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Process benefits of ozone/BAC as pretreatment to membrane-based advanced treatment for direct potable reuse

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ABSTRACT

The state of California, USA, has developed regulations for projects that want to pursue direct potable reuse. One of the most significant requirements is that the treatment train must include ozone and biological activated carbon (ozone/BAC) as pretreatment to a membrane-based treatment train. Ozone/BAC mitigates chemical peaks and diversifies the removal mechanisms of low molecular weight compounds likely to persist in advanced treated water. This paper will present the process benefits of ozone/BAC as pretreatment to the membrane-based treatment train based on testing at a 3,785 m^3/d demonstration facility in San Diego, California, USA. One of the most significant benefits of ozone/BAC pretreatment is the improved water quality that benefits not only the product water produced for potable consumption but also the residual stream that is generated with the implementation of the RO process, commonly known as RO concentrate. This improved water quality originates from TOC reduction which is achieved through a combination of chemical oxidation with ozonation and biological growth in the BAC process that results in reduced operating pressures and chemical use for the membrane systems. These process benefits were quantified to develop an overall water cost comparison between a DPR and an indirect potable reuse train.

Key words: BAC, chemical peaks, cost of water, direct potable reuse, low molecular weight compounds, ozone

HIGHLIGHTS

- Benefits of O_3/BAC for potable reuse are substantial but underappreciated.
- O_3/BAC-MF-RO-UV/AOP treatment train provides a greater degree of public health protection.
- The experimental DPR treatment train operated at lower O&M costs compared to FAT.
- Benefits were quantified for a 30-year basis and show that this train has a similar cost despite higher CAPEX.
- O_3/BAC-based DPR treatment trains are economically viable.

INTRODUCTION

California has large agencies, serving 20 million people, that are planning and developing large-scale potable reuse projects that will be regulated as direct potable reuse (DPR). Significant investments will be made in new treatment processes and pipelines that will total more than $20 billion US. To support the development of these projects, California regulators have been working over the past decade to develop DPR regulations. One of the most significant requirements of the DPR regulatory criteria is a requirement to include ozone and BAC as pretreatment to the membrane-based full advanced treatment (FAT) train, commonly comprised of membrane filtration (MF), reverse osmosis (RO), and ultraviolet light (UV) advanced oxidation process (AOP), that is already in operation at more than a half dozen facilities in California with more than 8 m^3/s (>180 million gallons per day (MGD)) production capacity today. California is currently the second state after Colorado with DPR regulations. In Colorado, ozone/BAC are optional treatment processes in contrast to California but Colorado also requires specific pathogen removal goals. Ozone is specifically identified as an alternative treatment for disinfection and ozone/BAC as an example of an alternative filtration process. Both disinfection processes, whether by ozone or UV, and filtration are required in Colorado for DPR. Other states such as Texas have implemented a case-by-case approval of DPR projects that rely on a blending of purified water with other waters to achieve regulatory approvals. Other past studies considered ozone/BAC as a carbon-based advanced treatment as an alternative to the RO-based treatment trains to avoid generation of RO concentrate waste streams that are challenging for disposal inland and to reduce treatment costs (Gerrity *et al.* 2011; Gerrity *et al.* 2014; Sundaram *et al.* 2020; Vaidya *et al.* 2020; Hogard *et al.* 2021; Teel *et al.* 2022). The growing interest in ozone/BAC can be explained by the successful demonstration of its ability to provide a robust organics removal barrier for a variety of compounds present in wastewater, including compounds of emerging concern (CEC). The organics removal occurs by both ozone and biological filtration, oxidation by ozone, and biological removal of bulk organic matter (Bourgin *et al.* 2018; Sari *et al.* 2020; Sundaram & Pagilla 2020; Zhiteneva *et al.* 2021; Hogard *et al.* 2023).

The requirement for the inclusion of ozone/BAC in California for DPR projects is to enhance the protection of public health. This is based on past research projects that showed these two processes help address a variety of concerns besides potential improvements in the treatability of feed water to the FAT train. For example, the work carried out by the authors during the Water Research Foundation (WRF) Project 4765/Reuse-14-12 resulted in a quantitative microbial risk assessment that demonstrated that a full-scale DPR treatment train employing ozone/BAC-MF-RO-UV/AOP treatment train can reliably meet performance goals and produce water that provides public health protection equivalent to, or greater than, conventional drinking water supplies (Trussell *et al.* 2018). This project utilized routine performance monitoring and performed chemical and viral surrogate challenge tests that assessed the benefits of the enhanced treatment train. This project demonstrated how a combination of treatment redundancy, robustness, reliability, and resilience can ensure DPR safety (Pecson *et al.* 2017; Pecson *et al.* 2018; Tackaert *et al.* 2019). The WRF Project 4991, 'Defining Potential Chemical Peaks and Management Options,' was another recently completed research project that evaluated data from the world largest indirect potable reuse (IPR) facility–Orange County Water District's Ground Water Replenishment System (100 MGD or 4.4 m^3/s) as well as Singapore's Public Utility Board that operates several NEWater (Chew *et al.* 2010; Lefebvre 2018) advanced treatment reuse facilities (combined capacity of 175 MGD or 7.7 m^3/s), as well as results from Pure Water San Diego's demonstration scale facility (1 MGD or 0.044 m^3/s) that has been operating the California regulator proposed DPR train with ozone/BAC (Debroux *et al.* 2021) since 2015. Data from these facilities were used to assess removals of various chemicals by conventional wastewater treatment and advanced treatment to evaluate occurrence of chemical peaks and treatment options. Ozone/BAC was found to provide significant benefits in attenuation of certain types of organics, especially those with lower molecular weight including *N*-nitrosodimethylamine (NDMA), acetone, formaldehyde, and 1,4-dioxane as documented by Tackaert *et al.* (2019). Debroux *et al.* (2021) summarized four key strategies for utilities to 'average' chemical peaks and recommended the use of a balanced approach that includes two or more of these strategies: source control, monitoring, treatment, and blending. Another recent WRF study, project 4832–'Evaluation of CEC Removal by ozone/BAF Treatment in Potable Reuse Applications' evaluated the effectiveness of ozone with biologically active filtration (O_3/BAF)-based treatment trains to address CECs in order to meet compliance with removal performance-based regulations, and to identify and address knowledge gaps with respect to public health (Robinson *et al.* 2023). This project highlighted ozone/BAC as being such an effective treatment to address CECs that non-membrane treatment trains can be safely used for IPR if supplemented by additional treatment steps such as granular activated carbon to meet drinking water standards.

