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Three years operational experience with ultrafiltration as SWRO pre-treatment during algal bloom

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ABSTRACT

In the period 2009–2012 Evides conducted extensive research with an open intake UF-SWRO desalination demonstration plant in the Oosterschelde area, Netherlands. Major attention was devoted to the performance of ultrafiltration (UF) as pre-treatment. It was established that in the period from July to March, i.e. outside Spring, limited UF fouling occurred and the UF could be operated continuously without coagulation and at limited chemical consumption. However, during the period April–June, UF fouling rate (i.e. permeability decline) increased severely. This coincided with the occurrence of algal bloom, as manifested by peak levels of algal count, chlorophyll and transparent exopolymer particles (TEP, as measured by Unesco-IHE). During the algal bloom, implementation of inline coagulation by ferric chloride was required. In 2010, coagulation was conducted by dosing in the UF buffer tank. However, UF operation appeared unstable, requiring increased coagulant doses (1–4 mg Fe/L). In Spring 2011, the dosing point was relocated to the UF feed pump suction side i.e closer to the UF skid. Now, a stable UF operation was accomplished for several weeks continuously at low doses (~0.5 mg Fe/L). Therefore, the latter setup appeared promising for restoring a stable UF operation during algal bloom. The exact impact of the various regimes of mixing, floc formation and waste water recirculation on the interaction with (algal) foulants and UF membrane capillaries and the resultant operational stability of UF performance during algal bloom warrant further research efforts.

Keywords: Seawater desalination; Ultrafiltration pre-treatment; Algal bloom; Coagulation

1. Introduction

Evides is the leading utility in South-Western Netherlands in drinking water supply and industrial water operations. In 2009, Evides has established a demonstration-scale ultrafiltration-reverse osmosis (UF-SWRO) seawater desalination plant in the province of Zeeland, the Netherlands. Aim of the research is to gain experience in sea water desalination with UF pretreatment under North-Western European conditions of raw water composition. Hereto, an extensive research programme is being conducted from 2008 to 2012, covering operational and scientific aspects.

A major topic of research has been the behaviour of the UF pre-treatment in relation to raw water characteristics and operational settings, especially in relation to algal blooms which are known to be critical in upsetting

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open intake—UF pre-treatment [1,2]. Specific attention was dedicated to UF-feed coagulation as remediative measure, since this implies significant operational, environmental and investment effort and cost. Ideally, UF operation would be conducted without coagulation and/or significant use of (oxidizing) chemicals. If coagulation cannot be avoided, a straightforward way i.e. inline rather than intermediate flocculation and sedimentation stages are preferred [3–5].

Open intake abstraction followed by UF pre-treatment, both with and without coagulant application, is performed in several cases in pilot and full-scale plants, especially in recent years. These sites are mainly located in the Gulf region, China, Caribbean and Mediterranean, where generally lower turbidity and higher temperatures occur than the Evides demonstration pilot. Furthermore, reported cases are not always explicit in results during algal bloom.

This paper presents the operational results as obtained in the demonstration plant during the period December 2008–April 2012, in terms of:

- raw water quality;
- relation between UF fouling rate and occurrence of algal bloom, notably transparent exopolymer particles (TEP);
- efficacy of UF permeability maintenance by application of in-line coagulation during algal bloom. Variables included dosing and mixing regime in order to minimize coagulant dose requirements and optimize UF stability;
- impact of coagulation on UF permeate quality and downstream processes, notably SWRO membrane fouling.

2. Materials and methods

2.1. Location and raw water source

The demonstration plant was located at the Oosterschelde bay in the South-Western Netherlands, which is at the North Sea seaboard. The locality was subjected to severe tidal currents, and the water at the intake site could be considered as fully mixed (non-stratified) sea water.

2.2. Treatment equipment

The demonstration plant comprised a submerged open sea water intake, microstraining, UF, 2-stage RO and remineralization (Fig. 1). Net water production capacity amounted to $14\,m^3/h$, whereas in the raw water intake rated at $45–55\,m^3/h$.

