the UF fibers. The size of this pre-UF self-cleaning filter was selected based on a compromise between not being too coarse to potentially let sand particles or shell fragments through, but also not too tight to create potential issues of cell rupture due to excessive shear in case of algae presence.

The DOW™ UF system has a capacity of 32,250 m^3/d of net ultrafiltrate flow and consists of five independent trains, each one designed with four DOW IntegraPac™ skids with 12 vertical modules IP-77 each (77 m^2 membrane area). Besides, each DOW IntegraPac™ skid has two extra spare positions for a potential future plant capacity expansion of ~15–20%, or alternatively, to allow operating the UF system with only four trains online and one offline without increasing the flux significantly, if eventually it is decided to remove the buffer tank between the UF and the RO system and operate the UF system at a constant flow.

Fig. 3 depicts a DOW IntegraPac™ skids at Maspalomas-I Plant.

The UF trains are fed with a common feed water pump battery, in a configuration of three pumps in duty and one in standby. There is one backwash pump for all trains, where the standby feed pump also serves as backup for the backwash pump. An even production is achieved through motorized feed valves and individual flow meters in each train.

The ultrafiltrate is accumulated in a tank with a retention time of around 25 min, which works as a buffer tank for a better control of the inflow to the RO system. A direct coupling UF/RO was initially studied, but eventually discarded due to the higher complexity of the plant design and control, due to the issues associated to ensuring a constant pressure and flow at the RO system inlet without a buffer tank. However, due to the potential for contamination of the filtrate tank, it was deemed appropriate to install 1 μm cartridge filters at the RO system feed.

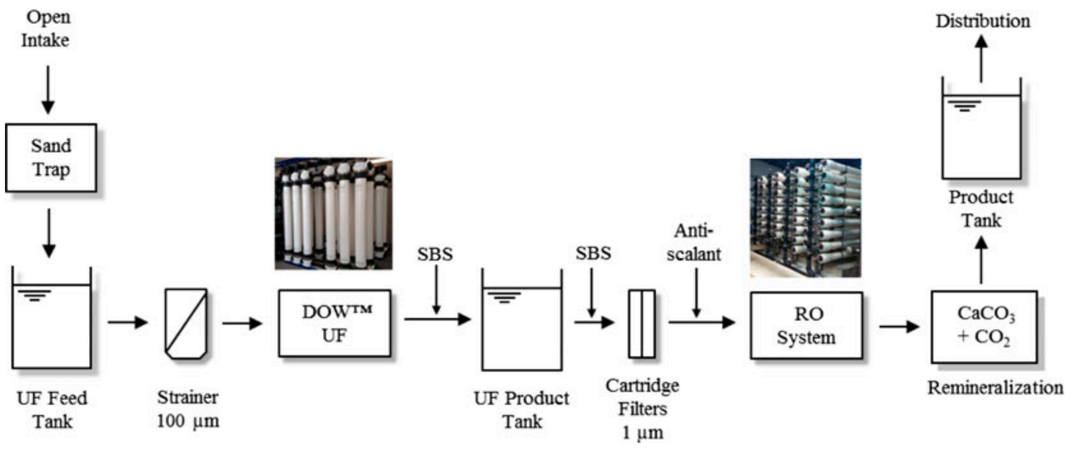

Fig. 2. Process flow diagram of Maspalomas-I UF/RO system.

Fig. 3. DOW IntegraPac^{TM} skid.

The RO system consists of four trains with three of them featuring DOW FILMTEC™ elements. Two of the trains are suitable for a production of 1,250 m^3/d of permeate each. They consist of 15 pressure vessels with seven DOW FILMTEC™ SW30HRLE-400i elements per vessel.

A larger third train includes 68 pressure vessels, also with seven elements per vessel. For this one, elements with higher active area were selected, in order to maximize production capacity. To ensure suitable permeate water quality, the system includes a hybrid configuration with a combination of two DOW FILMTEC™ SW30XHR-440i followed by five elements DOW FILMTEC™ SW30HRLE-440i per vessel. The final permeate water TDS is lower than 250 ppm and the boron content below 1 ppm.

