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The fate of transparent exopolymer particles (TEP) in seawater UF-RO system: A pilot plant study in Zeeland, The Netherlands

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ABSTRACT

For many years, transparent exopolymer particles (TEP) were found abundant in various marine and freshwater environments, which are currently the main sources of raw water in desalination plants. Just recently, TEP have been identified as a potential foulant capable of causing organic and biological fouling in membrane systems. A pilot plant study was conducted to monitor the fate of TEP through the treatment process and to investigate their effects on the operational performance of a seawater UF-RO plant. Using spectrophotometric measurements, particulate (p-TEP > 0.4 μm) and colloidal ($0.05 <$ c-TEP < 0.40 μm) species of TEP were measured at selected points in the plant. TEP monitoring in the raw water recorded a significant increase in both p-TEP and c-TEP starting in early spring (March). This period was also marked by an increase of chlorophyll-a and total organic carbon (TOC) mainly attributed to an algal bloom occurrence in the water source. Total TEP from the raw water were partially removed by the micro-strainer (11–21%) and the UF system ($\sim$28%). Low fouling rates in the UF were observed in January and February but severe fouling were observed in late March and April, coinciding with the increase in TEP level. The severe fouling was mitigated by applying in-line coagulation before the UF for which irreversible fouling was significantly reduced. Deposition analyses indicated that significant amounts of p-TEP and c-TEP were deposited in the RO system. However, there was no significant decrease of RO normalized flux during the 4 months of operation in the plant. Long term monitoring is needed to better assess the adverse effects of TEP accumulation in the RO systems.

1. Introduction

A few years ago, transparent exopolymer particles (TEP) were relatively unknown in water treatment. However recently, a number of and wastewater treatment studies had focused on TEP as a potential foulant in membrane systems [1–5]. The discovery of TEP can be traced back in 1993, when Dr. Alice Alldredge and co-workers, discovered an abundant type of extracellular polymeric substances (EPS) for which until that time, have been overlooked for many years [6]. A vast number of studies followed after the discovery, producing comprehensive information about TEP and its significance to oceanography and limnology. It was not until 2005, through an article by Berman and Holenberg [7], that the relevance of TEP to desalination was proposed.

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Table 1
Typical size range of DOC fractions that can be detected by LC-OCD (DOC-Labor, Karlsruhe)

DOC fractions	Size range (Da)	Composition
Biopolymers	>>20,000	polysaccharides (e.g. TEP) and proteins
Humic substances	~1,000	humic and fulvic acids
Building blocks	300–500	weathering and oxidation products of humics
LMW organic acids	<350	all aliphatic low-molar-weight organic acids
LMW neutrals	<350	alcohols, aldehydes, ketones and amino acids

TEP are distinct from other EPS in many ways. Unlike most EPS, TEP mainly exist as discrete particles rather than as cell coatings or dissolved slimes [6]. They are transparent, sticky and gel-like substances, comprising mainly of acidic polysaccharides. TEP are hydrophilic substances which naturally exist in different shapes (blobs, clouds, sheets, fibers or clumps) and sizes (~0.4–200 μm) [7]. As a planktonic type of EPS, they are ubiquitous in most fresh (inland surface water) and marine waters [8,9] and have also been found in wastewater [1,2]. Most TEP originates from polysaccharides released by phytoplankton and bacterioplankton, which had subsequently coagulate to form TEP [10,11]. However, they are also exuded or lysed out from macroalgae [12,13] and some higher marine organisms (e.g. oysters; [14]). The majority of TEP are formed abiotically from colloidal polysaccharides of about 1–3 nm in diameter by hundreds of nanometers long of which some are flexible enough to pass through 8 kDa pore size membranes [10]. Thus, these colloidal polysaccharides or as we called ''colloidal TEP'' are capable of passing through MF/UF pre-treatment and may potentially compromise the operation of the downstream RO system.

Berman and Holenberg [7] were the first to describe the potential link of TEP with RO fouling. They consider TEP as a ''major initiator'' in biofilm formation and its subsequent build-up in RO membrane systems [15]. TEP are very sticky substances, with stickiness of around 2–4 orders in magnitude higher than most particles [8]. They can easily accumulate on most surfaces, providing favourable conditions for bacterial colonization and initiating biofilm development in the process. Moreover, TEP may carry a significant bacterial population because of the biologically conducive micro-environment within its matrix [16]. Therefore, TEP may not only serve as an initiator but may also play a vital role in enhancing biological growth in RO systems. Currently, the most common anti-biofouling strategies are to limit the influx of nutrients to the RO system by pre-treatment and/or by applying a biocide in order to control formation of biofilm. Nonetheless, limiting biological activity may not be enough to prevent organic fouling, considering that TEP may still accumulate on RO membranes. Because of its glue-like characteristic, TEP can entrap or bind organic and inorganic colloids in the feed stream onto membrane surfaces. In this way, TEP is not only a potential risk to cause biological fouling but organic and particulate/colloidal fouling as well.

