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Assessment of Ultrafiltration Cleaning Protocols in Drinking Water Treatment Processes

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Abstract

Membrane-based processes efforts are focused on mitigating membrane fouling by optimizing operating conditions, especially when low quality surface waters are treated. The study conducted here was driven to evaluate the current measures applied to mitigate fouling in Ultrafiltration (UF) stages when integrated as a pre-treatment of the Reverse Osmosis (RO) in a Drinking Water Treatment Plant (DWTP). First, the effect of coagulants in fouling and water quality was evaluated by using synthetic and surface waters in bench-scale. Both aluminum and iron-based coagulants rejected the organic compounds when dosed above 1 $mg \cdot L^{-1}$. Also, micro-coagulation with $FeCl_3$ previous to the UF impacted positively the membrane performance. Then, two modes of operation were proposed and tested in bench-scale to improve the cleaning strategies when filtering waters from different sources. The results highlighted the feasibility to apply a different cleaning protocol when groundwater was filtered as it would improve the water yield and production by elongating the filtration times. To conclude, an exploratory analysis reviewed the membrane performance and cleaning strategies in the Ultrafiltration stage at full-scale during 1 year of operation. The results showed high variations in Specific flux (Js) throughout the year and, also, suggested that chemical cleaning procedures were being applied in excess.

Keywords: Water treatment; Ultrafiltration; Fouling indices; Cleaning strategies; Micro-coagulation; Water blends; Surface and ground water

Introduction

The decrease of water availability in many regions suffering water scarcity is forcing the need of using surface waters of poor quality. To achieve the water quality standards in such scenarios, it is necessary to integrate pressure driven membrane technologies. Reverse Osmosis (RO) and Nanofiltration (NF) are common solutions to remove both excess of salinity and undesired levels of microbiological pollutants. These membrane treatments are usually linked to a pre-treatment stage incorporating Ultrafiltration (UF) membranes to ensure the safety of RO/NF membranes by accomplishing low levels of particulate matter (SDI<4) and low residual levels of Al-based coagulants (below 100 μg/L). Successful operation of the UF treatment stage depends upon a proper membrane fouling control, which is especially complex in treatment trains fed with waters of different quality, such as sand filtered water (SFW) and groundwater (GW) blends. This is the case presented here in which river water and groundwater sources are exploited depending on the low river quality associated to water droughts and rainfall events.

Membrane fouling control is especially critical in Drinking Water Treatment Plants (DWTPs) located in semiarid climate regions where production of tap water depends upon the resources availability as water composition, especially in terms of dissolved organic matter (DOM), changes substantially.

Monitoring fouling is essential to properly control filtration performance as fouling is the main obstacle during filtration. Fouling leads to a partial or total blocking of the membrane pores negatively affecting its operation either by increasing transmembrane pressure (TMP) and/or reducing the permeate flux [1]. Foulants can deposit at the top of the surface layer, or they can also get trapped inside the pores, hindering partially or totally the pass of water. The latter case is usually more problematic and can lead to irreversible fouling [2].

The potential of water compounds to foul the membranes also depend on the synergistic effects of the organic and inorganic fractions. Hao et al. studied the effect of humic substances in combination with metal ions in UF membranes [3]. Also, Qin et al. studied the contribution that humic substances in combination with silica particles had on fouling [4].

In order to mitigate fouling, membranes need to be cleaned periodically. In hollow fiber UF membranes, current efforts focus on optimizing the cleaning protocols. Hydraulic cleaning is applied periodically and consists in circulating clean water in reverse mode during a specific period of time. By doing so, foulants detach from the membranes and the water solution is discarded. This procedure is commonly known as backwash (BW) and the fouling removed by BW is known as hydraulically reversible fouling [5-7]. Fane et al. studied the effect of the operational conditions (BW duration, BW strength and air scouring) when using low pressure hollow fiber PVDF membranes BW [8,9].

Since the membrane permeability does not fully recover in every BW, there is a moment in which the operation of the membrane becomes unfeasible [10]. When this occurs, a chemical cleaning (CC) must be applied. The CC strategies can include the chemical enhanced backwash (CEB), in which a BW is performed with chemical agents which

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enhance removal of foulants, and the cleaning-in-place (CIP), in which membranes are soaked in a chemical solution for a specific period of time [11]. When this period of time is relatively short, the CIP can also be called as maintenance cleaning (MC). Some chemicals are preferred over others depending upon the type of fouling to be removed. The most commonly used are sodium hypochlorite (NaOCl), citric acid ($C_6H_8O_7$), phosphoric acid (H_3PO_4) and hydrogen peroxide (H_2O_2) [12]. Among these chemicals, NaOCl is the agent most used and is applied primarily when organic fouling occurs. When utilized in concentrations around 1%, it has been found to reduce the presence of undesired compounds adhered to the membrane with an efficiency close to 95% [13,14].

The frequencies at which membranes need to be cleaned depend, among other factors, on the quality of water to be treated. Because of that, efforts have focused on developing methodologies to predict and quantify how a specific water would affect membrane performance. In order to measure the potential of water to foul membranes, different fouling indices have been developed. They are used by membrane suppliers to fulfill the membrane specifications. Water streams with index values above the specified ones are not suitable to be treated by the considered membrane. Among the different indices, the silt density index (SDI) and the modified fouling index (MFI) are the most used (mostly in RO systems). In these tests, fouling is quantified by filtering water through 0.45 micrometer membranes at a constant pressure and are widely used because of their simplicity [15]. However, they are not very accurate and their applications can lead to overestimations. For instance, the methods ignore the fact that, when tested in real membranes, the diameter of pores is much smaller than 0.45 micrometers [16]. Regarding UF membranes, more appropriate indices have been developed. Boerlage et al. improved the modified fouling index (MFI) procedure by using a membrane with a lower molecular weight cut off (MWCO) that better mimicked full-scale UF systems [17]. Sim et al. introduced the Cross flow Sample Modified Fouling Index Ultrafiltration (CFS-MFI-UF), which accounts for the hydrodynamics of the system [18]. Further modifications include the normalized silt density index (SDI+) developed by Alhadidi et al., which introduces corrections for temperature, pressure and membrane resistance [19].

