

## Recycle of waste backwash water in ultrafiltration drinking water treatment processes

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### ABSTRACT

In drinking water treatment, ultrafiltration (UF) membrane systems are generally operated at 90 to 95% recovery with production losses resulting from waste residual streams such as backwash water and clean-in-place (CIP) liquid residuals. In drought-prone regions, it may be desirable to apply alternative UF plant design configurations to increase recovery rates and minimize water loss. This approach could consist of adding a secondary stage UF membrane for treatment of first stage UF residuals, or recycling the first stage UF waste residuals by blending a percentage of the backwash water with the raw water at the front of the treatment train. For small systems, the second option may present a more cost-effective solution. The overall objective of this research project was to investigate the potential impacts to UF permeate water quality and coagulation pretreatment efficacy in a bench-scale submerged UF membrane system operating with and without waste backwash water recycle. The results of the study showed that blending 10% waste backwash water with raw water did not negatively impact UF permeate water quality. The results also demonstrated that recycling waste backwash water prior to coagulation–UF treatment may improve organic removal and reductions in neat coagulant dosage may be possible to achieve specific DBP precursor removal targets.

**Key words** | coagulation, filter backwash water, natural organic matter, ultrafiltration

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### INTRODUCTION

The market for low-pressure membrane technology continues to grow in the drinking water industry because of increased concerns over the impacts of water quality on human health and more stringent environmental regulations. Low-pressure membranes (i.e. microfiltration (MF) and ultrafiltration (UF)) are capable of achieving complete removal of pathogens and particulate matter through physical sieving based on size exclusion (Jacangelo *et al.* 1989, 1995; Dwyer *et al.* 1995; Hagen 1998; MacPhee *et al.* 2002; LeGouellec *et al.* 2004). Low-pressure membranes are classified by the size of their pores. MF membranes have nominal pore sizes that range from 0.1 to 1  $\mu\text{m}$  whereas UF membrane nominal pore sizes range from 0.01 to 0.1  $\mu\text{m}$ .

Although UF membranes are extremely effective at removing suspended solids and pathogens from the feed stream, this situation is not the case with organic and

inorganic dissolved contaminants such as natural organic matter (NOM) and metals. Coagulation using metal salts such as aluminium sulphate (alum) or polyaluminium chloride (PACl) is the most common and effective form of pretreatment employed before UF to achieve enhanced removal of NOM. Coagulation is commonly used to precipitate or adsorb NOM such that it can be removed through clarification and/or filtration (Edzwald 1993). In UF treatment systems, coagulation pretreatment allows for more efficient removal of dissolved contaminants such as NOM (Lahoussine-Turcaud & Wiesner 1990). Previous studies have demonstrated that combining coagulation pretreatment using inorganic coagulants such as alum with the UF membrane process can significantly improve NOM removal and increase the operational time between cleaning (Lainé *et al.* 1990; Bérubé *et al.* 2002; Wend *et al.* 2003).

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When treating surface water, UF membranes typically operate at 90 to 95% recovery (Peck & Russell 2005). The remaining 5 to 10% of the total feed water is converted to a concentrated waste residual stream, which is generated from backwashing and chemical cleaning operations, with backwash flows generally representing 95 to 99% of the total residuals volume (AWWA 2008). The characteristics of MF and UF backwash waste residual streams have been shown to be consistent with the raw water quality with respect to dissolved inorganic and organic constituents, and with elevated concentrations of particulate matter that is rejected by the membrane, including pathogens and suspended solids (Adham *et al.* 1996; MacPhee *et al.* 2002; LeGouellec *et al.* 2004). A study that investigated treatment requirements for MF residuals (MacPhee *et al.* 2002) found that bulk backwash samples collected from four membrane water utilities exhibited very similar qualities to conventional waste filter backwash water (FBWW) samples collected in Cornwell & MacPhee (2001).

In regions where water efficiency is a priority, the recovery and reuse of membrane backwash streams can offer benefits to water conservation strategies and management plans. In general, the management of MF and UF backwash residuals is directed by the same regulatory controls as conventional water treatment residuals (AWWA 2008), with disposal options including discharge to surface water,

sewer collection, land application or in-plant recycling (Mickley 2006). The *Filter Backwash Recycle Rule* (FBRR) was promulgated by the United States Environmental Protection Agency (USEPA) to address concerns over potential impacts of increased contaminant loads in waste FBWW recycle streams (i.e. *Cryptosporidium* oocysts) on overall plant efficacy and finished water quality (USEPA 2001). The FBRR does not regulate the percentage of backwash water that can be included in the feed water stream, but it does make reference to the Ten States Standards, which recommend that the recycle rate be maintained below 10% of the raw water flow entering the plant (SPEHM 2007). The recycle of MF and UF backwash waste residual streams is not directly addressed in the FBRR or the current version of the Ten States Standards, and published information on potential impacts to finished water quality in designs including these waste residual streams intended for recycle is limited.