At present, low pressure membranes such as ultrafiltration (UF) and microfiltration (MF) are among the preferred choice for pre-treatment in RO systems, primarily due to their effectiveness in removing potential foulants from the RO feedwater [17–19]. However, these technologies have some limitations. In treating surface water, MF and UF are susceptible to fouling for which backwashing without chemicals are not always effective. This may result to an increase in chemical consumption for membrane cleaning as well as for in-line coagulation pre-treatment. Several studies reported that polysaccharides are the main cause of fouling in MF/UF membranes [20–22]. But so far, their origin and removal are still not well understood.

A recent study by Villacorte *et al.* [3,4] reported significant amounts of TEP in the raw water and after MF/UF pretreatment in a number of RO plants. It was also found that acidic polysaccharides smaller than 0.40 μm were up to 5 times more abundant than those larger than 0.40 μm. Although the operational definition of TEP suggests that they are mainly particulate (based on oceanographic and limnological literature), studying the presence of colloidal TEP is also important considering that MF/UF pre-treatment may not completely remove this fraction from the RO feed water.

The main objectives of this study were to monitor the fate of TEP including its colloidal and particulate fractions in a seawater UF-RO system and to evaluate their implications to the operational performance of the UF and RO systems.

1.1. Background

This study was conducted in a pilot desalination plant located in Zeeland Province, The Netherlands. The owner and operator of the plant is Evides, a drinking water utility as well as provider of industrial water

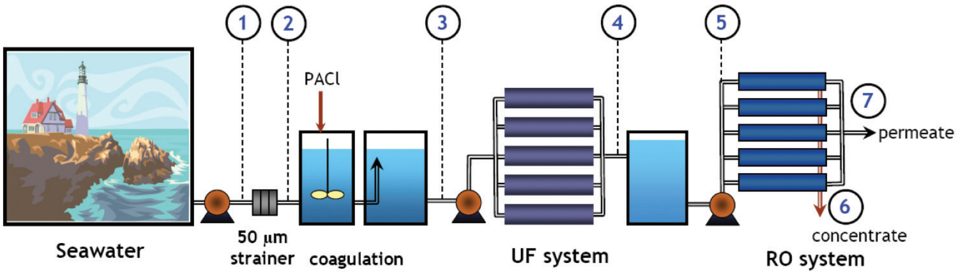

Fig. 1. Simplified treatment scheme of the UF-RO pilot plant and location of TEP monitoring points (with numbers).

and wastewater operations in southwestern part of the Netherlands. Recently, Evides completed the first seawater membrane desalination plant in the Netherlands for the purpose of optimising innovative UF-RO seawater treatment. The system has been put to operation in December 2008 with the following features:

- objectives are research and innovation in seawater desalination on a semi-real scale format;
- application of innovative pre-treatment i.e. UF rather than conventional coagulation, flocculation, sedimentation;
- in accordance to the Netherlands drinking water standards for product water quality; and
- operating under the environmental conditions of northwestern Europe (temperature, water composition, etc.).

The hardware setup comprises of:

- seawater submerged intake and micro-straining (50 µm Amiad strainer);
- addition of hydrochloric acid for pH and antiscaling conditioning;
- addition of coagulant (poly-aluminium chloride, PACl); optional according to UF fouling behaviour;
- UF pre-treatment (Norit Xiga Seaguard, 800 m^2, 50–60 $L/m^2/h$ flux);
- UF backwash water recovery and recycling (to coagulation tank);
- RO membrane desalination (Dow Filmtec, 13 $L/m^2/h$ permeate flux, 40% recovery);
- boron removal in the second pass RO (not covered in this study); and
- remineralisation by marble filtration (not covered in this study).

2. Materials and methods

2.1. Seawater UF-RO plant

All data presented in this study are based on the analyses results of water samples collected from the pilot plant as well as the operational data obtained from the UF and RO systems. Samples were collected at different stages of pre-treatment and in the RO system (Fig. 1).

2.2. Water samples, collection and storage

Water samples were collected from the pilot plant between January and April, 2009. Special samples for TEP measurements were collected in January 22, February 5 and 24, March 10 and 30, and April 7 and 21. Sample volumes of 1 L were collected in clean glass bottles. The samples were tested within 6 hours after sampling, otherwise kept in storage at a temperature of about 4 °C for less than a week.

2.3. Chlorophyll-a, total organic carbon (TOC) and turbidity

Raw water quality parameters such as TOC (ppm-C), turbidity (FTU), chlorophyll-a (µg/L) as well as water temperature were regularly monitored in the raw water and selected points in the plant. Turbidity and temperature were measured on site with standard portable instruments. TOC was measured using a Shimadzu TOC-V_{CPN} analyzer with combustion catalytic oxidation/NDIR method. Some of the samples were analysed by Aqualab B.V. (Netherlands) for chlorophyll-a using a spectrophotometric method based on the Dutch standard protocol [23].