Finally, the RO permeate goes through a remineralization step by addition of CO_2 and flow through limestone contactors, to correct parameters like alkalinity, pH, and Langelier saturation index (LSI), and is sent to the final product water tank. After that the water is chlorinated and sent to distribution.

5. Dow UF technology description

The DOW IntegraPac™ UF modules are made from high strength, hollow fiber membranes engineered to reduce design and fabrication requirements with features and benefits including:

(1) 0.03 µm pore size for effective removal of micro-organisms, particulates, and colloidal matter, to protect downstream RO system.
(2) PVDF fibers which offer strength, chemical (especially chlorine), and fouling resistance; which allows for extended membrane life and consistent long-term performance.
(3) Outside-in flow configuration allows higher TSS feed waters, while maintaining reliable system performance and producing high-quality filtrate.
(4) Innovative end caps enable direct coupling of modules, eliminating the need for piping manifolds.

These modules are an ideal choice for systems requiring a small footprint. The IP-77 module offers 77 m^2 effective membrane area, which contributes to a more economical membrane system design.

On the other hand, The DOW IntegraPac™ skid is a pre-engineered, standardized skid design consisting of DOW IntegraPac™ UF modules, auxiliary parts, and piping. It significantly streamlines design, assembly, and installation, resulting in lower skid costs, easy assembly, smaller footprint, and shortened delivery schedule. These were critical aspects for Maspalomas-I Plant expansion.

DOW IntegraPac™ skid features include:

(1) Modular and scalable for design across a wide range of flow rates.
(2) Materials of construction selected for corrosion resistance and chemical compatibility.
(3) Shipped unassembled to lower transportation cost and prevents damage in transit.
(4) Individual end caps with built-in interconnectivity allow modules to be connected directly, and eliminate ancillary piping, manifolds, and connections.
(5) Standardized and pre-fabricated components and parts eliminate measuring, cutting, gluing, and welding.
(6) Compact design and footprint saves space.
(7) Easily accessible for physical inspection or replacement at end of life.
(8) Operator-friendly transparent filtrate elbow designed and located for easy visual integrity inspection.

6. UF plant performance

A summary of the raw water quality feeding the UF system is shown in Table 1.

The UF system operates in dead-end mode at a variable gross flux (depending on the water demand) of 65–80 L/m^2/h and with filtration cycles of 60 min. After each filtration cycle, a backwash with ultrafiltrate water is initiated, to flush out contaminants accumulated in the membranes and restore the TMP. The backwash is aided by a few seconds of air scour at the external wall of the fibers (feed side). Regularly, a chemically enhanced backwash (CEB) is carried out in each train, where chemicals are added into the backwash stream for better removal of contaminants or disinfection of the system. In this respect, a CEB with around 200 mg/L of sodium hypochlorite is carried out every 24–48 h (depending on the train, i.e. the two furthest trains from the feed pumps battery seem to experience a higher fouling rate, most likely due to hydraulic inefficiencies) for organic fouling control and disinfection, while an acid CEB with HCl at pH 2.0–2.2 is executed every 72 h as a maintenance cleaning for potential inorganic scale formation removal. No other chemical (e.g. caustic soda) is used for these regular CEB's.

Table 1
Raw water quality summary (feed to UF system)

Parameter	Unit	Value
Temperature	℃	20–25
pH	–	7.5–8.1
Conductivity	mS/cm	50–56
Total organic carbon	mg/L	<1
Turbidity	NTU	<10
Total suspended solids	mg/L	<20

In addition to these regular automatic cleanings described before, an offline intensive cleaning may be done via the cleaning in place (CIP) system, which allows preparation of the chemical solution with low total dissolved solids RO permeate water, and optionally heating the solution, for a higher cleaning efficiency. However, after almost one year of operation the UF trains have not been subjected to any CIP cleaning.

This operating procedure achieves a global recovery of the UF system of 97.1% and a system availability (i.e. online time) above 95%.

The TMP in the UF trains ranges from 0.55 to 0.80 bar depending on the operating flux (i.e. it increases when the flux increases, and vice versa, but remains quite stable at a fixed flux and with no significant signs of fouling).