One approach to residual management in low-pressure membrane plants is to use dedicated secondary membrane units to recover waste backwash water streams from the primary membrane units (Figure 1). In this type of process design, the first stage MF or UF units treat the raw water and are not exposed to the waste backwash streams. The second stage MF or UF units dedicated to backwash processing could, at various times, be exposed to raw water or raw

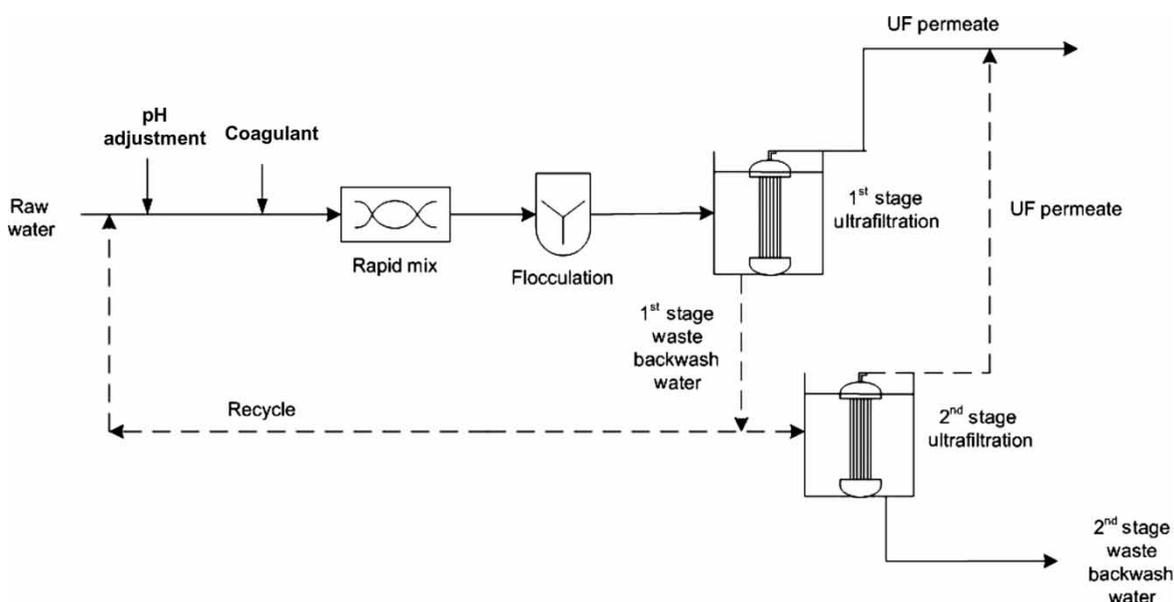


Figure 1 | Waste backwash water recovery options in UF plant design.

water blended with treated or untreated backwash water. Another approach to residual management that has not been widely researched is to blend a portion of the waste backwash water with the raw water prior to processing in the main treatment train (Figure 1). For small systems, this type of process design would be a more cost-effective solution with regard to capital investment.

Previous studies have reported both benefits and problems with recycling waste backwash water in conventional filtration plants, suggesting that optimum operating and water quality conditions exist that may minimize potential adverse effects associated with this approach to waste residual management (Arora *et al.* 2001; Cornwell & MacPhee 2001; Edzwald *et al.* 2001). In particular, several studies have found that blending untreated waste FBWW with raw water can improve the overall removal of certain contaminants from the source water. A pilot-scale study by Cornwell & MacPhee (2001) found that sedimentation basin performance was improved with respect to *Cryptosporidium* oocyst removal when untreated FBWW was recycled at a location upstream of the coagulation process. Full-scale studies have also demonstrated that FBWW streams generated in plants that use a coagulant and/or polymer aid contain low dissolved organic carbon (DOC) concentrations relative to the raw water and destabilized particles that do not exert a coagulant demand in recycle designs (Edzwald *et al.* 2003; Tobiason *et al.* 2003). Similarly, a bench-scale study by Gottfried *et al.* (2008) showed that blending 5 and 10% by volume of FBWW with a low turbidity, high specific UV absorbance (SUVA) source water prior to coagulation and sedimentation resulted in significantly higher removal of DOC from the source water compared with a control trial where backwash water was not added.

The overall objective of this research project was to investigate the potential impacts on UF permeate water quality and coagulation pretreatment efficacy in a bench-scale submerged UF membrane system operating with and without waste backwash water recycle. The efficacy of NOM removal with alum coagulation pretreatment and UF for two low turbidity surface waters was compared with system performance with source water blended with 10% by volume waste FBWW prior to coagulation–UF treatment. Alum coagulation was tested at two different doses to

investigate the possibility of reducing the primary coagulant dose through recycling of backwash streams.

## MATERIALS AND METHODS

### Source and filter backwash water

Two surface water treatment plants (WTPs) were chosen as sample locations for this study. The Hantsport WTP is a 0.8 MLD surface water treatment plant that serves the town of Hantsport and the Glooscap First Nation in Nova Scotia, Canada. The plant is a direct microfiltration (MF) membrane plant that uses a process train consisting of two parallel skids of 12 membrane units followed by ultraviolet (UV) disinfection and chlorine for secondary disinfection. Coagulant is not used in the Hantsport treatment train. The Bridgewater WTP has a design production rate of 10 MLD and a conventional filtration treatment train with anthracite-sand filters and an average alum dosage of 25 mg l<sup>-1</sup>. Filter backwash water was collected from the Bridgewater WTP for use in this study to represent low-pressure membrane residuals. As outlined in an American Water Works Association (AWWA) Residuals Management Research Committee white paper, if coagulants, PACl or other pretreatment chemicals are applied, the characteristics of MF and UF residuals become more similar to the residuals of a conventional treatment plant (AWWA 2003).