2.4. TEP measurement and monitoring

The TEP method used was based on the spectrophotometric assay (TEP > 0.40 µm) developed by Passow and Alldredge [24]. The latest modifications of the method as proposed by Villacorte *et al.* [3] were adopted in this study to measure both particulate (>0.40 µm) and colloidal (0.05–0.40 µm) TEP. TEP were measured based on the amount of Alcian Blue which reacted with acidic polysaccharides on polycarbonate filters (0.4, 0.2, 0.1 and 0.05 µm) after vacuum filtration (0.1 bar) of water samples. In the absence of calibration, TEP concentrations were expressed in terms of absorbance per cm of eluted Alcian Blue in sulfuric acid per liter of filtered sample volume (abs/cm/L). To monitor possible variations of Alcian Blue solutions, stain concentrations were monitored for both prepared and pre-filtered staining solutions. Previous results [3] showed that variations of pre-filtered (0.05 μm) stain concentrations of different batches of stain did not significantly affect the staining capacity of acidic polysaccharides (e.g. Gum Xanthan) when concentrations were higher than 80 mg AB.L^{-1}. In this study, pre-filtered stain concentrations were all above this concentration. Therefore, the variations in staining capacity among different batches of stain were assumed to be minimal.

In the field of Oceanography and Limnology, TEP are operationally defined as particulate (>0.4 μm) based on the original method of measuring it (filtration through 0.4 μm pore size filters; [24]). Those not retained on 0.4 μm filters were considered TEP precursors (~0.001–0.4 μm) [10]. Most of the latter will aggregate at a certain point to reach particulate size and be considered as TEP. In this study, the modified/extended method [3] was applied to cover a significant portion of TEP precursors. Hence we defined particulate TEP or p-TEP as acidic polysaccharides retained on 0.4 μm polycarbonate filters while colloidal TEP or c-TEP are those that passed through 0.4 μm filters but retained on 0.05 μm filters. Colloidal TEP (0.05–0.4) represents a large fraction of the TEP precursors (~0.001–0.4 μm).

2.5. LC-OCD biopolymer analyses

Selected water samples were analysed in DOC-Labor (Karlsruhe, Germany) using liquid chromatography–organic carbon detection (LC-OCD). A number of membrane related studies had demonstrated the use of LC-OCD in characterising dissolved organic matter (DOM) in surface waters and identifying the constituents that caused organic fouling [22,25,26]. Each LC-OCD system has an online organic carbon detector (OCD) capable of measuring organic carbon down to a low ppb-range. It has also an online organic nitrogen detector to measure levels of organic nitrogen. The fractional organic carbon concentrations of biopolymers, humic substances, building blocks, low molecular weight (LMW) acids and neutrals (Table 1) were obtained by area integration, calibrated based on the ''Suwannee River'' Standard IHSS-FA and IHSS-HA in relation to the humic peak in the OCD chromatogram (DOC-Labor, Karlsruhe).

Since LC-OCD measures DOC for water samples that were pre-filtered through 0.45 μm filters, it was only with the c-TEP results (0.05–0.40 μm). However, comparison is relative since the latter is not expressed in mass concentration but rather in absorbance units per volume of filtered water samples.

2.6. TEP deposition analyses in RO system

Particle transport in cross-flow RO membranes involves three process streams: the feed, permeate and concentrate. Unlike dead-end filtration, cake formation is limited by back diffusion in cross-flow filtration, where most of the rejected particles remain in suspension towards the concentrate stream. A simple TEP balance can be formulated based on this principle in order to estimate the rate of TEP deposition on RO membranes [25,3].

$$Q_f = Q_c + Q_p$$

$$Q_f TEP_f = Q_c TEP_c + Q_p TEP_p + \left(\frac{dm}{dt}\right)_{membrane}$$

The TEP deposition factor (β) was calculated to represent a fraction of TEP from the recovered portion (RQ_f) of the RO feedwater which had accumulated in the RO system, assuming a 100% rejection of TEP. This assumption fits well in this case, since TEP could not be detected in the RO permeate and thus assumed to be totally rejected by RO. The deposition rate of TEP can be expressed as a function of β such as follows:

$$\frac{dm}{dt} = \beta R Q_f TEP_f$$

where R is the recovery of the RO system.

Considering that $TEP_p = 0.0$ abs.L^{-1}, the mass balance relationship is:

$$Q_f TEP_f = Q_c TEP_c + \beta R Q_f TEP_f,$$

The deposition factor β can now be derived as a function of RO recovery (R) and TEP concentrations [27].

$$\beta = \frac{1}{R} + \frac{TEP_c}{TEP_f}\left(1 - \frac{1}{R}\right)$$

if $\beta < 0$: TEP depletion/scouring from the membrane
if $\beta > 0$: TEP deposition on the membrane.

Fig. 2. Location of the UF-RO plant and its raw water intake (satellite image from Google Earth).

3. Results and discussion

3.1. *TEP and water quality variations in the raw water*

The raw water of the UF-RO plant was extracted through an submerged seawater intake, positioned at 200–300 m away from the coastline. The water in the intake area was influenced by two water bodies namely: the Oosterschelde estuary and the North Sea (Fig. 2). The intake point is on the Oosterschelde side of Oosterscheldekering, a sluice-gate-type storm surge barrier. The gates are normally open in which case seawater from the North Sea can go in and out of the estuary; but it can be closed under adverse weather conditions. The gates were open during the entire sampling period. The water in the area can be categorised as seawater with electrical conductivity values of 4,400–5,000 mS/m (seawater ~ 4,800 mS/m) and pH values of 7.5–8.5. Raw water quality conditions vary on different seasons (e.g. biological activity) but can also be influenced by tidal movements and storm events (e.g. turbidity).