The unified membrane-fouling index (UMFI) developed by Huang et al. presents the advantage of accounting for the membrane-specificity and for being independent of filtration scale. Huang et al. demonstrated the significance of developing indices to quantify the fouling potential of different waters to assess membrane performance in bench-scale and pilot plant experiments [20,21]. Also, Nguyen et al. developed the same mathematical expression although they approached it using a resistance in-series method [22]. They also differentiated the fouling indices into total fouling index (TFI), hydraulic-irreversible fouling index (HIFI) and chemical irreversible fouling index (CIFI).

The present work was conducted (i) to evaluate the MCs performed in a full-scale DWTP by identifying Specific flux improvements before and after cleaning the membranes and measuring the frequencies in which MCs were applied, (ii) to quantify the fouling potential of two water sources feeding the UF stage of a full-scale DWTP by using the fouling indices developed by Nguyen et al. and (iii) to quantify, in bench-scale, the benefits and disadvantages of coagulation with Fe(III) and Al(III) in terms of rejections and fouling rates regarding water quality and operation, respectively. As a model system, a DWTP incorporating a UF stage as a pre-treatment of a RO stage feeding surface and groundwater resources has been used.

Materials and Methods

Full-scale DWTP description

The Drinking water treatment plant (DWTP) of study is located in the lowest part of the Llobregat River basin (Sant Joan Despí, NE Spain) and has a nominal capacity of approximately 5.3 m^3/s. The raw water used by the DWTP comes from the Llobregat River and, also, from its aquifer. The proportion of both source waters in the UF is ruled mainly by the Llobregat River water quality. Since the plant is located in a European semi-arid region, the river suffers from water draughts and poor quality. On the one hand, the average flow rate during the year is 20 m^3/s with episodes of dryness in which the flow rate can go down to 5 m^3/s. Moreover, the river is subject to high changes in quality due to heavy rainfall events (turbidity values above 500 NTUs), problems of dilution of large inputs of industrial and urban origins and episodes of pollution.

The whole treatment process of the DWTP is displayed in Figure 1. It includes a conventional pre-treatment comprised of preliminary screening, pre-chlorination with ClO_2, coagulation/flocculation by the addition of aluminium coagulant, subsequent sedimentation and sand filtration. It is at this stage where groundwater, when required, is incorporated. From this point on, water flow is split into two lines: (i) the conventional line undergoes ozonation and granular activated carbon (GAC) filtration, while the (ii) membrane-based line (implemented in 2009) undergoes in-line coagulation with $FeCl_3$, ultrafiltration (UF), UV irradiation, reverse osmosis (RO) filtration and mineralization. The use of the micro-coagulation stage with Fe(III) is justified by the need to achieve residual levels of Aluminum below 100 µl Al/L. Both treated streams are blended and the resulting stream is post-chlorinated prior to distribution.

The membranes in the UF stage are subject to cleaning protocols to sustain permeability values. A hydraulic BW is applied approximately every 50 minutes to remove the reversible fouling. The chemical cleaning (CC) procedures are applied in a lower frequency to mitigate the hydraulic irreversible fouling. The chemical agents used to conduct the CC are sodium hypochlorite, citric acid and phosphoric acid. There are two types of CC procedures conducted in the UF: a Maintenance cleaning (MC) is applied in which the membranes are soaked in solution for approximately 45 minutes. A more aggressive cleaning procedure, known as Recovery cleaning (RC), must be applied when episodes of sever fouling occurs.

Bench-scale membrane ultrafiltration system

A bench-scale UF setup was used to conduct the experiments. The configuration was in dead-end mode and Zenon/GE provided PVDF hollow-fiber membranes in order to use the same configuration and membranes as in the DWTP. The membranes had a nominal pore size of 20 nm and an effective membrane area of 0.042 m^2. The system operated under vacuum with a pressure ranging from 0 to 0.5 bar. Pressure was monitored using a micro-processor based pressure transducer (Model LEO3 from KELLER). The permeate flow was controlled with a peristaltic pump (Heidolph, Pump drive 5201) and was set constant during each run; the flux was measured by collecting and weighting water at the outlet over a known period of time. The membrane was immersed in a 15 L tank with a thermostat to set the temperature at 10°C. A second tank of 50 L was used to continuously recirculate water to the first in order to sustain the water level and keep the concentration of feed water constant. Data from the manometer and the balance was continuously logged over time via a data logger (Pico log 1216) and loaded using an in-house made program (created with MATLAB 2013). Figure 2 shows a scheme of the bench scale set-up.

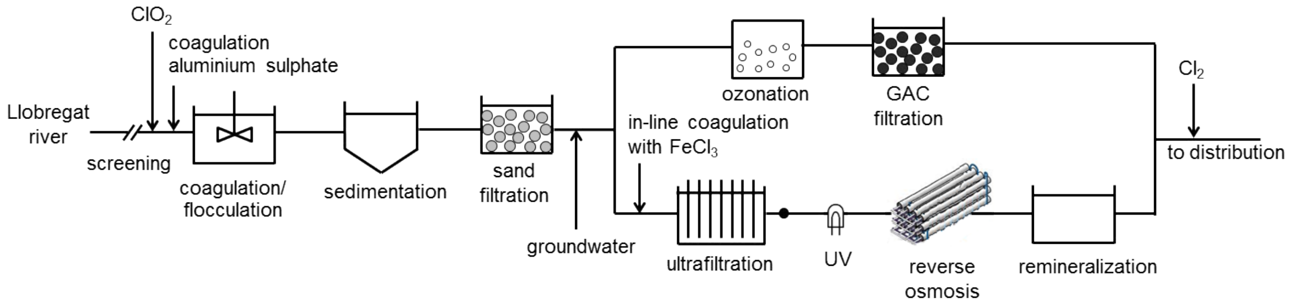

Figure 1: Schematic representation of the DWTP in SJD.