Fig. 4 depicts the average permeability for the five UF trains, where it can be observed that it has been quite steady during the whole operational period, with average values above 100 L/m^2/h/bar. A slight decline in permeability can be observed however, during the winter period due to the lower water temperature (i.e. around 5° drop). The permeability values have not been normalized in this graph because the water temperature is pretty constant throughout the year at 20–25℃.

Colloidal fouling can seriously impair performance of the of RO elements. The silt density index (SDI) is a commonly used offline test used to evaluate the RO feed water quality in terms of particulate and colloidal matter, and although it has some limitations, it is generally a good indicator of the fouling tendency of the RO membranes. An SDI_{15} at the RO system inlet below 3.0%/min is generally considered to have a low fouling potential, although the average SDI_{15} value of the raw water in Maspalomas-I Plant (after the UF pre-strainers) is around 5.0%/min (with some episodes of immeasurable SDI_{15} and SDI_5 above 15%/min).

However, following the UF pretreatment, the SDI_{15} at the RO system inlet has been kept at an average

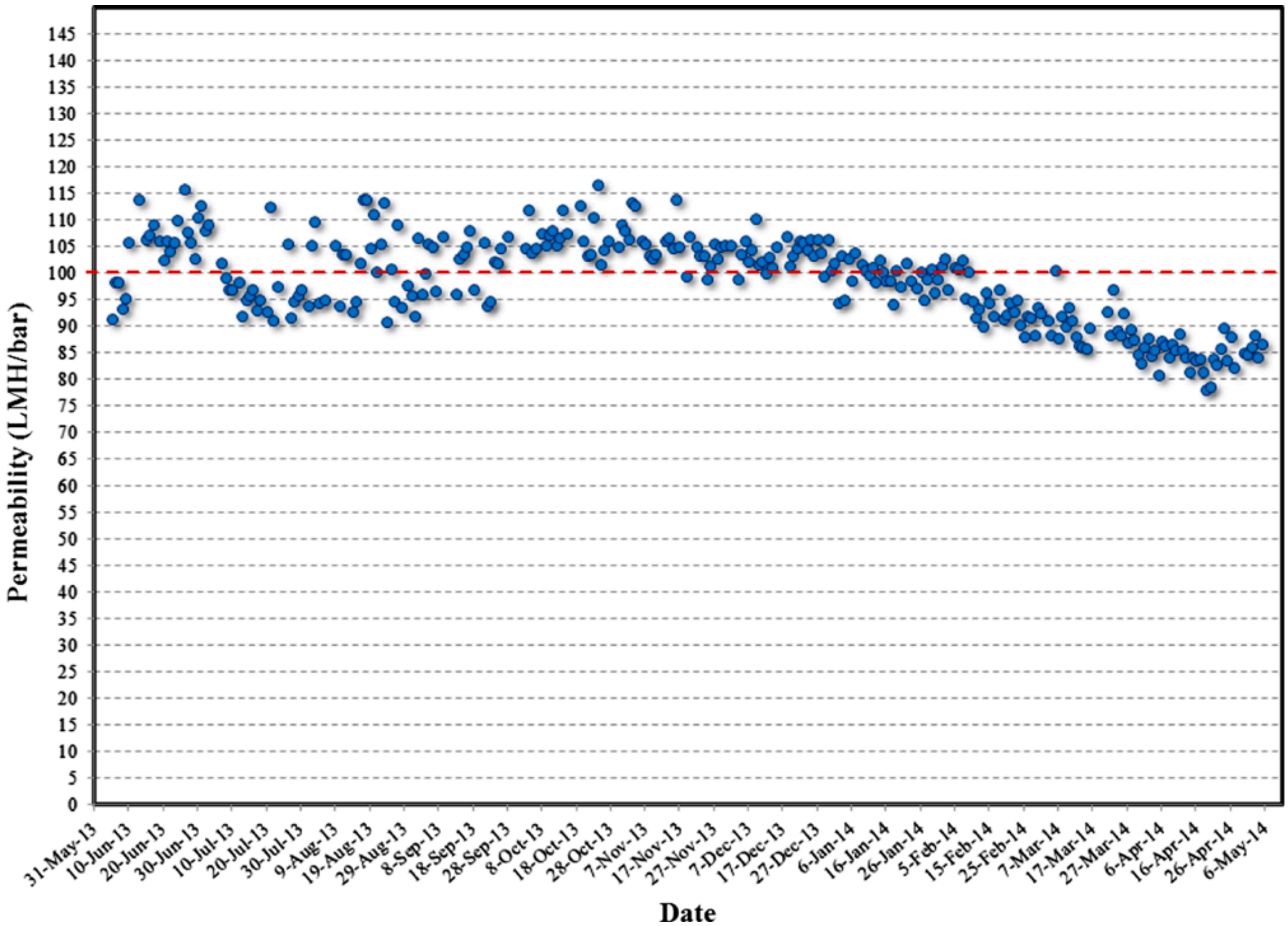

Fig. 4. Average permeability ($L/m^2/h/bar$) for the five UF trains.

value of 1.99%/min, with 90% of the time below 2.50%/min. But note this is the value after having gone through the UF product tank and the pre-RO cartridge filters, where it is expected that some contamination may occur. The SDI_{15} values at the UF system outlet have actually shown an average of 1.73%/min, with 90% of the time being below 2.30%/min.