Current DPR projects being pursued in California are most commonly a combined project with some water being delivered as DPR water and other applications defined as IPR with different regulatory requirements because the advanced treated water is not delivered directly to the customers but will first reside in either a large reservoir, or groundwater basin, which serves as an environmental buffer that provides response time and attenuation of any deviations in treatment, or water quality. With the confidence established from the industry's success with IPR facilities, a significant concern facing the water industry today is 'over treating' the water for IPR applications, when the facility is a combined IPR/DPR facility. While many configurations are being considered to provide the additional treatment requirements described by California's DPR regulations, there is currently a gap in understanding the impacts of ozone/BAC pretreatment on the additional cost over the life cycle of these facilities.

The goal of this paper is to provide engineers and researchers with a balanced perspective on the cost implications of incorporating ozone/BAC as pretreatment to a membrane-based potable reuse train. The paper is organized into two parts. Part 1 starts with providing an overview of improvements to feed water quality, enhancements in the performance of membrane systems, optimized control of biological fouling, and overall reductions in operating costs based on previously conducted studies. Part 2 considers a case study of a potable reuse facility currently in a design phase to assess life-cycle costs and compares costs of a membrane-based treatment train with and without ozone/BAC pretreatment. Cost comparison includes a discussion of the differences between capital costs and operation and maintenance (O&M) costs.

MATERIAL AND METHODS

Test facility information: Testing was conducted at Pure Water San Diego's demonstration-scale facility with 1 MGD (0.044 m^3/s) capacity employing a DPR treatment train consisting of ozone/BAC-MF-RO-UV/AOP. Non-disinfected tertiary effluent (fully nitrified, partially denitrified secondary effluent filtered by conventional filter with anthracite media) is fed through a containerized ozone system supplied by Wedeco (Herford, Germany). The ozone generator had a capacity of up to 190 lbs per day (86.2 kg/day) and operated with an applied dose of 8–9 mg/L to achieve 1-log removal of *Cryptosporidium*. Following ozone injection, the water was passed through a serpentine contactor with a hydraulic residence time of approximately 7 min. Following this, the process water was fed into two parallel gravity-fed filters with 6 feet (2 m) of coal-based granular activated carbon (Calgon, Pittsburgh, USA) with a mesh size of 8 × 30. The empty bed contact time was approximately 15–16 min. The third treatment barrier was membrane filtration consisting of microfiltration (MF) and ultrafiltration (UF) systems operated in parallel each with 0.75 MGD (2 m^3/min) capacity. The MF system used 50 UNA-620A modules with 0.1 μm nominal pore size supplied by Pall Corporation (Port Washington, USA). The UF system supplied by H_2O Innovation used 33 HFU-2020 modules supplied by Toray (Poway, USA). The combined filtrate was then fed to two RO trains supplied by Enaqua (Vista, USA). One of the RO trains was a two-stage with a 10:5 pressure vessel array and the other a 3-stage system with a 10:5:3 array. Both RO trains used full-scale sized 8' Toray TMG20D-400 RO elements. RO trains were operated at 85% feed water recovery with a combined capacity of 1 MGD (0.044 m^3/s) to feed a single UV/AOP system supplied by TrojanUV (Ontario, Canada). The UV/AOP system was operated to achieve 0.5-log removal of 1,4-dioxane with a reduction equivalent dose of 850 mJ/cm^2 and 2 mg/L of free chlorine (HOCl). Additional methods and test equipment descriptions were previously reported (Pecson *et al.* 2017; Pecson *et al.* 2018; Tackaert *et al.* 2019). The process flow diagram is shown in Figure 1.

Test conditions: To evaluate exactly what concentrations of chloramines are necessary when ozone/BAC provide membrane pretreatment, over a course of several years, various operating conditions were evaluated in series: (1) variable flux 30–60 gfd (51–102 LMH), no ozone/BAC, chloramines dose of 3 mg/L as Cl_2; (2) testing with ozone/BAC pretreatment, chloramines at 3 mg/L as Cl_2 over flux conditions of 30–72 gfd (51–122 LMH); (3) 60 gfd (102 LMH) flux, ozone/BAC, and chloramines at a reduced dose chloramines dose of 1.2 mg/L; (4) 60 gfd (102 LMH) flux, ozone/BAC with enhanced flux maintenance (EFM) cleans on the ultrafiltration system and intermittent chloramine spikes (up to approximately 4.5 mg/L as Cl_2 for variable duration of 1–8 h) on the RO system. A membrane flux of 60 GFD (102 LMH), a flux well above the typical industry design point, was used for testing the UF system to demonstrate the difference in performance between test conditions 1 and 2. Test conditions 3 and 4 were used to assess whether the operating costs (energy and chemical) can be further optimized as compared to conditions 1 and 2. Operational data were collected daily to track the performance for each treatment process, including power and chemical use.

RESULTS AND DISCUSSION

Table 1 provides analysis results for feed water quality that was collected monthly for a period of 1 year to develop a comprehensive understanding of seasonal variability as well as ozone/BAC performance operating continuously on tertiary treated wastewater. The tertiary effluent was well nitrified and limited nitrification occurred in the BAC filter over this test period.

