Desalination 401 (2017) 22–31

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Self-adaptive cycle-to-cycle control of in-line coagulant dosing in ultrafiltration for pre-treatment of reverse osmosis feed water

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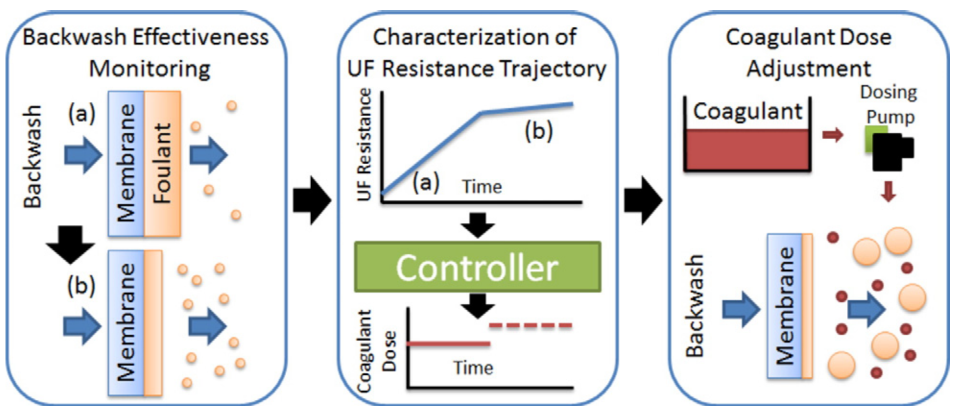
HIGHLIGHTS

- UF coagulant dose controller was successfully developed and field tested.
- Self-adaptive in-line UF coagulant dosing reduced coagulant consumption.
- Real-time tracking of fouling resistance and backwash effectiveness.
- Robust UF operation during conditions of deteriorating source water quality.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 August 2016
Received in revised form 22 September 2016
Accepted 26 September 2016
Available online 4 October 2016

Keywords:
Ultrafiltration
Fouling
UF backwash
In-line coagulation
Desalination
Coagulant controller

ABSTRACT

Real-time self-adaptive approach to in-line UF coagulant dosing was developed and field demonstrated for integrated UF-RO seawater desalination. A novel coagulant dose controller was designed and successfully implemented in a pilot UF-RO seawater desalination plant. The coagulant controller, which tracks the UF resistance during filtration and backwash, adjusts coagulant dose to the UF feed with the objective of reducing the incremental cycle-to-cycle UF post-backwash (PB) resistance change (i.e., Δ_n). Real-time tracking the above UF resistance metrics, as well as the rate of change of Δ_n with coagulant dose, enabled the controller to quantify the progression of both irreversible fouling and UF backwash effectiveness. The above information was then utilized by the controller to make the appropriate coagulant adjustment. Field tests of the proposed self-adaptive coagulant dosing approach demonstrated measurable coagulant dose reduction while maintaining robust UF operation even during periods of both mild and severe water quality degradation. The approach to real-time coagulant dose control developed in the present work should be suitable for both seawater and brackish water UF treatment and has the potential of providing both effective UF operation as well as reduction in coagulant use.

1. Introduction

Over the past two decades, reverse osmosis (RO) desalination has emerged as the leading technology for seawater and brackish water desalination [1,2]. However, membrane fouling remains a major challenge

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http://dx.doi.org/10.1016/j.desal.2016.09.024
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for robust operation of RO desalination plants [1–6]. Hence, effective RO feed pre-treatment is vital for long-term operation of an RO desalination system [6,7]. Among existing RO pre-treatment technologies, ultrafiltration (UF) membrane filtration has proven to be effective for providing high quality filtrate water compared to conventional feed pre-treatment options (e.g., sand filters, cartridge filters), leading to longer lifespan of RO membranes downstream [7–16]. It is important to note that when relying on UF pre-treatment for RO, the burden of alleviating the adverse impact of membrane fouling (e.g., higher required applied pressure for a given water production level), is assumed by the UF system [7–16].

Despite the above challenges, UF feed pre-treatment is attractive for RO operation since UF membrane resistance (i.e., inverse of UF membrane permeability), which increases during filtration due to fouling, can in principle be reduced by removing the foulant layer through effective backwashing (i.e., reversing the flow direction) [7–10]. However, physical UF backwash (i.e., without employing chemical cleaning) is typically insufficient for completely reducing UF membrane resistance to its original state. Consequently, UF foulants that are not removed during backwash result in UF irreversible fouling. When UF backwash is no longer sufficient for effective UF membrane cleaning, chemical cleaning-in-place (CIP) can be used to remove the irreversible fouling layer [14,17,18]. However, due to the logistics (e.g., handling of chemicals) and added capital costs (e.g., plant shut-down, chemical costs), it is desirable to educe the frequency of CIP. Therefore, it is critical to optimize UF backwash.

Various studies have investigated backwash effectiveness as impacted by various factors such as backwash water composition [19–24] or membrane properties [25–28]. Previous studies have concluded that varying operational parameters such as backwash frequency can significantly increase UF operational duration before the need for CIP [29–31]. There is also a body of work regarding coagulant use for UF feed pretreatment demonstrating improved UF product quality and reduced UF fouling [32–38]. It is generally accepted that coagulant dosing promotes the formation of flocs (i.e., aggregation of fine particles and colloidal matter) which improves both UF and MF membrane filtration and hydraulic cleaning [33,38,39]. Also, UF pore plugging and irreversible fouling have been reported to decrease with increasing coagulant dose up to an optimal maximum limit [40] beyond which there is little added benefit. However, excessive coagulant dosing increases process cost and the potential for coagulant passage across the membrane to the permeate stream. Accordingly, the common approach to UF operation is to search for the optimal coagulant dose via the combination of jar testing (i.e., introduced nearly 100 years ago) [32,37,40,41] and preliminary pilot-plant runs [33,35]. However, in reality, UF feed water quality and fouling propensity vary significantly with time in the short term, as well as seasonally [4,10,29,30,41]. Therefore, the optimal coagulant dose can change as feed water quality changes, hence operating at a fixed coagulant dose can lead to suboptimal UF operation that can then increase membrane resistance. Clearly, under conditions of variable feed water quality, determination of the optimal coagulant dose(s), which is dependent on source water quality, is infeasible by off-line methods (e.g., jar testing). Hence, real-time adjustment of coagulant dose is needed where variable source water quality is encountered.

Real-time adjustment of coagulant dose through feed-forward control was introduced in [42] for particulate matter removal from river water via sedimentation aided by coagulation. The approach relied on formulating an empirical relation, based on historical data of sedimentation under coagulant treatment, that correlates the suitable coagulant dose with feed water turbidity, conductivity, and temperature [42]. The above approach was successfully implemented for the one specific feed water source for which the correlation was determined, but the control approach was found to be deficient at two other sites. More recently, a feed-back control approach was reported for coagulant dose adjustment, also for a coagulant-sedimentation process, whereby the residual aluminum concentration in the mixing tank served as the metric for assessing coagulation efficiency [43,44]. Deployment of the approach was successful for reducing source water of turbidity from 0.5–100 NTU to below 1 NTU.

