EFFICACY OF HYBRID ADSORPTION/MEMBRANE PRETREATMENT FOR LOW PRESSURE MEMBRANE

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ABSTRACT

Fouling by natural organic matter (NOM) is a major obstacle when water from natural sources is treated using low-pressure membranes. Prior research by our group has demonstrated that passing natural water through a thin, pre-deposited layer of heated aluminum oxide particles (HAOPs) can remove substantial amounts of NOM from the feed and thereby reduce the fouling rate of downstream membranes. The work reported here explored the technical efficacy of such a pretreatment process under more challenging (and therefore realistic) conditions than reported earlier. Several analytical techniques were applied to the feed and permeate in an attempt to identify the key fouling components. The results demonstrate that a HAOPs layer can be pre-deposited on a stainless steel mesh and then be readily washed off at the end of a filtration cycle with very little irreversible fouling due to residual NOM or HAOPs

left on the mesh. In addition, the pretreatment step removes enough foulant to allow a downstream UF membrane to operate at significantly higher fluxes than when conventional pretreatment is applied. HAOPs pretreatment also reduced the formation of chlorinated and brominated trihalomethanes (THM₄) by more than 67% and of haloacetic acids (HAA₉) by 64% to 88% in simulated distribution system (SDS) tests.

Keywords: Membrane fouling; Natural organic matter; Aluminum oxide particles, HAOPs, precoat filtration

INTRODUCTION

Ultrafiltration (UF) membranes are widely used in drinking water treatment because they are capable of removing most colloidal and particulate matter from the feed while operating at relatively low transmembrane pressure (TMP). However, their flux and long-term performance are limited by membrane fouling, a complex physicochemical phenomenon caused by dissolved organic matter, inorganic and organic colloids, and biological growth and its byproducts (Hilal et al. 2005). Natural organic matter (NOM), comprising both allochthonous inputs such as terrestrial and vegetative debris and autochthonous inputs from algae (Cipollina et al. 2009), is often implicated as an important contributor to both the reversible and irreversible fouling (Huang et al. 2009, Hilal et al. 2005, Judd and Hills 2001). In addition to contributing to fouling, NOM has the potential to transport metals and hydrophobic organic chemicals, contribute to color, taste, and odor of the water, and react with disinfectants to form disinfection byproducts (DBPs).

Numerous studies have been carried out to identify the properties of NOM that cause, or at least are correlated with, membrane fouling. These studies have often focused on the molecules' hydrophobicity or molecular weight (Howe and Clark 2002, 2006, Yuan and Zydney 1999, 2000, Cho et al. 2000, Lin et al. 2000, Hua et al. 2015). While many researchers have suggested that humic substances are responsible for most of the fouling of low-pressure membranes (Yuan and Zydney 1999, 2000, Combe et al. 1999), others have argued that the hydrophilic fraction of the NOM, especially polysaccharides and proteins, might be more significant (Jermann et al. 2007, Lin et al. 2000, Carroll et al. 2000). According to some studies, hydrophilic NOM leads to rapid flux decline and the formation of a cake or gel layer, while hydrophobic NOM induces a steady flux decline without obvious formation of such a layer (Gray et al. 2007). TEP (Transparent Exopolymer Particles) are suspected to be major contributors to biofouling, since they can adhere to the membrane surface and provide a nutritious substrate for microbial growth and establishment of biofilm (Bermana et al. 2011, Tsuneda et al. 2003, Nguyen et al. 2009).

Proper pretreatment to minimize fouling is essential for successful UF operation. The most common and economical pretreatment process is coagulation, which invariably removes a portion of the NOM (typically, 20-60%) and usually mitigates fouling, but not always (Lee et al. 2000, Choi et al. 2004, Judd and Hills 2001, Kabsch-Korbutowicz et al. 2006, Pikkerainen et al. 2004). For example, Li et al. (2010) reported that reversible fouling was reduced by coagulation pretreatment, but irreversible fouling was unchanged, and Zhang et al. (2014) found that the most severe membrane fouling was caused by dissolved organic matter (DOM), which was the most difficult foulant to remove by backwashing. Fan et al. (2008) reported that

pretreatment with coagulation does not prevent the formation of a gel layer, but does reduce fouling.