The treatment equipment line-up and design considerations are as follows:

1. *Open intake*: submerged set of pipes at 4 m below sea level, coarse screening and intake pump. No chlorine dosing is conducted in order to prevent byproduct formation and risk of SWRO-membrane damage [3].
2. *Microstraining*: 50 μm mesh filter cage in order to retain mussel seed.
3. *Buffering, chemical dosing*: two tanks in series for the purposes of flow buffering and optional pH conditioning and coagulation. Refer to Section 2.3 for more details.
4. *pH correction*: pH is optionally lowered by HCl dosing to establish optimum pH for coagulation and/or filtration.
5. *Inline coagulation*: according to the general research objective of establishing UF performance without applying a separate intermediate floc separation stage, inline coagulation has been adopted. For further elaboration is referred to Section 2.3. Ferric chloride was used as coagulant species in 2011 and 2010.
6. *UF*: hollow-fibre, dead-end filtration with Pentair Xiga Seaguard UF membranes. In order to minimize the need for coagulation, standard settings were moderately conservative: filtration flux 55 L/m^2h for 30–45 min and hydraulic backwash at 250 L/m^2h for 1:00 min with UF permeate. Chemically Enhanced Backwash (CEB) was performed if permeability became less than 200 $L/m^2h\,bar$. CEB chemicals employed comprised NaClO, NaOH and HCl.
7. *UF backwash waste water handling*: if UF coagulation was applied, UF waste water was treated by secondary coagulation, lamella separation and optionally either recirculated to the mixing tank or discharged directly.
8. *Sea water RO*: by Dow Filmtec SW30XHR400i elements, operated on a fixed permeate production rate of 15 m^3/h at 40% recovery and a flux of 13 L/m^2h.
9. *Brackish water RO*: by Dow Filmtec BW30LE400 brackish water membranes for boron removal.
10. *Remineralization*: by CO_2-dosing and marble filtration.

2.3. UF-coagulation regimes

In order to optimize UF performance, several coagulation regimes were applied with characteristics

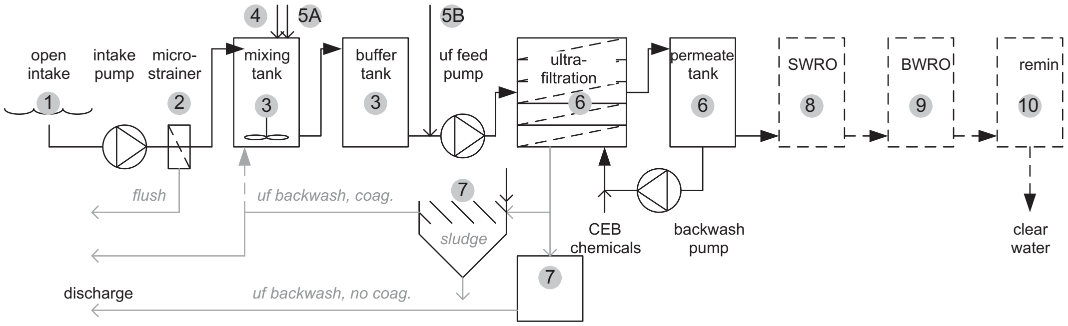

Fig. 1. Diagram Evides UF-SWRO demonstration plant.

as presented by Table 1 and denoted by “A” and “B” in Fig. 1.

The coagulation setup “A” originated from the initial system design, and was deliberately modified in 2011 to setup “B” in an attempt to improve UF performance during coagulation. The applicable velocity gradients and residence times were as resultant from the existing equipment. pH was adjusted to resemble the lowest coagulant solubility [6].

2.4. UF performance assessment

The performance of the UF under various conditions e.g. (seasonal) fluctuations in raw water quality and operational regimes (e.g. coagulation) has been assessed by the following indicators:

(a) *Temperature-corrected permeability*: the quotient of actual flux and transmembrane pressure differential (TMP), with inclusion of a temperature correction factor. 200 $L/m^2\,h\,bar$ was adopted as the lowest threshold of acceptability in order to prevent irreversible fouling or physical damage by excessive TMP.

(b) *Permeability decline rate*: the permeability differential over elapsed time. 15–20 $L/m^2\,h^2\,bar$ was set as upper limit of acceptance, since otherwise untenably short CEB intervals (<6 h) would result, being unfavourable in terms of downtime, chemical consumption and UF chlorine exposure.