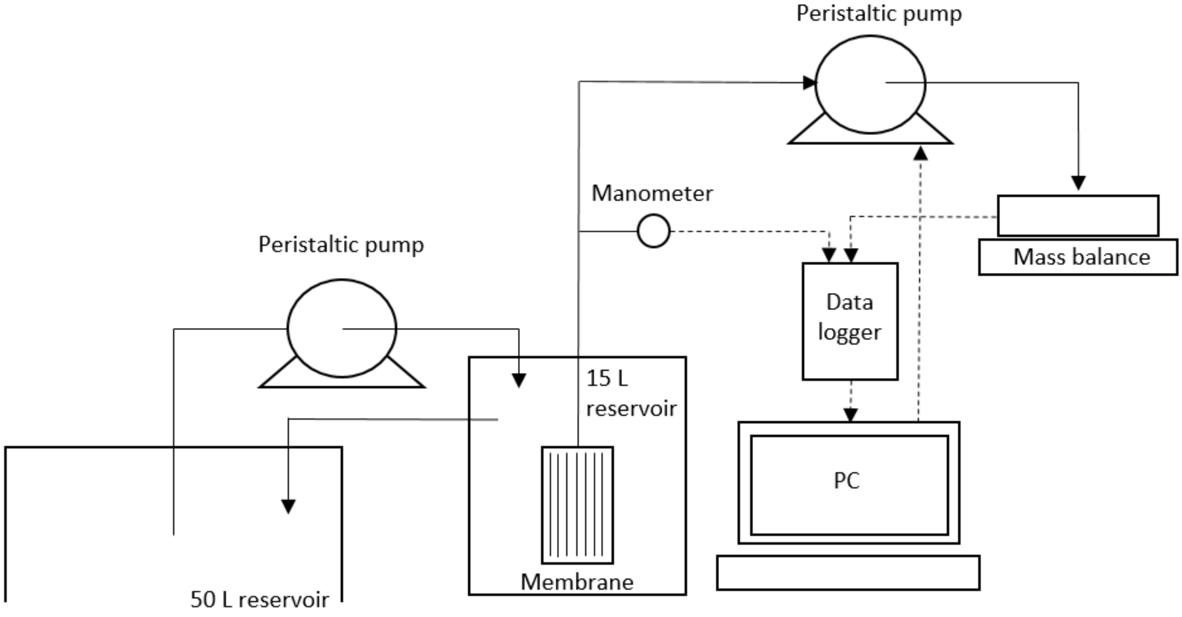

Figure 2: Scheme of the bench-scale UF dead-end set-up.

In order to properly study fouling for extended periods of time, it was necessary to automatize the filtration sequences. This was achieved by using an in-house program (created with MATLAB 2013) designed to mimic the operating conditions used in the DWTP. The filtration process was constituted by the following steps: (i) filtration for 60 minutes, (ii) 2 minutes relaxation (iii), 2 minutes backwash filtration (iv) 6 minutes relaxation. From experiment to experiment, membranes were chemically cleaned in place (CIP) either with NaOCl (400 mg·L^{-1}) or citric acid (1000 mg·L^{-1}) and the permeability was checked at the beginning of every experiment to ensure proper cleaning.

Analytical techniques

Absorbance spectroscopy at a wavelength of 254 nm was used to track variations in DOM. A DR5000 spectrophotometer (Hach Lange) equipped with 1 cm cuvettes was used for absorbance measurements (5 cm cuvettes were used in solutions of BSA). To measure particulate matter, the 1720E Low Range Process Turbidimeter and sc100 Controller (Hach Lange) were used. Also, a Particle counter (Particle Sense, Izasa Scientific) to measure particle ranges from 2 µm up to 100 µm.

Data treatment: Principal component analysis

A Principal Component Analysis (PCA) was conducted to compare the water quality originating from surface and ground sources. The analysis reduces the complexity of a system by projecting objects and variables in a lower dimensional space. It applies restrictions of orthogonally and maximum variability, which makes data easier to interpret.

The PCA results are usually discussed in terms of component scores and loadings. The scores are projections of the samples in the new space defined by principal components (PCs). Regarding the loadings values, they indicate the magnitude of the contribution of every original variable to every principal component (the weight by which each standardized original variable should be multiplied to get the component score). Variables with large values of loadings on the same component are assumed to correlate. If they present the same sign, they present a positive correlation whereas if they present opposite signs, they correlate inversely [23].

Parameters used to evaluate membrane performance

In this study, operation data (transmembrane pressure, TMP, and specific Flux, Js) were treated to calculate the total fouling index (TFI), the hydraulically irreversible fouling index (HIFI), the BW efficiency, the permeate flux capacity and the percentage of water wasted from BW.

The pressure driven flux through the membrane (J, flow per unit area) can be described by Eq. 1:

$$J = \frac{TMP}{\mu R} \tag{1}$$

Where TMP is the transmembrane pressure through the membrane, μ is the viscosity of the water and R is the coefficient of resistance that accounts for the resistance of the membrane and the resistance associated to fouling. In this model, it is assumed that fouling increases linearly with the specific volume (Vs, volume filtered per unit area). The Specific flux can be defined by Eq. 2:

$$J_S = \frac{J}{TMP} = \frac{1}{\mu(\mathrm{R}_{\mathrm{mem}} + \Upsilon_{\mathrm{fouling}}\ \mathrm{V}_{\mathrm{s}})} \tag{2}$$

The Specific flux can also be normalized by the Specific flux at the beginning of the operation when there is no fouling (Vs=0) as indicated by Eq. 3:

$$\frac{J_S}{J_S(\mathrm{vs}=0)} = \frac{\mathrm{R}_{\mathrm{mem}}}{\mathrm{R}_{\mathrm{mem}} + \Upsilon_{\mathrm{fouling}}\ \mathrm{V}_{\mathrm{s}})} \tag{3}$$

Thus, the expression can be rearranged as shown by Eq. 4:

$$\frac{J_S}{J'S} = 1 + FI.Vs \tag{4}$$

Where J's is the normalized permeability and FI accounts for the fouling index. Depending upon the interval of data used to calculate the FI, the index provides different information. For instance, if the FI is calculated from one chemical cleaning operation to the next one the HIFI is obtained, whereas if the range evaluated is only between two hydraulic cleanings, the TFI is obtained [21,22].

The BW efficiency was calculated by Equation 5:

$$BW_{eff}(\%) = \frac{JS_{afterBWi}}{JS_{afterBWi-1}}.100 \tag{5}$$

The water wasted due to BW was also calculated by Eq. 6:

$$BW_{ww}(\%) = (1 - \frac{J_f.t_f - J_{bw}.t_{bw}}{J_f.t_f}).100 \tag{6}$$

Finally, the MC improvements (%) were also calculated by Eq. 7:

$$MC_{improvement}(\%) = (\frac{Js_{bMC} - Js_{aMC}}{Js_{bMC}}).100 \tag{7}$$

Where $\mathrm{Js}_{\mathrm{bMC}}$ and $\mathrm{Js}_{\mathrm{aMC}}$ are the Specific fluxes before and after the MC were conducted [24].