Heated aluminum oxide particles (HAOPs) are a new adsorbent that is effective at removing NOM, including much of the NOM responsible for membrane fouling (Kim et al. 2007, 2008, 2010). Early research on HAOPs focused on the amounts and properties of NOM molecules that HAOPs bind, using test systems that could not easily be backwashed. HAOPs were shown to preferentially remove foulant over non-foulant NOM molecules, especially when the HAOPs were applied to the membrane as a pre-deposited (pre-coat) layer (Cai et al. 2008, Cai 2012, Kim et al. 2007, 2008, 2010). More recent work demonstrated that, in systems receiving equal doses of Al (i.e. mg Al per liter of water treated), passing the raw water through a layer of pre-deposited HAOPs was more effective at removing NOM and mitigating fouling than adding either alum or HAOPs to the bulk feed, even though the former system was backwashed only one-tenth as frequently as the latter two (Malczewska et al. 2015). This study explored the performance of HAOPs in backwashable systems under more challenging conditions and characterized the interactions of HAOPs with NOM using several analytical techniques.

MATERIALS AND METHODS

Raw water

Water was collected near the shoreline of Lake Union (LU) adjacent to the University of Washington in Seattle, WA. Water flows into LU from Lake Washington through the Montlake Cut and out via the Fremont Cut on its way to Puget Sound. The lake has a surface area of ~2.3 km² and a mean depth of ~10 m, and most of the NOM in the lake is thought to be allochthonous. Typical values of water quality parameters

during the study were: pH 6.8, UV_{254} 0.0495 m^{-1} , DOC 2.0 mg/L , $SUVA_{254}$ $2.5\text{ cm}^{-1}(\text{mg/L})$, and turbidity 0.68 NTU .

HAOPs and HAOPs Support Tubes

HAOPs were prepared according to the method of Cai et al. (2008). Briefly, a solution of alum (10 g/L as Al) was neutralized to pH 7.0 with NaOH, and the suspension containing $Al(OH)_3$ precipitate was heated in a closed container at 110°C for 24 h. Particles generated in this way have diameters in the range $1.5\text{--}30\mu\text{m}$. The suspension was cooled and stored at room temperature until use. Just before use, the portion of the suspension to be used in the upcoming experiment was dosed with bleach to achieve a free chlorine concentration of 50 mg/L as Cl_2 .

In the experiments, HAOPs were deposited on the interior surface of stainless steel mesh tubes fabricated by Cascade Designs, Inc. (Seattle, WA). The mesh was a 200×1400 twilled Dutch weave with nominal $10\text{-}\mu\text{m}$ openings (Howard Wire Cloth Co., Hayward, CA). The tubes were 60 cm long, with an internal diameter of 2.54 cm (Figure 1).

Ultrafiltration membrane

A UF membrane mini-module (Seccua GmbH, Steingaden Germany) containing polyethersulfone (PES) hollow fibers with a nominal pore size of 8 nm and total membrane surface area of 0.079 m^2 was used. The contact angle for water on this membrane was not measured, but reported contact angles for water on other PES membranes are typically near 45° .

117 Operating conditions

118 A schematic diagram of the experimental setup is shown in Figure 2. To initiate a run,
119 a stock solution of HAOPs was circulated axially through the mesh tube while
120 maintaining a water flux of 225 liters per square meter per hour (LMH) across the
121 wall. The flux carried the HAOPs to the wall, where they were captured and
122 deposited in a thin layer (120 μ m). The typical duration of this deposition step was 2.5
123 min.

124 LU water was then delivered to the mesh tubes by peristaltic pumps at a constant flux
125 in dead-end filtration mode. After passing through the HAOPs and the mesh, the
126 water was collected in a reservoir and fed to the UF module. The mean hydraulic
127 residence time in the reservoir varied from 8 to 24 hours, depending on the fluxes
128 through the two units in the given experiment. The pressure drops across the
129 HAOPs/mesh pretreatment unit and the UF module were measured online using
130 transducers (Omega, PX302-100GV). In this paper, both pressure drops are referred
131 to as transmembrane pressures (TMPs), even though the pretreatment unit is not
132 truly a membrane.

133 The HAOPs filtration process and the cleaning of the HAOPs unit were automated,
134 with a cleaning step triggered when the run-time reached 24 hours or when the TMP
135 reached 55 kPa (8 psi), whichever came first. However, in the experiments reported
136 here, the TMP never reached the trigger point, so all cycles lasted 24 hours. Treated
137 water samples were collected at pre-selected intervals for analysis. The cleaning step
138 lasted approximately 2.5 min and included backwashing in conjunction with four to six
139 10- to 15-s pulses during which water and air were injected into the interior of the

tube, and a final flush with water only. Fresh HAOPs were deposited on the mesh before the next treatment cycle.