The relative concentrations of TEP in the raw water of the UF-RO plant were monitored between January and April 2008. Water quality indicators such as turbidity, TOC, chlorophyll-a and water temperature were also measured to check for some consistencies with the TEP results. Total TEP were found below 20 abs/cm/L from January 22 to March 10. However, this level had increased by up to 8 times from March 30 to April 21. The increase coincided with a sharp increase in chlorophyll-a (Fig. 3), an indication of an algal bloom occurrence in the area. Water temperatures were gradually increasing towards the spring season (mid-March to mid-June), from 3 to 11 degree Celcius. Raw water turbidities were fluctuating below 10 FTU and was down to 2.8 FTU by the end of March. The TOC of raw water was also increasing between the range of 1.5 and 2.3 mg-C/L. The over-all increase of TEP during the spring season can be linked to an increase of biological activity in the seawater source as demonstrated by the increase of chlorophyll-a and TOC.

Using an optical microscope and sample slide staining with Alcian Blue, a considerable amount of phytoplankton and TEP were observed from samples collected in March and April (Fig. 4). This supports water quality indications of an algal bloom in the water source during this period. Most phytoplankton release a considerable amount of acidic polysaccharides, which later aggregates to form colloidal TEP and then particulate TEP [10,28]. Since algal bloom is a yearly occurrence in the Oosterschelde area, the rapid increase in chlorophyll-a and TEP is expected, especially during the spring season. Moreover, the increase in TOC is likely due to the dissolved organic carbon released by algal micro-organisms. In contrast, the gradual decrease in turbidity can be due to the sinking of suspended particles that had aggregated in the

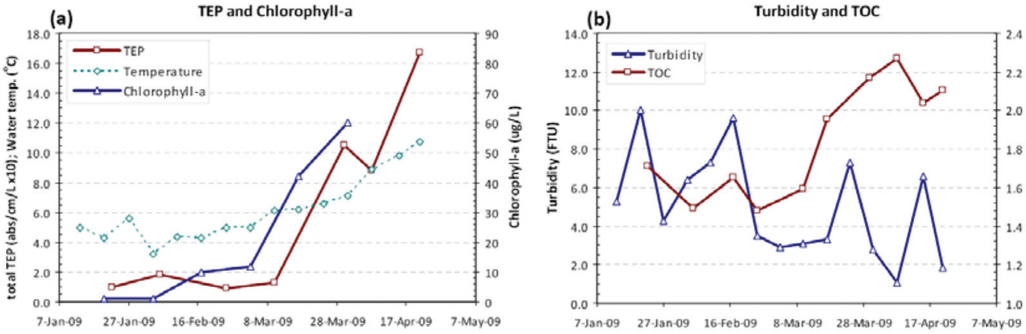

Fig. 3. Variations in total TEP, Chlorophyll-a, turbidity, TOC and water temperature during the sampling period (January–April, 2009).

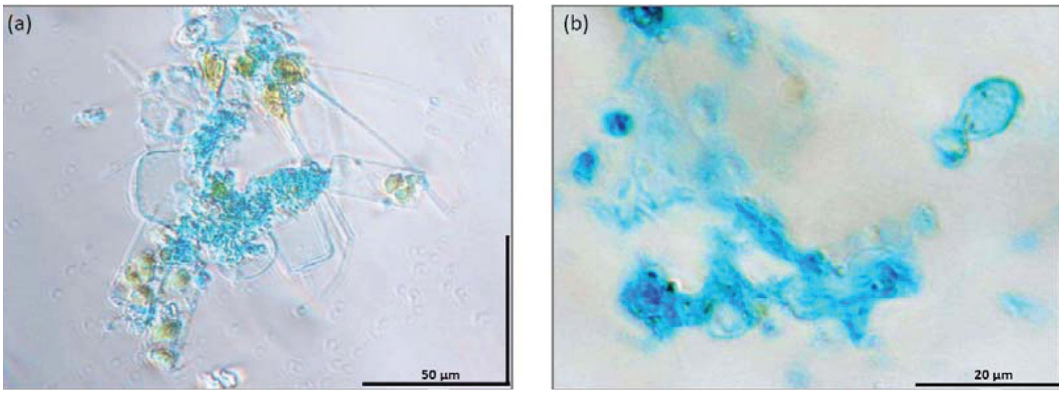

Fig. 4. Optical microscope photographs of Alcian Blue stained TEP in the raw water: (a) TEP aggregates (blue) around a group of phytoplankton (possibly diatoms); (b) a more detailed picture of TEP aggregates at a higher magnification.

presence of TEP [29]. However, the decrease could be mainly due to the changes in weather conditions and tidal movements in the North Sea.

The presence of the different size fractions of TEP in the raw water was assessed based on absorbance results. This was obtained after serial filtration of water samples using different pore size filters (0.4 > 0.2 > 0.1 > 0.05 µm) to isolate and measure the different TEP fractions. The level of different fractions of TEP varied considerably during 7 sampling events between January and April, 2009 (Fig. 5a). However, it was apparent that the significant increase in total TEP in March and April was mainly contributed by the increase of c-TEP (0.05–0.4 µm). Particulate TEP or p-TEP (>0.4 µm) ranged from 1.6 to 9.7 abs/cm/L while c-TEP ranged from 6.3 to 160 abs/cm/L. In terms of the specific fractions, results were significantly higher in the smaller size fractions than the larger size fraction. Colloidal TEP in the size range of 0.05–0.1 µm comprised around 45–65% of total TEP while p-TEP (>0.4 µm) contributed only about 7–18% of total TEP (Fig. 5b). The percentage difference between the two fractions tends to increase from winter to spring season. The increase was attributed to substantial production of colloidal TEP during an algal bloom event.