Results and Discussion

Evaluation of micro-coagulation on natural organic matter removal by bench-scale UF Experiments

Groundwater (GW) and Sand filtered water (SFW) differ in terms of natural organic matter (NOM) but also by the presence of coagulants; SFW contains residual aluminum coagulants dosed in the pre-treatment as well as iron coagulant dosed previous to the UF stage. In this section, a two-step method consisting in a jar test and a filtration using 0.45 µm membranes was conducted to evaluate the effect that dosing aluminum and iron coagulants have in water quality.

First of all, synthetic foulants were used to assess selectivity between humic-like and protein-like substances as they have been identified as the main NOM components. Next, SFW replaced the synthetic compounds to estimate the benefits of filtering pre-treated water regarding quality. Finally, the effect of micro-coagulating Sand filtered water (doses below 1 mg Fe/L) prior to the UF was assessed not only from a quality stand point but also by conducting bench-scale experiments in the UF. This will help assess the benefits of coagulating pre-treated water (at such low doses).

Evaluation of model NOM foulants removal by micro-coagulation: First, synthetic model compounds typically found in water were studied; humic acid (HA) and bovine serum albumin (BSA) were selected because they resemble the humic-like and protein-like fractions found in water and have been previously used to evaluate fouling in membranes [25,26]. The solutions were prepared using ultrapure water in which known amounts of salts were added to account for the effect of ions on coagulation and removal of dissolved organic matter (DOM) (277 $mg \cdot L^{-1}$ $MgCl_2$, 300 $mg \cdot L^{-1}$ Na_2SO_4 and 300 $mg \cdot L^{-1}$ Na_2CO_3 was added). In every jar test run, six different one litter beakers were used and concentrations of coagulant ranging from 0 to 10 $mg \cdot L^{-1}$ were dosed during constant agitation. The coagulants used to conduct the experiments were Fe(III) (PIX-511, Kemira Water Solutions) and Al(III) (PAX18, Kemira Water Solutions). After fifteen minutes, agitation was stopped and the beakers were left to settle for another 15 minutes. Water from each beaker was then filtered using 0.45 µm PVDF membranes and the resulting solution was analyzed.

Figure 3a and 3b exhibit UV_{254} and rejection values measured for HA and BSA when coagulated with Fe(III) and Al(III), respectively. Both coagulants showed no DOM rejection when dosed at 1 $mg \cdot L^{-1}$. From 1 to 3 $mg \cdot L^{-1}$ the rejection of HA and BSA increased significantly. Then, the rates at which the coagulants initially increased were reduced. Also, based on the results obtained, there were almost no differences between coagulants and within the rejections obtained for both model compounds.

As it could be seen, improvement on the removal of NOM in the pre-coagulation stage were only efficient at doses of Fe above those coagulated in the UF pre-treatment stage. Next, Sand filtered water (SFW) was coagulated following the same procedures as with synthetic compounds. The objective was to quantify the effect of aluminum and $FeCl_3$ when using SFW. Figure 4 shows no DOM rejections below 1 $mg \cdot L^{-1}$ as when model compounds were used. Unlike the previous case study, lower rejections were found when Al(III) was used.

Evaluation of NOM removal by UF bench experiments using Fe(III) micro-coagulation: As stated earlier, there is a micro-coagulation chamber in the full-scale DWTP in which iron coagulant ($FeCl_3$) is dosed at low concentrations (below 1 $mgFe \cdot L^{-1}$). A battery of bench-scale UF assays, using 1 mgFe/L, were conducted to evaluate its impact on membrane performance. Figure 5a and 5b show fouling indices obtained from the different runs. Both total fouling index (TFI) and hydraulic irreversible fouling index (HIFI) showed slight improvements in membrane filtration upon coagulation. Rojas-Serrano et al. also found similar results when testing the coagulants at a larger scale. Higher coagulant doses decreased its beneficial effect. Zupančič et al. also studied the effects of coagulation with $FeCl_3$ prior to the UF stage using TFI and HIFI values. They found that coagulation had a

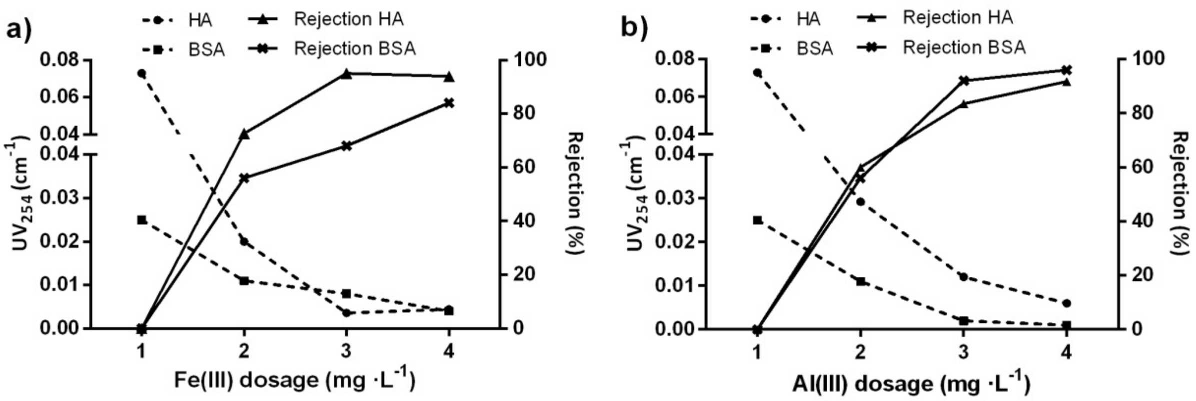

Figure 3: Results from jar tests evaluating synthetic solutions of HA and BSA. The dashed lines exhibit the absorbance values after coagulation whereas the regular lines show rejections of HA and BSA upon coagulation of a) Fe(III) and b) Al(III).