3. Results

3.1. Raw water quality

The abstracted water originated from the Oosterschelde water body, and could be considered to be nearly undiluted North Sea water as manifested by its salinity (30–33 g/L) and temperature (winter: 3℃, spring: 10–15℃, summer: 18℃). Due to severe tidal

Table 1
Experimental regimes (all at 45 m^3/u UF feed rate)

Experimental regime of UF-coagulation	A: in-line, tank	B: in-line, flash	No coagulation
Period, algal bloom conditions	Algal bloom period April–June 2010	Algal bloom period April–June 2011	No bloom, outside April–June 2009, 2010, 2011
UF coagulant dosing point	In mixing/buffer tank	In suction of UF feed pump	No UF coagulation applied
Coagulant dose	1–5 mg/L Fe, continuously dosed	0.4–0.6 mg/L Fe, continuously dosed	(n.a.)
Initial rapid mixing conditions	$\sim$300 s^{-1} (0.4 kW mixer in 2.3 m^3 for 3 min)	$\sim$3.10^4 s^{-1}, <1 s	(n.a.)
Slow mixing conditions	$\sim$3.10^4 s^{-1}, <1 s in UF feed pump, +1 × 10^3 s^{-1} for 2 min in piping to UF	1 × 10^3 s^{-1} for 2 min in piping to UF	(n.a.)
pH during coagulation	$\sim$7.7 average (6.6–8.3)	$\sim$7.6	6.6–8.4
UF waste water handling	Treatment and recirculation to UF mixing tank	Treatment, but generally discharge i.e. no recirculation	Direct discharge i.e. no recirculation
Backwash interval	45 min	30 min	30–120 min

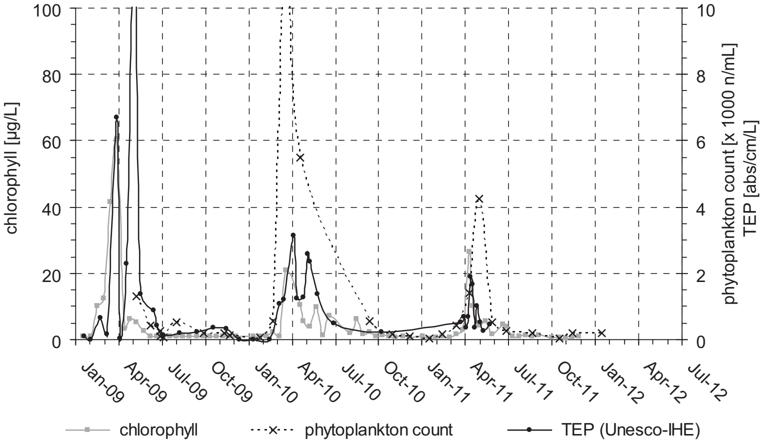

Fig. 2. Algal parameters in Oosterschelde raw water.

currents at the intake location raw water turbidity oscillated between 5 and 15 FTU. During storms, turbidity reached up to 50–100 FTU, lasting from several hours to multiple days.

Fig. 2 presents raw water chlorophyll content, algal density and Transparent Exopolymer Particles (TEP) levels. The latter was analysed at the Unesco-IHE laboratory using a spectrophotometric method modified from Passow and Alldredge [7].

The highest values of these parameters were repeatedly concentrated in the period February till June, indicating the occurrence of algal bloom during this period. Identification yielded that the (non-diatomean) species *Phaeocystis* [8], *Chrysochromulina*, *Rhodomonas/Plagioselmis* dominated in the Springs of 2010 and 2011, next to increased levels of diatoms (e.g. *Thalassiosira* [9], *Chaetoceros* and the more general class of *Centrales* in all years). Several of these (e.g. *Phaeocystis* and diatoms) are known to produce significant amounts of TEP [10,11].

