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# Performance of ultrafiltration and coagulation in an UF-RO seawater desalination demonstration plant

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ABSTRACT

Evides Water Company is conducting extensive test work in an open intake ultrafiltration reverse osmosis (UF-RO) sea water desalination demonstration plant in the Oosterschelde area, South-Western Netherlands. Efficacy of chemically enhanced backwash (CEB) and coagulant in maintaining UF permeability were studied. It appeared that long CEB intervals (>3 – >7 d) and hence low chemical consumptions were attained for the period July–February without coagulant and at moderate flux (55 l $m^{-2}h^{-1}$). For the period March–June, UF fouling accelerated, shortening CEB interval to 0.5 d. For 4 weeks in April–May severe UF fouling rendered operation without coagulant practically impossible. Therefore, coagulation was still required to overcome that period, whereas for the remainder of time (i.e., 90%) no benefit of coagulation became yet apparent, neither in filtrate quality, nor in UF operation. Observed UF fouling coincided with algal bloom, whereas raw water turbidity up to 50 FTU did not affect UF performance. If coagulation was applied, low doses (PACL, 0.3–0.5 mg $l^{-1}$ $Al^{3+}$ and ferric, 1 mg $l^{-1}$ $Fe^{3+}$) sufficed to restore long CEB intervals. However, PACL caused unacceptable degradation of SWRO membrane condition, whereas effects of ferric are still to be determined.

*Keywords:* Coagulation; Seawater desalination; Ultrafiltration; Pretreatment; Algal bloom

## 1. Introduction

Evides is the leading utility in South-Western Netherlands in drinking water supply and industrial water operations. Evides has established a demonstration-scale ultrafiltration–reverse osmosis (UF-RO) seawater desalination plant in Zeeland province, the Netherlands. The aim is to gain experience in sea water desalination with UF pretreatment under North-Western European conditions of raw water quality and drinking water standards. Hereto, an extensive research programme is being conducted in the time frame 2008–2012, covering operational and fundamental aspects.

It is noted that open intake UF pretreatment, 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. It is noted that these operate under generally lower turbidity and higher temperatures ([1–7] and most other literature cited in the references) than the Evides demonstration pilot.

Main topic of research in the first year of operation of the demonstration plant has been the behaviour of the UF pretreatment in relation to raw water characteristics

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and operational settings. A major issue in this framework is the assessment of the efficacy of UF-feed coagulation, since this implies significant operational, environmental and investment effort and cost [1,2].

This paper presents the operational results as obtained in the demonstration plant during the period December 2008 to April 2010, in terms of:

- Raw water quality
- UF permeability performance, restoration by chemically enhanced (CEB) and regular backwashing
- Efficacy of permeability maintenance by application of coagulant
- Resultant UF permeate quality
- Evaluation of benefits and drawbacks of application of coagulant in operational and investment effort and cost.

## 2. Demonstration plant site and specifications

### *2.1. Location and raw water source*

The demonstration plant is located in the estuarine region of South-Western Netherlands, Zeeland Province. It abstracts raw water near the southern terminus of the Oosterschelde storm surge barrier at the North Sea seaboard. The locality is subjected to severe tidal currents, and the water at the intake site can be considered as fully mixed (non-stratified) sea water.

### *2.2. Treatment equipment*

The demonstration plant comprises a submerged open sea water intake, microstraining, UF, two-stage RO and remineralisation (Fig. 1). Net water production capacity amounts to 14 $m^3 h^{-1}$, whereas in practice raw water intake rates of 45–55 $m^3 h^{-1}$ apply.

The treatment equipment line-up and design considerations are in more detail as follows (emphasis on intake, straining and ultrafiltration):