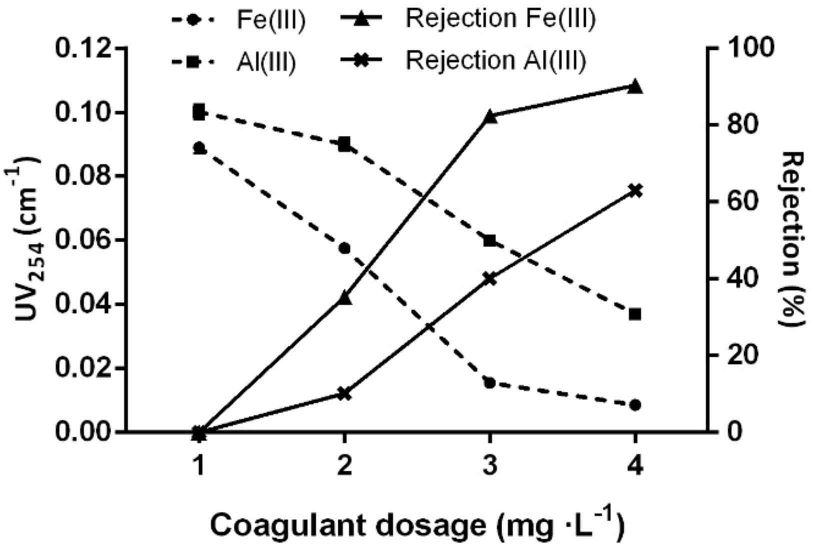

Figure 4: Variation of NOM removal efficiency by following changes of the molar UV absorption at 254 nm as a function of the coagulant dose for Al(III) and Fe(III) salt by using jar tests.

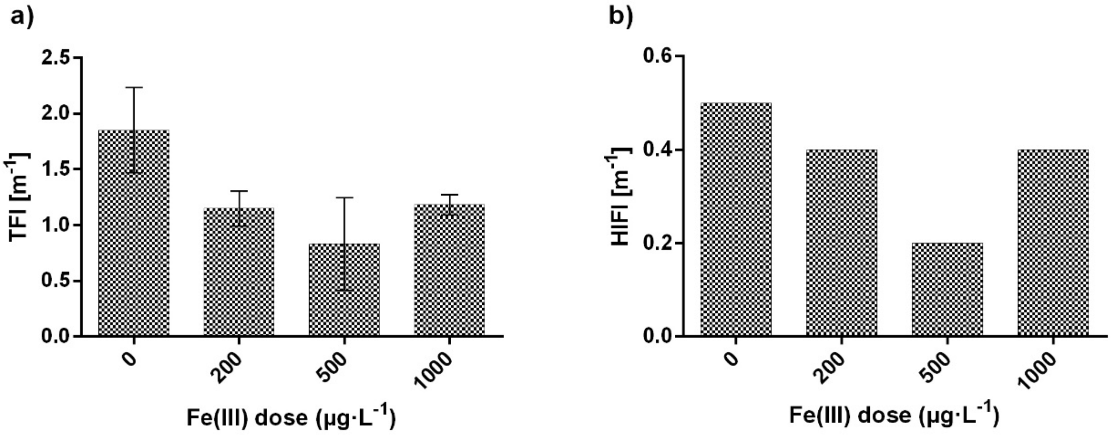

Figure 5: TFI values and b) HIFI values obtained from bench-scale UF experiments with type SW water at different coagulant doses. The error bars indicate the standard deviations observed.

positive impact on both reversible and irreversible fouling. However, in their system the turbidity was much higher (>5 NTUs) [27-30].

Overall, the experiments conducted showed no improvements in terms of membrane performance when dosing $FeCl_3$ at concentrations higher than 500 µg Fe·L^{-1}. In fact, $FeCl_3$ may act as a foulant compound itself. The results are in agreement with the study conducted by Wray et al. found an optimal $FeCl_3$ dose with a beneficial impact on membrane filtration and water quality [31].

The water quality changes due to micro-coagulation were also considered. Figure 6a and 6b show an increase in rejection of particulate matter (analyzed as turbidity and particle counts) associated to micro-coagulation dosage. Permeate was also analyzed for UV254 but no differences in absorbance were appreciated at different $FeCl_3$ doses.

Exploratory analysis of the cleaning protocols and membrane performance in the full-scale UF stage

Figure 7a shows the dynamics of the Specific flux (Js) in the UF stage of the DWTP of SJD measured during 1 year of operation. The Js experienced high oscillations throughout the year with occasional episodes in which Js dropped drastically. Figure 7b shows Js values and highlight the maintenance cleanings (MCs) conducted over a shorter period of time (1 month of operation). During this period, it is observed that the MCs conducted were not regularly spaced. Instead, the MCs for phosphoric acid and sodium hypochlorite occurred closely spaced whereas the MCs conducted with citric acid were more spread out.

Since the frequencies at which the MCs are applied are fixed either by time or by volume of permeate, there is no actual frequency or protocol that account for the type of water being filtered (GW/SFW). Finally, the chemical cleans (CCs) conducted in plant alternate the chemical agents used so that the same number of MCs are conducted throughout the year.

Figure 8a shows averaged values of Specific flux measured before each MC conducted throughout 10 month of operation: Js exhibits high variability among the different MCs conducted which denotes that the cleaning protocols were not optimally applied. Figure 8b exhibits the improvements (%) among the MCs conducted: citric acid, phosphoric acid and sodium hypochlorite improved Js by 11 ± 6%, 9 ± 6% and 10 ± 5% respectively. Also, the values were especially low during months 9 and 10 probably because Js values before the MC were especially high (Figure 8a). Martín-Pascual et al. also found high variations in permeability improvements after chemically cleaning the membranes

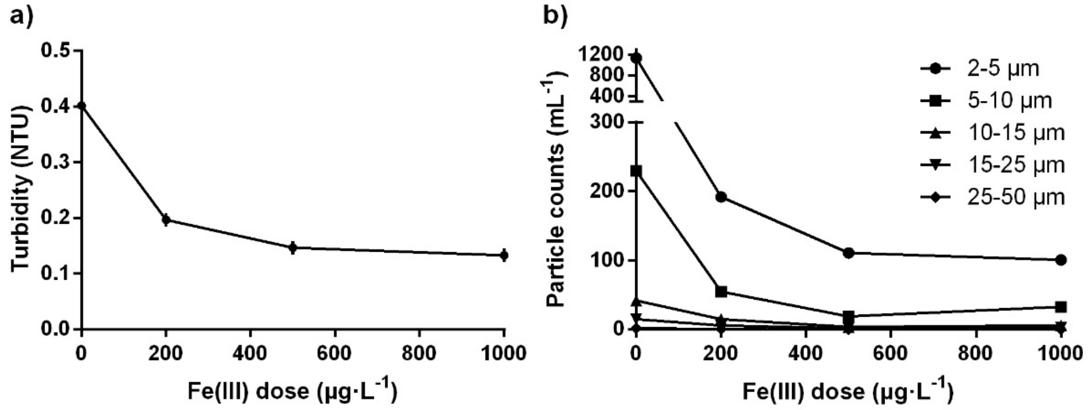

Figure 6: a) Turbidity values and b) particle counts analyzed from water samples after micro-coagulation and bench scale ultrafiltration.