As shown by Table 1, BAC provided total organic carbon (TOC) removal of 35% on average TOC concentration changes. This level of TOC removal is similar to other studies (Gerrity *et al.* 2011; Gifford *et al.* 2018; Vaidya *et al.* 2020). The effects of the ozone/BAC on the organics are quite remarkable as can be seen in the differences in fluorescence intensities at various locations downstream as shown by Figure 2. Reductions in fluorescence and absorbance are primarily attributed to ozone's oxidation of organics (Wert *et al.* 2009; Gerrity *et al.* 2011; Gerrity *et al.* 2012; Liu *et al.* 2015). Typically changes in

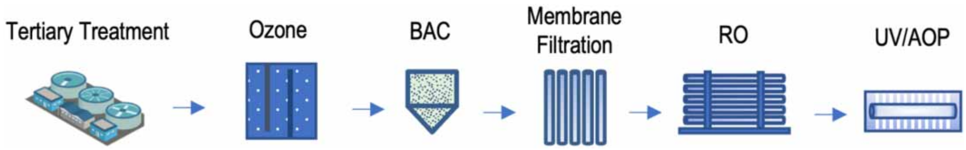

Figure 1 | Process flow diagram of the 1 MGD (158 m^3/h) testing facility in California, USA.

Table 1 | Average (± standard deviation) feed water quality and changes after ozone and BAC treatment ($n = 13$)

Parameter	Units	Tertiary effluent	Ozone effluent	BAC effluent
Total dissolved solids	mg/L	920 ± 111	935 ± 121	927 ± 133
pH	pH	6.83 ± 0.23	6.81 ± 0.16	6.77 ± 0.18
Total alkalinity	mg/L	101 ± 14	100 ± 14	98.9 ± 15.6
Conductivity	mS/m	1,404 ± 85	1,409 ± 82	1,409 ± 80
Total hardness	mg/L	285 ± 43	286 ± 42	286 ± 42
Calcium hardness	mg/L	162 ± 29	162 ± 28	162 ± 28
Bromide	mg/L	0.266 ± 0.06	0.228 ± 0.053	0.260 ± 0.053
Calcium	mg/L	62.3 ± 7.0	59.0 ± 19	61.5 ± 10.4
Chloride	mg/L	241 ± 7.0	242 ± 7.0	242 ± 7.0
Sulfate	mg/L	174 ± 46	175 ± 45	176 ± 46
Orthophosphate as P	mg/L	1.33 ± 0.57	1.34 ± 0.55	1.33 ± 0.57
Total organic carbon	mg/L	7.39 ± 0.41	7.35 ± 0.40	4.80 ± 0.32
Iron	μg/L	65.8 ± 9.6	67.2 ± 8.6	54.5 ± 11.5
Magnesium	mg/L	27.9 ± 3.0	25.8 ± 7.5	27.8 ± 2.9
Sodium	mg/L	161 ± 12	161 ± 13	160 ± 12
Ammonia as N	mg/L	0.054 ± 0.024	0.076 ± 0.033	0.039 ± 0.016
Nitrate as N	mg/L	13.3 ± 1.34	13.3 ± 1.38	13.8 ± 1.43
Nitrite as N	mg/L	0.041 ± 0.050	0.0056 ± 0.0013	0.0051 ± 0.0006
Total phosphorus as P	mg/L	1.94 ± 0.36	1.96 ± 0.33	2.55 ± 1.93
Total nitrogen	mg/L	15.4 ± 1.3	15.2 ± 1.3	15.9 ± 2.3
Silica	mg/L	10.4 ± 2.1	10.4 ± 2.2	10.4 ± 2.1
Aluminum	μg/L	6.9 ± 3.1	6.1 ± 4.2	5.0 ± 2.7
Barium	μg/L	16.8 ± 7.8	16.7 ± 7.4	15.3 ± 6.8
Boron	μg/L	335 ± 15	331 ± 19	333 ± 20
Manganese	μg/L	99 ± 30	85 ± 29	2.58 ± 1.00
Strontium	μg/L	579 ± 174	582 ± 167	572 ± 169

fluorescence can be hard to discern with the naked eye, but not in this case. Figure 3 shows photographs with evident visual differences in the RO concentrate water quality. The removal of organics ahead of the membrane systems leads to improved performance of membrane systems (less fouling) at the same time also improving the water quality of the waste stream (RO concentrate). These benefits were further quantified as discussed in the next section. The ozone/BAC also effectively removes manganese by 97%, which can have a significant impact on long-term membrane life and performance as it can be difficult to eliminate from membrane pores with chemical cleaning solutions.

Membrane filtration performance with ozone/BAC pretreatment

One of the most significant process benefits of incorporating ozone/BAC is the significant reduction in the fouling rate of micro- and ultrafiltration (UF) membranes (Nguyen & Roddick 2010; Hamid *et al.* 2019). This is due to the transformation and partial removal of organic carbon (TOC < 5.0 mg/L as shown in Table 1) by ozone/BAC, which significantly lowers the potential for organic fouling. As shown in Figure 4, the membrane performance is stable and predictable at a membrane flux of 50 gfd (85 LMH), which is higher than a typical tertiary-fed membrane system with a flux of 30 gfd (51 LMH). The UF membranes performed well at 72 gfd (122 LMH) with ozone/BAC pretreatment which is more than double the flux of the system without pretreatment and yet, based on changes in the observed temperature-corrected specific flux (gfd/psi), a lower rate of flux decline was observed when comparing the two test runs. These results at 72 gfd can also be compared with a performance at 41 gfd conditions without pretreatment that showed a more rapid decline in performance with the

