

## Comparison of dissolved air flotation and ballasted sedimentation for the treatment of an algal impacted water

Juan P. González-Galvis<sup>a</sup>, Richard M. Hérard<sup>b</sup>, Elise Berthier<sup>c</sup>, Roberto M. Narbaitz<sup>d,\*</sup>

<sup>a</sup>Faculty of Civil Engineering, Universidad Santo Tomás Tunja, Colombia, email: juan.gonzalezga@usantoto.edu.co

<sup>b</sup>Department of Civil Engineering, University of Ottawa, email: rhera045@uottawa.ca

<sup>c</sup>École Nationale Supérieure de Chimie de Rennes, Rennes, France, email: eliseberthier28@gmail.com

<sup>d</sup>Department of Civil Engineering, University of Ottawa, 161 Louis Pasteur Pkt., Ottawa, Ontario K1N6N5, Canada, email: narbaitz@uottawa.ca

Received 11 May 2021; Accepted 10 November 2021

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### ABSTRACT

Dissolved air flotation (DAF) is considered better than conventional gravity settling (CGS) for the treatment of algal-laden waters, and ballasted sedimentation (BS), a high-rate separation process, is now often used instead of CGS. Our initial literature search did not identify DAF-BS comparisons for the removal of algae and cyanobacteria from algal laden waters. The objective of this bench-scale study was to compare DAF with BS and CGS for the treatment of water from a eutrophic waterway (Bay of Quinte, ON). The study was performed mid-summer when there was substantial algal growth. The optimized BS jar tests had 3% lower average turbidity removal than the DAF jar tests, however BS required 33% more coagulant, as well as 0.25 mg/L anionic polymer and microsand additions. The removal of cyanobacteria and algae (quantified using chlorophyll-a and c-phycoerythrin concentrations) by DAF and BS were very similar, and they were superior to that achieved by CGS. The DOC removals and the disinfection by-products formation potential (DBPFP) of DAF and BS treated water were also similar. Based on the chlorophyll-a and c-phycoerythrin removals, both BS and DAF performed better than CGS and can be considered suitable for the treatment of algal/cyanobacteria laden waters.

*Keywords:* Cyanobacteria; Chlorophyll-a; c-Phycocyanin; Ballasted sedimentation; Dissolved air flotation

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### 1. Introduction

The efficiency of coagulation, flocculation, and separation processes at water treatment plants (WTPs) is generally assessed based on the removals of turbidity and natural organic matter (NOM). In addition to aesthetic considerations, turbidity may reflect the presence of suspended solids including bacteria, Giardia cysts and Cryptosporidium oocysts [1]. One aspect that will need to be considered in creating sustainable water treatment systems is their climate change adaptability. Some of the predicted impacts of climate change are warmer water temperatures,

extended dry periods, more intense storms, and lower river water levels in the summer. The more intense storms should lead to more wash-out of fertilizers from agricultural fields. Due to this fertilization, the extended dry (sunny periods) and the higher water temperatures the receiving waters are expected to become more eutrophic and experience more and larger algal and cyanobacterial blooms. In addition, the higher water temperatures are expected to favour cyanobacteria over algae, and will likely lead to greater problems associated with cyanobacterial toxins. At WTPs, these blooms will cause more taste and odour problems, may impact filtration, and possibly experience

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\* Corresponding author.

cyanobacterial toxins. The adaptation to this climate change scenario is important to many WTPs, as more WTPs will likely experience algal and cyanobacterial related problems.