1. *Open intake*. Submerged set of pipes, coarse screening and intake pump, depth 4 m below sea level. No chlorine dosing is conducted.
2. *Microstraining*. 50 µm mesh filter cage. This relatively fine mesh is to remove clamshell spores, though the UF on itself would be able to handle a larger mesh pretreatment [1,2,8,9].
3. *Buffering, chemical dosing*. Two tanks in series for the purposes of flow buffering and chemical dosing. Total residence time approaches ~13 min, whereas the first tank is equipped with an electromechanical propeller mixer.
4. *pH correction*. pH is lowered by HCl dosing in the first buffer tank, with the aim of:
   a. Prevention of $CaCO_3$ scaling in the SWRO. Antiscalant dosing has been deliberately omitted in order to minimize operational and environmental impact. Based on precipitation calculations a pH of 6.6 has been applied.
   b. Establishment of proper pH conditions for coagulation (pH 6.6 for PACL, 8.0 for ferric, *see* below) [10].
5. *Inline coagulation*. Coagulant, if applied, is introduced in the first mixing tank mentioned under item 3). This relatively simple system was adopted since the establishment of fully developed flocs, for example as for sedimentation is not purported. In the design phase, poly-aluminium chloride (PACL) was selected as coagulant species because of the assumed need for DOC removal, later (2010) also ferric was applied.
6. *Ultrafiltration (UF)*. Comprising of hollow-fibre, dead-end filtration Norit Membrane technology Xiga Seaguard UF membranes [11].

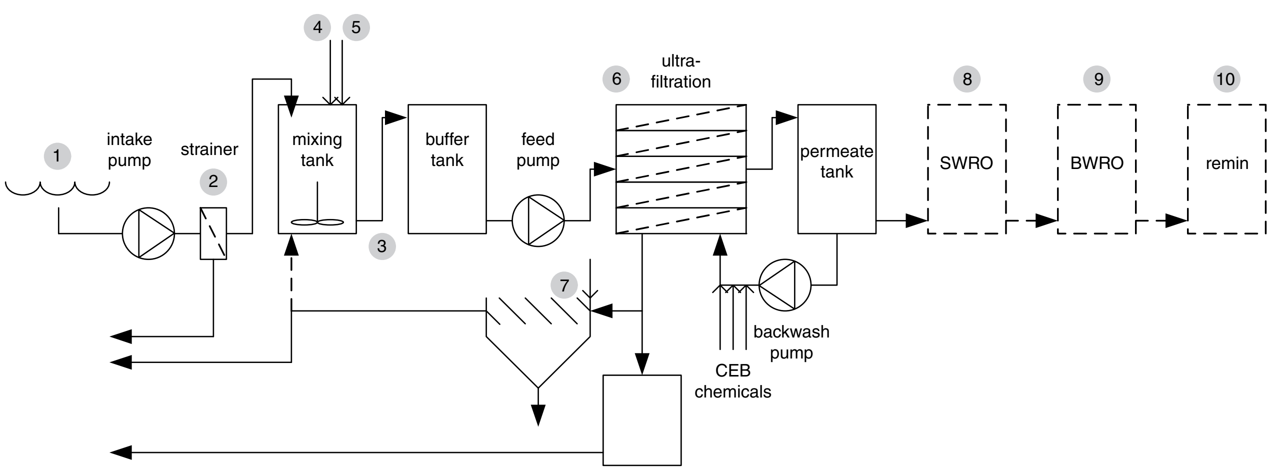


Fig. 1. Diagram Evides UF-SWRO demonstration plant.

a. *Filtration*. A comparative moderate flux of 55–60 l $m^{-2}h^{-1}$ (references as in Section 1) was adopted since the system performance for Oosterschelde conditions was not yet known in the design phase.
b. *Backwash.* Interval and rate were generally set at 45 min and 250 l $m^{-2}h^{-1}$ of UF permeate, respectively (membrane manufacturers design data).
c. *Chemically enhanced backwash (CEB)*. CEB was performed upon timed interval and/or if minimum allowable permeability is reached. CEB phasing, duration, chemical type (NaClO, NaOH and HCl) and strength have been varied during the experiments.

7. *UF backwash waste water handling:* by a secondary coagulation, lamella separation and recirculation to UF feed buffer tank. This equipment was activated at occasions of UF coagulation, since discharge of coagulant residuals to open water is not allowed. Without UF coagulation, backwash waste water treatment is optional but was in practice not used during the experiments.
8. *Sea water RO*. [12] Filmtec SW30XHR400i elements, operated on a fixed permeate production rate of 15 $m^3$ $h^{-1}$ at 40% recovery and a flux of 13 l $m^{-2}$ $h^{-1}$ [12].
9. *Brackish water RO*. [12] Filmtec BW30LE400 brackish water membranes for boron removal [13].
10. *Remineralisation*. Contents of calcium, bicarbonate and aggressivety are restored to legal drinking water standards by $CO_2$-dosing and marble filtration.