The UF module was cleaned intermittently by simultaneous backwashing and flushing with water. In some cases, the backwash water was amended with bleach to make a 1% NaOCl solution; in these instances, the membrane was rinsed with deionized water before being put back into service. The goal of this chemical cleaning was to reduce or eliminate fouling; the NaOCl concentration was not optimized and, in all likelihood, could have been reduced substantially.

ANALYTICAL METHODS

UV₂₅₄, DOC

Ultraviolet absorbance at 254 nm (UV₂₅₄) and total organic carbon (TOC) concentrations were used to quantify the concentration of organics in the water. UV₂₅₄ was measured using a dual-beam spectrophotometer (Perkin-Elmer Lambda-18) with a 1-cm quartz cell. Spectral data were acquired at wavelengths of 200–400 nm at 1-nm resolution. DOC was determined on filtered samples with a TOC analyzer (Shimadzu TOC-VCSH). Reliable DOC values could not be obtained in a few experiments due to instrumental malfunction. However, strong correlations were obtained between UV₂₅₄ and the DOC concentration, so UV₂₅₄ was used as the primary indicator of NOM concentration in those cases.

Size Exclusion Chromatography (SEC)

SEC analyses used a DIONEX Ultimate 3000 HPLC system coupled to a SIEVERS turbo total organic carbon analyzer. Isocratic flow of 0.01 M NH₄HCO₃ was delivered through a column (300x7.5, 8 µm) at 0.5 mL/min.

Excitation Emission Matrix (EEM) Fluorescence

Three-dimensional EEM spectrometry was carried out at ambient temperature to help characterize the organic material in the feed and treated waters. A spectrofluorometer (HORIBA Scientific Fluorescence Spectroscopy, Edison, NJ) equipped with a 150-W xenon lamp was used in conjunction with a 1-cm quartz cuvette with four optical windows. Emission scans were performed from 200 to 500 nm after excitation at wavelengths from 300 to 450 nm, both at 4-nm intervals. The scanning speed was 1200 nm/min, and the slit widths for excitation and emission were both 4 nm. The fluorescence spectrum of Milli-Q water, obtained under the same conditions, was subtracted from all the spectra to eliminate water Raman scattering and to reduce other background noise.

Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR spectra of the raw water and HAOPs-treated water were recorded on a Bruker Biospin Corporation Spectrophotometer at wavenumbers from 4000 to 400 cm^{-1} with a resolution of 4 cm^{-1} . The samples were dried in an oven 105°C, and then pellets were prepared by pressing, under vacuum, a mixture of ~1 mg of sample and 200 mg of KBr (spectroscopy grade).

Transparent Exopolymer Particles (TEP)

A version of the spectrophotometric technique developed by Silvia et al. (2004) was applied for the determination of TEP. In this method, TEP reacts with excess alcian blue to yield a low solubility dye–TEP complex. After centrifugation, the concentration of the remaining dye in the supernatant was determined based on the sample's absorbance at 602 nm (A_{602}), and the concentration of TEP in the original sample was inferred based on comparison of that value with A_{602} when the same procedure

was applied to a blank (DI water). A standard curve was prepared by applying the procedure to solutions of DI water amended with known concentrations of xanthan gum.

Disinfection byproducts (DBPs)

DBP formation was evaluated in simulated distribution system (SDS) tests on the raw water and composites of treated water from 24-h filtration runs. The chlorine doses were selected to yield residual concentrations of free chlorine of ~1.0 mg/L as Cl₂. Trihalomethane (THM) and haloacetic acid (HAA) concentrations were determined using USEPA Methods 501.1 and 552.2, respectively.

RESULTS AND DISCUSSION

In drinking water treatment applications, UF membranes are typically operated in a flux range of 50 to 100 LMH, with lower fluxes used for feed waters with high suspended solids and/or fouling potential. For the initial experiment, the treatment system was operated with a HAOPs loading of 7.5 g Al/m² on the upstream mesh, and fluxes of 150 LMH and 87 LMH applied to the mesh and UF stages, respectively. The UF module was operated continuously without any backwashing or other cleaning steps for the whole duration of this experiment (11 d).