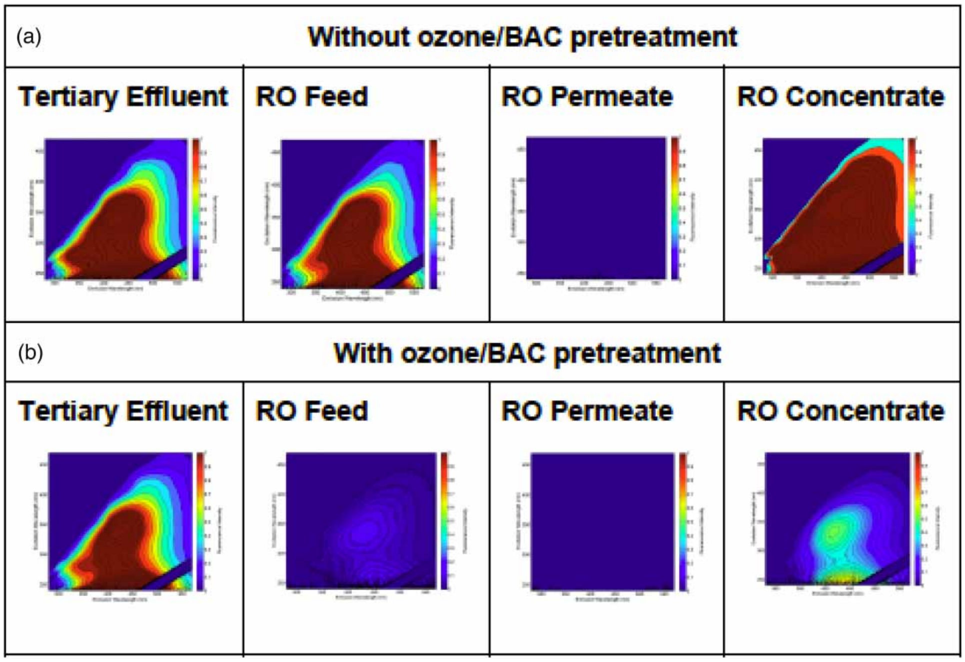

Figure 2 | Changes in fluorescence excitation emission matrices between (a) with no ozone/BAC pretreatment and (b) with ozone/BAC pretreatment at various steps of the advanced treatment train.

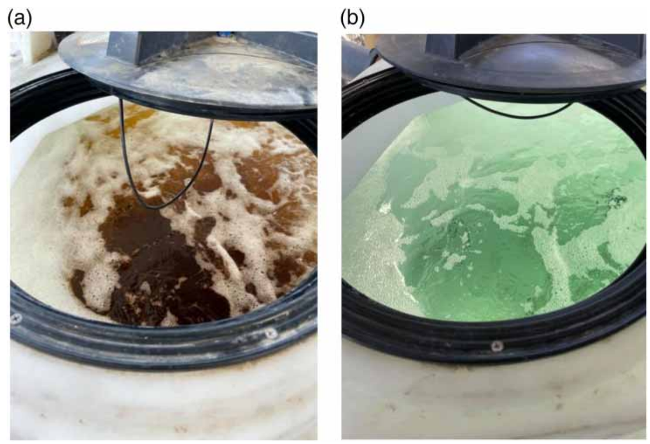

Figure 3 | Photos of RO concentrate from the same treatment train that either had no ozone/BAC pretreatment (a) and (b) with ozone/BAC pretreatment. This was achieved by running advanced treatment with ozone/BAC in bypass.

specific flux dropping down to 2 gfd/psi within 1,000 run hours, while the system ran at 72 gfd with pretreatment for more than 4,500 h with a specific flux above 3.5 gfd/psi. The initial specific flux of approximately 9 gfd/psi (225 LMH/bar) between test runs was achieved by using chemical cleaning of this membrane system with 3,000–3,500 mg/L as Cl_2 sodium hypochlorite solution (typical cleaning for PVDF hollow fiber membranes). It is also important to note that operating at these increased membrane flux rates resulted in high, stable specific flux values that could always be restored with a sodium hypochlorite clean. Additionally, these membranes are not new and have been in service for more than 80,000 h and this is the performance that is observed.

In addition to lowering organic fouling, ozone/BAC also effectively minimizes the potential for biological fouling. This is due to the consumption of assimilable organic carbon (AOC) by the BAC (Table 2) and the elimination of complex (ringed)

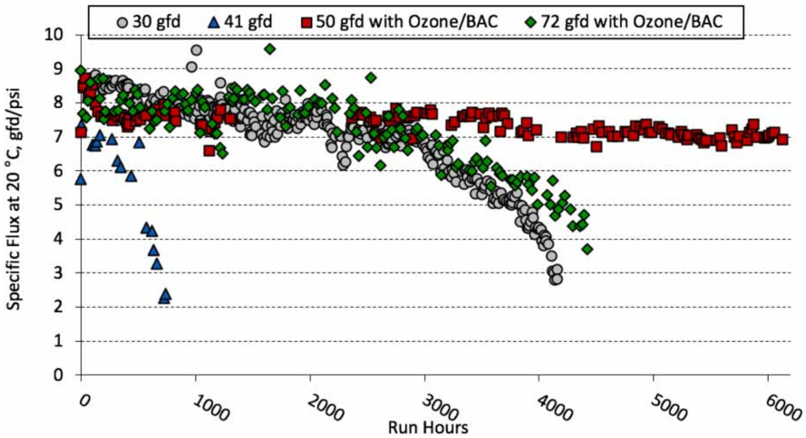

Figure 4 | Changes in specific flux of a ultrafiltration membrane system with and without ozone/BAC pretreatment at various flux, chloramines dosed at 3 mg/L for all conditions. *Note:* GFD, gallons per squared feet per day. 1 GFD = 1.7 litres per m^2 per hour (LMH).