3.2. *The fate of TEP through the treatment process*

The TEP removals over the treatment processes were evaluated by collecting and analysing samples from selected points along the treatment line. Since TEP levels were varied through the sampling period, results were normalised based on the initial TEP level measured in the raw water (TEP = 1.0) of each sampling event (see Fig. 5a). The fate of TEP through the treatment processes of the pilot plant was notably different in late winter (January to March) compared to early spring (March to April). Total TEP removal by the 50 µm strainer was 21% in late winter and it decreased to 11.4% in early spring. On average, no significant

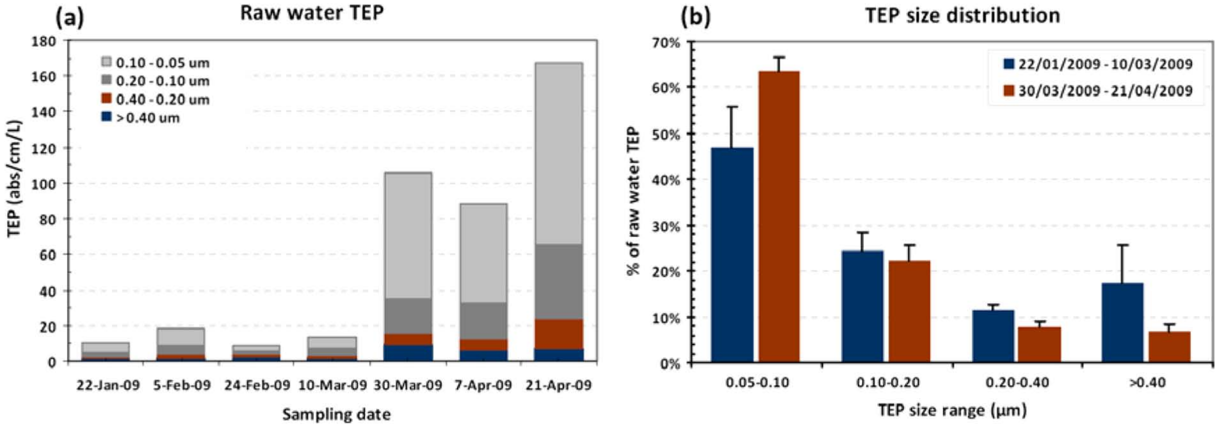

Fig. 5. TEP levels in the raw water: (a) variations within the sampling period; (b) average size distribution in late winter and early spring.

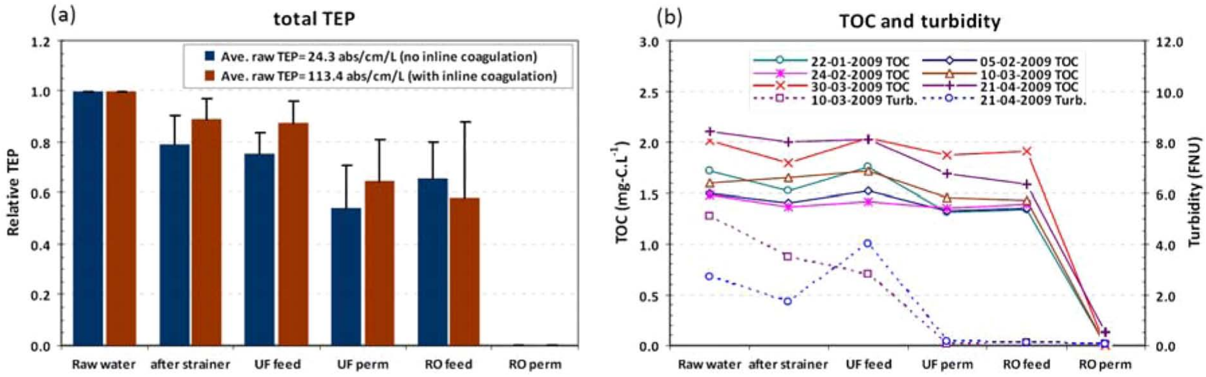

Fig. 6. Treatment performance of the UF-RO plant between January and April, 2009: (a) the fate of total TEP through the treatment process when operating with and without inline coagulation; (b) TOC and turbidity levels through the treatment process.

change of TEP was observed after the strained water pass through the buffer and coagulation tank. The retention time of water in the two tanks is around 15 mins. The coagulation system of the plant was not activated until March 30 due to low fouling rates in winter. This means that the coagulation tank only functioned as a secondary buffer tank in winter. Nevertheless, there was no apparent change in total TEP even after the addition of coagulant (PACl) in spring.