The two source waters and FBWW from Bridgewater were sampled in January, May and June 2008 and were analysed for a variety of water quality parameters. Both of the plants' source waters are low turbidity (<2 NTU), low alkalinity (<5 mg l<sup>-1</sup> as CaCO<sub>3</sub>) with a pH of approximately 6.0. The primary difference between the Hantsport and Bridgewater source waters is in relation to NOM characteristics. The water used in the Bridgewater WTP has a moderate concentration of total organic carbon (TOC) (3.7 ± 0.7 mg l<sup>-1</sup>), a UV254 measurement of 0.161 ± 0.037 cm<sup>-1</sup> and a calculated specific UV absorbance (SUVA) value of 5 l/mg · m. In contrast, the water from Hantsport has a lower TOC concentration of 2.0 ± 0.3 mg l<sup>-1</sup>, UV254 absorbance of 0.081 ± 0.021 cm<sup>-1</sup> and SUVA value of 4 l/mg · m. The SUVA, calculated as the ratio between UV absorbance at 254 nm and DOC mass concentration is often used as an

indicator of the aromatic, hydrophobic characteristics of DOC. High SUVA values often indicate high molecular size, hydrophobic and aromatic components, and good removal of DOC with NOM controlling coagulation processes is generally expected for source water with SUVA values greater than  $4.0 \text{ l/mg} \cdot \text{m}$  (Edzwald & Van Benschoten 1990; Edzwald 1993; Weishaar *et al.* 2003). As outlined in Table 1, the characterization of the Bridgewater and Hantsport source waters showed calculated SUVA values greater than  $4.0 \text{ l/mg} \cdot \text{m}$ , indicating that the test waters would be amenable to coagulation pretreatment.

Analysis of the FBWW samples collected from the Bridgewater WTP showed significantly higher levels of particulate material compared with the source water. Specifically, the turbidity of the FBWW was  $38.2 \pm 12.5$  NTU and TOC concentrations were found to be  $38.6 \pm 17.0 \text{ mg l}^{-1}$  on samples collected for this study. The low FBWW DOC concentrations ( $2.8 \pm 0.6 \text{ mg l}^{-1}$ ) and UV254 measurements ( $0.036 \pm 0.003 \text{ cm}^{-1}$ ) demonstrate that the organic material present in the FBWW samples represents organic material that has been enmeshed in alum floc through coagulation processes in the main treatment train of the Bridgewater WTP.

## Experimental design

For each source water, the feed and permeate water quality generated using the following process trains were evaluated: (1) source water without coagulation pretreatment followed by UF (control); (2) source water with alum coagulation

pretreatment followed by UF; (3) source water blended with 10% by volume FBWW from Bridgewater WTP without coagulation pretreatment followed by UF; and (4) source water blended with 10% by volume FBWW from Bridgewater WTP with coagulation pretreatment followed by UF. Based on previous coagulation–UF work conducted with the Hantsport and Bridgewater source waters (Zhao 2006; Walsh *et al.* 2009), an optimum alum dose of 10 and  $20 \text{ mg l}^{-1}$  for Hantsport and Bridgewater source waters, respectively, was selected for this study. To evaluate the potential impact of residual aluminium hydroxide ( $\text{Al OH}_3$ ) precipitates present in the FBWW recycle, slightly lower alum dosages than the optimum were also evaluated for both source waters (e.g. 5 and  $10 \text{ mg l}^{-1}$  for Hantsport and Bridgewater, respectively).

Coagulated feed water was prepared in a standard jar tester (Phipps & Bird, Fisher Scientific, USA) consisting of six 2-l square jars filled to the 1.0-l mark before being transferred to the UF process tank. For all of the experimental trials, the pH was maintained at 6.0 using a  $5 \text{ g l}^{-1}$  sodium hydroxide (NaOH) stock solution. Alum was injected using graduated syringes, and rapid mixed at 150 rpm for 30 seconds followed by a 3-minute slow mix at 20 rpm for flocculation. This coagulation–flocculation procedure was adapted from work conducted by Bérubé *et al.* (2002) that was used to simulate conditions in a system where coagulant is added before the membrane feed pump. For the FBWW recycle trials, 4.5 l of raw water was blended with 0.5 l of FBWW. The composite sample was then treated with the UF module, or coagulated and flocculated at the respective dosages and mixing conditions described above for each source water before passing through the UF module.

The bench-scale UF test apparatus consisted of an immersed, hollow-fibre UF membrane module system (ZeeWeed<sup>TM</sup>-1, GE Zenon Water & Process Technologies, Burlington, ON, Canada) operated in an outside-in flow configuration. The ZW-1 module has a total membrane surface area of  $0.047 \text{ m}^2$  with a rated nominal pore size of  $0.04 \mu\text{m}$  and an absolute pore size of  $0.1 \mu\text{m}$ . For the experiments, the membrane was operated at a constant flux of  $40 \text{ l h}^{-1} \text{ m}^{-2}$ . All of the prepared feedwater streams were manually transferred to the UF process tank and vacuum pressure was applied on the permeate side of the membrane using a variable speed pump (Masterflex, Cole Parmer, UK). The