## 3. Results

### 3.1. Raw water quality

The quality monitoring programme yielded raw water quality and occurrence pattern over the seasons as presented by Table 1.

The raw water turbidity oscillates continuously in concurrence with the tidal movement at the intake. At storm occasions, happening about 10 times a year (generally concentrated but not exclusively in Spring and Autumn), turbidity up to 50–100 FTU occurs, lasting from several hours to days.

Fig. 2 presents results of raw water chlorophyll, algal count and TEP. Obviously their highest values occur in the first half of the year, although not necessarily simultaneously. Algal counts and identifications are available from May 2009 onwards.

Species identification yielded that *Phaeocystis* and *Chaetoceros* spiked in March 2010, whereas *Thalassiosira* dominated in May. For the remainder of the year algal counts were much lower, though a reoccurrence of *Rhodomonas* and *Plagioselmis* in August is noted.

The occurrence of biopolymeric excreta of some aquatic organisms (algae, possibly also shellfish which are locally abundant) as transparent exopolymer particles (TEP) has been studied [14]. High levels were observed in May (290 abs $cm^{-1}l^{-1}$), July and October (~80 abs $cm^{-1}l^{-1}$).

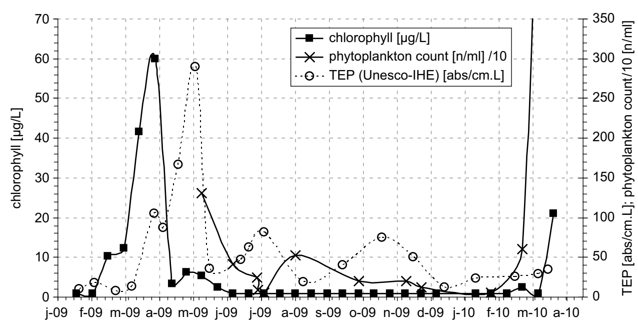


Fig. 2. Algal parameters in Oosterschelde raw water.

Table 1
Raw water quality data (January 2009–March 2010)

| Parameter | Unit | Winter (Dec.–Feb.) | Spring (Mar.–May) | Summer (Jun.–Aug.) | Autumn (Sept.–Nov.) |
|---|---|---|---|---|---|
| Temperature | °C | 4–9 | 6–17 | 17–19 | 19–9 |
| Conductivity | mS $cm^{-1}$ | 43–45 | 43–45 | 43–45 | 43–45 |
| pH | – | 7.9–8.2 | 8.2–8.5 | 7.9–8.2 | 7.9–8.2 |
| Turbidity | FTU | 3–18–43 | 1–3–15 | 2–6–36 | 7–23–70 |
| Suspended solids | mg $l^{-1}$ | 12–25–43 | 7–16–46 | 10–15–20 | 15–25–30 |
| Dissolved organic carbon | mg $l^{-1}$ | 1.5 | 1.5–3.0 | 2.0 | 1.8 |
| Ammonia | mg $l^{-1}$ | 0.20 | 0.06 | 0.10 | 0.20 |
| Chlorophyll | μg $l^{-1}$ | 2 | 5–60 | 2–5 | <2 |
| Algal count | n $ml^{-1}$ | ~60 (2010) | 1300–12,000 | 60–530 | 100–200 |
| TEP[1] | abs $cm^{-1}$·$l^{-1}$ | 8–16–25 | 13–116–290 | 19–53–81 | 37–54–75 |

Legend: minimum – average (where appropriate) – maximum.
[1]By UNESCO-IHE [14], values are not corrected for salinity.

### 3.2. UF performance

As demonstrated by Fig. 3, observed UF permeability (temperature corrected) ranged from 500–350 l $m^{-2}$ $h^{-1}$ $bar^{-1}$ just after CEB to 350–200 l $m^{-2}$ $h^{-1}$ $bar^{-1}$ before subsequent CEB.

In this paper the UF performance, that is resistance to fouling, is expressed as projected time interval between two subsequent CEB's since this has the most straightforward meaning in operational interpretation. This projected CEB time interval is determined by the UF permeability just after CEB, the permeability decline rate (i.e., permeability profile) and lowest acceptable permeability at which the subsequent CEB is initiated.