The application of real-time adjustment of coagulant dose for in-line coagulation in dead-end UF filtration systems was first reported in [45]. The approach involved the formulation of an empirical correlation of the trajectory of initial UF filtration cycle resistance (i.e., UF filtration resistance immediately post UF backwash, termed hereinafter UF "PB" resistance) with respect to the filtered volume based on a series of short-term pilot tests. The deviation of the measured UF PB resistance from the value calculated from the empirical UF PB resistance-filtered volume (PBR/FV) trajectory correlation was used as input to a proportional-integral controller to adjust the coagulant dose. The controller function was set to adjust the coagulant dose so as to drive the UF system operation toward the selected PBR/FV trajectory. The above approach should be useful when water quality is essentially time-invariant. As noted in [45], however, the selection of an optimal UF PBR/FV trajectory was arbitrary and the authors did not demonstrate that it is feasible to arrive at an optimal trajectory. The above limitation of the approach is understandable given that a specific PBR/FV trajectory could not be used to establish optimal operation for situations in which water source quality (i.e., in terms of its fouling potential) is temporally variable.

Determination of an optimal coagulant dose in real-time for the wide range of water quality conditions that may occur in various locations is a daunting task. Therefore, it would be beneficial to develop and deploy a coagulation controller, capable of adjusting the coagulant dose, without the need for establishing specific pre-determined empirical relationships of coagulant dose with multiple measurements of water quality and/or UF resistance metrics. Accordingly, in the present work, a novel approach is presented of in-line UF coagulant dose control which relies on real-time tracking of cycle-to-cycle UF PB resistance in response to coagulant dose adjustments. The controller increases or decreases the coagulant dose depending on improvements in the cycle-to-cycle change in UF PB resistance. The coagulant dose adjustment is self-adaptive and thus the current coagulant dose controller is suitable for a wide variety of feed water conditions. The developed coagulant dose controller was implemented and field demonstrated on a pilot seawater desalination plant (i.e., capable of 18,000 GPD production of fresh water). A series of field experiments, for periods ranging from a few days to two weeks, were undertaken to assess UF operation and coagulant savings in addition to reducing UF fouling under real-time coagulant dose control. Moreover, the response of the UF system to coagulant controller dose adjustments was evaluated during a period of decreased water quality.

2. Self-adaptive cycle-to-cycle coagulant dose controller

2.1. UF and backwash performance metrics

UF operation consists of successive filtration cycles, defined as the duration of a filtration period and of the subsequent UF backwash period. During a filtration period, particulate matter in the feed water remains on the surface of the UF membrane or within its pores, forming a foulant layer which gradually increases in thickness as a function of filtration time. The impact of the foulant layer is typically quantified by UF resistance to fluid permeation through the UF module:

$$R_T = \frac{\Delta P_m}{\mu \cdot J_{UF}} \tag{1}$$

where R_T is the total UF resistance (i.e., membrane and foulant layer), ΔP_m is the UF transmembrane pressure, μ is the water viscosity, and J_{UF} is the UF filtrate flux. It is noted that the resistance as determined in Eq. (1) was normalized to 20 °C following the recommended correction factor [46] for the specific UF modules used in the present study (i.e.,$R_{T=20^{\circ}C} = R_T \exp[0.019(T-20)]$). As filtration proceeds, coagulant is added to the feed stream at a constant dose rate (e.g., ppm) and the overall UF membrane resistance increases. UF backwash is triggered once the resistance reaches a critical level or after a prescribed time period. Upon the completion of a given UF module backwash, the module is reverted back to filtration mode. Illustrations of UF membrane resistance during UF operation are shown schematically in Fig. 1. The change in UF PB resistance for cycle n (i.e., also equivalent to the initial UF resistance for cycle $n+1$) relative to the previous cycle ($n-1$) is expressed as $\Delta_n = R_n - R_{n-1}$.

The cycle-to-cycle change in UF PB resistance as quantified by Δ_n governs the rate of UF PB resistance trajectory during UF operation. An illustration of the implication of Δ_n tracking is provided in Fig. 1 for a hypothetical series of UF cycles. A decrease in Δ_n, signifies improved backwash effectiveness and/or reduction in the cycle-to-cycle buildup of membrane fouling resistance, while an increase in Δ_n indicates reduced backwash effectiveness and greater rate of foulant buildup on the membrane. Values of Δ_n can be positive (e.g., the typical case as illustrated for Δ_n, for cycles $n = 1$–3 and $n-1$ through $n+1$ in Fig. 1) or negative (e.g., Δ_4 and Δ_5 in Fig. 1) indicating increased fouling (i.e., buildup of unbackwashed resistance) or effective backwash that results in removal of previously unbackwashed foulant buildup, respectively. When the overall system UF operation is such that $\Delta_n > 0$ is the dominant behavior then the unbackwashed UF resistance will gradually increase. The slower UF resistance increase is apparent for cycles $n-1$ through $n+1$ (i.e., lower Δ_n) compared to operation during cycles 1–3. UF operation with such gradual resistance increase will typically be allowed to continue until chemical cleaning will be required (i.e., when the prescribed resistance or transmembrane pressure threshold for the UF operation limit is reached) in order to restore the membrane to its original clean state. Given the above, the overall coagulant control strategy is to reduce Δ_n in order to reduce the rate of increase of unbackwashed (i.e., or irreversible) UF fouling and reduce the frequency of chemical cleaning.

2.2. Coagulant dose adjustment strategy and control logic

Based on previous UF studies [33,38–40], which demonstrated that increasing coagulant dose improves backwash effectiveness, it can be argued that Δ_n is expected to decrease with increasing coagulant dose (i.e., UF backwash effectiveness improves and UF fouling is reduced as coagulant dose increases) up to a critical threshold above which Δ_n is not appreciably affected. The latter regime is where coagulant dose is at a high level where it no longer impacts UF backwash effectiveness. Accordingly, two distinct regions are expected with respect to the dependence of Δ_n on coagulant dose: a) a region where an increase in coagulant dose leads to decreased Δ_n hereinafter is termed the "underdosed region," and b) a region in which the coagulant dose is at or above a certain critical threshold (i.e., no further improvement in Δ_n with increased dose) designated as "overdosed region." The quantitative functional behavior of the above trends (i.e., an example is shown in Section 4.1) is expected to be specific for the UF system configuration and capacity and for the given source water quality. Accordingly, in the present approach, the objective is to adjust the coagulant dose such that there is proper reduction or increased coagulant dose in the underdosed region. Moreover, system drift to the overdosed region is detected and where the appropriate control action is to reduce the coagulant dose.

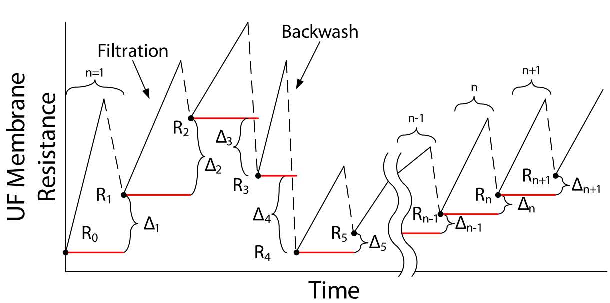

Fig. 1. An illustration of UF membrane resistance-time profiles for multiple filtration/backwash cycles. R_n is the UF post-backwash (PB) resistance for filtration cycle n (i.e., also same as the initial UF resistance for cycle $n+1$). A given cycle n begins with UF resistance of R_{n-1} and ends after backwash with UF resistance of R_n. The cycle-to-cycle change in UF post-backwash (PB) resistance for cycle n relative to the previous cycle ($n-1$) is defined as $\Delta_n = R_n - R_{n-1}$. Cycles $n = 1$–2 are examples of the build-up of unbackwashed UF resistance, which resulted in positive values of Δ_n. Cycles 3–4 illustrate situations where previously unbackwashed resistance is removed, resulting in negative Δ_n values.