Algal and cyanobacterial cells have a very low density; so, they are difficult to separate by sedimentation. Dissolved air flotation (DAF) preceded by coagulation, flocculation (C/F/DAF) is considered the standard technology for the removal of algae and cyanobacteria cells [1]. This technology has also been shown to sometimes provide somewhat better NOM removals than coagulation, flocculation, and conventional gravity settling (C/F/CGS) [1]. In recent years, ballasted sedimentation (BS) has become a very popular high-rate separation process due to its compactness and its ability to handle large variations in raw water quality [2,3]. While these separation processes can remove cyanobacterial toxins while they are within the cyanobacterial cells they cannot remove dissolved cyanobacterial toxins. In their original literature search, the authors identified that while there were some BS-DAF comparison studies [3,4] there was a gap in that none of these studies compared the performance of these separation processes for the same algal impacted waters. Such a comparison should incorporate: (a) turbidity removals as the algal/cyanobacterial cells cause turbidity; (b) organics removals as the algae/cyanobacteria contribute to the organics; (c) the removal of algae and cyanobacteria as they may be removed to a different extent; and (d) disinfection by-product removals as the organics removed by the separation processes may differ. Therefore, the objectives of this bench-scale study were to (a) optimize the coagulation process for CGS, DAF and BS process in the treatment of an algal-laden water for turbidity removal; and (b) compare the performance of the bench-scale CGS, DAF and BS for the removal of algae and cyanobacteria, NOM and disinfection by-products formation potential (DBPFP). The overall goal being to ascertain how well these separation processes will perform in the treatment of an algal-laden water. Such a comparison is important because these high rate technologies are being increasingly used in new plants instead of gravity settling and used in plant expansions because of their smaller footprint. In addition, such a comparison will identify the different chemical requirements of BS and DAF which impact the operational costs of these systems.

## 2. Materials and methods

### 2.1. Water tested

The experiments were conducted using water collected at the Belleville WTP, which treats water from the Bay of Quinte (Belleville, ON, Canada). This water was chosen because of the eutrophic conditions in the Bay of Quinte leading to relatively frequent algal and cyanobacterial blooms in mid to late summer [5,6]. The Belleville WTP has a pre-oxidation step within the intake (1.25 mg/L  $\text{KMnO}_4$  & 2–4 mg/L chlorine) for taste, odor and zebra and quagga mussel control. Thus, this water will be referred to as pre-treated Belleville water (PBW). The CGS, DAF and BS jar test comparison was conducted at the Belleville WTP using water collected after the pre-oxidation step in late July of 2018. Coagulation at the Belleville WTP uses alum (ALS,

Kemira, Montreal, QC:  $4.30 \pm 0.1\%$   $\text{Al}^{3+}$ ) with a dose of 60 mg/L as  $\text{Al}_2\text{O}_3$  (5.45 mg Al/L) year around.

The water quality characterization of PBW in late July 2018 (mid-summer) is presented in Table 1. PBW water characteristics show a water with a slightly above neutral pH, relatively low turbidity, moderate hardness, intermediate alkalinity, and intermediate SUVA (Table 1). The water's SUVA is between 2.0 and 4.0; therefore, the most probable composition of the NOM is a mixture of aquatic humics, hydrophobic and hydrophilic NOM [1]. The C-phycocyanin (cyanobacterial) levels found in the PBW has a concentration close to the range reported by previous studies [5,6]. Logistical considerations, the extensive preparation required, as well as the plant and personnel availability restricted the field testing to a three-day period in late July 2018. Unfortunately, due to a severe storm two days prior to our testing the algal/cyanobacterial concentrations were not at a peak level. Yet, the algal/cyanobacterial concentrations were close to the range reported by previous studies (i.e., 12 – 25  $\mu\text{g}$  chlorophyll-a/L) [6]. Based on the World Health Organization criteria for cyanobacteria bloom at the first alert level (i.e., cyanobacteria concentrations higher than 2,000 cells/mL, or 1  $\mu\text{g}$ /L chlorophyll-a) [7], the Bay of Quinte water sample used still could be described as having as moderate cyanobacterial bloom characteristics.