#### 3.2.1. UF permeability restoration by CEB

A two-phase CEB of NaClO (100 ppm $Cl_2$) with NaOH (125 mg $l^{-1}$) followed by HCl (225 mg $l^{-1}$) proved to be generally successful in restoring permeability above 400 l $m^{-2}$ $h^{-1}$ $bar^{-1}$ (Fig. 3). However, CEB efficacy dropped if either one of the chemicals was omitted (e.g., March 2009 and July 2009) and when low temperatures occurred (e.g., January 2010).

#### 3.2.2. CEB initiation

CEB was initiated upon reaching a permeability of 200 l $h^{-1}$ $m^{-2}$ bar, specified by the membrane supplier as lower boundary value, or alternatively at a fixed number of backwashes and at process shutdown exceeding 2 d as a membrane conservation measure. In practice, CEB has been conducted more frequently than strictly required that is, before reaching the lower permeability boundary of 200 l $h^{-1}m^{-2}bar^{-1}$ *see* Fig. 3.

#### 3.2.3. Cleaning-in-place (CIP)

In the 14 months of operation no additional CIP has been executed.

#### 3.2.4. UF permeability profile

During the experiments, several distinct UF permeability profiles were encountered, as depicted by Fig. 4:

A: Autumn, no coagulation: full stabilisation, little inter-backwash fluctuation.
B: Winter, no coagulation: moderate decline, little inter-backwash fluctuation.
C: Spring, no coagulation: steep and rapid decline, little inter-backwash fluctuation.
D: Spring, coagulation: full stabilisation, severe inter-backwash fluctuation.

Although a more fundamental elaboration on the permeability profiles is beyond the scope of this paper, they are nevertheless presented since they are a major factor in assessing CEB interval projection.

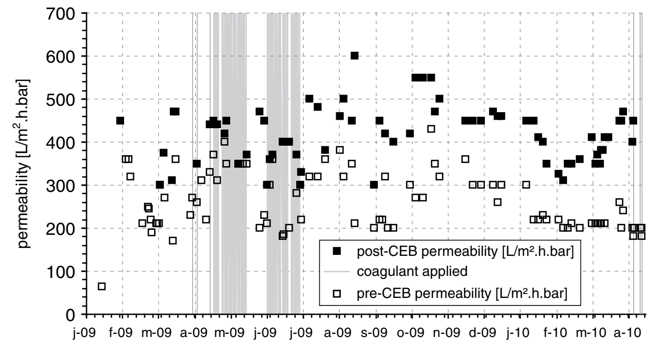


Fig. 3. UF permeability before and after CEB.

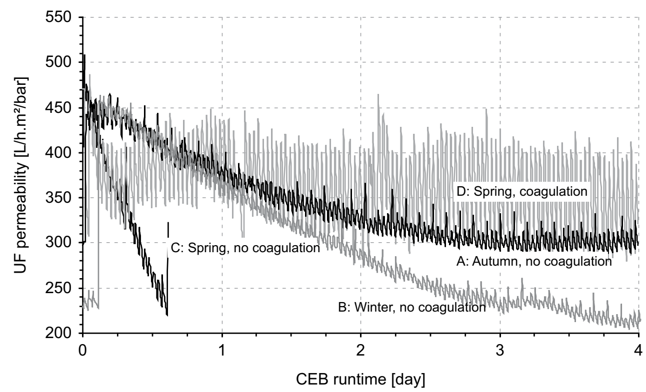


Fig. 4. UF permeability profiles after CEB (CEB at $t$ = 0).

#### 3.2.5. CEB interval projection

Projected CEB intervals have been obtained by extrapolating all experimentally available permeability profiles to a value of 200 l $h^{-1}m^{-2}bar^{-1}$. Projected CEB interval has been cut off at 7 d where extrapolations exceeded that figure, that is, where a permeability stabilization occurred. Fig. 5 presents the derived figures for the cases with and without UF coagulant application.

CEB intervals >0.5 d without use of coagulant were established for nearly the whole year. For the period July–December even intervals ≥7 d were attained, whereas a temporary shortening (~1–2 d) in August–September is noted. However, in March and April 2009 and April 2010 very rapid UF fouling occurred, with CEB intervals lasting only 1 to 4 h.