Table 1 | Raw and waste backwash water quality

Analyte	Bridgewater WTP		Hantsport WTP
	Raw water	FBWW	Raw water
pH	6.0	5.8	6.1
Turbidity, NTU	$1.4 \pm 0.4$	$38.2 \pm 12.5$	$1.5 \pm 0.7$
True colour, TCU	$31 \pm 10$	$2 \pm 0$	$12 \pm 4$
UV254, $\text{cm}^{-1}$	$0.161 \pm 0.037$	$0.036 \pm 0.003$	$0.081 \pm 0.021$
TOC, $\text{mg l}^{-1}$	$3.7 \pm 0.7$	$38.6 \pm 17.0$	$2.0 \pm 0.3$
DOC, $\text{mg l}^{-1}$	$3.4 \pm 0.5$	$2.8 \pm 0.6$	$2.0 \pm 0.3$
SUVA, $\text{l/mg} \cdot \text{m}$	$4.7 \pm 0.7$	$1.5 \pm 0.4$	$3.7 \pm 0.8$
Zeta potential, mV	$-14.9 \pm 1.5$	$-8.2 \pm 1.0$	$-15.2 \pm 4.0$

permeate flowrate was measured every 15 minutes using a graduated cylinder and a timer and permeate was back-pulsed through the membrane with air scour every 30 minutes using a programmed controller (Picosoft, Rockwell Automation/Allen-Bradley, Milwaukee, WI, USA). During the experiments, transmembrane pressure (TMP) was monitored continuously using a pressure transducer (Omega Engineering, UK) and recorded using a data logger (ES120, Dickson Company, Addison, IL, USA). The initial permeate sample volume of 157 ml generated in the first 5 minutes of the filtration cycle was wasted to ensure a representative sample was obtained for analysis. Two-hour long batch trials were run for each of the four membrane treatment process configurations, during which UF permeate samples were taken at 30-, 60- and 90-minute intervals.

### Analytical methods

pH was monitored in all of the experiments using an Orion pH meter with combination electrode (Model 210A, Fisher Scientific). Turbidity was measured using a HACH 2100 AN Turbidimeter (Hach Company, Loveland, CO, USA). The mean zeta potential of raw and feed water streams was measured using a Zetaphormeter IV instrument (Laval Lab Inc., Laval, Quebec, Canada). Zeta potential was calculated from the streaming potential using the Smoluchowski Equation.

TOC, DOC, true colour and UV absorbance were measured on the raw, feed and UF permeate samples for all trials. Samples used for DOC, true colour and UV-absorbance analysis were filtered through a 0.45 µm pore-size membrane filter (Cole-Parmer® Nylon Membranes) and rinsed with deionized water as described in *Standard Methods for the Examination of Water and Wastewater*. TOC and DOC samples were collected headspace-free in 40-ml glass vials and preserved with concentrated phosphoric acid. Measurements were performed with a TOC VCPH analyser (Shimadzu Corporation, Kyoto, Japan) using a high temperature catalytic oxidation process. Colour was measured using a DR 4000 Spectrophotometer (Hach Co.). Ultraviolet light absorbance was measured using a DR 5000 UV-Vis Spectrophotometer (Hach Co.). UV spectra were measured from 200 to 500 nm. UV254 was measured as part of a UV-absorbance spectrum. The

differential UV-absorbance spectrum ( $\Delta$ UV spectrum) for each trial was calculated by subtracting the UV absorbance of the UF permeate from that of the raw water.

Analysis of variance (ANOVA) tests were used to determine whether significant differences existed between the experimental trials. All ANOVA tests were conducted at the 95% confidence level where a *p*-value greater than 0.05 implies that the two data sets could have come from the same underlying pool of data, whereas a *p*-value less than 0.05 suggests that the two data sets are significantly different from one another. In all cases, error bars on graphs represent standard deviation from the mean.

## RESULTS AND DISCUSSION

In all of the experimental trials with the Bridgewater and Hantsport source waters, the UF membrane presented an absolute barrier to the suspended solids present in the feed water, resulting in a UF permeate turbidity reading consistently below recommended provincial guidelines (i.e. < 0.1 NTU).

### Control and coagulation pretreatment trials

Without alum coagulation pretreatment, UF treatment of the two source waters resulted in minimal removal of dissolved organics as quantified by DOC, UV254 and true colour measurements (Figures 2 and 3). For Bridgewater, DOC removal was significantly increased from 6 to 44% with 10 mg l<sup>-1</sup> alum, and further increased to 47% DOC removal with 20 mg l<sup>-1</sup> alum pretreatment upstream of UF. Similarly, there was a significant increase in removal of UV254 from the Bridgewater source water from 16% in the control trials (e.g. 0 mg l<sup>-1</sup> alum) to 71 and 77% when 10 and 20 mg l<sup>-1</sup> of alum, respectively, were added. In the Hantsport source water trials, the addition of 5 and 10 mg l<sup>-1</sup> alum increased DOC removal from 22% to an average of 24%, respectively. A more significant reduction in UV254 was observed with coagulation pretreatment at both 5 and 10 mg l<sup>-1</sup> dosages (71% UV254 removal) compared with the control trial (19% UV254 removal). In both the Bridgewater and Hantsport source water trials, true colour removal was significantly improved by the addition