### 2.2. Bench-scale experiments

#### 2.2.1. DAF jar tests

C/F/DAF jar test experiments were conducted in a DAF jar test apparatus (PJT02 Capital Controls Group, Didcot, GB). The DAF jar test apparatus includes one coagulation–flocculation–flotation cell (jar), which has an internal diameter of 9 cm, a height of 22 cm, and a maximum volume of 1.4 L. The unit is equipped with a rotating flat paddle stirrer connected to a motor with adjustable mixing speeds to control the velocity gradients within the jars. The unit also includes a saturated water injection apparatus, which has a nozzle and valves at the bottom side of the jar. Plastic tubing connects the nozzle apparatus to an 8 L volume pressurized saturator tank (Capital Controls Inc/Trent Severn Ltd, England), which is pressurized by

Table 1  
Pre-treated Belleville water characterization summer 2018

Parameter	Pre-treated Belleville water
pH	$8.32 \pm 0.14$
Turbidity (NTU)	$8 - 12 \pm 0.15$
Alkalinity (mg/L as $\text{CaCO}_3$ )	$116.7 \pm 6.5$
UV-254 ( $\text{cm}^{-1}$ )	$0.14 \pm 0.001$
DOC (mg/L)	$5.49 \pm 0.02$
SUVA (L/mg m)	$2.55 \pm 0.01$
True color (Pt-Co)	$6.7 \pm 0.65$
Total hardness (mg/L)	$119.3 \pm 2.6$
Chlorophyll-a ( $\mu\text{g}/\text{L}$ )	$12.9 \pm 2.95$
C-phycocyanin ( $\mu\text{g}/\text{L}$ )	$44.3 \pm .14$

\*(average  $\pm$  one standard deviation) ( $n = 3$ )

a compressor (TAW-0308, PSI Compressors Inc. Ottawa, ON). The operational conditions used in this study were those recommended by the jar test manufacturer’s manual (Capital Controls Group, Didcot, GB, 2001). The manufacturer’s recommended conditions are: (a) add a 1,000 mL sample of water to the flotation jar; (b) mix the jar content at 400 rpm ( $G = 240 \text{ s}^{-1}$ ) for one minute; (c) add the coagulant to the liquid and mix it for 1 min (coagulation); (d) then mix the liquid at 30 rpm ( $G = 12 \text{ s}^{-1}$ ) for 10 min (flocculation); (e) stop the mixing and transfer 110 mL of saturated water through the connecting tubing into the jar to initiate the flotation step; and (f) allow a 10 min flotation period for the bubble-floc aggregates to form and float, this results in the clarification. The floated water samples were collected using the sampling port near the bottom of the jar. The saturator pressure (SP) used was 482 kPa (70 psig). These experiments used a 10% recycle ratio (RR), which was achieved by introducing 110 mL of saturated water. Earlier testing with this jar test apparatus showed that the turbidity removals could be closer to those of full-scale systems by using an alternative pressurized water delivery system which provided better bubble size control [8]. In the current study, this alternative bubbling system was used for the DAF jar tests instead of the Capital Control jar tester’s pressurized water delivery system. The alternative bubbling system delivered the pressurized water to the bottom of the jar using a

6.35 mm (1/4 inch) OD stainless steel tubing with a needle valve at the end. The optimum coagulant dose was chosen in terms of particle destabilization, measured through the zeta potential (ZP) and the turbidity removal. The DAF experiments, except those examining the impact of coagulant dose, used the same alum coagulant as the Belleville WTP. A set of C/F/DAF experiments were conducted in duplicate to assess turbidity, DOC, UV-254, Chlorophyll-a, and C-phycoyanin and the DBPFP reductions. DAF jar tests were conducted in duplicate, and some tests were performed in triplicate to obtain a confirmatory result. From them the average percentage removals and their 95% confidence limits were calculated and then compared to establish if two different treatments were statistically the same.

2.2.2. BS jar tests

BS jar tests were conducted using a regular jar test apparatus (Phipps and Bird, Inc. Richmond, VA, US) using 1L round beakers. The BS jar test procedure used in this research was adopted from Desjardins et al. [9]. The BS experimental procedure is outlined in Fig. 1. The microsand had an effective diameter of 80  $\mu\text{m}$  (Veolia Inc., Montreal, QC).