#### 3.2.6. UF coagulation

For the period April–June, coagulation by PACL (2009) respectively ferric (2010) had an immediate positive effect in restoring and maintaining high and stable

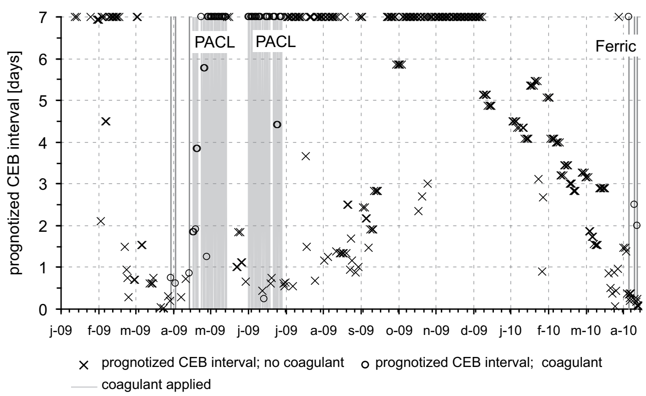


Fig. 5. CEB interval projected from initial permeability and permeability profile (cut-off at 7 d).

UF permeability and henceforth long CEB intervals (Figs. 4 and 5). A dose of 0.3–0.5 mg $l^{-1}$ $Al^{3+}$ respectively 1.0 mg $l^{-1}$ $Fe^{3+}$ sufficed to attain the aforementioned this behaviour. A higher dose did not demonstrate any benefit. However, lower doses caused immediate collapse of UF permeability, reverting to a situation resembling that of no coagulant dosing at all. It is noted that application of PACL had a significant effect on SWRO performance, as described by Section 3.2.9.

### 3.2.7. Backwash

In general, backwash intervals of 45 min have been applied at 250 l $m^{-2}$ $h^{-1}$ for 45 s, equalling a backwash water loss of 10%. In June and July 2009 a filtration runtime shortening to 30 min proved beneficial (though not consistently) for permeability stabilization. However, runtime shortening during the rapid fouling in April 2010 was not effective, since the permeability restoration by backwash was offset by the higher fouling rate due to the higher flux in order to make up for the increased water loss.

As shown in Fig. 4, coagulant dosing radically alters the shape of the UF permeability in between subsequent regular backwashes (filtration run). Nevertheless, backwash restored permeability completely, hence overall long CEB intervals were attained with coagulation.

### 3.2.8. UF feed turbidity

From the experimental results it appeared that all encountered turbidities, that is up to 50–100 FTU did not have any impact on UF permeability. For some cases, not consistently though, a higher FTU had either none, or sometimes even beneficial effect on UF permeability. It is noted that the microstraining stage, which precedes the UF, reduced suspended solids by ~30%, whereas turbidity remained unaffected.

### 3.2.9. UF permeate quality

UF permeate quality is presented by Table 2.

The UF filtrate quality has met applicable turbidity and SDI, regardless of feed turbidity ([12,15], other cases contained in references). However, no beneficial impact of coagulant on the parameters in Table 2 is apparent. Moreover, for PACL coagulation levels of residual aluminum exceeded the specifications of the RO feed quality [12]. Significantly, a sharp and immediate degradation of SWRO membrane performance (normalized mass transfer coefficient declined 30% in 4 d) occurred upon commencing supply of coagulated UF–permeate to the system. Attempts to decrease residual levels by pH manipulation yielded even higher permeate aluminium levels of ~0.4 mg $l^{-1}$ at either lower (6.2) and higher (8.0) pH. For ferric, residual content and SWRO behaviour are still under study.

However, apart from the aforementioned coagulant event, the SWRO membrane performance indicators (MTC, NPD) have remained constant throughout the test period.