Table 2 | Concentration of assimilable organic carbon (μg/L) before and after ozone/BAC ($n = 7$)

	Tertiary effluent	Ozone effluent	BAC effluent
Average	221	917	190
Minimum	30	800	90
Maximum	620	1,240	450

organics that would normally deposit and adsorb to an RO membrane surface, eventually serving as a food source for opportunistic bacteria that establish biofilms. This combination of eliminating the complex organics (Figure 1(a)) along with reducing the AOC means that the biofouling potential is minimized. As a result, the reliance upon chloramines becomes less important as presented in Figure 5 with the ozone/BAC pretreatment providing the best performance results at an operating flux of 60 gfd (102 LMH) as compared to conditions with and without chloramines and no ozone/BAC pretreatment. The data in Figure 5 are all from the same UF system treating either tertiary effluent in a bypass mode or treating the ozone/BAC effluent with representative water quality provided in Table 1 (tertiary effluent and BAC effluent).

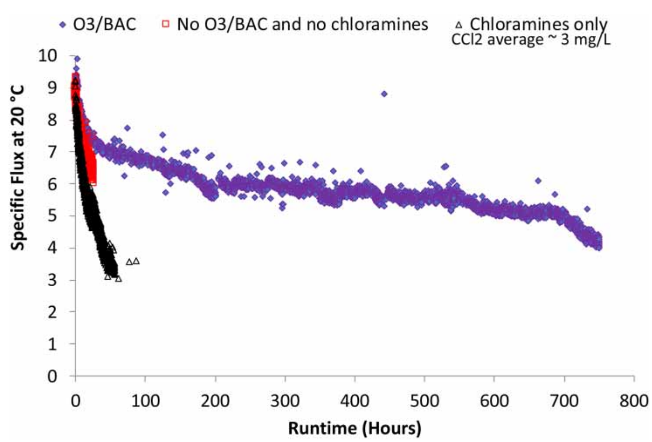

Figure 5 | Changes in specific flux of a UF membrane system with and without chloramines to control biological fouling and with ozone/BAC but without chloramines at 60 gfd (102 LMH). *Note:* Specific flux is in units of gfd/psi. 1 gfd/psi = 24.65 LMH/bar.

The example provided in Figure 5 shows that with the right pretreatment, there is potential to optimize biological fouling control as well as to minimize organic fouling. Based on the results of this study, it was shown that operating with ozone/BAC and no chloramines was feasible for the UF with more than 30 days of operation without requiring a shutdown for a chemical clean. After several consecutive runs, the study found that lower transmembrane pressure could be achieved by introducing weekly maintenance cleans as preventive maintenance. Maintenance cleans are common practice in the water reuse industry and entail a brief recirculation step and soak of 20–30 min with 500 mg/L as Cl_2. The maintenance cleans with sodium hypochlorite provided even better performance than with the use of continuous chloramines and ozone/BAC at a reduced cost. With ozone/BAC pretreatment, the UF operation used 17.5% less power and 30% less chemicals.

The results of these tests have two significant implications. The first is that ozone/BAC allows for a membrane design and operation at a significantly higher flux, which reduces capital costs and footprint. The second is that the ozone/BAC pretreatment allows for a lower operating cost, due to a decreased rate of fouling (lower pumping costs) and less frequent cleaning (lower chemical costs).

Reverse osmosis membrane performance with ozone/BAC pretreatment

Past studies reported positive benefits of pre ozonation and filtration by BAC for reducing fouling rates of reverse osmosis membranes (Stanford *et al.* 2011; Pramanik *et al.* 2015; Yin *et al.* 2020). Here the RO system was evaluated for 3-month test periods at two test conditions to evaluate the power and chemical requirements for controlling organic and biological fouling. Operating without continuous chlorination was again determined to be not only feasible but a significant process enhancement. Chloramines were intermittently used at a frequency of twice a week, once a week, once every 2 weeks, and even once every 4 weeks. Dosing chloramines twice a week for 5–6 h resulted in the lowest power and chemical consumption as compared to the conventional continuous chloramines strategy. However, with ozone/BAC both power and chemical use were 15% lower.

Another important benefit is the reduced chemical exposure to chloramines and the reduced oxidation of RO membranes by chloramines. As shown in Figure 6 membrane aging can vary by the membrane product and can be correlated to exposure of chloramines. Other past studies also reported negative effects of long-term exposure to chloramines (Gabelich *et al.* 2005; da Silva *et al.* 2006; Knoell 2006; Cran *et al.* 2011). The typical RO membrane life is typically determined by either irreversible fouling and/or degradation of RO permeate water quality and typical RO membrane life is 3–5 years. While declines in conductivity rejection are already significant, rejection of specific constituents can be even more dramatic. For example, nitrate rejection may drop to only 60% for some RO membrane products after accumulating just 50,000 ppm h. Considering a typical chloramine concentration of 3 ppm, this equates to less than 2 years. Membrane replacement costs are quite significant (>5.5% of total O&M costs) and therefore extending RO membrane life is of paramount importance. Ozone/BAC

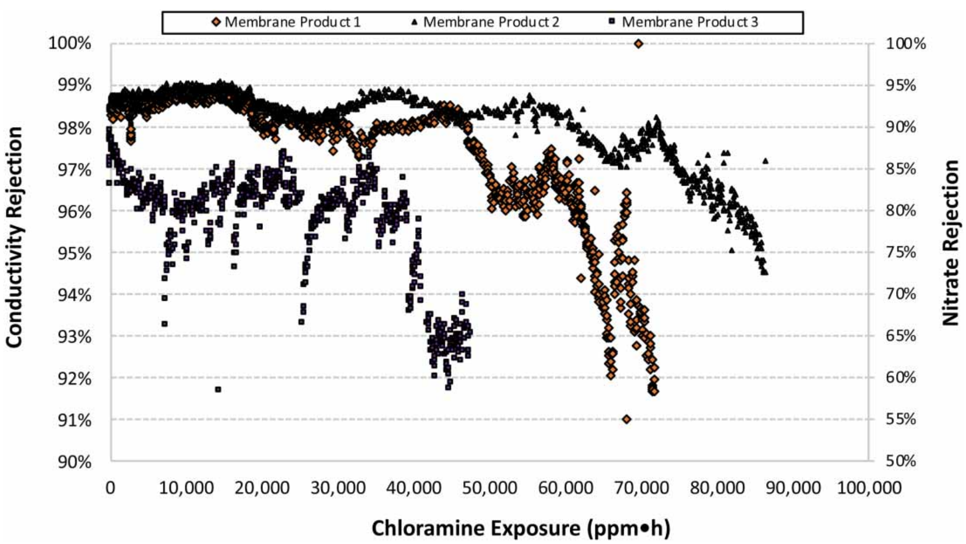

Figure 6 | Changes in conductivity and nitrate rejection for three different commercial RO membranes.