In order to determine the required coagulant dose adjustment, the present control approach is to monitor Δ_n for each filtration/backwash cycle as impacted by the coagulant dose. This information is then utilized to establish the appropriate coagulant dose change as per the logic flow chart of Fig. 2 (additional specific details of the algorithm are provided in flow chart in the Supplementary Materials). As described previously, the condition of $\Delta_n > 0$ signifies an incremental buildup of unbackwashed foulant that adds to the accumulated foulant layer. When the above condition is encountered for the current cycle (n) and the previous one ($n-1$) (i.e., $\Delta_n > 0$ and $\Delta_{n-1} > 0$), the control system first determines the difference in cycle-to-cycle change in UF PB resistance (i.e., Δ_n relative to Δ_{n-1}) with respect to the coagulant dose quantified as $\delta = \frac{\Delta_n - \Delta_{n-1}}{u_n - u_{n-1}}$, where u_n and u_{n-1} are the coagulant doses that impact cycles n and $n-1$, respectively. The parameter δ, which is a measure of the slope of Δ_n vs u_n and termed hereinafter the resistance-dose (RD) factor, is essentially a first order sensitivity of Δ_n with respect to u_n. If $\delta = 0$ this indicates that a cycle-to-cycle change coagulant dose did not produce a measurable difference in the cycle-to-cycle change in UF PB resistance (i.e., $\Delta_n - \Delta_{n-1} = 0$). Therefore, the controller concludes that the system is in the overdose region (with respect to coagulant dose) and thus the coagulant dose is decreased. If, however, it is determined that $\delta < 0$ and where $\Delta_n - \Delta_{n-1} > 0$ (i.e., backwash effectiveness is declining due to the decrease in coagulant dose and/or increased in feedwater fouling potential) then UF operation is determined to be in the underdosed region (since $u_n < u_{n-1}$) with respect to the coagulant dose (see Fig. 2). The controller action is then to increase the coagulant dose in order to improve backwash effectiveness. For the same conditions of $\delta < 0$ if $\Delta_n - \Delta_{n-1} < 0$ (i.e., cycle-to-cycle decrease in the incremental buildup of unbackwashed resistance) given that the increasing coagulant (i.e., $u_n > u_{n-1}$) then the control action is to continue increasing the coagulant dose so as to further improve backwash effectiveness. The condition of $\delta > 0$ can also arise when: (a) $\Delta_n - \Delta_{n-1} < 0$ (e.g., due to improvement in backwash effectiveness and/or improved feedwater quality) while the coagulant dose is decreased (i.e. $u_n < u_{n-1}$). Thus, the appropriate control action is to further reduce the coagulant dose; and (b) Coagulant dose is increasing $u_n > u_{n-1}$ but the incremental buildup of unbackwashed UF is rising, (i.e., $\Delta_n - \Delta_{n-1} > 0$) which suggests that the coagulant dose is too low and thus the control decision is to increase the coagulant dose.

It is generally expected that the accumulated unbackwashed fouling will increase over the period of UF operation (i.e., $\Delta_n > 0$). However, it is also possible for the UF PB resistance to decrease (i.e., $\Delta_n < 0$) under certain conditions (i.e., when previously unbackwashed foulant is removed). The logical control action is to keep the coagulant dose unchanged. Here we note that, in principle, one can employ a conservative control action by decreasing the coagulant dose once the trend of $\Delta_n < 0$ persists for a prescribed number (m) of cycles. It is noted that in the situation where $\Delta_n > 0$ and where the previous performance was such that $\Delta_{n-1} < 0$, a control action to change the coagulant dose must be undertaken to avoid a situation where δ cannot be calculated (i.e., since potentially $u_n = u_{n-1}$); a conservative control action is to reduce (rather than increase) the coagulant dose so as to avoid inadvertent overdosing.