Table 2
UF permeate quality

| Parameter | Unit | Without UF coagulation | With UF coagulation |
|---|---|---|---|
| Turbidity | FTU | 0.05 (>99%) | 0.05 (>99%) |
| Particle count (≥0.5 µm) | n $ml^{-1}$ | 2–10 (≥3.6 log) | 2–10 (≥3.6 log) |
| MFI-UF (100 kD)[1] | s $l^{-2}$ | 145 (94–97%) | 127–138 (94–97%) |
| $SDI_{15-500}$ (0.45 µm)[2] | % $min^{-1}$ | 1.0–1.7 | No data |
| DOC | mg $l^{-1}$ | 1.2–1.8 (20%) | 1.8 (20%) |
| Aluminum | µg $l^{-1}$ | 10–50 (0–80%) | 100–500 (<–100%) |
| TEP[3] | abs $l^{-1}$ | Variable (30–40%) | Variable (30–40%) |

Legend: (–) : range; (%): reduction over UF.
[1][16].
[2]Al-Hadidi, forthcoming.
[3][14].

## 4. Evaluation

### 4.1. UF as SWRO pretreatment

#### 4.1.1. Impact of raw water quality – algal components

In the period March–June algal count, chlorophyll content and increased pH indicate algal bloom. This coincides with the observed period of accelerated or rapid UF fouling.

In March 2010 *Phaeocystis* peaked. This is a non-diatomic foam forming species due to presence of large quantities of extracellular polymeric material, which may explain the observed high UF fouling rate [16].

The diatoms *Chaetoceros* and *Thalassiosira* were dominant in March 2010 respectively May 2009. Diatoms are known to produce significant amounts of TEP in the ocean [17]. TEP levels during this period were considerably higher than what was recorded previously in other Dutch water sources [18]. However, moderate reoccurrences of TEP (~80 abs $l^{-1}cm^{-1}$) in July and October did not noticeably affect UF performance.

In August a distinct peak in *Rhodomonas* occurred, simultaneously with a separate temporary decline in UF stability. Because *Phaeocystis* and *Rhodomonas* are both relatively small in size (5–10 µm), most passed the screening pretreatment (50 µm) and may also have acted as foulants themselves to the UF system. These species are non-diatoms, and are usually not associated with high TEP-levels [17].

Therefore, algal matter is likely the major factor in the UF fouling process, although the actual vector (algae themselves or their excreta products, for example TEPs, saccharides, proteines, either on their own or in combination with other raw water constituents) is yet to be determined in more detail [19]. During such algal bloom UF fouling rate become temporarily so severe that operation without coagulation was practically impossible. In 2009 this condition lasted approximately 4 weeks from mid-April onward (i.e., when PACL was dosed continuously).

#### 4.1.2. Impact of raw water quality – turbidity

The UF performance is insensitive towards the relatively high turbidity as permeability remained unaffected (or even improved) up to values of 50–100 FTU. At the same time, permeate quality displays constant and low turbidity (0.05 FTU) and SDI which is favourable for RO applications [12,15].

#### 4.1.3. Efficacy of (chemically enhanced) backwash

UF as SWRO pretreatment has demonstrated a good process robustness, low fouling rates (CEB intervals >0.5 – >7 d) without coagulant addition beyond Spring and moderate backwash water losses (~10%) under the applied flux (50–60 l $m^{-2}$ $h^{-1}$). For a limited duration (mid April–mid May) very rapid permeability decline occurred, requiring excessive CEB frequency (>4 daily).

In all cases a CEB sequence employing the "common" chemicals NaOH, NaClO and HCl was effective in restoring permeability to 350–450 $m^{-2}$ $h^{-1}$ $bar^{-1}$. No CIP has been required in the 1.5 y of operation since no long-term downward trend in membrane performance became apparent.

Backwash water losses remained below 10%. Since permeability restoration by regular backwash was limited and filtration runtime shortening did generally not impact positively, it appears that a fouling mechanism removable by CEB is dominant over backwashable fouling.

The equivalent chemical consumption was calculated as 0.05 g NaClO; 0.07 g NaOH; 0.13 g HCl and 0.5 g SMBS $m^{-3}$ UF permeate, based on a 5 CEB day interval (~50% of the time). These figures are relatively low compared with other UF cases [1,2,20].

#### 4.1.4. Efficacy of coagulation

For the period of rapid UF fouling, both Al and Fe coagulant proved to be effective in maintaining a constant and high UF permeability, thereby restoring CEB intervals to ≥5 d. Doses of (but not lower than) 0.3–0.5 mg $l^{-1}$ $Al^{3+}$ respectively 1.0 mg $l^{-1}$ $Fe^{3+}$ sufficed (in line with data for ferric, for example, [1,2,8,9,12,21–23,31]. So, coagulant was effective in intercepting the UF fouling occurring in Spring.