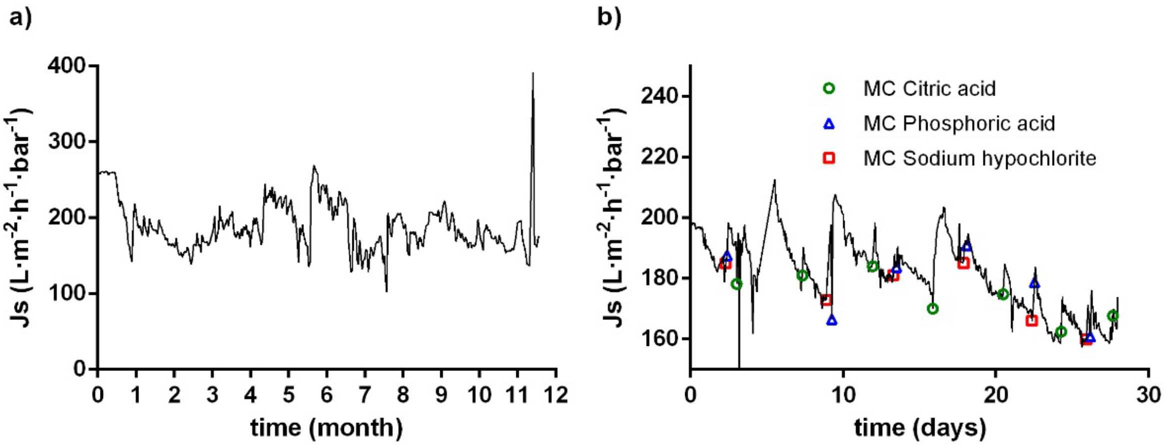

Figure 7: Full-scale membrane specific flux values during a) 1 year of operation and b) 1 month of operation.

although they obtained higher improvements (20-68%) [32]. Based on the analysis conducted, the MCs evaluated here may be ineffective due to a slightly high cleaning frequency.

During this period, a MC was performed approximately every 1200 L/m^2; which corresponds to approximately 2.5-3 MCs per week. Porcelli et al. reviewed 85 MF/UF plants and showed that less than half of the plants carried more than 1 MC per week [33]. An excess of MCs was found to affect the membrane integrity as the fibers suffer from breakage and degradation. Akhangelsky et al., in their study regarding the effect of NaOCl in polymeric membranes, showed a diminution in the mechanical strength of fibers (rupture stress and Young modulus) associated to an increase in the concentration of NaOCl and exposure time [34]. Also, Childress et al., when studying the effect of MCs in the lifetime of PVDF membranes, detected a total degradation of the superficial layer translated in an increase in their hydrophilic properties. An optimal NaOCl concentration between 0.5% and 1.0%, depending upon the operational conditions was suggested [35].

Accordingly, it is concluded that MC may be over-applied in the DWTP. Future work should focus on reducing the number of MC performed by: (i) being selective with the chemical reagents [36] and (ii) determining the frequency of the MCs based on the water quality.

Influence of water source and quality on membrane fouling

The physicochemical properties of water feeding the UF stage were analyzed through a Principal component analysis (PCA) by filtering either mostly SFW or mostly GW in full-scale. Figure 9 shows a bi-plot in which the scores (observations) and loadings (physicochemical parameters within water) are plotted. The abscissa axis provides information regarding the first component (PC1): it segregates the water sources completely. Also, the position of the physicochemical variables can be used to depict correlations. Thus SFW exhibited higher TOC, UV$_{254}$ and turbidity values whereas the correlation was inversed for GW. Also, it is observed that SFW shows much higher variability than GW throughout the year.

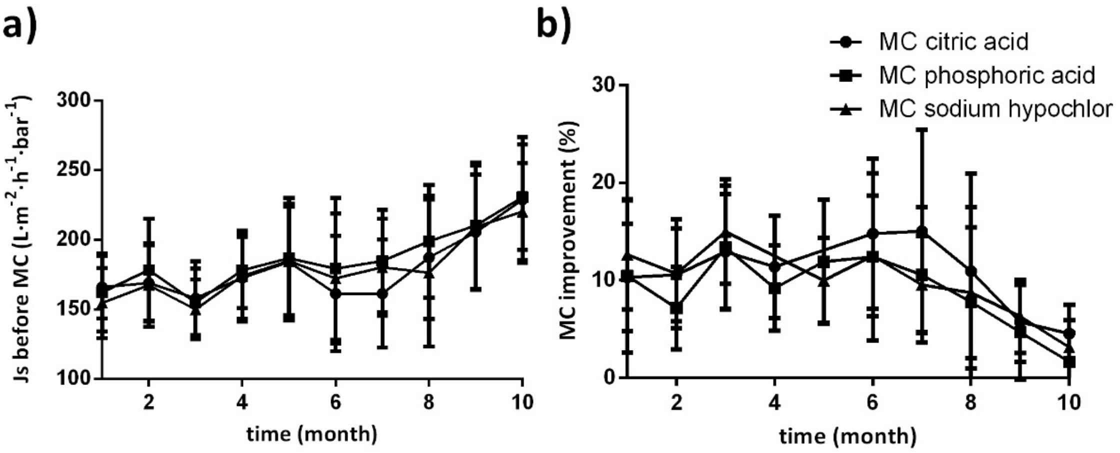

Figure 8: a) Averaged permeability values measured before a MC and b) averaged permeability improvements (%) measured during 2014. The error bars indicate the standard deviations observed.