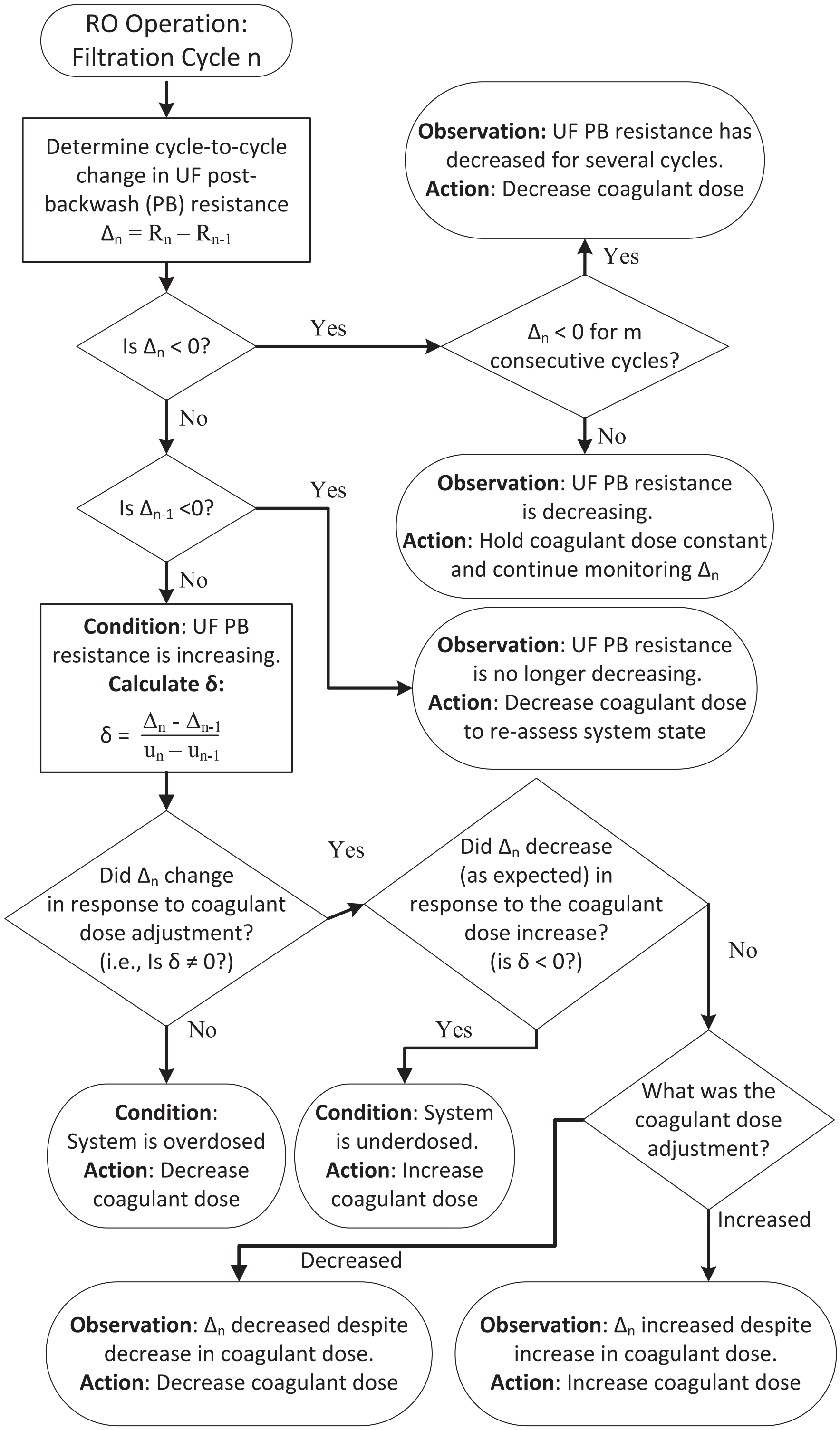

Fig. 2. A flow diagram of the self-adaptive coagulant control logic. Upon completion of a given filtration cycle n, the cycle-to-cycle change in UF resistance (Δ_n) is determined to establish the appropriate control action.

2.3. Coagulant dose controller

The control strategy as described in Section 2.1 was implemented as a coagulant dose controller shown schematically in Fig. 3. In this control scheme, the coagulant dose change that may be required for a new cycle $(n+1)$ is determined based on information regarding the impact of the dose change on UF PB resistance as quantified by Δ_n, u_n and δ. It is noted that in a practical setting, inevitable process variability and sensor noise must be considered with respect to establishing the condition for δ being above, below or at zero. Accordingly, in the present coagulant controller implementation a threshold ε is introduced such that when $\delta < -\varepsilon$, $-\varepsilon < \delta < -\varepsilon$ or $\delta > \varepsilon$ the RD factor (Section 2.2) is considered negative, vanishingly small (i.e. ~0) or positive, respectively.

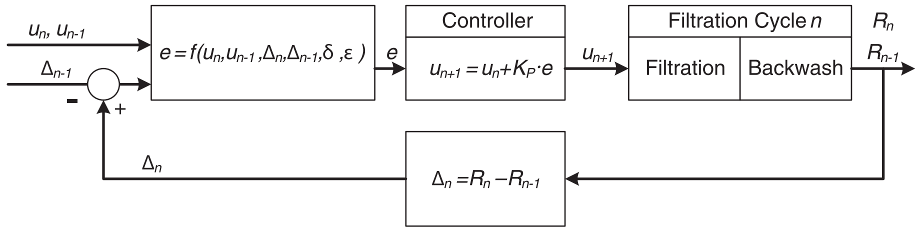

Fig. 3. Illustration of the control system for a self-adaptive coagulant dose controller as per Eqs. (2) and (3).

The control algorithm is specified as per the following relation:

$$u_{n+1} = u_n + K_P \cdot e(u_n, u_{n-1}, \Delta_n, \Delta_{n-1}, \delta, \varepsilon) \tag{2}$$

in which K_P is the proportional gain (i.e., $K_P > 0$) and the function e takes on the values of +1, −1 or 0 corresponding to the control action of coagulant dose increase, decrease or no-action based on the categories described in Section 2.1,

$$e(u_n, u_{n-1}, \Delta_n, \Delta_{n-1}, \delta, \varepsilon) = \begin{cases} 1. & 0, & \text{if} & \Delta_n < 0 \\ 2. & -1, & \text{else if} & \Delta_n \geq 0 \& \Delta_{n-1} < 0 \\ 3. & +1, & \text{else if} & \delta < -\varepsilon \\ 4. & -1, & \text{else if} & -\varepsilon \leq \delta \leq \varepsilon \\ 5. & \text{sgn}(u_n - u_{n-1}), & \text{else if} & \delta > \varepsilon \end{cases} \tag{3}$$

in which conditions 1 and 2 are for cases when the condition of $\Delta_n < 0$ or Δ_{n-1}, while conditions 3–5 apply when $\Delta_n > 0$ (Section 2.1, Fig. 1). The proportional gain, K_P, which is the incremental dose change set by the controller, can be tuned with initial UF field performance data with respect to coagulant dose (Section 4.1). It is critical for the proportional gain to provide sufficient incremental coagulant dose increase that will materialize in observed change in UF backwash performance. A reasonable value for K_p can be established based on series of short-term UF filtration/backwash tests at different coagulant dose as detailed in Section 4.1. If needed, K_P can be refined throughout the course of UF operation based on the history of variation of UF backwash effectiveness with coagulant dose, along with sensor input regarding feed water quality (i.e., turbidity, fluorescence).

3. Experimental

3.1. UF-RO system

The present approach to UF operation with real-time control of UF coagulant dosing was demonstrated in the operation of an integrated seawater UF-RO plant (Fig. 4) having permeate production capacity of 45.4 m^3/day (12,000 gal/day). The UF pre-treatment unit consisted of three multi-channel hollow-fiber (inside-out) UF elements (50 m^2 each; Dizzer 5000 +, Inge, Greifenberg, Germany). Each element was housed in a module that enabled inlet for feed or backwash outlet at either the module bottom or top. The UF unit was directly integrated with the RO desalination unit and was backwashed using the RO concentrate [31]. Raw feed water to the UF unit was first filtered using a self-cleaning 200 μm screen filter (TAF-500, Amiad, Mooresville, NC) installed upstream of the UF unit. In-line coagulant dosing into the UF feed line was achieved using a dosing pump (DDA, Grundfos, Downders Grove, IL). While the approach presented in the present study is not specific to the coagulant used, Ferric Chloride ($FeCl_3$; Gallade Chemical, Santa Ana, CA) was selected given its widespread use for filtration pre-treatment [47].

A centrifugal low-pressure UF pump (XT100 SS, 5 hp., Price Pump, Sonoma, USA) with VFD control (VLT AQUA Drive FC 202, 4.0 kW, Danfoss, Nordborg, Denmark) served for both delivering the water feed to the UF unit and for directing the UF filtrate to the RO feed pump. UF backwash was achieved with the RO concentrate delivered directly from the RO unit also making use of two hydraulic accumulators (C111ND, Blacoh Fluid Control, Riverside, CA, USA). The above backwash strategy as described in detail in [31] eliminates the need for both backwash storage tank and UF backwash pump. UF-RO system was equipped with a network of various sensors (conductivity, pH, temperature, turbidity, and flourometer), flow meters, and pressure transducers interfaced with an embedded controller (cRIO-9022, National Instruments, Austin, TX USA) and data acquisition system. Real-time water quality data of the feed water was provided through sensors (chlorophyll *a*, turbidity) equipped in the feed line.

