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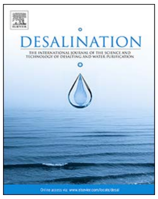

# Fouling indicators for field monitoring the effectiveness of operational strategies of ultrafiltration as pretreatment for seawater desalination

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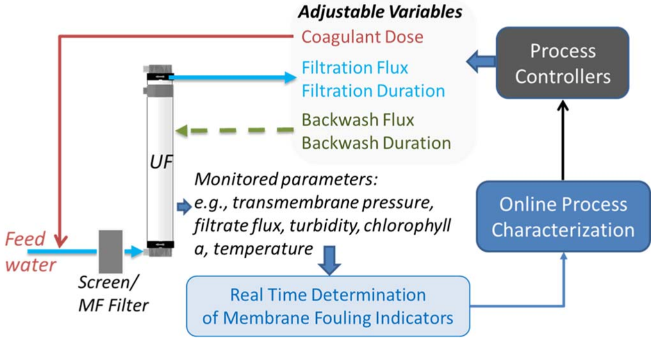
## GRAPHICAL ABSTRACT

Real-Time Monitoring of UF Fouling Indicators.



## ARTICLE INFO

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## ABSTRACT

The applicability of fouling indicators for real time performance assessment of UF feed pretreatment in RO seawater desalination was explored in a field study using an integrated seawater UF-RO desalination pilot plant. Fouling indictors were evaluated with respect to quantification of UF backwashability, unbackwashed fouling resistance and UF fouling rate. Feed water quality and coagulant dose demonstrated measurable impact on both UF fouling rate and effectiveness of foulant removal via UF backwash. Increased coagulant dose promoted higher rate of cake formation and in turn improved backwash efficiency. However, there was a maximum coagulant dose beyond which there was no further backwash improvement. Backwash effectiveness increased with higher backwash flux and duration, up to threshold upper limits, but declined as the filtration period increased above a threshold limit. Field tests during periods of temporally varying feed quality demonstrated that higher fouling rate (promoted by inline coagulation) resulted in more effective backwash and correspondingly lower progressive rise in post-backwash UF resistance. The study results suggest that real-time UF fouling indicators, based on UF filtration resistance metrics and backwash effectiveness, should be potentially useful for tracking UF performance and thus for deployment of UF feed-back control for optimal performance of UF feed pretreatment.

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## 1. Introduction

Dwindling fresh water supplies from traditional sources, such as ground and surface water, coupled with frequent drought conditions across the globe, intensify the need to develop alternative and sustainable potable water supplies [1–3]. In recent years, seawater and brackish water desalination and water reuse technologies have been implemented in various regions of the U.S. and around the globe as part of the movement to diversify the portfolio of available water resources. In the generation of the above non-traditional water resources reverse osmosis (as well as nanofiltration) membrane technology is often utilized for desalination and as a barrier against multiple contaminants. However, membrane fouling is a major challenge for effective operation of both seawater and brackish water RO plants [4–7]. In the absence of effective RO feed water pretreatment, membrane fouling by particulate/colloidal matter, biofoulants, extracellular polymeric substances (EPS) that are abound in seawater (particularly in littoral water) [8–10] and organics degrades membrane performance (e.g., reduced permeability and thus increased applied pressure requirement for a given target flux, decreased permeate quality), increase the frequency of required chemical cleaning and consequently shortening of membrane longevity and as a consequence increased water treatment cost [11–14]. Therefore, RO feed water pre-treatment is critical for (complete or partial) removal of potential foulants such as particulates, colloids, and organic matter [5,6,9,11].

In recent years, ultrafiltration (UF) has emerged as an effective method for pre-treatment of RO feed water compared to conventional feed pre-treatment options (e.g. sand filters, cartridge filters) [6,9,15–18]. UF membranes having a pore size typically in the range of 0.1–0.01 μm can remove particulates, colloids, microorganisms and some dissolved organics matter (often with the aid of coagulant dosing), and accordingly producing high quality filtrate. Both UF filtration and backwash effectiveness [19] can often be improved through coagulant dosing of the UF feed [10,12,20]. Coagulant dosing promotes floc formation (i.e., aggregation of fine particles and colloidal matter), thereby improving both UF and MF membrane filtration and hydraulic cleaning [21–24]. Given the above attributes, UF is becoming increasingly the choice method for RO feed water pre-treatment, particularly since UF membrane permeability loss (due to fouling) can be recovered with periodic backwashing and/or air scouring [15,25,26].