Preliminary tests with conventional square jars led to significant sand deposition in the corners, this was the case even when the mixer paddles were lowered within 3 mm of

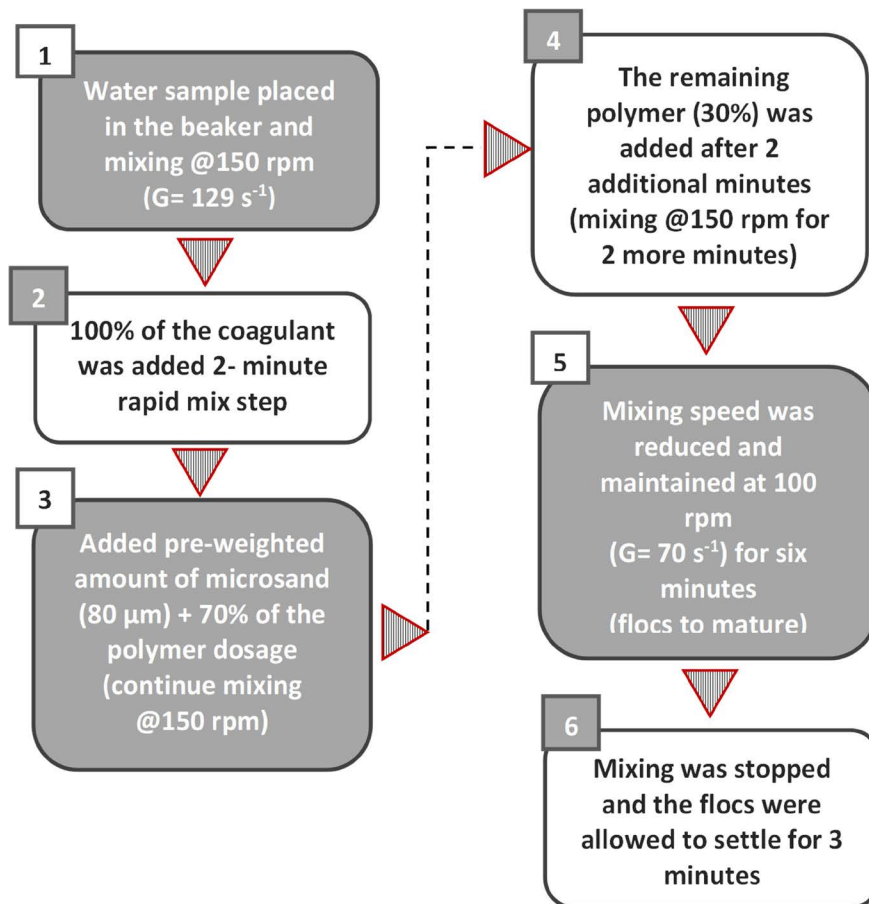


Fig. 1. Ballasted sedimentation jar test procedure.