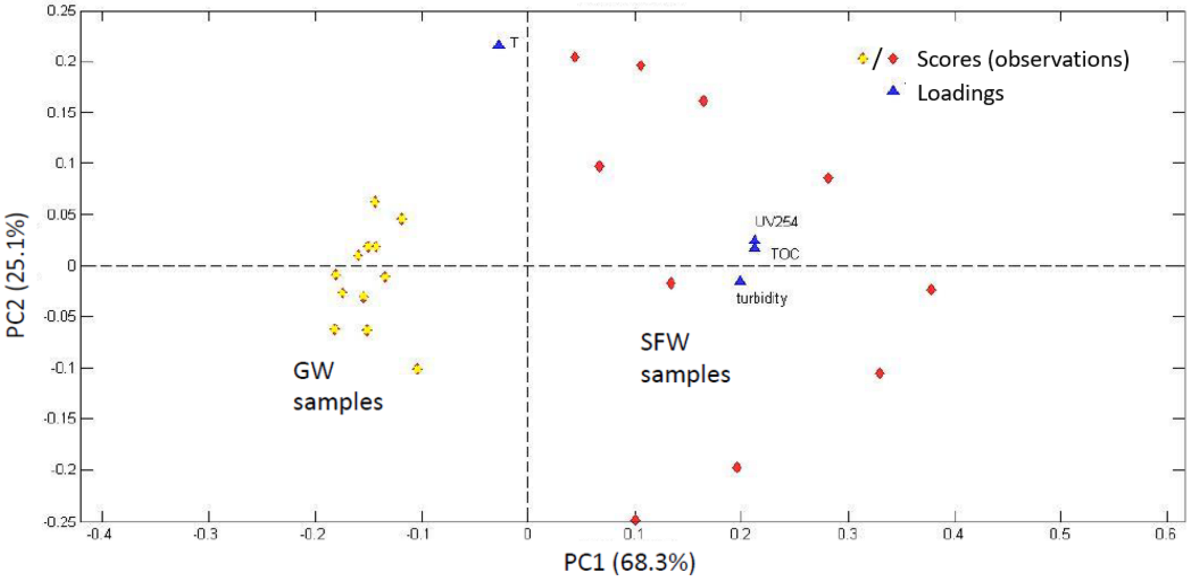

Figure 9: Principal component analysis (PCA) conducted on physicochemical parameters from two water sources.

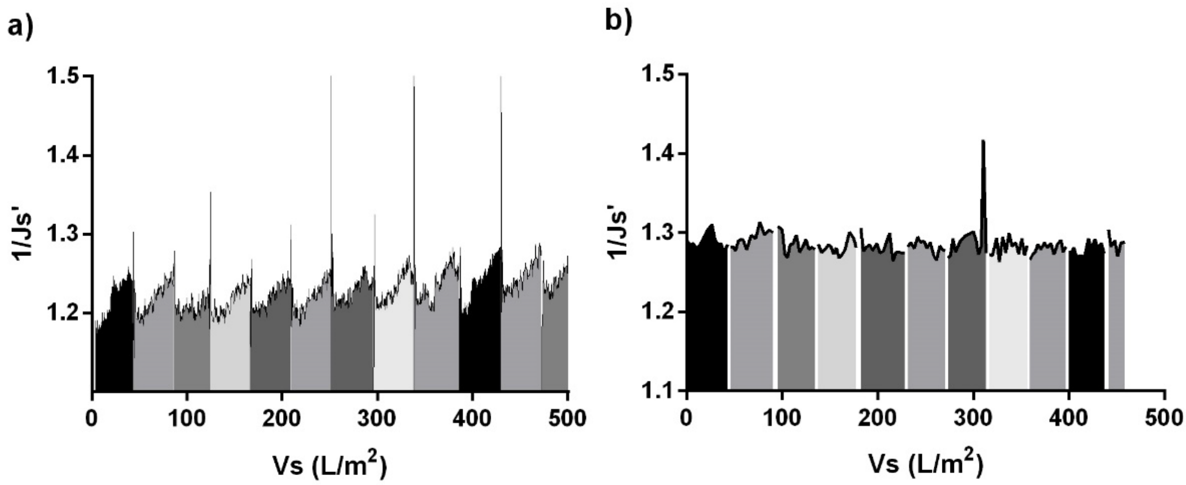

Figure 10: Full-scale fouling data of a) type SW and b) type GW water during 1 day of operation.

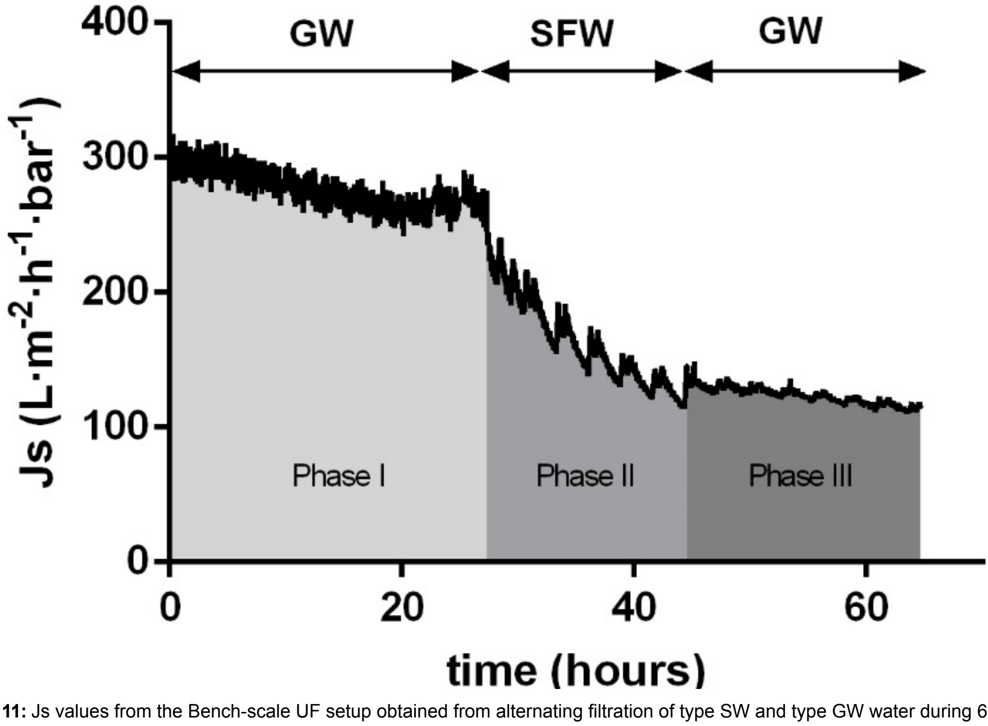

Figure 11: Js values from the Bench-scale UF setup obtained from alternating filtration of type SW and type GW water during 65 hours.

Finally, PC2 (axis of ordinates) was influenced by the temperature variations observed during the year but do not segregate the samples between SFW and GW. Again, the variability shown by SFW samples is much higher (the temperature ranges from 7-27 °C throughout the year).