pretreatment significantly improves biological and organic fouling control and incorporating intermittent chloramines (or even operation without chloramines) should lead to an increase in life expectancy. Even assuming two chloramine dosing events per week, the same 50,000 ppm h would take 19 years to accumulate. In addition, because of lower TOC concentration (<5 mg/L) organic fouling is eliminated and as a result, the biofilm growth is also dramatically reduced. These water quality enhancements may allow for further optimization of the RO system with a more aggressive design flux and increased feed water recovery (e.g. > 90%). It is estimated that with ozone/BAC a 5–10% higher feed water recovery may be achieved than without. The test facility is currently undergoing testing at higher recoveries and has achieved 6-week runs without needing a chemical cleaning at 93% recovery (unpublished data).

UV/AOP performance with ozone/BAC pretreatment

With the significant reduction in the reliance on chloramines for biological fouling control (e.g. practically resulting in no chloramines), the UV/AOP system experienced a dramatic performance improvement. First, the power to achieve a target UV dose (mJ/cm^2) dropped as chloramines were turned off due to the fact that monochloramine (NH_2Cl) and dichloramine ($NHCl_2$) are strong absorbers of light at 254 nm. The effect of monochloramine concentration and required power to meet the target UV fluence (dose) of 850 mJ/cm^2 were tested at the 1 MGD scale UV/AOP reactor and shown in Figure 7. While typically chloramine residual is present as a mixture of monochloramine and dichloramine, for simplicity the associated concentration at respective UVT was converted to monochloramine concentration. With no monochloramine the UV transmittance at 254 nm is essentially that of water and at least 99%. Power requirements expressed as electrical energy dose in units of kWh/kgal (1 kgal = 1,000 gallons) are more than double at typical design conditions equivalent to 95% UVT and 4.0 mg/L monochloramine (NH_2Cl) as Cl_2.

Monochloramine and dichloramine at typical concentrations in UV/AOP feed (e.g. 1–3 mg/L as Cl_2) also impose significant scavenging demand on hydroxyl radicals as evidenced by their rate constants of $k_{OH} = 5.1 \times 10^8$ and 2.6×10^8 $L{\cdot}mol^{-1}{\cdot}s^{-1}$, respectively, as shown by Figure 8 (Poskrebyshev *et al.* 2003). The modeled removal of 1,4-dioxane shown in Figure 8 is based on 1,4-dioxane rate constant $k_{OH} = 2.4 \times 10^9$ $L{\cdot}mol^{-1}{\cdot}s^{-1}$ (Anbar *et al.* 1966), UV fluence (dose) of 850 mJ/cm^2, hypochlorous acid (HOCl) concentration of 2.0 mg/L as Cl_2, at various concentration of monochloramine (NH_2Cl) and dichloramines ($NHCl_2$).

It was estimated that for every 1 mg/L as Cl_2 of chloramines residual present in RO permeate an additional 0.05 kWh/kgal (0.0132 kWh/m^3) was needed to maintain the same level of UV dose to achieve disinfection and advanced oxidation process based on modeled removal of 1,4-dioxane at various concentration of monochloramine. Thus, when operating without

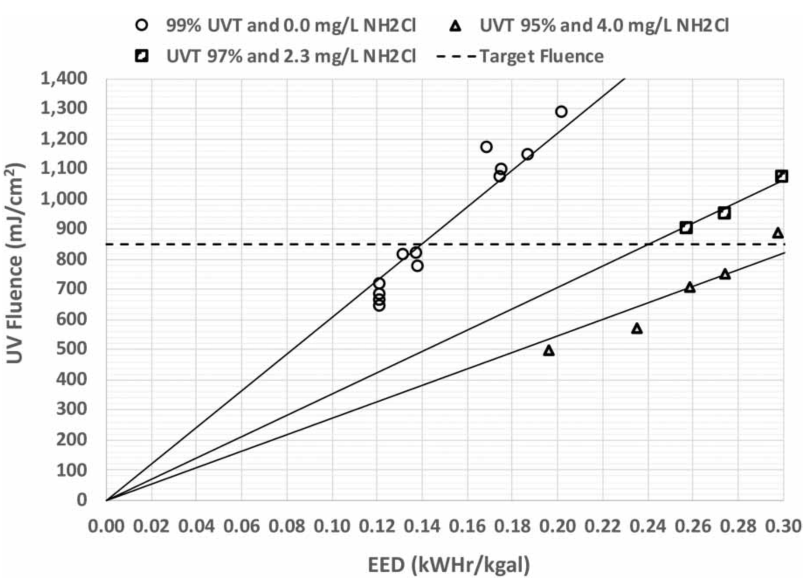

Figure 7 | Electrical energy dose (EED) for a target UV fluence (dose) of 850 mJ/cm^2 at various concentrations of monochloramine and associated UVT. Note 1 kWh/kgal = 0.264 kWh/m^3. Solid lines are fitted trendlines (forced through zero intercept with axis).