the jar bottom. Accordingly, cylindrical beakers were used instead. The BS optimization required many more runs than DAF tests because in addition to the coagulant dose, the polymer type, the polymer dose, and the microsand dose also had to be optimized. The BS preliminary optimization experiments were conducted in our lab with Bay of Quinte water collected a week prior to the field tests. In the first part the preliminary tests the following polymers were evaluated: Superfloc C-492PWG (a high MW, low charge density cationic polyacrylamide polymer obtained from Kemira, Montreal, QC), Magnafloc LT22S (high MW, low charge density cationic polymer from BASF, Mississauga, ON), and Magnafloc LT27 (very high MW, medium-low charge density anionic polymer also from BASF, Mississauga, ON). While Crittenden et al. [1], a standard design textbook, states that cationic polymers are used for BS, it should be noted that many BS systems use anionic polymers [9,10] including at a nearby treatment plant (i.e., Rockland, ON WTP). The preliminary tests showed that for the treatment of Bay of Quinte water the anionic Magnafloc LT27 polymer was superior to the two cationic polymers tested, and thus it was used in the field testing. The second set of preliminary tests included testing six different doses of aluminum sulfate coagulant (ALS, Kemira, Montreal, QC) doses, five different doses of anionic polymer (Magnafloc LT27) doses (0.20, 0.25, 0.30, 0.35 and 0.45 mg/L), five different microsand doses (1, 2, 3, 4 and 5 g/L) and three different sedimentation times (1, 2 and 3 min). Preliminary BS tests results showed that coagulant doses lower than 6.0 mg Al/L, polymer doses lower than 0.20 mg/L and micro-sand doses lower than 4.0 g/L did not yield good turbidity removals (i.e., final turbidity  $\geq 1.5$  NTU). These results could be due to the lack of attachment between particles and the micro-sand, which is necessary to increase the floc's density sufficiently to produce rapid settling. In fact, in some tests it was observed that in the maturation step, a significant amount of the micro-sand was not integrated into the flocs and precipitated to the jar bottom in spite of the mixing. In addition, polymer doses higher than 0.25 mg/L did not improve the BS turbidity removal performance. The BS jar tests conducted during the field-testing assessed the impact of coagulant dose on particle destabilization through ZP measurements and turbidity removals, these tests used a polymer dose of 0.25 mg/L, a microsand dose of 4 g/L and a settling time of 3 minutes. The BS water samples were collected near the surface of the beaker. The BS experiments were conducted in duplicate, and some tests were performed in triplicate to obtain a confirmatory result. From them the average percentage removals and their 95% confidence limits were calculated. Subsequently, the 95% confidence limits were compared to establish if two different treatments were statistically different.

### 2.2.3. CGS jar test

CGS experiments were conducted using a regular jar test apparatus with six 2 L square beakers (Phipps & Bird, Inc. Richmond, VA). All the C/F/CGS jar test were conducted with the following conditions: (a) rapid mix at 100 rpm ( $G = 70 \text{ s}^{-1}$ ) for 1 min; (b) slow mixing at 30 rpm ( $G = 12 \text{ s}^{-1}$ ) for 15 min and (c) sedimentation for 30 min. These are the conventional conditions for C/F/CGS jar tests

in water treatment treatability tests [11]. The C/F/CGS optimization experiments were performed using six different alum doses. After the CGS experiments, settled water turbidity was measured immediately and water samples for conducting DOC, UV-254, chlorophyll-a, C-phycoerythrin and DBPFP analysis were collected near the surface of the square jars. The C/F/CGS experiments were conducted in duplicate, and some tests were performed in triplicate to obtain a confirmatory result. From them the average percentage removals and their 95% confidence limits were calculated. Subsequently, the 95% confidence limits were compared to establish if two different treatments were statistically different.

### 2.3. Analytical methods

The pH of all the water samples was measured using a pH meter (HQ40D, HACH, Loveland, Co.). Turbidity was determined using a turbidimeter (2100AN, Hatch, Loveland, Co.). The DOC is the dissolved organic carbon concentration, and this was obtained by vacuum filtering the water samples through a 0.45  $\mu\text{m}$  nylon membrane filter (PALL Sciences Corp; Pensacola, FL) and then performing total organic carbon (TOC) analysis on the filtrate. TOC analysis was conducted using a UV-persulfate oxidation-based TOC analyzer (Phoenix 8000, Tekmar-Dohrmann, Cincinnati, OH). The TOC analysis followed the Standard Method 5310 C [12]. Ultraviolet absorbance at 254 nm (UV-254) measurements of the filtered samples were conducted using a UV spectrophotometer (DU-40 Beckman Instruments Inc.; Mississauga, ON) with a 1.0 cm path length quartz cell. The specific UV absorption (SUVA) was calculated by dividing the UV-254 nm by the DOC concentration, it was then multiplied by 100 to convert it in terms of L/mg m. The alkalinity and the total hardness of the raw water were determined according to Standard Methods 2320 and 8226 (2340), respectively [12]. ZP measurements of the coagulated water samples were conducted using a Zetasizer Nano Particle Analyzer (Nano ZS, Malvern Instruments Ltd., Worcestershire, UK). Algae were quantified in terms of chlorophyll-a and cyanobacteria were quantified in terms of the concentrations of C-phycoerythrin, a freshwater cyanobacteria specific pigment [13]. Chlorophyll-a was extracted using an ethanol extraction method and quantified spectrophotometrically [14]. C-phycoerythrin extraction was conducted using 10 mL sodium phosphate buffer solution (pH = 6.8) followed by quantification by the spectrophotometric analytical procedure developed by Horváth et al. [15].