Fig. 5 depicts the average SDI_{15} values of the UF system inlet (upstream the pre-strainers) and the RO inlet (downstream UF filtrate tank and cartridge filters).

One of the main operational challenges faced by the plant is to keep under control the biogrowth of the UF system and specially the UF water tank, in order to minimize the fouling in the RO membranes installed downstream, especially, when the nutrient sources (i.e. dissolved organics) are not significantly reduced by the UF process.

The use of oxidants for disinfection, however, requires special considerations due to the sensitivity of the RO membranes to even small amounts of oxidants. On the other hand, chlorination of the feed water followed by de-chlorination prior to the RO system can also create issues. It has been widely documented that chlorination leads to organic matter breakdown which is then more easily assimilated by the post-dechlorination surviving bacteria and actually increase the biofouling potential in the UF and RO systems, so continuous in-line chlorination was discarded.

As mentioned above, the UF system goes through disinfection CEB with Sodium Hypochlorite every 24–48 h. This ensures that the UF system remains disinfected and the organic fouling under control. However, in order to minimize the chlorine residual going to the RO system downstream, a thorough rinse via backwash is carried out in the UF trains after being exposed to chlorine. Moreover, as an extra safety measure, once any UF train comes back to filtration after cleaning with chlorine, the initial ultrafiltrate volume produced is sent for a few minutes to drain through an out of spec line until the residual chlorine is below 0.20 ppm, and besides, sodium bisulfite (SBS) is dosed temporarily at the UF product tank inlet.