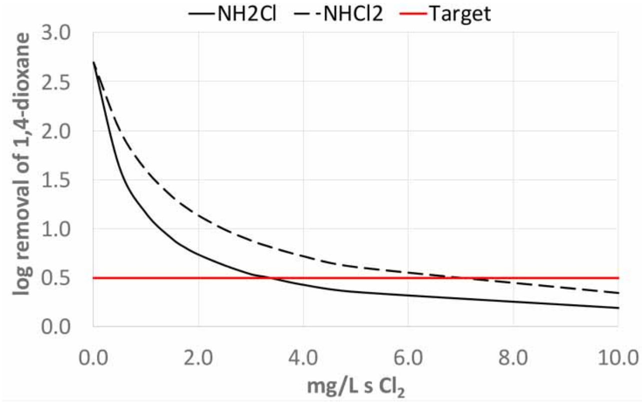

Figure 8 | Predicted removal of 1,4-dioxane as a function of monochloramine and dichloramine concentrations at UV fluence (dose) of 850 mJ/cm^2, HOCl concentration = 2.0 mg/L as Cl_2, background scavenging rate of 5,353 s^{-1}.

continuous chloramines, UV/AOP power consumption will be reduced by 55%. Incorporating the intermittent chloramine strategy, the total power reduction is still significant at 41% on average.

Full-scale costs comparison

An opinion of probable total capital cost (capital cost) was prepared for two treatment train alternatives: one for an IPR (Figure 9) and the other for a DPR (Figure 10) scenario delivering the same product flow of 10.0 MGD (26.3 m^3/min). Total capital cost represents the estimated cost to design, construct, and implement this capital project and consists of 'Construction' and 'Non-Construction' cost components. Figures 9 and 10 provide the process flow diagrams for the IPR and DPR trains, respectively. Table 3 presents the two case studies' design criteria assumptions.

Table 4 provides unit cost assumptions that were used to calculate operating and maintenance (O&M) costs for IPR and DPR trains based on the flows and chemical dosing provided in Table 3. Table 5 provides an estimate of the total annual operating and maintenance O&M costs for the two treatment trains. As discussed in the first part of the paper, the DPR treatment relies on a lower average chloramine dose, while MF and RO membrane systems operate at lower energy, higher feed water recoveries, and lower cleaning frequencies. Due to reduced background chloramines, the power use by UV/AOP is dramatically lower as well as benefits from upstream BAC that lowers the overall TOC in the product water as well as constituents such as NDMA that allows UV/AOP to target a lower UV dose as noted in Table 3.

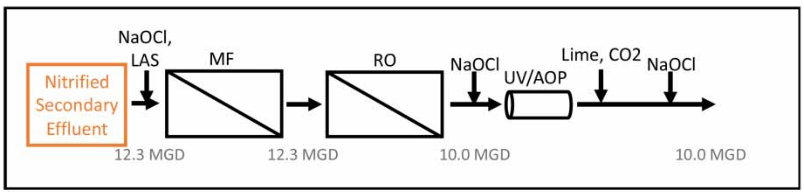

Figure 9 | Flow diagram for an IPR-type treatment train.

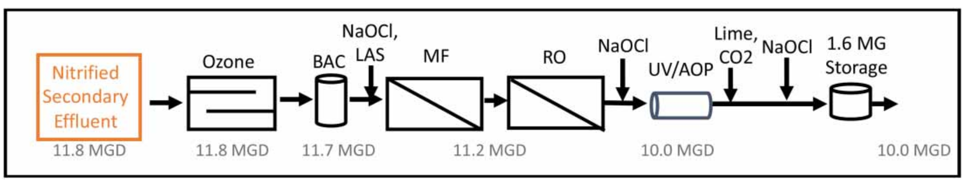

Figure 10 | Flow diagram for a DPR-type treatment train.

Table 3 | Design criteria assumptions for IPR and DPR treatment trains

Parameter	IPR train	DPR train
Ozone flow (MGD)	**N/A**	**11.8**
Ozone dose	N/A	10 mg/L
Sodium bisulfite dose	N/A	2.4 mg/L
Feed water pressure	N/A	10.8 psi (0.75 bar)
BAC flow (MGD)	**N/A**	**11.7**
Feed water recovery	N/A	99%
Loading rate	N/A	3.5 gpm/feet^2 (0.14 m)
Backwash frequency	N/A	1/week
Backwash high rate	N/A	15 gpm/feet^2 (1.0 m/min)
Backwash low rate		5 gpm/feet^2 (0.2 m/min)
Air scour rate	N/A	4 scfm/feet^2 (1.22 m/min)
MF filtrate flow (MGD)	**12.3**	**11.2**
Feed water recovery	95%	96%
Flux	25 GFD (42.5 LMH)	50 GFD (85 LMH)
MF feed pressure	15 psi (1.0 bar)	7.5 psi (0.5 bar)
EFM frequency	3 days	None
CIP frequency	1 month	6 months
Membrane replacement frequency	10 years	10 years
RO permeate flow (MGD)	**10.0**	**10.0**
Feed water recovery	85%	89%
Flux	8 gfd (13.6 LMH)	10 gfd (17 LMH)
CIP frequency	3 months	12 months
Feed water pressure	150 psi (10.3 bar)	120 psi (8.3 bar)
Membrane replacement frequency	5 years	8 years
UV/AOP flow (MGD)	**10.0**	**10.0**
Oxidant dose (HOCl) as Cl_2	2.0 mg/L	1.0 mg/L
Dose	1,500 mJ/cm^2	850 mJ/cm^2
Lamp replacement frequency	1.8 years	1.8 years
Average chloramines dose	**4.0 mg/L**	**1.0 mg/L**
Post treatment		
$Ca(OH)_2$ dose	70 mg/L	70 mg/L
CO_2 dose	2.5 mg/L	2.5 mg/L

Bold values indicates separation between process steps and indicate flows for each process.