Special attention was focused on the removal efficiency of the UF system as it serves as the main pre-treatment of the RO system. The average total TEP removal by UF was 28.6% in late winter and was slightly lower at 26.4% in early spring. Due to the high fouling rate in the UF, inline coagulation was activated in early spring. Based on average results, TEP removal had decreased even with the presence of coagulant. However, total TEP in the UF feed were much higher in spring than in winter, due to high TEP in the raw water as well as the lower percentage removal by the micro-strainer. The high fouling rate was partially mitigated by the coagulant addition, reducing the permeability decline to a manageable level (see Section 3.4). Although coagulant addition apparently did not improve TEP removal by the UF, it was able to control fouling in the UF system. Nonetheless, total TEP removal in the UF was significantly lower compared to what was previously reported in fresh (river) water RO plant (ca. 70%; [4]). Both p-TEP and c-TEP were present in the UF permeate, which was not the case in the previous study where p-TEP were totally removed.

Other water quality parameters such as TOC and turbidity were also monitored through the treatment processes (Fig. 6b). As expected, TOC was just slightly removed by pre-treatment as majority of TOC in seawater are in the dissolved phase (>90%). The micro-strainer removed around 7% of raw water TOC while UF removed 14% of the strained water TOC. In terms of turbidity, the micro-strainer removed 31% of raw water turbidity while the UF system removed 98% of the remaining turbidity. A significant increase of turbidity was observed in the UF feed in April due to the addition of coagulant (Fig. 6b).

3.3. Biopolymer and TEP removal

LC-OCD was used to analyse the presence and removal of dissolved organic carbon (DOC), specifically biopolymers, in the UF-RO plant. Two raw water samples collected in winter (February 24) and spring (March 30) were analysed. DOC results were 1.6 mg-C/L in winter and 2.0 mg-C/L in spring. The DOC in the raw water consisted of 9–14% biopolymers, 28–35% humic substances, 16–17% building blocks, 34–36% LMW neutrals and 5–6% LMW organic acids. The biopolymer concentrations were 0.14 mg-C/L in winter and it doubled to 0.28 mg-C/L in spring (Fig. 7a). The organic nitrogen to organic carbon ratios in the raw water were relatively low from 0.05 to 0.09, an indication that the biopolymers were mainly consisted of polysaccharides. Only proteins and not polysaccharides like TEP are known to contain significant amount of organic nitrogen. Colloidal TEP results in spring were about 15 times higher than in winter.

In addition to the raw water, samples collected from the UF system were also analysed using LC-OCD. These include samples from the UF feed and permeate (with and without inline coagulation). DOC removal through the UF system was close to zero but removal improved to about 10% after in-line coagulation was activated. Most of the DOC fractions, including biopolymers, were partially removed. Biopolymer removals by UF were 34% and 13% with and without inline coagulation, respectively while c-TEP removals were 19% and 17%, respectively. In general, UF removals for both

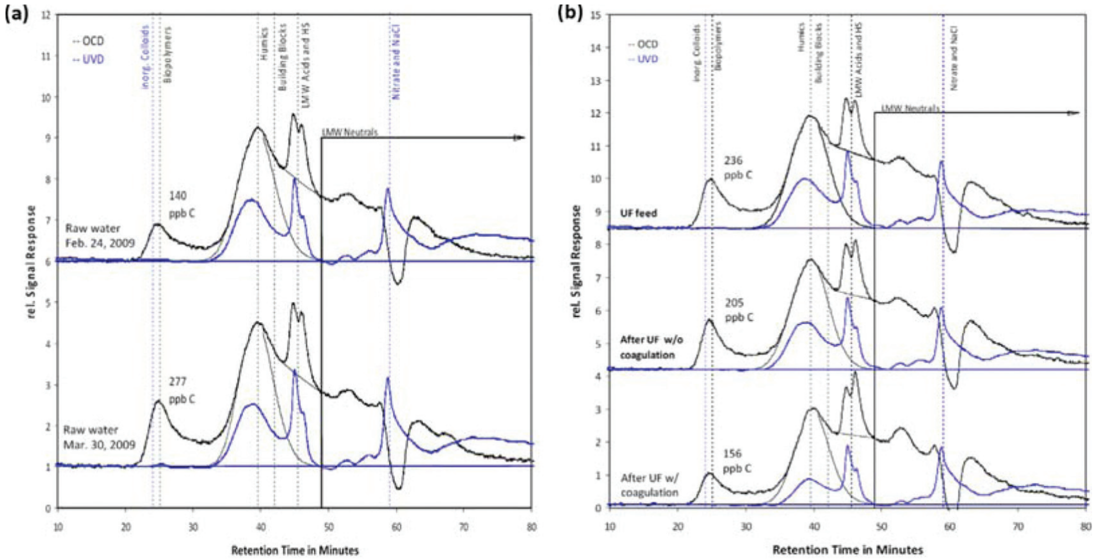

Fig. 7. LC-OCD chromatograms of water samples collected from the UF-RO plant. Each peak in the OCD chromatogram represents a specific fraction of DOC; the lower the retention time of the peak, the higher the molecular weight of the fraction. Biopolymers are the largest among DOC fractions (retention time between 20 and 50 mins) and colloidal TEP technically belong to this fraction.

biopolymers and c-TEP were less than what was reported in an earlier study of an IMS plant treating estuarine water (ca. 70% biopolymers, 69% c-TEP; [3]). The difference in pore size and porosity of UF membranes might be the main factor but a much higher level of colloidal TEP in the seawater source is a likely reason as well.