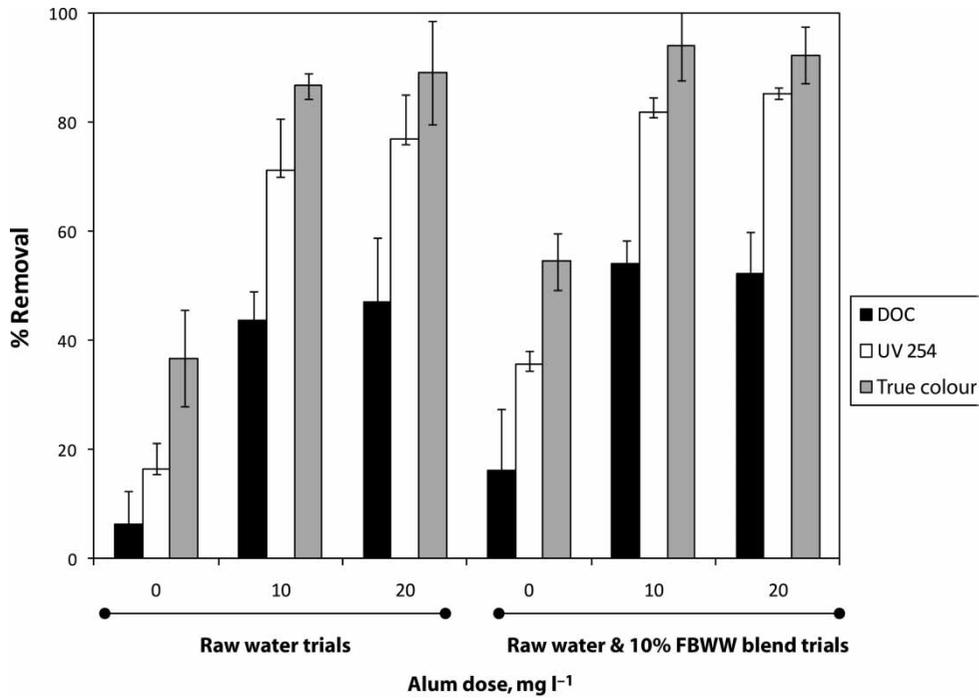


Figure 2 | UF treatment performance for Bridgewater source water experiments.

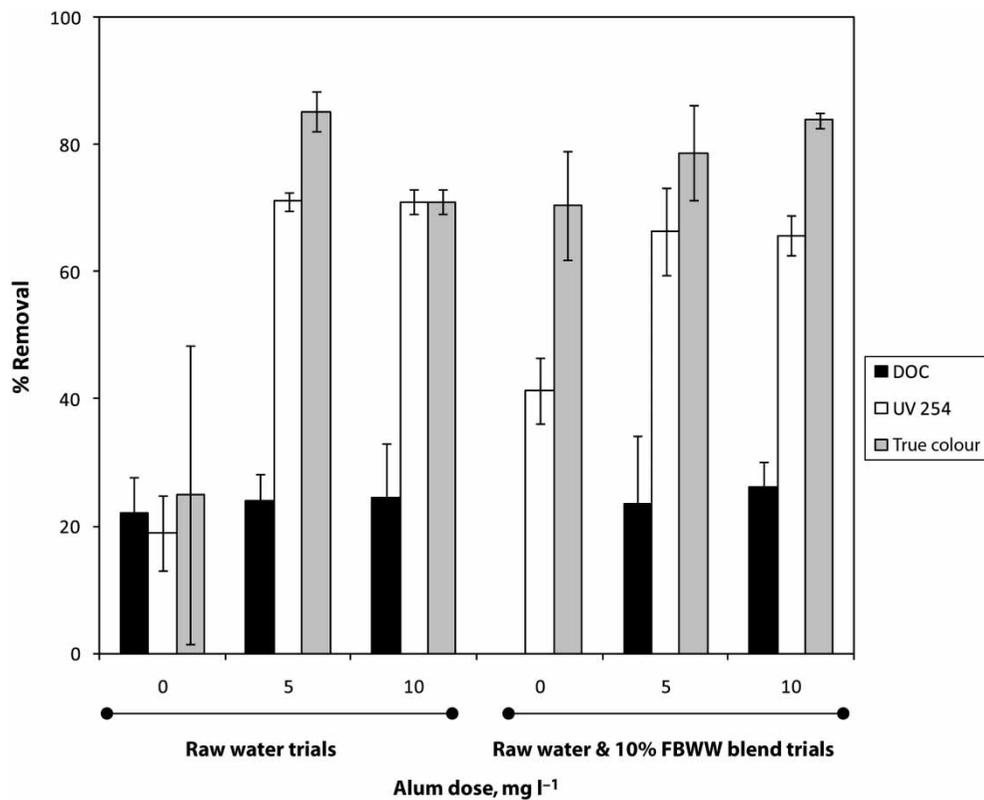


Figure 3 | UF treatment performance for Hantsport source water experiments.

of alum coagulant prior to UF treatment. In the Bridgewater experiments, true colour removal increased from 37% without coagulation pretreatment to 87 and 89% true colour UV254 removal with 10 and 20 mg l<sup>-1</sup> alum, respectively. In the Hantsport experiments, true colour removal increased from 29% without coagulation pretreatment to 85 and 89% true colour UV254 removal with 5 and 10 mg l<sup>-1</sup> alum pretreatment, respectively. The increase in dissolved organic removal with coagulant pretreatment prior to UF was expected as increased NOM removal in low-pressure membrane systems employing coagulation pretreatment has been noted in previous studies (Lainé *et al.* 1990; Schafer 2001; Bérubé *et al.* 2002; Walsh *et al.* 2009).