The pilot plant was deployed at the NAVFAC Seawater Desalination Test Facility in the Naval Base Ventura County (Port Hueneme, CA, USA). Raw seawater feed was pumped from an open-sea intake through a strainer to the pilot plant. Feed salinity (33,440–36,800 mg/L total dissolved solids) and pH (7.5–8.2) varied within a relatively narrow range; however, variations of the feed total suspended solids (0.1–5.2 ppm), turbidity (0.4–14 NTU), and temperature (11.2–19.7 °C) were significant. The feed pretreatment system (200 μm screen filter and UF) provided water of turbidity <0.1 NTU which was sufficiently below the recommended maximum limit for RO desalting. Field tests included: (a) determination of the impact of step changes in coagulant dose on UF fouling and backwash effectiveness, (b) demonstration of the

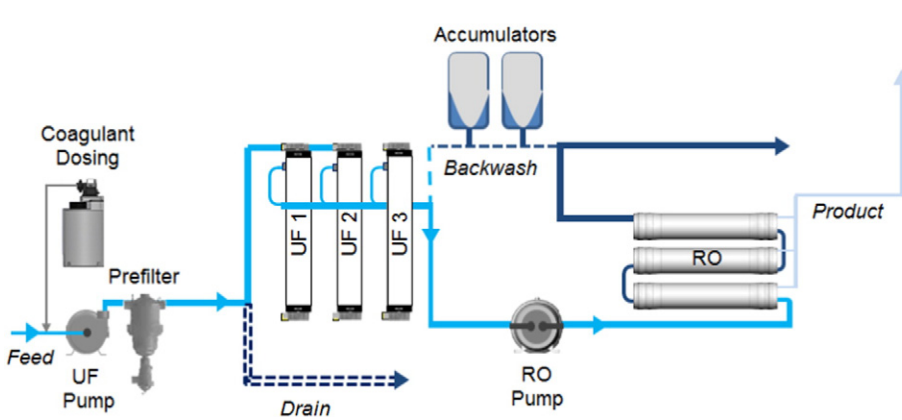

Fig. 4. Process diagram of integrated UF-RO pilot plant. RO concentrate is used as the UF backwash water source.

controller's ability to self-adjust the coagulant dose so as to maintain effective UF filtration and backwash during a period of changing feed water quality conditions, and (c) demonstration of the controller's ability to reduce coagulant consumption.

3.2. Field studies and demonstration of coagulant dose control strategy

For the duration of this study, the UF system was operated in a self-adaptive mode whereby backwash was triggered based on a maximum allowable resistance of $1.36 \cdot 10^{11}$ m^{-1} as described in a previous study [31] with a typical filtration cycle being about 16–22 min. It is noted that the UF modules were operated in dead-end filtration mode and given that UF backwash was with the RO concentrate, UF recovery was maintained at 100%. The UF filtration resistance was recorded at a frequency of 1 Hz. The UF PB resistance for a given cycle n (i.e., the initial UF resistance for cycle $n+1$) was taken as the average of the first 60 data points post-backwash. UF backwash was accomplished sequentially such that when one membrane module was being backwashed, the other two remained in filtration mode, but with increased operational flux in order to ensure that the RO system was provided with uninterrupted feed flow at the prescribed level [31]. Filtration with the UF modules (positioned in the vertical configuration) was also alternated between top filtration (i.e., UF module fed from top) and bottom filtration (i.e., UF module fed from bottom). The UF PB resistance used by the controller was then averaged over eighteen complete filtration/backwash cycles (i.e., consisting of three sets of sequential filtration/backwash for the three UF modules).

Pilot plant experiments were first carried out (Section 4.1) with the objective of arriving at a preliminary quantification of the impact of coagulant dose (0–4.9 mg/L Fe^{3+}) on the cycle-to-cycle change in UF PB resistance (Δ_n) (Section 2.1). The pilot plant was operated at feed flow rate of 75.7 L/min with the UF filtration flux being 15.1 L/m^2 h and with self-adaptive backwash triggering along with pulse backwash as described in [31]. These short-term (i.e., each of 5–6 h duration) tests were conducted in order to establish the existence of the coagulant underdosed and overdosed regions and the control action thresholds for establishing whether a change in Δ_n can be considered to be significant (Section 2.2). Subsequently, a series of field tests were conducted with UF operation at two different constant coagulant doses (1.9 and 4.1 mg/L Fe^{3+}). These were followed by a series of field demonstrations (i.e., duration of 70–140 h) of the effectiveness of UF operation with real time coagulant dose control.

4. Results & discussion

4.1. Coagulant dose regimes and coagulant controller tuning

The impact of coagulant dose on the change in UF PB resistance (Δ_n) was evaluated in a series of short-term experiments (Fig. 5) revealing, consistent with previous coagulation studies [40], the existence of: (a) an underdosed (i.e., low coagulant dose) region, where Δ_n decreases linearly with respect to coagulant dose, and (b) an overdosed (i.e., high coagulant dose) region where Δ_n is invariant with respect to coagulant dose.

Based on the filtration runs at different coagulant doses, the value of Δ_n at a given dose (obtained from multiple runs) was determined within a standard deviation of $\sigma = 1.128 \cdot 10^{-10}$ m^{-1}. A change in Δ_n equivalent to σ in the underdosed region (Fig. 5) would be expected to be due to a coagulant dose change of 0.241 ppm Fe^{3+} (Fig. 5). Therefore, the controller proportional gain, K_P, was set to the above value. A significant change in backwash effectiveness is considered to have occurred if the change in Δ_n relative to Δ_{n-1} is such that $|\Delta_n - \Delta_{n-1}| > \sigma$ and where this change occurs due an incremental dose change of K_p. Accordingly, the RD factor threshold (Eqs. (2) and (3)) is set to $\varepsilon = \sigma/K_P$. In principle, one can establish a strategy of refining K_p as feed water quality varies and long-term performance data are accumulated (i.e., gain

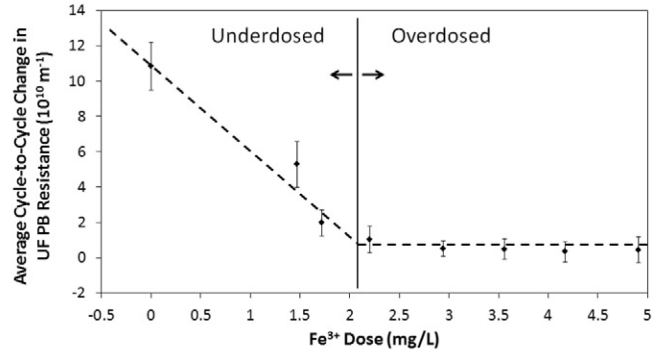

Fig. 5. The averaged cycle-to-cycle change in UF PB resistance (Δ_n) with respect to coagulant ($FeCl_3$) dose. At low coagulant dose, Δ_n decreases with increasing coagulant dose. Above a critical dose of about 2.1 mg/L Fe^{3+}, Δ_n is insensitive to further increase in coagulant dose.

scheduling). It is stressed that such an approach, however, will not change the essence of the controller but can serve to increase or decrease the rate at which the coagulant dose adjustment responds to changes in UF backwash effectiveness. In the current study, a K_p that is sufficiently low, but adequate for producing a measurable change in Δ_n (i.e., when in the underdosed region), was selected for a conservative UF coagulant dose adjustment in order to avoid unintended overshoot of coagulant dose.