3.4. Operational performance of UF system at different levels of TEP

The normalised permeability of the UF membranes was monitored during the sampling period. Fouling in the UF system was measured in terms of backwashable (BW) and non-backwashable (nBW) fouling rates. The rate of BW fouling is computed based on the slope of the line connecting points (normalised permeability versus time graph) just before each backwashing event while the rate of nBW fouling is the slope of the line connecting points after each backwashing event. BW fouling rates were 2.40 L/m^2.h^2.bar in February and was 80.33 L/m^2.h^2.bar in late March (Fig. 8). The permeability started to improve when in-line coagulation was applied to the system in April. However, average BW fouling rate (11.58 L/m^2.h^2.bar) was still significant compared to the level of late winter season. Moreover, average UF fluxes were reduced from 59 L/m^2.h in February to 56 L/m^2.h in March and down to 51 L/m^2.h in April, to partially mitigate the increase in fouling rates. The high fouling rate in March and April coincided with the increase of TEP levels in the UF feed. The high TEP level can be a major factor in UF fouling but other factors such as suspended particles and some aquatic microorganisms that could have pass through the strainer may have contributed as well.

In terms of nBW fouling in the UF system, the average rate was relatively low in February (2.29 L/m^2.h^2.bar) and very high in late March (61.75 L/m^2.h^2.bar). When inline coagulation was activated, nBW fouling significantly reduced to 2.67 L/m^2.h^2.bar, which was almost at the same level in February. Apparently, inline coagulation enhanced the reversibility of fouling in the UF by physical cleaning (backwashing) even with a much higher level of TEP from the feed water. This finding was in agreement with a previous study by Kennedy *et al*. [1].

3.5. TEP deposition in the RO system

The TEP deposition factor (β) was computed to provide insight into the degree of TEP deposition in the RO system. Fig. 9 shows the theoretical TEP concentration in the RO concentrate at different recoveries when $\beta = 0$ (no deposition) and $\beta = 1$ (100% deposition). Also shown are the measured p-TEP and c-TEP in the RO concentrate of the plant, normalised to the TEP level in the RO feed ($TEP_f = 1.0$).

The β of actual samples were calculated based on p-TEP and c-TEP results for 4 set of samples collected

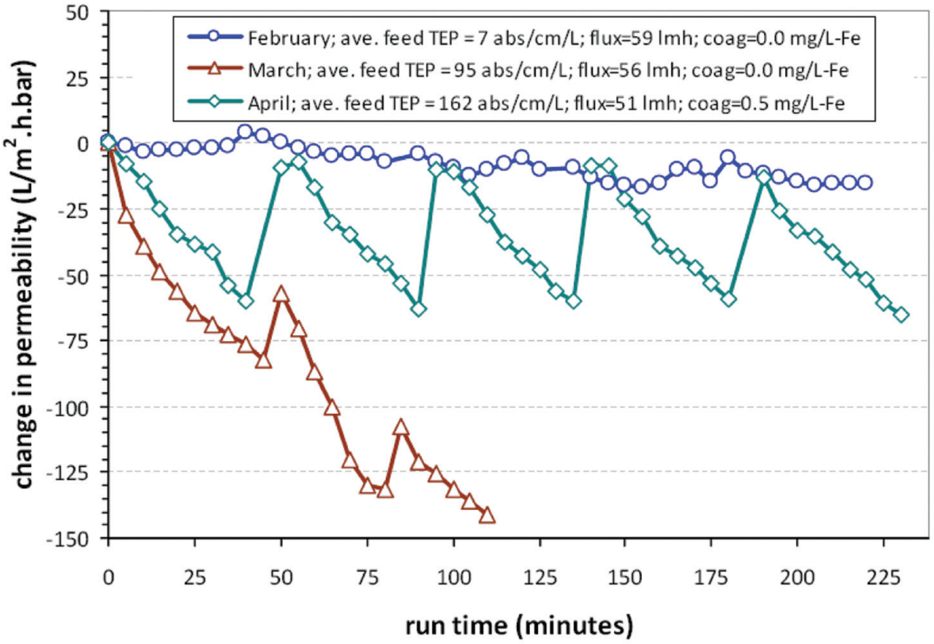

Fig. 8. Permeability drop in the UF system at different levels of TEP and at different UF operational conditions (flux and coagulant). Flux = L/m^2.h.

at different dates. The calculated deposition factors were between 0.25 and 1.15 (Table 2). In general, β results indicate accumulation/deposition ($\beta > 0$) of TEP in the RO system. In terms of p-TEP, deposition factors were significantly varied, from a 100% deposition ($\beta = 1$) in one sampling to 25% deposition ($\beta = 0.5$) in another. However in one sampling, a β of more than 1 was recorded as a result of having less p-TEP in the concentrate than in the feed. Theoretically, this is not possible since there is no more than 100% removal. However, there is a possibility that some of the TEP in the concentrate stream were lost in the piping outside the membrane modules or some of the p-TEPs were sheared off in the system and turned into c-TEP. Otherwise, sampling and measurement errors were also possible. Meanwhile, the deposition factors in terms of c-TEP were in a narrower range of 0.61–0.92. Deposition of c-TEP was more than 80% in 3 out of 4 samplings. Overall, deposition factors showed both p-TEP and c-TEP were largely deposited on RO membranes. However, inconsistencies in the p-TEP results indicate that β should be considered only as a rough indicator of how well TEP are deposited in the RO system.