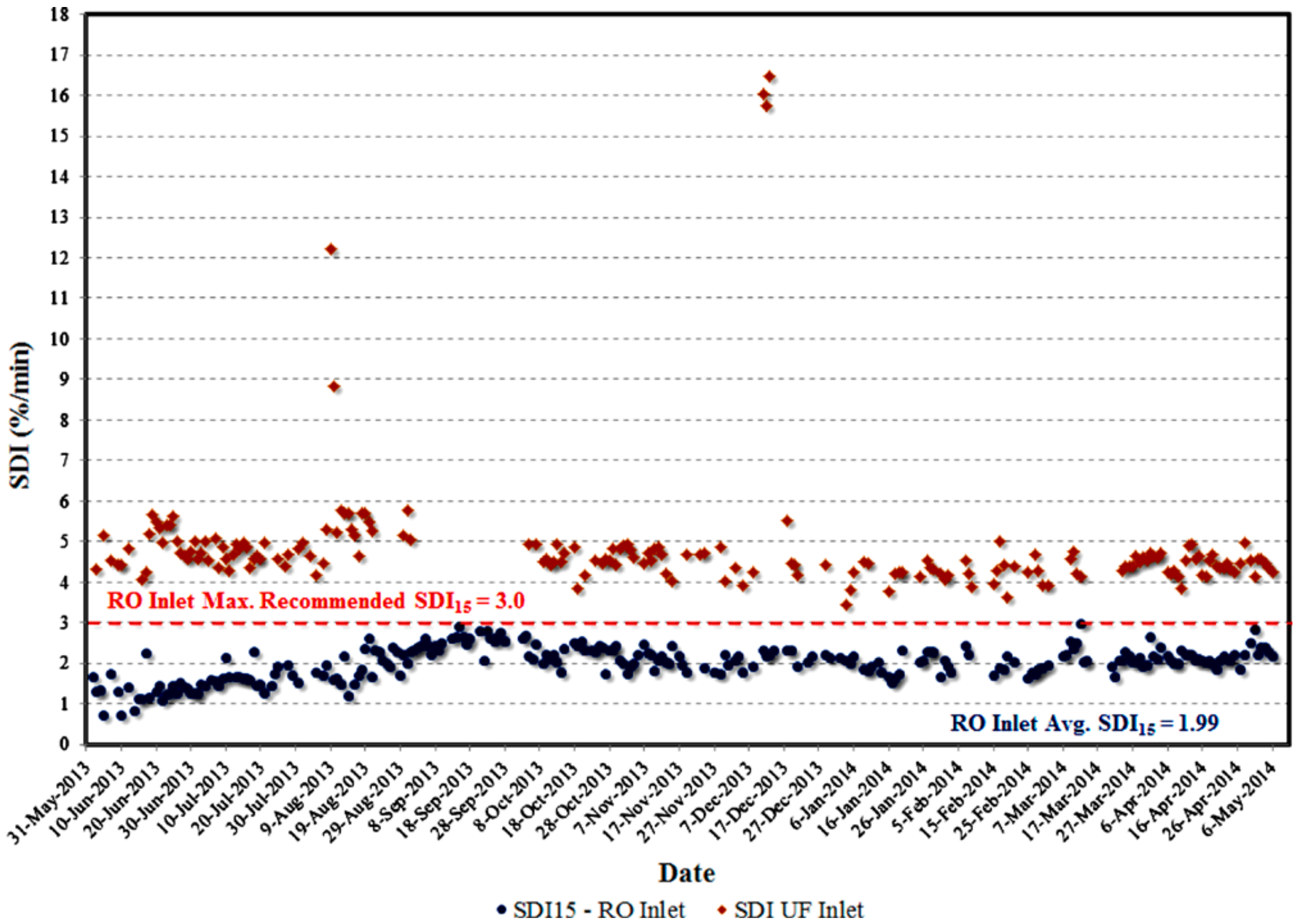

Fig. 5. SDI_{15} of UF system inlet and RO system inlet.

However, this leaves the UF product water tank with virtually little or no residual chlorine exposure at all, so the chances for biogrowth to appear in the tank are high, especially, if it is not properly sealed and equipped with vent filters. This phenomenon has happened in Maspalomas-I Plant after few months from start up.

The measures taken in order to minimize the UF filtrate tank biogrowth and potential RO membranes fouling have been the following:

(1) Substitute the previous tank internal wall lining based on PVC panels to food-grade cement coating.
(2) Modify the tank internal flow pattern to avoid dead zones. This was achieved by configuring the tank inlet and outlet in opposite walls and feeding the tank along one of its sides by means of multi-branch feeding pipe.
(3) Reduce the water level in the filtrate tank around 35% in order to minimize the retention time.
(4) Apply a disinfection strategy based on monthly to bi-monthly chlorine shock with 50 ppm and 30–45 min soaking, followed by thorough rinsing of the tank to drain, refill with chlorine-free fresh water, and temporary SBS addition at the RO feed when back in operation as a safety measure. The chlorine is added at the feed of the strainers (upstream the UF system) in order to disinfect as well the whole UF plant, taking advantage of the high tolerance of PVDF UF membranes to chlorine.
(5) Regular flushing (i.e. every 3–4 d, for around 2 h) of the RO system with a blend of RO brine and UF filtrate at a mixed conductivity of 63 mS/cm. This is done in filtration mode (i.e. the RO continues producing water, although at a lower flow due to the higher feed water conductivity).
(6) Regular dosage (i.e. every 3–4 d) of SBS at the RO inlet.