### 10% FBWW recycle without coagulation pretreatment trials

The direct addition of 10% by volume of waste FBWW to the Bridgewater raw water prior to UF treatment resulted in a 2.5-fold increase in DOC removal compared with the control trial (no coagulation pretreatment), with DOC removal improving from 6 to 16% (Figure 2). Both UV254 and true colour removal were also significantly improved in the FBWW recycle trials (36% UV254 removal and 55% true colour removal) compared with the control (e.g. 16% UV 254 removal and 37% true colour removal).

In contrast with the results from the Bridgewater source water experiments, the addition of 10% FBWW to the Hantsport raw water prior to UF treatment did not result in improved removal of DOC concentrations from the raw water. Specifically, DOC concentrations measured in the UF permeate samples increased slightly from 1.9 to 2.2 mg l<sup>-1</sup> for the control and 10% FBWW recycle trials, respectively. However, UV254 removal from the Hantsport source water increased from 19% during the control trial to 41% when the raw water was blended with 10% FBWW prior to UF treatment (Figure 3). A reduction in UF permeate true colour measurements was also observed from 10 TCU (i.e. 25% removal) during the control trial to 5 TCU (i.e. 70% removal) during the 10% FBWW recycle trial, as presented in Figure 3.

Similarly, the plots of differential light absorbance versus wavelength in the ultraviolet range, or  $\Delta UV$

spectrum, for both the Bridgewater and Hantsport source water experiments showed higher removals of UV-absorbing compounds along the spectrum when 10% FBWW was added prior to UF treatment compared with the control trials with no UF pretreatment (Figure 4(a) and 4(b)). UV absorption in the wavelength range from 200 to 400 nm is widely attributed to the aromatic chromophores (e.g. light-absorbing sub-units) present in DOC, primarily in humic substances (Peuravuori *et al.* 2002). The plots of differential absorbance presented in Figure 4(a) and 4(b) demonstrate that with the addition of 10% FBWW to the raw water, moderate improvements in removal of UV-absorbing compounds was achieved. Significant differences in the UV-absorption measurements of the UF permeate when the FBWW was added to the raw water was more apparent during the Bridgewater experiments than in the Hantsport experiments, and agree with the significant improvement in DOC removal observed during the Bridgewater removal when 10% waste FBWW was blended with the raw water prior to UF treatment.

The results of the FBWW recycle trials in this study suggest that blending the waste FBWW directly with the raw water may have allowed for coagulation mechanisms to act on dissolved organic material in the source water owing to the presence of aluminium hydroxide precipitates in the waste FBWW stream. Previous studies have demonstrated that settling of spent filter backwash water was enhanced with addition of only polymer (Cornwell & MacPhee 2001), and improved sedimentation of MF and UF backwash water required addition of a metal salt coagulant when the source water was not coagulated (LeGouellec *et al.* 2004). Zetapotential (ZP) measurements showed that the particles present in the FBWW samples were predominantly destabilized (i.e.  $ZP = -8.2 \pm 1.0$  mV) compared with the source waters that contained predominately stabilized particles (i.e. mean  $ZP = -14.9$  to  $-15.2$  mV). An increase in the number of collision sites consisting of destabilized FBWW particles and residual aluminium hydroxide precipitates present in the FBWW volume blended with the raw water prior to UF treatment could explain the improved UV254 and true colour removal found for both source waters evaluated in this study. For the Bridgewater source water experiments, the improved DOC removal observed with the FBWW recycle experiments would