4.2. Impact of coagulant dose on continuous UF/RO operation

The impact of a coagulant dose on UF performance was initially evaluated over a 10-day field operation for which water turbidity and chlorophyll varied as shown in Table 1. The pilot plant was operated at UF average module filtration flux of 15.1 L/m^2 h (overall UF feed flow rate of 76 L/min), with the RO unit operating rate at recovery of 30%. Self-adaptive backwash triggering was implemented as described previously [31]. During the first 90 h, at constant coagulant dose of 1.9 mg/L Fe^{3+} to the UF feed, noticeable UF and RO performance deterioration was encountered (Fig. 6). UF membrane resistance increased by 38% relative to the beginning of operation, while RO membrane permeability decreased by 8%. At $t = 90$ h the coagulant dose was increased to 4.1 mg/L Fe^{3+} (i.e., a dose level utilized in a previous long-term desalination study at the same location [31]) and a dramatic performance improvement was observed for both the UF and RO units. Backwash effectiveness improved as indicated by UF resistance decreasing, within 20 h, to a level of only 12% above the initial value; the above UF performance improvement is attributed to removal of some of the previously unbackwashed UF foulants. UF performance at the higher coagulant dose remained relatively stable for the remainder ~8 days of the field test illustrating the well accepted knowledge base that proper coagulant dose is critical to ensuring robust UF and in turn RO operations. It is emphasized that at the above high (constant) coagulant dose, and with variability of field water source quality and absent coagulant dose control, UF operation was likely (and unnecessary) in the overdosed region (Fig. 5) over portions of the test period.

4.3. Effectiveness of self-adaptive coagulant dosing strategy

In order to demonstrate the self-adaptive coagulant dosing strategy via the coagulant dose controller (Section 2), four consecutive field tests

Table 1
Source water turbidity and chlorophyll *a* during the test period.

Water quality	Average	Standard deviation	Range
Turbidity (NTU)	2.98	±2.44	0.29–83.26
Chlorophyll *a* (RFU)	74.6	±15	9.7–269.1

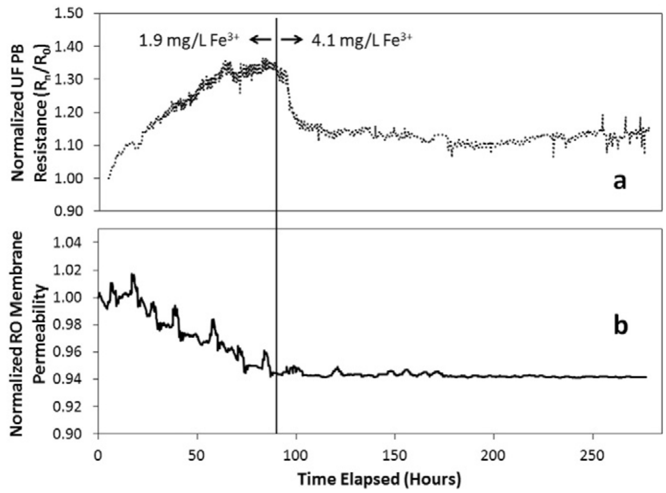

Fig. 6. (a) Normalized UF PB resistance with respect to initial UF resistance (R_0), and (b) normalized RO membrane permeability (i.e., normalized with respect to initial RO membrane permeability) during two operational periods: (i) UF filtration with coagulant dose of 1.9 mg/L Fe^{3+} demonstrating increased UF resistance and decline in RO membrane permeability, and (ii) At hour 90, the coagulant dose was increased to 4.1 mg/L Fe^{3+} leading to improved UF performance (i.e., reduction in UF resistance) and stable RO membrane permeability. UF system operated at average flux of 15.1 L/m^2 h.

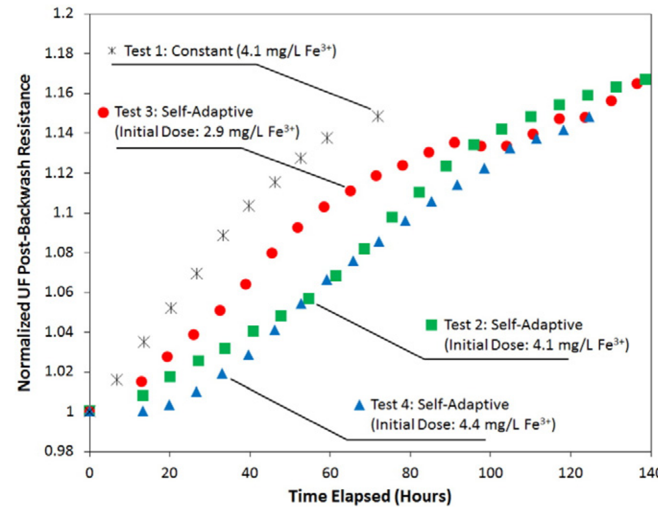

Fig. 7. Progression of UF post-backwash resistance (equivalent to initial UF cycle resistance) comparing self-adaptive (at different initial coagulant dose) and constant coagulant dosing strategies. Post-backwash UF resistance is normalized with respect to the initial run value.

of 70–140 h duration were carried out (Table 2) with the UF system operating at a flux of 15.1 L/m^2 h and RO system seawater desalting at recovery of 30%. The initial coagulant dose for three self-adaptive coagulation runs (2–4, Table 2) was in the range of 2.9–4.4 mg/L Fe^{3+} and these tests were compared to UF operation at constant coagulant dose of 4.1 mg/L Fe^{3+}. The range of water quality in terms of chlorophyll *a* and turbidity during each of the four runs is provided in Table 2 with the detailed time-series given in the Supplementary Materials (Fig. 9, Figs. S4–S6).

UF operation at constant coagulant dose (Run 1) resulted in increased UF PB resistance that was measurably above that for the self-adaptive coagulant dosing (Fig. 7). For example, after 60 h of operation the UF PB resistance increase for constant coagulant dose operation was ~13% above the initial UF resistance (i.e., constant dose operation at 4.1 mg/L Fe^{3+}) compared to ~7% increase for self-adaptive dosing also at initial dose of 4.1 mg/L Fe^{3+}. While the above improvement may seem small, it is important to note that the ranges of coagulant dose for the self-adaptive Runs 2–4 were 2.2–4.4, 2.5–3.6, and 1.7–5.1 mg/L Fe^{3+}, respectively and resulted in significant reduction in coagulant consumption rate (i.e., by about 12%–29%, shown in Table 2). The coagulant dose was adjusted by the controller as water quality varied over the course of the different field tests (Fig. 9, Figs. S4–S6 Supplementary Materials) which in turn impacted the rate of UF fouling and backwash effectiveness. UF operation with self-adaptive coagulant dosing led to superior UF performance, relative to constant coagulant dosing (i.e., expected operation duration before required CIP increased by ~57%), and reduced coagulant consumption relative to constant dose operation.