7. Capital and operative costs

The capital cost of Maspalomas-I UF plant was around 55 Euros/m^3/d of UF net output. This includes civil works, UF building, tanks, mechanical and electrical equipment, strainers, UF modules and racks, auxiliary systems like chemicals (i.e. CEB and CIP) and blower, installation and engineering. It is important to mention, however, that Elmasa Tecnología del Agua, S.A. engineered, procured and installed the UF plant themselves, not through an external contractor, and that land acquisition to accommodate the UF system was not necessary.

Note that the capital cost for a conventional pretreatment (i.e. two-stage pressure filters) in this case would have been significantly higher than the UF option mainly due to the factors already mentioned before: high transportation costs of the vessels and media filter to the island, and the needs of land acquisition to accommodate the filters.

As per the operating costs, the energy consumption for the whole UF plant (i.e. including strainers, UF filtration, backwash, air scour, chemical cleanings, instrumentation, ultrafiltrate backpressure, plus lighting, and air conditioning of the UF building) is around 0.11 kWh/m^3 (m^3 refers here to ultrafiltrate), where 0.07 kWh/m^3 corresponds to filtration mode only (i.e. strainers plus membrane TMP plus filtrate backpressure of around 0.5 bar).

The total energy consumption for the pretreatment at Maspalomas-I Plant including UF and the RO low-pressure feed pumps is 0.43 kWh/m^3 (m^3 refers here to final RO permeate). As a comparison, a twin plant which works with conventional pretreatment (i.e. two-stage pressure filters) and that is located just a few kilometers away from Maspalomas-I has a similar energy consumption.

Table 2
Total energy consumption per m^3 of RO permeate

Item	kWh/m^3
Seawater intake	0.96*
Ultrafiltration (Inc. strainers)	0.23**
Low-pressure pump (transfer to RO)	0.20
RO process (Inc. energy recovery)	2.50
Total	3.89***

*Note that Maspalomas-I Plant is at +90 m above sea level.

**This refers to RO permeate. Referred to UF filtrate would be 0.11 kWh/m^3.

***Assuming plant location at sea level, the total energy consumption would have been ~3.3 kWh/m^3.

Table 2 shows the itemized and total energy consumption for Maspalomas-I Plant.

In terms of chemical consumption, only sodium hypochlorite (13%) and hydrochloric acid (35%) are used for the regular chemical cleanings of the UF membranes (i.e. CEB's). The total consumption for both chemicals (i.e. around 35 kg/d of NaOCl and 12 kg/d of HCl) accounts for 0.016 cents of Euro per cubic meter of net ultrafiltrate produced.

8. Conclusions

(1) In order to get the most out of the latest developments in RO membranes and system performance, pretreatment needs to provide a consistent, reliable, and high water quality.
(2) UF has gained widespread acceptance in the last years as pretreatment for seawater RO, especially in those cases where the feed water quality has high variability, like open intakes.
(3) RO systems downstream of UF are serviced by the high-quality UF filtrate, increasing the reliability and sustainability of their operation.
(4) The new developments and evolution of the UF technology have made it more affordable and viable vs. conventional pretreatment.
(5) In case of remote islands and with high land cost, the capital cost of UF may be significantly advantageous vs. conventional pretreatment, due to the lower footprint. Besides, lower weight and volume for UF modules also means lower transportation costs as opposed to media.
(6) Since the start up of the UF system, in April 2013, the quality of the UF filtrate has been stable and according to the expectations (i.e. average SDI_{15} 1.73, with 90% of the time below 2.30) and with a steady permeability trend.
(7) The use of intermediate tanks between the UF and the RO makes the operation much simpler but requires a careful maintenance and follow-up in order to avoid lessening the benefits of the UF due to tank biofouling issues.
(8) The integration of UF and RO requires special precautions, where it is needed to adapt their operational philosophy from the distinctive features of conventional treatment (e.g. regular backwashes and chemical cleanings to sustain stable operation, or proper control of residual chlorine to avoid RO membranes oxidation).

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