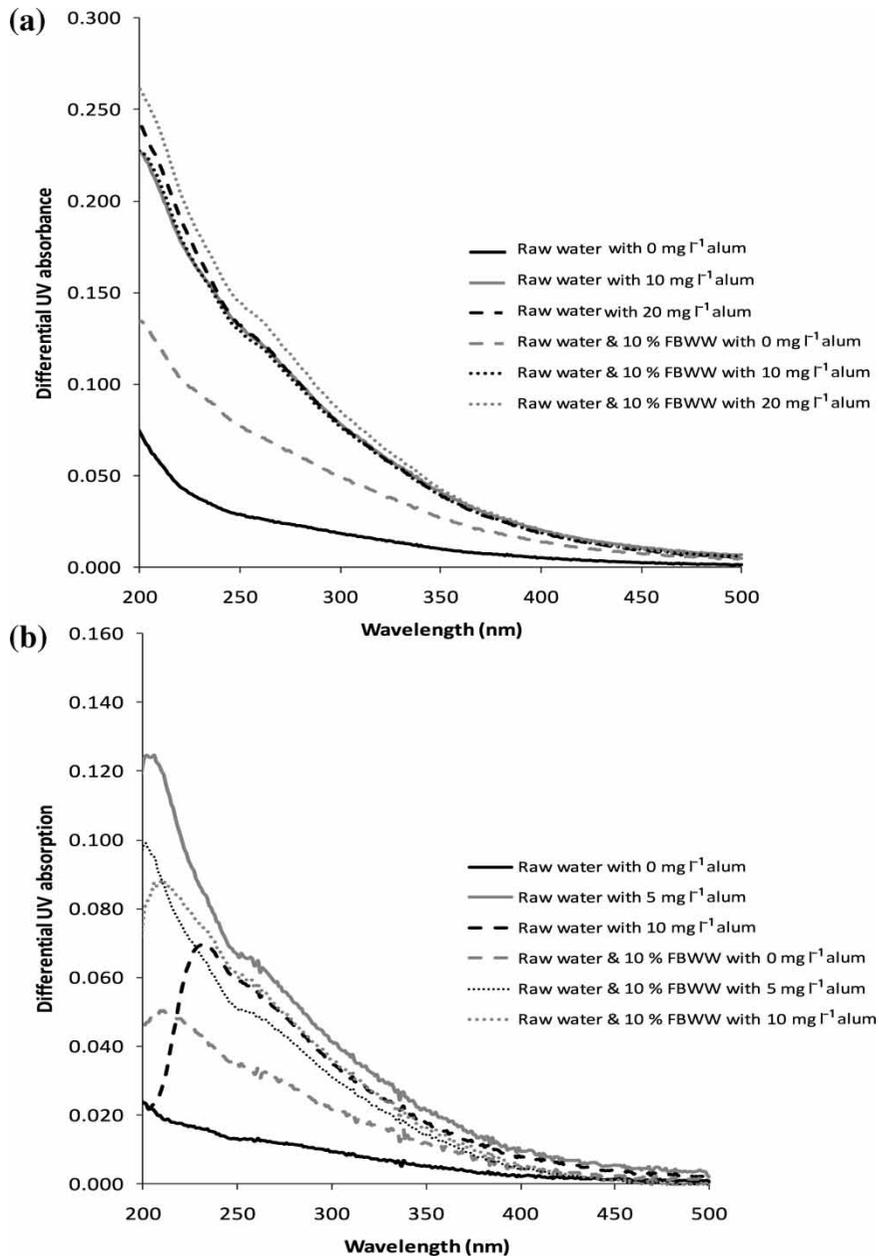


Figure 4 | Average differential UV absorbance ( $\Delta UVA = UVA_{\text{raw}} - UVA_{\text{permeate}}$ ) for: (a) Bridgewater and (b) Hantsport source water experiments.

support this theory. For the Hantsport source water experiments, DOC concentrations in the UF permeate were maintained within the range of the control trial ( $1.9 \pm 0.3 \text{ mg l}^{-1}$ ) during the FBWW recycle experiments ( $2.2 \pm 1.1 \text{ mg l}^{-1}$ ). However, the significant reductions found for both UV254 and true colour indicate that the destabilized particles and/or residual aluminium hydroxide precipitates present in the FBWW may have promoted the

coagulation of stabilized organics present in the source water prior to UF treatment.

It has been demonstrated that to achieve enhanced removal of NOM in UF systems, lower doses of coagulant are required than those in conventional granular filtration units. This factor is due to the size-exclusion mechanism of low-pressure membrane systems, in which the size of floc required to be rejected by the membrane need only be

larger than the rated pore size of the membrane (i.e. 0.01 to 0.1  $\mu\text{m}$ ) (Bérubé *et al.* 2002; Walsh *et al.* 2009). Although the concentration of aluminium hydroxide present in the FBWW samples was not measured in this study, the results are in agreement with previous work that examined the potential impacts of FBWW recycle on organic removal in conventional coagulation–flocculation–sedimentation processes (Gottfried & Walsh 2008; Gottfried *et al.* 2008). The results of that study showed that the addition of 10% FBWW to surface water prior to conventional treatment did not have a negative effect on TOC removal, and increased the removal of DOC from raw water levels after settling. The authors hypothesized that this was a result of an increased number of collision sites during the coagulation and flocculation steps owing to the added solids combined with an influx of new charge neutralization sites on the destabilized alum particles. These mechanisms improved floc aggregation, thus improving the removal of NOM. Similar processes may have been at work in the bench-scale coagulation pretreatment and UF filtration process evaluated in this study.

The improved DOC, UV254 and true colour removal observed with introduction of the 10% FBWW prior to UF treatment compared with the control trials may also have been a result of changes in the permeability of the membrane because of the additional organic loading introduced with the FBWW recycle prior to UF treatment, leading to cake formation or pore blocking on the surface of the membrane (Carroll *et al.* 2000; Schafer 2001; Broeckmann *et al.* 2006). This problem may have prevented the passage of larger NOM molecules that would have gone through the membrane otherwise. However, monitoring of the transmembrane pressure (TMP) of the bench-scale UF module during the experiments demonstrated that vacuum pressure was maintained within range of the TMP operated during control trials for both the Bridgewater and Hantsport experiments of  $2.5 \pm 0.3$  psi and  $3.0 \pm 1.2$  psi, respectively. The bench-scale UF module was operated in constant flux and variable TMP mode at a mean temperature of  $20 \pm 2^\circ\text{C}$  throughout all experimental trials.