The coagulant controller action is illustrated in Fig. 8 for Run #2 (Table 2) showing incrementally increasing UF PB resistance for the first 55 h (Segment (i) in Fig. 8). For segment (i) the coagulant dose was incrementally decreased as condition $|\delta| \le \varepsilon$ was met (Section 2.2, Eq. (3), Condition 4). Although chlorophyll *a* was relatively high (Fig. 9) during the above period, there was no appreciable change in Δ_n and it is clear that the progressive reduction in coagulant dose did not adversely impact UF performance. In the subsequent operational period (ii) (i.e., $t = 55$–85 h) the cycle-to-cycle change in UF PB resistance increased despite the fact that the source water turbidity and chlorophyll *a* readings did not seem to change with time (Fig. 9) and resulted in a faster rate of increase of UF PB resistance. In period (ii), the conditions $\delta < -\varepsilon$ and $\delta > \varepsilon$ (where $u_n > u_{n-1}$) were encountered and thus the coagulant controller action (Eq. (3), Conditions 3 and 5) was to incrementally increase the coagulant dose; this action ultimately (i.e., toward the end of period (ii)) led to a decline in the rate of cycle-to-cycle change in UF PB resistance (Fig. 8b) which continued essentially throughout period (iii). In period (iii) the conditions $|\delta| \le \varepsilon$ and $\delta > \varepsilon$ (where $u_n < u_{n-1}$) were met and thus the coagulant dose was decreased (Eq. (3), Conditions 4 and 5). Details of the control action for Runs #3 and #4, provided in Figs. S2 and S3 (Supplementary Materials), also demonstrated that the coagulant controller action was to reduce or elevate the coagulant dose in response to the progression of UF backwash effectiveness. The trend in water quality was complex (Fig. 9, Figs. S4–S6) and while a clear correlation with the coagulant controller actions could not be ascertained, the controller clearly enabled stable UF performance. Overall, the series of field tests demonstrated that relying on the cycle-to-cycle change in UF PB resistance (Δ_n) and the RD factor (δ) as a metric of UF backwash effectiveness, as an alternative to using traditional feed water quality sensors (i.e., turbidity, chlorophyll *a* measurements), is a reliable metric for establishing real-time adjustment of coagulant dose and for reducing coagulant use.

Table 2
Field tests of UF operation at constant coagulant dose and self-adaptive coagulant dosing strategy.

Test	Coagulant dosing strategy	Coagulant dose, mg/L Fe^{3+}	Field test duration (hours)	Water quality: Turbidity (NTU)	Water quality: Chlorophyll *a* (RFU)	Coagulant consumption rate relative to Run #1[b]
1	Constant dose	4.1	70	1.05 ± 0.3	151.7 ± 45.3	1
2	Self-adaptive	2.2–4.4 (4.1[a])	140	1.53 ± 0.4	102.9 ± 39.2	0.83
3	Self-adaptive	2.5–3.6 (2.9[a])	123	1.08 ± 0.4	139.1 ± 48.4	0.71
4	Self-adaptive	1.7–5.1 (4.4[a])	124	0.42 ± 0.2	73.3 ± 26.1	0.88

[a] Initial coagulant dose for self-adaptive operation. The coagulant dose is subsequently adjusted as per the determination of the coagulant-dose controller.
[b] The rate of coagulant consumption in Test #1 was 311.6 mg/min. Note: Values expressed in the water quality columns are the averages given along with the standard deviations of sensor readings.

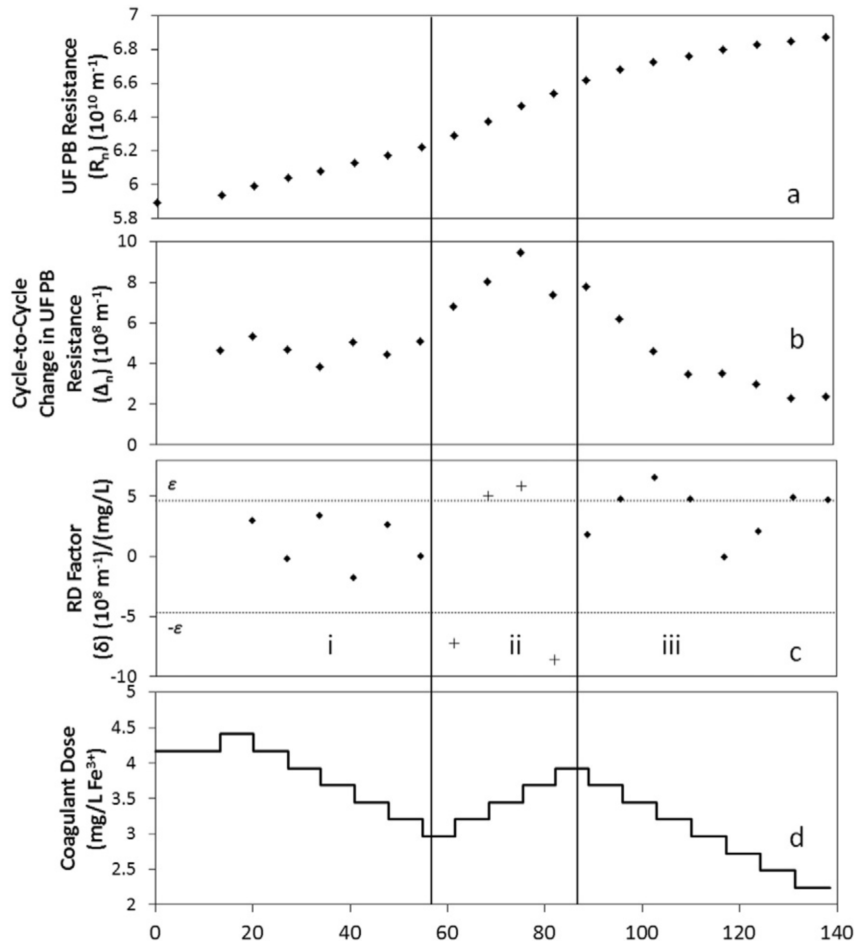

Fig. 8. UF performance and coagulant impact for Run 2 (Table 2) demonstrating the time-profiles for (a) UF PB resistance (R_n), (b) cycle-to-cycle change in PB UF resistance (Δ_n), (c) Resistance Dose (RD) factor (δ) and (d) coagulant dose, in mg/L of Fe^{3+}. The controller gradually decreased the coagulant dose in period (i) since the unbackwashed UF resistance did not significantly change over the test duration. In period (ii) the coagulant dose was increased in response to the rise of the change initial UF cycle resistance. Toward the end of period (ii) and through period (iii) backwash effectiveness increased (i.e., unbackwashed UF resistance buildup decreased) and correspondingly the controller decreased the coagulant dose.

4.4. Performance of coagulant dosing controller during a storm event

During the field study, a looming storm event provided a unique opportunity for a stress test of the UF coagulant dose controller. The integrated UF-RO system was operated for a period of ~7 days at the same total flow rate and UF flux as in the previous short-term tests (Section 4.2). For a period of ~55 h, prior to the storm event, the plant operated with UF coagulant dosing of 3.7 mg/L Fe^{3+}. The UF performance was such that the cycle-to-cycle change in UF PB resistance was reasonably maintained. The storm event led to a significant increase in water source turbidity (~1500%) and chlorophyll *a* (~220%) relative to the pre-storm conditions. Deterioration of feed water quality led to increased UF PB resistance (Fig. 10b), as well as increased Δ_n (Fig. 10c). At ~15 h past the storm onset (i.e., $t = 70$ h), the coagulant controller was activated and reacted to the increase in Δ_n by increasing the coagulant dose for three consecutive filtration cycles (Fig. 10d). This action improved UF performance, despite the ongoing storm event, resulting in decreased cycle-to-cycle change in PB UF resistance. As the UF backwash efficiency improved and the storm subsided, previously unbackwashed UF resistance was removed through UF backwash, leading to the condition $\Delta_n < 0$. The above condition of $\Delta_n < 0$ persisted for the remaining period after $t = 105$ h, (Eq. (3), Condition 1) and thus the coagulant dose was maintained at ~3.9 mg/L Fe^{3+}. The above field test demonstrated that: a) change in Δ_n is indeed a relevant and strong indicator of the impact of varying feed water quality, b) UF performance is sensitive to the coagulant dose, and c) self-adaptive coagulant dosing enabled robust UF performance even under conditions of deteriorating feed water quality.