However, significant aluminium residuals (>100 µg $l^{-1}$) occurred in the UF permeate at PACL dosing, with immediate sharp SWRO MTC decline as a result. Therefore, application of Aluminium coagulant is considered to be unfeasible in the current UF-RO desalination setup [10,12,24,25], unless the residual levels could be lowered by improvement of for example mixing and pH [26]. Furthermore, enhancement of DOC removal by aluminum coagulant was limited due to the low SUVA, and the coagulation pH of 6.6. coincides unfavourably with low solubility of Al-compounds in the RO [12,27,28].

#### 4.1.5. UF permeate quality

The UF permeate quality was in line with other cases and met appropriate standards for RO applications ([12,15,29] and other cases contained in references). However, the passage of TEPs and especially their potential effect on RO require further attention [14]. The detrimental effect of PACL has been described in the preceding section. For ferric, residual content and SWRO behaviour still have to be assessed, though ferric is a common species in UF RO applications (references as in preceding section).

Table 3
Practical considerations in coagulant application, experimental data (all figures normalized to UF net permeate production)

| Evaluation factor | No coagulant dosing | 0.5 mg $l^{-1}$ coagulant dosing |
|---|---|---|
| CEB interval | 0.5 d | 5 d |
| Chemical consumption for pH conditioning | 39 g $m^{-3}$ | 35 g $m^{-3}$ |
| Coagulant for UF and waste treatment | 0 g $m^{-3}$ | 1 g $m^{-3}$ |
| CEB chemical consumption | 15 g $m^{-3}$ | 2 g $m^{-3}$ |
| Coagulant sludge to be disposed of | 0 g $m^{-3}$ | 27 g $m^{-3}$ |
| Intake water loss | 10% | 0% (Recycling) |
| Intake pumping energy | 0.21 kWh $m^{-3}$ | 0.19 kWh $m^{-3}$ |
| Equipment investment | 10% larger intake main and pump; CEB chemical storage | Wastewater treatment system; filter press |
| UF lifetime (CEB chlorine exposure) | 5 y | >>5 y |
| Impact on downstream processes | None/little | Unfavourable (SWRO) |
| Operational effort | Limited | Increased |

*4.1.6. Practical implications of UF coagulation*

From the process data obtained in the experiments a comparison on the practical implications of UF coagulation is derived (Table 3).

The options with and without coagulant are roughly equal in terms of consumables (chemicals, energy, waste, UF membrane replacement), and moreover, their costs are minor in comparison to the overall desalination treatment expenditures. Differentials in investment cost, operational effort and process robustness are less easy to quantify since these are strongly dependent on local conditions. For the cases of CEB intervals ≥0.5 d, that is >90% of the time, most factors favour the elimination of coagulant under the applicable SW-Netherlands conditions and applied moderate flux setting.

However, the observed excessive fouling rate in Spring implies that a coagulant system is nevertheless unavoidable, even if it is only actually activated for a limited time (<10%) in the year. An alternative drastic lowering in flux to mitigate fouling would mean additional UF equipment [30], and still be at risk if more severe algal bloom would occur.

## 5. Conclusion

Based on the first year results of the Evides demonstration plant it is concluded that UF as SWRO pretreatment for Oosterschelde raw sea water has demonstrated a good process robustness, manageable or low fouling rates (CEB interval >0.5 – >7 d) without coagulant beyond Spring, under moderate backwash water losses (~10%) and flux (55–60 l $m^{-2}$ $h^{-1}$). Rapid UF fouling occurred during algal blooms, whereas high turbidity (50 FTU) had no negative effect on UF performance.

For a short period (~4 weeks) in Spring, severe UF fouling resulted in excessive CEB frequency (>4 times daily), causing unacceptable UF downtime and CEB chemical consumption. For this case application of coagulant proved capable of restoring stable and acceptable UF permeability. This implies implementation of coagulant dosing and wastewater handling is still required, even if the equipment is only to be activated for a short time span. Both PACL and ferric coagulant were effective in low doses (~0.5–1.0 mg $l^{-1}$), although PACL caused unacceptable degradation of SWRO performance and is hence unsuitable in the current system.

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