The presence of TEP in the raw water of the plant has been studied extensively [12–14]. Preliminary TEP monitoring data for 2009 algal were reported in these studies. In 2010, the TEP analysis protocol has been further modified to incorporate the interference of high salinity in seawater. The interference was corrected by deducting the filter blank values for TEP-free seawater instead of ultra-pure water. Consequently, the 2009 data for TEP > 0.4um were theoretically corrected based on this technique. Hence, TEP data presented in this paper covers TEP > 0.4 µm for 2009 and TEP > 0.1 µm for 2010 and 2011. TEP or acidic polysaccharides smaller than 0.1 µm were not measured in this study.

3.2. UF performance

3.2.1. UF permeability

During the experiments UF permeability ranged from 200 (pre-CEB) to 300–400 L/m^2 h bar (post-CEB).

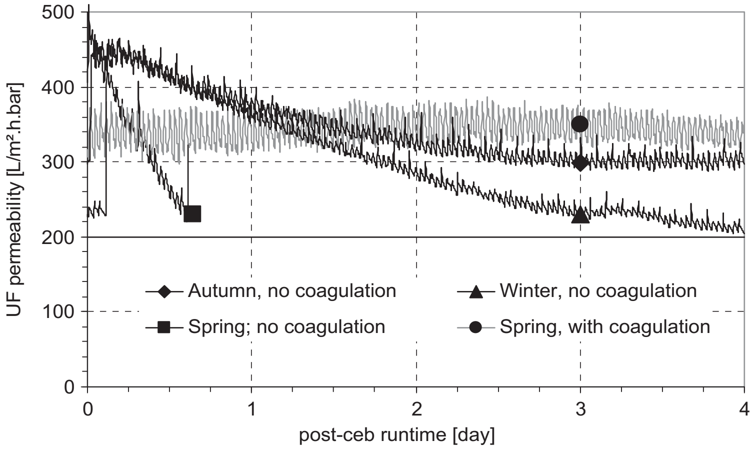

Fig. 3. Distinct UF permeability patterns after CEB (CEB at $t = 0$).

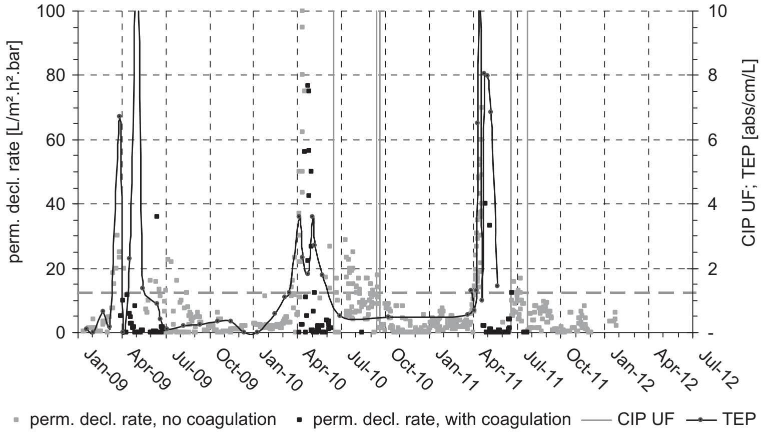

Fig. 4. UF permeability decline rate over the period 2009–2012.
Note: no distinction between filtration conditions except coagulation is made in this graph.

Several distinct patterns of UF permeability were typically encountered during the seasons [14], as depicted by Fig. 3.

For each day the actual slope of the permeability i.e. the permeability decline rate was determined as explained by Section 2.4, the results being depicted by Fig. 4.

From both Figs. 3 and 4 several seasonally-bound fouling regimes were clearly observable:

- low UF-fouling rate in the period June–March, enabling equivalent CEB-intervals of 2 to >7 days;
- a rapid acceleration in fouling rate in April with absence of UF coagulation. Eventually, CEB-intervals of only 4 to <12 h would result. For reference, the associated maximum allowable permeability decline rate has been indicated in Fig. 4;
- implementation of UF coagulation in the period April–June. Coagulation was performed in several configurations as described in Section 2.3.

A comparison between Fig. 2 with Fig. 4 learns that the occurrence of high UF fouling rates coincides with the occurrence of increased levels of algal-bloom indicators in Spring, e.g. TEP which has been included in Fig. 4 for reference.