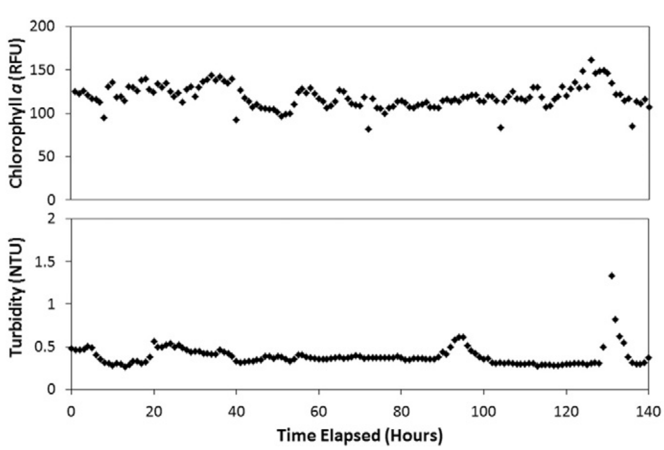

Fig. 9. UF feed water quality during UF Run #2 (Table 2) of self-adaptive coagulant dosing.

5. Conclusions

A novel approach for self-adaptive control of in-line UF coagulant dosing was developed and field demonstrated for integrated UF-RO

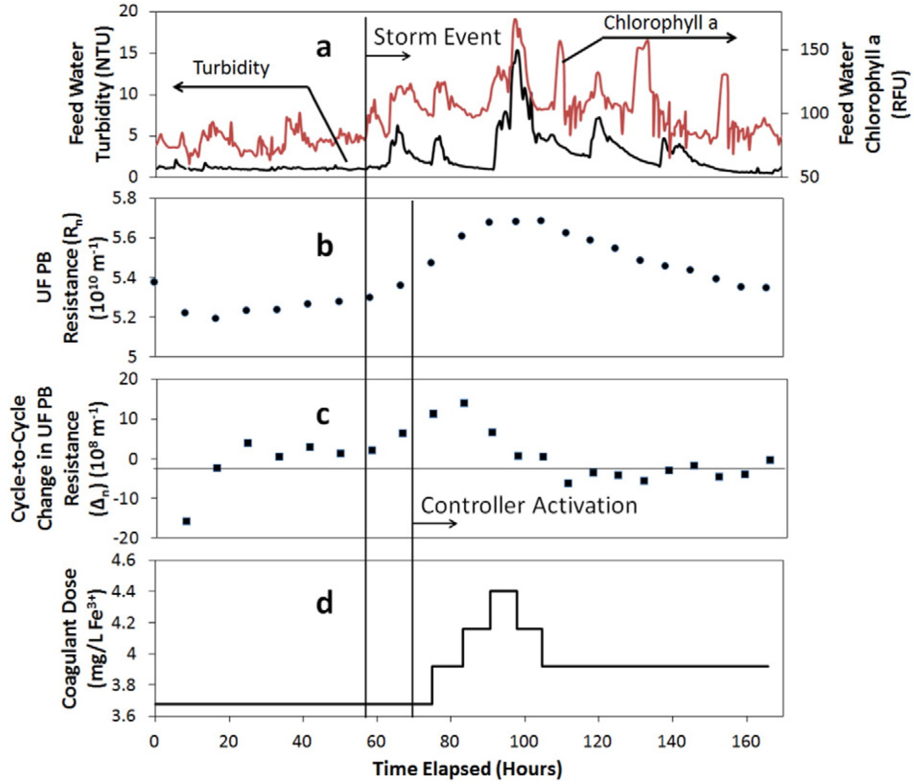

Fig. 10. UF Coagulant dose controller performance for UF operation during a storm event: (a) Feed water turbidity and chlorophyll *a*, (b) UF PB resistance (R_n), (b) cycle-to-cycle change in PB UF resistance (Δ_n), and (d) coagulant dose before and past storm event. UF system was operated at a constant coagulant dose of 3.7 mg/L Fe^{3+} for ~55 h prior to the storm event with the coagulant dose controller activated at t = 70 h.

seawater desalination. A coagulant dose controller was developed whereby UF filtration resistance is tracked in real-time, in addition to evaluating the change in post-backwash (PB) UF resistance in response to coagulant dose adjustments. The objective of the coagulant controller was to adjust the inline coagulant dose to the UF feed so as to reduce the incremental cycle-to-cycle PB resistance change (i.e., Δ_n). Tracking both Δ_n and the rate of change with respect to coagulant dose (labeled as "Resistance–Dose" or RD Factor) enabled the coagulant controller to quantify UF backwash effectiveness and accordingly establish the appropriate coagulant adjustment. The coagulant controller was successfully demonstrated in a UF-RO seawater desalination pilot plant with field tests ranging up to eight days over a period of 1 year. Field testing demonstrated that the proposed approach to self-adaptive coagulant dosing, in addition to self-adaptive backwash triggering, can be effective in: (a) reducing coagulant use while ensuring effective UF operation during periods of varying water quality, and (b) potentially reducing the required frequency of CIP. While the present coagulant controller was demonstrated for seawater UF-RO desalination, it is envisioned that the approach can be adapted to inland water UF treatment to provide both stable UF operation and significant savings in coagulant use.

Acknowledgments

This work was funded, in part, through grants by the United States Office of Naval Research (N00014-11-1-0950 ONR and ONR N00014-09-1-1132), the California Department of Water Resources (46-4120 and RD-2006-09), U.S. Bureau of Reclamation (R13AC80025), Naval Facilities Engineering Command (N62583-11-C-0630), and the UCLA Water Technology Research (WaTeR) Center. The authors would like to acknowledge the contributions of Dr. Richard Zhu, Dr. Alex Bartman, and John Thompson in the construction of the pilot. The authors also acknowledge contributions of equipment and materials by Danfoss Sea Recovery (Henrik Wendelboe and Christopher Okada), Inge GmbH (Peter Berg, Martin Heijnen, and Josef Wunram), George Fisher (Rick Hines), and Dow Water & Process Solutions (Michael Kim), Ahlstrom (Rod Komlenic and Denise Russell) for equipment contributions toward construction of the desalination plant. The personnel of the Seawater Desalination Test Facility at the US Naval Base Ventura County (William Varnava, Mark Miller, Paul Giuffrida, and Micah Ing) are also acknowledged for their assistance during the field study. The presented material is based, in part, upon research performed in a UCLA WaTeR Center laboratory renovated through National Science Foundation grant no. 0963183, which is an award funded under the American Recovery and Reinvestment Act of 2009 (ARRA).

Appendix A. Supplementary Data - Self-adaptive cycle-to-cycle control of in-line coagulant dosing in ultrafiltration for pre-treatment of reverse osmosis feed water

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.desal.2016.09.024.

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