Additionally, fouling arising from both water sources was evaluated at full-scale during one day of operation. Figure 10a and 10b show the variation of inverse of the flux normalized (1/Js') upon filtration of water (expressed as specific volume) which depict the rates at which membranes were fouled upon filtration of water. In comparison, SFW fouled the membranes at a much higher rate. The averaged TFI value for SFW water was 1.4 ± 0.5 m^{-1} and the HIFI value was $9 \cdot 10^{-4}$ m^{-1}. On the other hand, fouling upon filtration of GW was irrelevant (considering only the one-day period).

This operation behavior was analyzed and reproduced using bench experiments as it is shown in Figures 6 and 11 shows the Js values obtained upon filtration of water in bench-scale filtration. First, GW was filtered during 27 hours with BW intervals of 60 minutes (Phase I). During this period, the TFI was $3.0 \cdot 10^{-1}$ ± $1.9 \cdot 10^{-1}$ m^{-1} and the HIFI was $1.4 \cdot 10^{-1}$ m^{-1}. Then, the membrane started filtering SFW for which a significant permeability drop was observed; the TFI and HIFI values were 5.5 ± 1.6 m^{-1} and 1.6· m^{-1}, respectively (Phase II). Finally, the membrane started

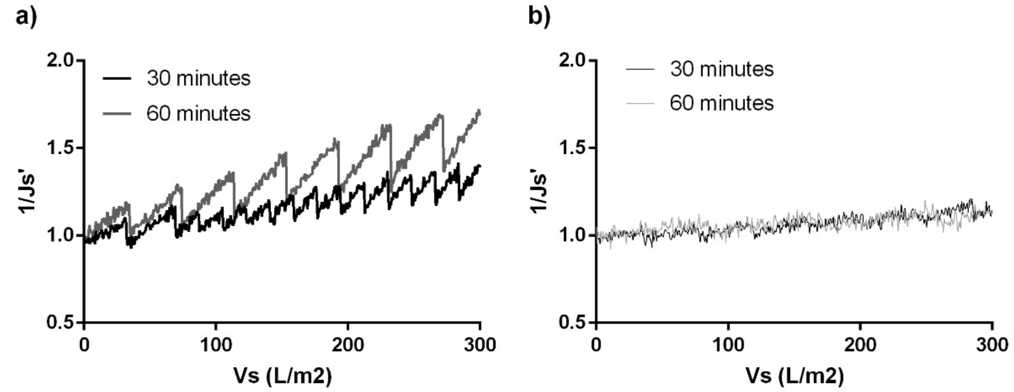

Figure 12: Operating conditions obtained during filtration of a) SFW and b) GW working at different frequencies.

SFW					
BW_{freq} (min)	TFI (m^{-1})	HIFI (m^{-1})	BW_{eff} (%)	BW_{WW} (%)	Water flux ($L·m^{-2}·h^{-1}$)
30	7.4 ± 1.4	1.1	94 ± 3	14	43
60	8.6 ± 1.3	2.1	98 ± 3	7	36

Table 1: Operating performance values obtained from filtration of type SW water for filtration cycles of 30 and 60 minutes.

filtering GW again during 20 hours (Phase III). During this period, the TFI and HIFI values dropped again ($5.1·10^{-1} \pm 1.4·10^{-1}$ m^{-1} and $5.7·10^{-1}$ m^{-1}, respectively). Even though GW in Phase III was visibly "cleaner" than SFW, it was not possible to recover the irreversible fouling inflicted in Phase II. In fact, the irreversible fouling increased as compared to the beginning of the experiments in which the same water was used, which could be related to the membrane being already partially blocked up. To conclude, when the full-scale data analysis and the bench-scale experiments conducted were compared, the latter results showed slightly higher overall TFI and HIFI values both when filtering GW and SFW.

Influence of BW frequencies on membrane filtration performance

Membrane performance and water quality properties behaved different when SFW and GW were filtered which made evident the need to use a different operating protocol depending on the nature of the feed water.

Figure 12a and 12b show the variation of inverse of the flux normalized (1/Js') upon filtration of water (expressed as specific volume) for two different BW frequencies when tested in bench-scale for SFW and GW, respectively.

Figure 12a shows a higher increase in 1/J' values upon BW conducted every 60 minutes than when BW was applied every 30 minutes. The fouling indices calculated for TFI_{30} and TFI_{60} were 7.4 ± 1.4 m^{-1} and 8.6 ± 1.3 m^{-1}, respectively. Higher differences were found regarding the irreversible fouling, in which the $HIFI_{30}$ and $HIFI_{60}$ were 1.1 m^{-1} and 2.0 m^{-1}, respectively. Also, the BW efficiencies dropped from 98 ± 3% to 94 ± 3% during filtration at 30 and 60 minutes, respectively. Moreover, the average TMP values were 0.21 ± 0.02 bar and 0.25 ± 0.04 bar for filtration cycles of 30 and 60 minutes, respectively (the values are summarized in Table 1. Raffin et al. also found that the BW frequency had a major effect on irreversible fouling [37].

Overall, the results showed significant improvements when working with 30 minutes filtration cycles as the irreversible fouling was reduced and the average TMP also decreased. However, this was in detriment of the production yield (Table 1). Thus, picking the optimal BW frequency is a tradeoff in which it is necessary to prioritize within different aspects.

On the contrary, Figure 12b show no differences between the two frequencies used as the data showed mild fouling upon filtration.

Conclusion

In this study, the cleaning procedures performed in the UF were reviewed. Also, the influence of groundwater and sand filtered water on the membranes as well as the role they play on the cleaning procedures was studied. The work included full-scale data, bench-scale tests and laboratory experiments.

The following conclusions can be drawn from the results:

- Membrane-based systems operating in water scarcity regions require the attention of special protocols to improve operation due to the strong changes on water quality streams (GW and SW) especially in terms of organic matter composition and content.
- The study conducted to review the maintenance cleaning in the DWTP concluded that there is room for optimization by (i) improving the selectivity between chemical reagents and (ii) modifying the frequencies based upon water quality information.
- Based on the significant differences observed when filtering GW and SFW, a bimodal system has been suggested to work with two different BW frequencies: filtering GW during longer times was feasible and could improve the water yield and production.
- The coagulants did not show significant selectivity in removing HA over BSA and both coagulants showed rejections when dosed above 1 $mg·L^{-1}$ but higher uses of coagulant doses will reduce water production yield due to the increase of cleaning stages.
- Micro-coagulation with $FeCl_3$ previous to the UF exhibited a positive impact in membrane performance and particulate matter but did not improve DOM rejections.

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