With regard to other raw water quality parameters, it was observed that the UF performance generally improved at conditions of increased turbidity. This was more prominent for the regime without coagulation.

3.2.2. *UF operation without coagulation*

UF filtration pH, flux and backwash interval were varied in an attempt to retain a workable UF operation while postponing (ideally: eliminating) the need for coagulation. Outside Spring and Summer, some further improvement of UF performance was achieved by these measures. However, since the UF fouling rate was already low during this period, the absolute gain was relatively insignificant.

No mitigation of the high fouling rates at the onset and during Spring was obtained by either filtration pH or backwash adjustment. Only a significant reduction (>50%) in flux was able to suppress UF fouling to some extent. However, even under these conditions sufficiently long CEB-intervals could still not be re-established, whereas a flux reduction would also imply a shortfall in UF production capacity.

Therefore, during Spring reverted implementation of UF coagulation was required to restore UF performance, of which the results are described in the next paragraphs.

3.2.3. *UF operation with coagulation in Spring, 2009*

In Spring 2009 UF coagulation was performed by poly-aluminium chloride, dosed in the setup as denoted in Section 2.3 by "A". Although a stable UF operation was achieved, residual coagulant caused severe fouling (MTC decline) in the downstream SWRO, and therefore this coagulant species had to be abandoned. Further details are given by [14].

3.2.4. *UF operation with coagulation in Spring, 2010*

Fig. 5 displays the UF performance as obtained by coagulant dosing in the mixing/buffer tank (setup "A") during Spring.

From Fig. 5 it is observed that the average permeability declined towards the lowest acceptance threshold of 200 L/h m^2 bar in approximately 2 weeks of continuous coagulation from May 10 onwards.

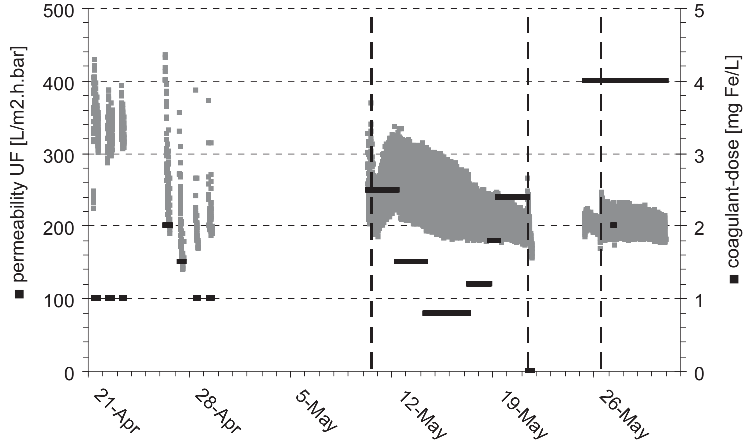

Fig. 5. UF permeability during coagulation Spring 2010: dosing in-line, in mixing/buffer tank (setup "A").

Furthermore, the permeability recovery by backwash (i.e. the differential between the upper and lower boundary of the shaded area in Fig. 5) decreased continuously, suggesting ever lower backwash efficacy. Neither lowering nor increasing coagulant dose, nor CEB was effective in restoring a high permeability, and therefore this regime was considered to be unsustainable.

Visual inspection of extracted UF elements revealed that significant amounts of coagulated material had accumulated in the capillaries [15].

3.2.5. *UF operation with flash-mixing coagulation in Spring, 2011*

During Spring 2011 UF coagulation was performed by the relocated dosing point as described by setup "B" in Section 2.3, with results as shown in Fig. 6.

As shown in Fig. 6, permeability remained between 200 and 400 L/h m^2 bar, and UF operation was generally stable for nearly 2 months, especially from May 10 onwards, at consistently low coagulant doses between 0.4 and 0.8 g/L.

It is remarked that in 2011 generally no recirculation of treated UF waste water was conducted, in contrast to the situation in 2010. Refer to Section 4.3 for further elaboration.