Figure 3a shows the TMP across each stage of treatment throughout this experiment. The average TMP increase across the HAOPs unit during a single (one-day) cycle was 5.3 kPa (0.78 psi), and that TMP increase was almost fully reversed by hydraulic cleaning. The TMP increase across the downstream UF module was only 7.0 kPa (1.0 psi) during the entire 11-d experiment, despite the fact that that unit was not cleaned at all.

Because UF removes a negligible portion of the UV_{254} from feed waters, essentially all the UV_{254} removal in this system occurred in the upstream HAOPs unit. The UV_{254} profiles fluctuated during the first four days of the test, but then stabilized and were very similar day-to-day thereafter (Figure 3b); the overall average removal over the full experiment was ~70%. The TOC removal efficiency (not shown) followed a similar pattern, typically declining from 55-60% at the beginning of a cycle to 45-50% at the end during days 5-11 of the test. Consistent with previous findings (Cai 2008, Kim et al. 2007, 2008, 2010), UV_{254} removal by the HAOPs was more efficient than DOC removal, suggesting that the HAOPs selectively bind more hydrophobic molecules (Cai 2012).

Next, the system was challenged by increasing the fluxes to both components: from 150 to 210 LMH for the HAOPs unit, and from 87 to either 261 or 400 LMH for the UF unit. The HAOPs unit performed well throughout this test, with TMP increasing from ~20 kPa at the beginning of each cycle to between 25 and 35 kPa at the end (Figure 4).

When the flux to the UF unit was 261 LMH, the TMP across the unit during the first cycle increased much more rapidly than it had during the prior test at 87 LMH (Figure 4). The module was therefore subjected to chemically-enhanced hydraulic cleaning (using water containing 1% NaOCl), which dramatically lowered the TMP buildup. The unit was then operated on a 24-hr filtration cycle with chemically-enhanced cleaning for five more cycles, during which the TMP buildup averaged less than 10 kPa per day.

Finally, the flux to the UF unit was increased to 400 LMH for three, 24-hour cycles, again applying chemically-enhanced cleaning between cycles. As would be

expected, both the TMP at the beginning of each cycle and the TMP increase during each cycle were higher than in the prior tests. Nevertheless, the TMP increase was less than 28 kPa (4 psi) per day (Figure 4), which might be considered an acceptable burden in exchange for operating at such a high flux (and thereby reducing the required size of the membrane plant).

The UV₂₅₄ removal efficiency during the first five cycles (i.e., five days) of this test was essentially identical to that in the prior test at lower flux, averaging close to 70%. In the sixth cycle, the composite UV₂₅₄ removal efficiency declined to ~50%, where it remained for the next four cycles (Figure 4). This change in performance coincided with a visible darkening of the feed water, although no significant change was detected in the TOC or UV₂₅₄. It was subsequently determined that the salinity of the feed (which was drawn from near the bottom of the lake) had increased and was approximately triple that of the surface water; unfortunately, the time when that discrepancy first occurred could not be determined ex poste facto. A plausible hypothesis for these observations is that saline water had entered the lake from the downstream locks separating the lake from Puget Sound and had migrated to near the sampling point. Prior experiments had indicated that increases in salinity on the order of those detected would not have a severe effect on UV₂₅₄ removal, but the changes in salinity and color nevertheless suggest that the water quality underwent a significant change, and other features of that change might have caused the observed behavior.

Because the TMP buildup in the HAOPs/mesh unit during a single cycle was modest throughout this test, it is difficult to determine whether that parameter was affected by the change in water quality. However, it is worth noting that the TMP across that unit did decline steadily during the period of changed feed quality, concomitant with the

deterioration in UV₂₅₄ removal. Thus, it is plausible that the decreased removal of NOM by the HAOPs led to decreased “fouling” of the HAOPs layer, and that correspondingly more foulant entered the UF unit during the latter stages of testing.

CHARACTERIZATION OF RAW AND HAOPs-TREATED WATER

NOM is a heterogeneous mixture of organic compounds that serve as the precursors of chlorinated disinfection by-products (DBPs) and contribute to fouling. In an effort to identify those components that are especially important for fouling, the apparent molecular weight (AMW) distribution and the EEM fluorescence and FT-IR spectra of the NOM were acquired, and the TEP concentration of the feed and HAOPs-treated water were analyzed. The latter samples were collected immediately downstream of the HAOPs/mesh unit (i.e., before the UF unit) when the unit was operating at a flux of 210 LMH and the UV₂₅₄ removal efficiency was ~70%.