As shown in the deposition analysis, considerable amounts of TEP may have deposited in the RO system. Surprisingly, there was no significant decrease of RO normalized flux in the 4 months of operation in the pilot plant. There are two possible reasons why there were no significant fouling problems in the RO system in spite of the accumulation of TEP: (1) biological growth and colonisation of accumulated TEP may have been limited due to low dissolved nutrient concentrations (C, P) in the RO feedwater and (2) due to limited presence of other particles/colloids in the RO feedwater after UF pre-treatment. Total organic carbon concentrations were below 2 mg-C/L at the RO feedwater while ortho-phosphate concentrations of untreated raw water were below 0.01 mg-P/L in April and May during which significant TEP accumulation had occurred. In theory, a synergistic interaction between TEP and other foulants (e.g. bacterial cells, colloidal materials) is necessary to cause significant fouling in

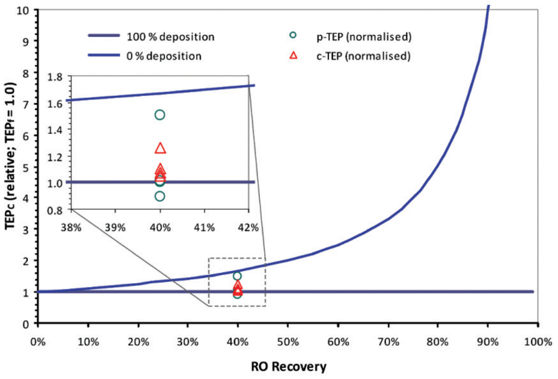

Fig. 9. The theoretical TEP concentration of RO concentrates if $\beta = 0$ (no deposition) and $\beta = 1$ (100% deposition), and the measured p-TEP and c-TEP levels in the RO concentrate, normalised relative to TEP levels in the RO feed water.

Table 2
The computed TEP deposition factor (β) in the RO system in terms of p-TEP and c-TEP

Date of sampling	RO recovery	Meas. TEP (abs/cm/L)		Norm. to $TEP_f = 1.0$		Deposition factor (β)	Remarks
		TEP_f	TEP_c	$TEP_{f,n}$	$TEP_{c,n}$		
p-TEP							
22-Jan-09	40%	2.0	3.0	1.00	1.50	0.25	deposition
5-Feb-09	40%	1.3	1.3	1.00	1.00	1.00	100% deposition
30-Mar-09	40%	3.9	3.5	1.00	0.90	1.15	$TEP_c < TEP_f$
21-Apr-09	40%	7.7	7.8	1.00	1.01	0.98	deposition
c-TEP							
22-Jan-09	40%	5.9	6.2	1.00	1.05	0.92	deposition
5-Feb-09	40%	8.5	9.1	1.00	1.07	0.89	deposition
30-Mar-09	40%	87.3	110.1	1.00	1.26	0.61	deposition
21-Apr-09	40%	124.3	137.1	1.00	1.10	0.85	deposition

TEP_f = feed TEP.
TEP_c = concentrate TEP.
$TEP_{f,n}$ = feed TEP (normalised).
$TEP_{c,n}$ = concentrate TEP (normalised).

the RO [30,31]. Thus, further studies are necessary to clearly explain the role of TEP in the fouling of RO systems.

4. Conclusions

The fate of TEP in a seawater UF-RO plant and its possible implications to the operation of UF and RO systems were evaluated, leading to the following conclusions:

(1) Colloidal TEP (82–93%) was more abundant than particulate TEP (7–18%) in the seawater source.
(2) An observed increase of total TEP in the raw water coincided with an increase in chlorophyll-a and TOC in spring. A substantial increase in TEP (p-TEP and c-TEP) starting in late March was attributed to an algal bloom event in the water source and was supported by microscopic observation.
(3) The average total TEP removal by UF pretreatment (January–April 2008) was 26% and 29% with and without inline coagulation, respectively. UF also removed 98% of turbidity and 14% of TOC.
(4) LC-OCD results showed that biopolymer concentration in the raw water doubled between February and late March. Around 13% of biopolymers were removed by UF alone while up to 34% were removed by UF with in-line coagulation.
(5) The occurrence of physically irreversible (nBW) fouling in the UF was low from January until mid-March but was remarkably high in late March to April. High fouling rates coincided with high TEP concentrations in the UF feed. The fouling problem was mitigated by applying in-line coagulation which adequately improved backwashing efficiency and significantly reduced irreversible fouling in the UF.
(6) Deposition analysis in the RO system revealed that significant amounts of p-TEP and c-TEP were deposited in the RO system. However so far, no significant decrease in RO normalized flux was observed in the last 4 months of operation. Further studies are necessary to understand the effects of TEP accumulation in RO systems.

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