3.2.6. *UF operation after coagulation, CIP*

In Fig. 4, the UF permeability decline rate remained relatively high upon suspension of Fe-coagulation at the end of each Spring season (e.g. June 2010 and July 2011). Therefore, several UF CIPs (Cleaning-In-Place) were conducted to verify the cause of this phenomenon i.e. foulants emanating from the raw water or applied coagulant. A combination of

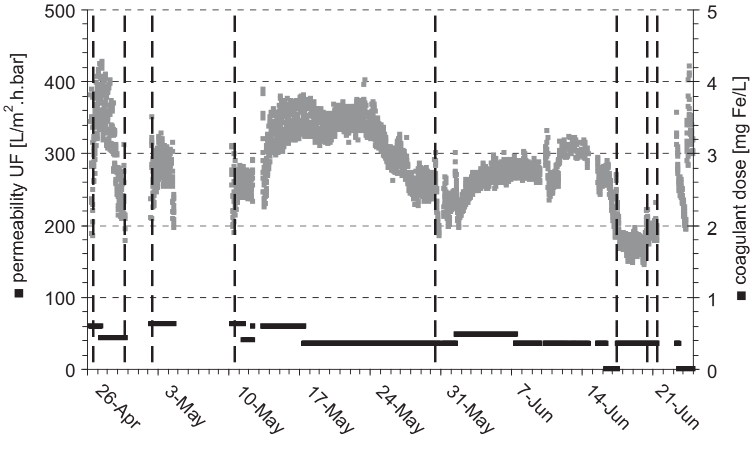

Fig. 6. UF permeability during coagulation Spring 2011: dosing in-line, flash-mixing by UF feed pump (setup "B").

Table 2
UF permeate quality

Parameter	Unit	Without UF coagulation	With UF coagulation
Turbidity	FTU	0.05 (>99 %)	0.05 (>99%)
Particle count ($\geq$0.5 μm)	n/ml	2–10 ($\geq$3.6 log)	2–10 ($\geq$3.6 log)
$\mathrm{SDI}_{15\text{–}500}$ (0.45 μm)[a]	%/min	1 to <2	1 to <2
$\mathrm{MFI}_{0.45}$ (0.45 μm)[a]	%/min	1 to <2	1 to <2
Iron (Fe)	μg Fe/L	<30 (dl); >100	Average 70 (2010); <30 (2011)
TEP > 0.1 μm[b]	abs/cm L	$\ll$1 (dl) to 1.23	$\ll$1 (dl) to 1.25
DOC[c]	mgC/L	2.0 mg C/L	1.8 mg C/L
Biopolymers[c]	mgC/L	0.2 mgC/L	0.15 mgC/L

…–…: range; (…%): reduction over UF; dl: detection limit.

[a] Alhadidi et al. [16]; data for 2010 at pH 6.6 and pH 8.1, coagulation 1 mg/L Fe.

[b] Villacorte et al. (unpublished).

[c] Villacorte et al. [13], data for 30 March 2009, coagulant dose = 0.5 mg Al^{3+}/L.

ascorbic acid and oxalic acid proved successful in establishing and subsequently maintaining permeability i.e. restoring profiles similar to those of Autumn/Winter in Fig. 3. Other CIP-compositions were less or not effective.

3.2.7. UF permeate quality

Relevant UF permeate quality data are presented by Table 2.

Under all circumstances the UF permeate met applicable quality indices such as turbidity, MFI, SDI, particle count.

Outside the algal bloom seasons, TEP levels in the UF permeate were all below the detection limit (~1 abs/cm L). During algal blooms, TEP levels increased up to 1.25 abs/cm L but 95% of the samples were still below the detection limit. Only limited data for TEP after UF treatment with in-line coagulation were available, however, they were not significantly different from the values obtained without coagulation. The presence or absence of the TEP fraction <0.1 μm in the UF permeate could not be assessed by the current analysis protocol.

With respect to residual iron, the applied analytical method had a relatively high detection limit. Furthermore, at several instances (in 10% of the total number of samples) increased levels of iron in the UF permeate were reported in the periods *without* coagulation, which is contrary to expectation and cannot yet be explained (system operation was stable when the deviating samples were collected, which suggests either an analys is artefact or unknown event). At specific trials later in 2011 with 0.5 mg/L Fe coagulation residual iron remained below 10 μg/L.