The SEC chromatogram of the raw water (Figure 5) had four substantial and partially overlapping peaks at retention times of 10-25 min, and several additional small peaks at longer and shorter times. The four major peaks are labeled in order of decreasing AMW in Figure 5. HAOPs removed some portion of all the fractions, with removal efficiencies of 85%, 78%, 54%, and 69% for peaks 1 through 4, respectively (based on peak heights).

Fluorescence of organics in natural waters is commonly analyzed with respect to five regions or peaks of the excitation/emission (EX/EM) spectrum (Chen et al. 2003, Fan et al. 2008). Region I is associated with protein-like extracellular organic matter containing aromatic amino acids such as tryptophan and tyrosine; Region II is attributed to aromatic proteins and BOD-type substances; Region III is associated with soluble microbial products (SMPs, mainly polysaccharides and proteins); Region

IV contains fulvic-like fluorophores; and Region V comprises humic acid-like substances. The fluorescence intensity of the peaks depends primarily on the identities and concentrations of the contributing components (You et al. 2015), but other factors (e.g., salinity) can also play a role (Gusso-Choueri et al. 2011). For example, amino acids or protein-like components in river waters are often bound with humic and fulvic substances, and this binding can cause significant variability in the emission wavelength (Mostofa 2005).

The EEM spectra of raw water and HAOPs-treated water had intense peaks at EX/EM wavelengths (nm) of 245/342 (Peak A), and 305/335 (Peak B) (Figure 6), most likely attributable to protein-like and fulvic-like matter, respectively. The peak for fulvic-like material is blue shifted relative to the normal location for such material, which might reflect heterogeneity of the fluorophores contributing to that peak or, possibly, the salinity of the sample. The presence of only fulvic-like and aromatic-protein-like fluorescence is unusual for a natural water and suggests that the NOM in the test water was richer in hydrophilic material than in humic-like material. The maximum fluorescence intensity of both peaks in the EEM spectra decreased by 48% when the water passed through the HAOPs layer, indicating that significant amounts of both aromatic protein-like substances and fulvic-like substances were removed by the HAOPs.

Figure 7 shows FT-IR spectra of these samples, normalized by assigning the highest peak an intensity of 1.0. In both cases, this peak was in the 3300~3400 cm^{-1} range, which is typically associated with the O-H vibrations in water and carbohydrate-like organic matter. Peaks in this region might also indicate the presence of aluminum silicates. However, aluminum silicates also have an intensive band between 1030 and 1020 cm^{-1} , which is not present in these samples.

308 The molecules responsible for the absorption in the 3300~3400 cm^{-1} range are
309 expected to be minimally affected by contact with HAOPs. In the limiting case where
310 these molecules are not removed at all by passage through the HAOPs layer, the
311 normalization procedure would fully account for any difference in the NOM masses
312 between in the two samples (raw water and HAOPs-treated water). In that case, the
313 ratios of the other peak heights in the two samples (that is, the ratio of a given peak
314 height in the HAOPs-treated sample to that in the raw water) would be a direct
315 indicator of the efficiency with which HAOPs removed the functional groups
316 responsible for those peaks.

317 Significant signals in the FT-IR spectra other than the one used for the normalization
318 include those associated with C=C stretching in aromatic compounds (1618 cm^{-1}),
319 N-C=O in amides (the amide I peak at 1636 cm^{-1}), COOH groups in humic and fulvic
320 substances (2200~2900 cm^{-1}), and methyl group CH bending (1385 cm^{-1}). The
321 relative peak heights in the two normalized spectra suggest that at least 78% to 95%
322 of the humic and fulvic acids in the raw water were removed by HAOPs treatment,
323 whereas aromatic proteins were removed much less efficiently (10% to 25%, based
324 on the change in height of the amide I peak). According to Howe et al. (2002),
325 polysaccharide-like materials, which are thought to be strong foulants of membranes,
326 have an IR absorption band near 1000-1100 cm^{-1} . The samples did have a broad
327 band in that region, and its height declined by about 70% when the water was treated
328 by HAOPs.

329 The average TEP concentration in the raw water was 65 $\mu\text{g/L}$ (as xanthan gum
330 equivalents). TEP removal by HAOPs was 64%, closely mimicking the estimated
331 removal of polysaccharide-like material based on the FT-IR spectra.