As may be expected, the capital costs are higher for the DPR treatment train. However, the cost per acre-foot is comparable for the IPR and DPR trains when the benefits to water quality are considered in the operating costs for the downstream membrane and UV systems. Although for a hypothetical 10 MGD (26.3 m^3/min) facility the combined construction costs were estimated to be approximately $29 million higher for the DPR treatment train as shown in Table 6, the O&M costs were more than $1.4 million less for the DPR configuration due to the water quality enhancements on downstream process performance. The capital costs included both construction costs and non-construction costs. Construction costs included equipment costs, electrical, mechanical, buildings, and any additional concrete structures (e.g. ozone contactor) and 25% contingency. Non-construction costs include estimates of typically required liability insurance, builder's risk insurance, contractor overhead, trade contractor profit and bond. Total capital costs were annualized over a 30-year period, which is the typical minimum life expectancy for major system components.

Table 4 | O&M unit cost assumptions

Parameter	Unit cost
Cost of electricity	$0.20/kWh
Ozone generation (10% wt O_3), cooling, injection	7.6 kWh/lbs
Liquid oxygen for ozone generation	$5.95/100 lbs
38% sodium bisulfite to quench residual O_3	$1.51/gallon
12.5% NaOCl for chloramines, UV/AOP, and MF CIP	$0.80/gallon
40% $(NH_4)_2SO_4$ for chloramines	$1.50/gallon
50% citric acid for MF and RO CIP	$5.0/gallon
25% NaOH for RO CIP	$1.50/gallon
93% sulfuric acid pH depression and RO CIP	$1.85/gallon
Anti-scalant scale control	$8.65/gallon
$Ca(OH)_2$ for post treatment	$17.87/2,000lbs
CO_2 for post treatment	$2.86/100 SCFM
MF module replacement cost	$3,000/ea
RO element replacement cost	$400/ea
UV lamp replacement	$415/ea

Table 5 | Estimate of annual O&M costs

Process	IPR train	DPR train
Ozone	$ –	$ 1,161,017
BAC	$ –	$ 42,400
Chloramines	$ 220,600	$ 73,500
MF	$ 1,779,400	$ 406,800
RO	$ 3,441,200	$ 2,822,000
UV/AOP	$ 867,600	$ 364,400
Product water stabilization	$ 838,200	$ 822,000
Annual O&M costs	$ 7,147,000	$ 5,692,100
Cost per AFY	$ 638	$ 508

AFY – acre-feet/year.

The lower O&M costs of $1.4 million per year for the DPR train are counterintuitive and the savings are high enough for this size of the facility to off-set the annualized increased capital cost associated with a DPR train. This finding highlights that the potential implications for the water industry are significant. First, this analysis illustrates that having ozone/BAC as part of a DPR train while adding significant capital and some additional O&M cost actually provides some enhancements to the water quality that reduce the capital costs of the downstream membrane and UV systems, allowing them to be more compact while producing the same volume of water and further enhancing water quality. Secondly, the downstream processes run more efficiently with lower average pressures and much fewer chemical cleanings. As a result, there is a reduction in chemical consumption due to the effective reduction in organics concentrations provided by the Ozone/BAC pretreatment that reduces the potential for biological fouling, and organic fouling, and adds to our treatment capabilities for low molecular weight compounds that have challenged membrane advanced treatment facilities in the past, such as NDMA. What the cost analysis did not consider is the increased reliability for public health protection that is provided by the addition of ozone/BAC to this treatment train. With ozone/BAC, the DPR treatment train's robustness and redundancy is enhanced with new treatment

Table 6 | Summary of capital and O&M costs

Description	IPR train	DPR train
Average yield (MGD)	10.0	10.0
Average yield (acre-feet/year, AFY)	11,200	11,200
Total construction cost	$ 122,656,600	$ 140,774,000
Non-construction cost	$ 73,594,000	$ 84,464,400
Total capital cost	$ 196,250,600	$ 225,238,000
Annualized capital costs[a]	$ 10,012,600	$ 11,491,500
Cost per AFY	$ 894	$ 1,026
Annualized O&M costs	$ 7,147,000	$ 5,692,100
Cost per AF	$ 638	$ 508
Annualized capital + O&M Costs	$ 17,159,000	$ 17,154,000
Cost per AFY	$ 1,532	$ 1,531

[a]Annualized capital costs are calculated using a 3% interest rate over a 30-year period.

processes that address toxic organic chemicals and provide significant attenuation for a wide range of pathogens (e.g. 6-log virus, 6-log *Giardia*, 1-log *Cryptosporidium*). Considering the public health benefits and improvements in water quality for both the product water and RO concentrate, ozone/BAC pretreatment offers the potential to transform conventional potable reuse treatment approaches and based on this analysis, an ozone/BAC based DPR train is as cost-effective as a conventional RO-AOP-based IPR train due to the improved water quality that reduces the overall O&M costs.

CONCLUSIONS

Chloramines have a proven track record of providing biological fouling control of membrane filtration, however, increased oxidative damage of RO membranes, shortening the useful life of these membranes, and increasing salt passage accompany their use. In addition, chloramines reduce the UV transmittance of the UV/AOP influent, increasing the energy use of the AOP system. The use of ozone/BAC pretreatment offers significant improvements in water quality by eliminating membrane foulants (complex organics and manganese) and reducing the biofouling potential of the water improves the efficacy of the MF and RO membranes, as well as the UV/AOP process currently employed for indirect potable reuse projects. Based on the presented capital and O&M costs over a period of 30 years, the DPR treatment train has a similar water cost and this finding is significant because it also provides a greater degree of public health protection for potable reuse as well as a significant enhancement to the RO concentrate water quality, which is a growing regulatory concern as all these RO concentrate streams will ultimately be discharged to the Pacific Ocean. The water quality benefits offered by ozone/BAC provide significant performance enhancements that close the gap between the higher capital cost with lower O&M costs over the project life and this is currently poorly understood and underappreciated by the industry.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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