### 10% FBWW recycle with coagulation pretreatment trials

For the Bridgewater source water experiments, the addition of 10% untreated FBWW to the raw water prior to

coagulation with  $10\text{ mg l}^{-1}$  alum resulted in significant improvements in DOC, UV254 and true colour removal in the raw water after UF treatment compared with the source water trials with alum coagulation alone (Figure 2). Specifically, the average DOC removal achieved increased from 44% during the trials with  $10\text{ mg l}^{-1}$  alum pretreatment to 54% in the trial with 10% FBWW blended with the raw water and coagulated with  $10\text{ mg l}^{-1}$  alum prior to UF treatment. UV254 removal achieved after UF treatment also increased from an average of 71 to 82% with the addition of 10% FBWW to the raw water prior to  $10\text{ mg l}^{-1}$  coagulation pretreatment. At the higher alum dose evaluated in this study (e.g.  $20\text{ mg l}^{-1}$ ), a significant improvement in UV254 reduction was also observed when 10% FBWW was blended with the source water prior to coagulation-UF treatment. The average UV254 removal increased from 77% (raw water with  $20\text{ mg l}^{-1}$  alum) to 85% (raw water blended with 10% FBWW and  $20\text{ mg l}^{-1}$  alum). As presented in Figure 4(a), the raw water blended with 10% FBWW and  $20\text{ mg l}^{-1}$  alum pretreatment showed the highest removal of UV-absorbing compounds along the spectrum. However, the differential UV-absorbance curve for coagulation with alum alone at 10 and  $20\text{ mg l}^{-1}$  and the raw water blended with 10% FBWW and  $10\text{ mg l}^{-1}$  alum pretreatment showed a similar trend of achieving high removal of UV-absorbing compounds. Both DOC and true colour removal were also improved with the addition of the FBWW prior to the  $20\text{ mg l}^{-1}$  alum coagulation and UF treatment; however statistical analysis showed that these differences were not significant.

In contrast to the Bridgewater source water experiments, blending 10% FBWW with the Hantsport raw water prior to alum coagulation and UF treatment resulted in slightly lower removal of DOC and UV-254 (Figure 3). These results were found at both the low ( $5\text{ mg l}^{-1}$ ) and high ( $10\text{ mg l}^{-1}$ ) alum doses evaluated in this study, although ANOVA tests showed that these differences in treatment efficacy were not statistically significant. As presented in the differential UV-absorption plot (Figure 4(b)), blending 10% FBWW with the raw water prior to  $5\text{ mg l}^{-1}$  alum coagulation and UF treatment negatively impacted removal of UV-absorbing compounds. At the higher alum dose of  $10\text{ mg l}^{-1}$ , minimal differences were found in the differential UV absorption spectrum between the raw

water and FBWW recycle trials. True colour measurements taken during the experiments with  $5 \text{ mg l}^{-1}$  alum pretreatment also showed no significant difference in removal achieved between the raw water and raw water blended with 10% FBWW prior to coagulation–UF treatment. However, true colour removal was found to be significantly improved from 71% (100% raw water) to 84% (raw water blended with 10% FBWW) during the higher alum dose experiments at  $10 \text{ mg l}^{-1}$ . As presented earlier, blending the 10% FBWW with the raw water during the control trials (no coagulation) was shown to significantly improve true colour removal. Although similar results were not observed in the lower alum dose experiments (i.e.  $5 \text{ mg l}^{-1}$ ), the improved removal of true colour at the higher alum dosage of  $10 \text{ mg l}^{-1}$  when FBWW was blended with the raw water prior to coagulation indicates that this process design influences organic removal. Collectively, these results demonstrate that although consistent improvements to UF permeate water quality were not realized in blending the 10% FBWW with the raw water prior to coagulation and UF treatment, the UF permeate water quality was not significantly negatively impacted under this process design.

## CONCLUSIONS

This study evaluated the potential impacts to UF permeate water quality and coagulation pretreatment efficacy in a bench-scale submerged UF membrane system operating with and without waste backwash water recycle. For the two low turbidity, high colour source waters used in the study, it was found that coagulation pretreatment with low dosages of alum (e.g.  $\leq 20 \text{ mg l}^{-1}$ ) significantly improved DOC, UV254 and true colour removal in the UF membrane test apparatus. For both source waters, blending 10% FBWW with the raw water prior to UF treatment resulted in significant improvements in both UV254 and true colour removal compared with the control trials in which alum coagulant was not added. The presence of predominantly destabilized particles in the FBWW samples compared with the source waters that contained predominantly stabilized particles, as quantified through zeta potential measurements, suggest that the presence of aluminium hydroxide precipitates in the waste FBWW stream promoted the occurrence

of coagulation mechanisms during the FBWW recycle experiments. The coagulation pretreatment experiments with the raw (100% source) and recycle (10% FBWW blended) water showed different levels of organic removal achieved with the two source waters evaluated in this study. For the Bridgewater source water trials, a significant increase UV254 removal was found when 10% FBWW was blended with the raw water prior to alum coagulation, flocculation and UF treatment compared with processing the source water alone through this treatment train. For the Hantsport source water trials, no significant differences were found in the permeate water quality between the raw and FBWW blended source waters treated in the coagulation–UF bench-scale treatment train.

Collectively, the results of this study demonstrated that UF permeate water quality was not negatively impacted when 10% FBWW was blended with raw water prior to coagulation, flocculation and UF treatment. The results also showed that, for some source waters, blending waste FBWW that contains residual metal salt coagulant with the raw water prior to coagulation–UF treatment may improve DOC and UV254 removal and reductions in neat coagulant dosage may be possible to achieve specific disinfection by-product precursor removal targets. Recycling liquid waste residual streams to the front of the treatment train in UF membrane plants would be a simple and relatively inexpensive way of improving the sustainable management of waste residual streams and possibly improving the organic removal efficiency of a drinking water treatment system. Further study would be required to investigate the impact of recycling untreated waste backwash water streams on fouling and membrane cleaning frequency requirements in UF systems.

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