UF foulants that are not removed during backwash result in UF irreversible fouling. When the buildup of irreversible fouling reaches a critical level (e.g., as indicated by increased transmembrane pressure for constant flux operation) and backwash is no longer effective in providing sufficient membrane permeability restoration chemical cleaning-in-place (CIP) is utilized [27,28]. However, plant operational costs (e.g., due to chemical costs and possible productivity loss) can increase significantly with increased CIP frequency [29,30]. Therefore, it is critical to optimize both UF filtration and backwash [31–33]; thus, efforts have been devoted to elucidate the impact of various factors on UF fouling and backwash effectiveness such as, for example, feed water quality [19,22], filtration period length [34], backwash flux [32,35], duration and frequency, backwash water composition [36,37], coagulant dosing, CIP strategies, and membrane properties [19,28,38,39].

A number of studies have proposed the use of fouling indices such as the Silt Density Index (SDI) and various forms of Modified Fouling Index (MFI) to quantify the feed water “fouling potential” [28,40–52] via measurements of flux decline through a surrogate membrane ex-situ. These fouling indices rely on off-line measurements and thus an inherent lag time relative to real-time UF system behavior. A large number of the studies on fouling indices studies with UF as well as MF systems did not consider coagulant dosing and have relied on synthetic saline, surface water or seawater blended with organic foulants [28,41,43–45,49,50,52–55]. Evaluation of seawater and algal-rich surface water UF fouling potential, associated with green and blue algae, was also recently investigated via real time fluorometeric measurements of chlorophyll-*a* [12,56–59]. These studies with laboratory-scale hollow fiber UF membrane setup demonstrated significant correlation of chlorophyll-*a* with UF membrane flux decline due to biofilm growth.

Invariably, arriving at effective UF filtration and backwash strategies requires tracking of the extent of UF fouling and assessment of backwash effectiveness. Conventional UF operations rely on tracking of UF fouling via the UF transmembrane pressure (TMP), UF filtration resistance or membrane permeability normalized with respect to their initial value in the filtration step just post CIP [10,22,26,60–63]. Such approaches, however, do not lend themselves to cycle-to-cycle tracking of backwash efficiency nor quantifying the contributions of reversible (i.e., backwashable) and irreversible (i.e., unbackwashable) fouling to UF resistance in progressive filtration cycles.

UF fouling is a complex phenomenon that is governed by water quality and temperature which can be temporally variable, as well as operating conditions. Therefore, in order to establish optimal UF operating conditions with effective process control [64,65], there is a need to develop real-time fouling indicators. Previously, backwash triggering controller, based on a maximum allowable filtration resistance change per cycle ($\Delta R_{T,max}$) was proposed and demonstrated as an effective and practical method to control backwash frequency [34]. Subsequent work demonstrated that real-time quantification of backwash efficiency, along with determination of the associated of coagulant dosing, can be utilized for determination of optimal coagulant dose adjustment in response to changing UF fouling as affected by varying feed water fouling potential [19]. However, assessing UF performance, with respect to the progression of fouling and backwash effectiveness, is complex as it requires real time quantification of multiple fouling indicators based on plant sensors' data.

The present work aimed to elucidate the complex relationship between various UF operational variables and UF fouling behavior as observed under field conditions for UF treatment of RO seawater feed water. Accordingly, a framework for online UF fouling metrics (or indicators) were determined to assess cycle-to-cycle filtration and backwash fouling and permeability recovery (or fouling resistance removal), respectively. The UF filtration period and fouling rate ($FR$), unbackwashed and post-backwash UF resistances ($\Delta R_{UB}$ and $R_{PB}$, respectively), and UF backwash efficiency ($BW_{eff}$) were determined in real-time for each filtration/backwash cycle over both short and long-term field tests. The above fouling metrics were then assessed with respect to filtration and backwash flux and duration coagulant dose and in relation to feed water turbidity and chlorophyll-*a* measurements in both the UF filtrate and feed water. The correlations between the UF system operational variables and the above fouling indicators can form the basis for performance forecasting and development of UF self-adaptive control.

## 2. Experimental

### 2.1. Integrated UF-RO system

The UF-RO seawater desalination system (Fig. 1) consisted of directly integrated UF and RO skids (i.e., without an intermediate UF or RO feed tank). The designed maximum system feed water capacity was 190.8 $m^3$/day (50,400 GPD) operating at a maximum RO unit recovery of 35% recovery (equivalent to desalted water production of 66.8 $m^3$/day (17,640 GPD)). Details of the integrated UF-RO system are available elsewhere [34]. Briefly, the UF skid comprised of an inline basket strainer (0.32 cm ID perforation, Hayward SB Simplex, Clemmons, NC), a 200 μm self-cleaning microfilter (TAF-500, Amiad Corp., Mooresville, NC), and three inside-out polyethersulfone (PES) multi-bore hollow fiber membranes (0.02 μm pore size) UF modules (Dizzer 5000 +, Inge, Greifenberg, Germany) arranged in parallel with each nodule having membrane surface area of 50 $m^2$.

Feed water to the UF modules was delivered by a feed pump (XT100