4. Evaluation

4.1. UF operation outside Spring

Outside the Spring bloom period, UF operation was consistently characterized by a low fouling rate and hence limited CEB requirements, without any need for UF coagulation. CEB intervals of average 2 to >7 days were obtained, equivalent to $\leq$0.7 mg/L of total associated chemical consumption including neutralization. Hydraulic backwash water losses amounted to 5–10%. These performance data are in line or better with figures for similar cases [2–4,17–21].

4.2. Impact of raw water quality and algal bloom

In the period March–June algal count, chlorophyll and TEP levels indicate algal bloom. This coincides well with the observed periods of accelerated UF fouling (without coagulation). The observed algal species are known to produce large quantities of extracellular polymeric substances. Therefore, such algal organic matter is likely to be the major factor in UF fouling, since they occur simultaneously whereas any other obvious foulant is lacking [1,22,23].

During such algal blooms, the UF fouling rate became temporarily so severe that operation without coagulation was rendered impossible. Other operational settings had either limited (flux) or no effect at all (pH, backwash) in mitigation of the fouling rate. This suggests that the foulant attached to the UF membrane and was not dislodged (sufficiently) by hydraulic backwash. Nevertheless, efficacy of CEB (NaOH, NaClO and HCl) remained reasonably in Spring, suggesting that the algal foulants are susceptible to degradation by these chemical species.

Turbidity was found to have no detrimental influence on UF performance, even at the highest observed peaks during storm. In fact, high turbidity tended to improve UF permeability.

4.3. Efficacy of UF coagulation during algal bloom

In-line UF coagulation by a flash mixing configuration (as in the setup of 2011 i.e. in the suction of the UF feed pump) yielded a sustainable UF performance at low coagulant doses (0.4–0.8 mg Fe/L) and limited overall chemical consumption during algal bloom. This compares favourably with the chemical doses applied in conventional intermediate SWRO pre-treatments (e.g. dual media filtration, flotation) [1,22,24].

In contrast, a coagulant dosing in the preceding mixing/buffer tank as in 2010 was unable to establish stable UF performance, as ever higher coagulant doses were required whereas permeability decline occurred. The background mechanism of the various applied coagulation setups in terms of floc formation regime (velocity gradient, residence time, waste water recirculation), interaction with waterborne foulants, UF membrane surface and capillaries, residual performance decline (i.e. as to be restored by CIP's) and their ultimate effect on operational performance of the UF require further research effort.

Furthermore, it appears that both in 2010 and 2011 coagulation was implemented in the latter half of the algal bloom period and the subsequent post-bloom period, rather than covering the complete peak of algal bloom from its onset onwards. Therefore, in the future the actual moments of starting as well as terminating the UF-coagulation are to be based on respectively presence and absence of algal matter in the raw water.

4.4. UF permeate quality

The UF permeate quality was in line with other cases and met appropriate standards for RO applications. However, the potential passage of residual coagulant and TEPs (<0.1 μm fraction) and other biopolymers in the UF permeate, and especially their effect on downstream RO membranes, require further attention.

5. Conclusion

The results as presented in this paper support the following conclusions for UF-SWRO pre-treatment at the Oosterschelde site:

- UF fouling was limited except during Spring at the occurrence of algal bloom, and the UF could be operated well without the need for coagulation.
- Acceleration of the UF fouling rate coincided with increased levels of algae and associated TEPs during algal bloom. Therefore TEP was likely the major UF foulant, since no other foulant was apparent [25].
- During such algal blooms, the UF fouling could be successfully countered by temporary implementation of UF coagulation. Low doses of ferric (∼0.5 mg Fe/L) appeared sufficient, whereas an inline configuration (flash-mixing coagulation) appeared favourable.
- Since the need for UF coagulation is related to algal/TEP presence, monitoring of these parameters should serve as indicator for inception and eventual termination of coagulation. This may result in a shorter period of coagulation than was performed until now.
- If coagulation indeed is only required for a short period of time and at only low coagulant doses, necessity for UF waste water treatment and discharge may be re-evaluated.
- Therefore, intimate knowledge, understanding and optimization of UF and coagulation are essential for a proper system performance and lay-out.

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