The effectiveness of pre-deposited HAOPs at removing DBP precursors was evaluated in SDS tests conducted in winter and spring; an additional test was conducted to check the impact of filtration time on DBP removal. The results of all these tests are shown in Table 1.

In all the tests, chloroform and DCBM were the dominant DBPs formed. The reduction in THM formation was greatest for chloroform and declined steadily as the Br content of the THM increased; the same trend applied to HAAs. HAOPs pretreatment reduced the THM4 concentration by more than 67% and the HAA9 concentration by 64% to 88%.

SUMMARY AND CONCLUSIONS

This project investigated a hybrid adsorbent/membrane process comprising a pretreatment step in which water is passed through a pre-deposited layer of HAOPs, followed by a conventional membrane filtration step. The process was effective for removal of NOM in general, including DBP precursors, and was selectively and remarkably effective for removal of membrane foulants. UF membranes receiving HAOPs-treated lake water as feed were operated at conventional fluxes for almost two weeks without backwashing and with no significant fouling, and others were operated successfully at fluxes as high as 400 LMH for filtration cycles of 24 hours.

HAOPs selectively removed high-AMW fractions from the raw lake water and also removed most fluorophores. EEM analysis indicated that humic and fulvic substances, as well as aromatic proteins, are effectively removed by HAOPS treatment. FT-IR data strongly supported the inferences about humics and fulvics, but were less supportive of the inferred removal of the proteins. FT-IR and TEP data suggested that HAOPs also remove (non-fluorescent) polysaccharide-like materials,

which might account for the substantial benefits of HAOPs with respect to fouling mitigation.

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485 Figure 1. SEM images for stainless steel mesh.

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488 Figure 2. Schematic diagram of the test setup.

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Figure 3. (a) Pressure loss across the system components during 11 days of filtration and (b) UV₂₅₄ removal by the system. Fluxes were 150 LMH to the HAOPs unit and

87 LMH to the UF membrane. HAOPs unit was backwashed daily, but UF unit was not backwashed at all.

Figure 4. UV₂₅₄ removal and TMP across the system components for operation at high fluxes.

Figure 5. SEC elution profile of LU water and HAOPs-treated water.

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508 Figure 6. EEM fluorescence spectra of (a) raw and (b) HAOPs-treated water.

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512 Figure 7. Normalized FTIR spectra of raw and HAOPs-treated LU water.

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514 Table 1. DBP formation in simulated distribution system (SDS) tests with raw and HAOPs-treated water.^(a)

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	Chlorine residual	TCM	DCBM	DBCM	TBM	THM4	MCAA	MBAA	DCAA	BCAA	TCAA	DBAA	BDCAA	CDBAA	TBAA	HAA9
	WINTER 2014 (24-h composite)															
Raw water	1.2	77.3	17.4	0.9	6.0	124.4	bdl.	0.2	24.2	2.8	39.0	0.2	3.8	0.2	0.0	70.5
HAOPs-Treated	0.8	17.7	7.8	2.5	5.2	33.2	bdl.	0.1	3.2	1.9	1.4	0.2	1.1	0.3	0.0	8.3
	SPRING 2015 (24-h composite)															
Raw water	1.1	65.8	14.1	6.3	0.7	86.9	bdl.	2.6	21.1	5.5	31.0	0.8	4.1	6.3	2.2	73.6
HAOPs-Treated	1.1	16.4	10.2	6.3	0.7	33.6	bdl.	1.1	5.1	4.0	7.2	0.7	2.5	4.0	1.7	26.3
	SPRING, 2015 (two discrete HAOPs-treated samples analyzed)															
Raw water	1.1	78.1	15.3	5.6	0.4	99.4	bdl.	0.4	17.9	4.3	16.1	0.6	2.7	5.3	3.7	68.0
HAOPs-Treated	1.1	14.6	4.3	4.2	0.6	23.7	bdl.	0.1	7.2	2.8	8.3	0.8	1.1	5.8	3.8	31.7
0.5 hr																
HAOPs-Treated	1.4	39.0	4.5	2.8	0.6	46.8	bdl.	0.5	10.2	1.8	16.9	0.4	1.9	4.6	0.3	39.8
20 hr																

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517 ^(a) Chlorine residual in mg/L as Cl₂; all other values in µg/L.

EFFICACY OF HYBRID ADSORPTION/MEMBRANE PRE-TREATMENT FOR LOW PRESSURE MEMBRANE

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