The DBPFP quantification was conducted using a modified version of Standard Method 5710, the trihalomethane formation potential test [12]. 1,000 mL of sample were measured with a graduated cylinder and filtered through a 0.45  $\mu\text{m}$  nylon membrane filter (47 mm diameter, PALL Sciences Corp, Mississauga, ON). The membrane filtration step was used to simulate the deep bed filtration that takes place at the full-scale WTP. The DBPFP tests used a 4.4 mg  $\text{Cl}_2/\text{L}$  dose, which is the total chlorine dose applied to the finished water at the Belleville WTP. A 24 h chlorine contact (incubation) time was chosen to simulate the maximum water age found in the Belleville drinking water distribution system. The disinfection by-products (DBPs) formed in

these tests were measured in terms of the trihalomethanes (THMs) and haloacetic acids (HAAs) formed, they were quantified by gas chromatography analysis.

### 3. Results and discussion

#### 3.1. DAF, BS and CGS jar test optimization

Optimization experiments of DAF, BS and CGS were conducted to obtain the optimum coagulant dose, to compare their performance in terms of turbidity removal, and to compare their turbidity removal with that obtained by the full-scale DAF units at the Belleville WTP. The tests were conducted in duplicate, and Fig. 2 shows the average results. As shown in Fig. 2, based on the ZP the minimum coagulant dose for good particle destabilization for DAF jar tests was 4.54 mg Al/L, which was lower than the dose used at the Belleville WTP (5.45 mg Al/L). The higher dose used at the plant was chosen to reliably remove disinfection by-product precursors. These dosages corresponded to near zero ZP measurement (−2.28 and −2.17 mV, respectively). ZP values close to neutrality have been reported as the optimum for the removal of cyanobacterial cells, NOM

and extracellular organic matter (EOM) [16]. Fig. 2 also shows that for coagulant doses greater than 4.54 mg Al/L, the changes in the particle's ZP were relatively small and do not continue to increase as expected with further additions of alum. A similar charge pattern, that is, the charge does not become positive with increasing coagulant dose, has been observed by others [17]. A possible reason for this is that fine colloid particles are not satisfactorily destabilized by the coagulant, this could be associated to the characteristics of the particular NOM, algae and cyanobacterial mix in the water. A number of studies [18,19] reported that the coagulant reacts first with free natural organic acids, and therefore the charge of small algae and cyanobacteria particles cannot be satisfactorily neutralised. In addition, the pre-chlorination step applied in the Belleville WTP make colloids more resistant to the coagulation process [20,21]. Although the ZP of the BS solution was not measured, the ZP of a 4 g/L microsand solution was −46 mV. So, the addition of the microsand and the anionic polymer additions should make the BS solution more electronegative than the one measured for the DAF tests at the same coagulant concentrations. Accordingly, it is unlikely that charge neutralization had a significant role in the BS separation. In addition, the significantly higher coagulant dose used in the BS processes to capture the large dose of microsand suggests that sweep flocculation is the controlling mechanism for BS.

It should be noted that the final pH of the jars decreased gradually from 7.4 to 6.4 as the coagulant dose increased from 2.73 to 7.27 mg Al/L. A pH decrease was expected as the alum additions consume alkalinity and reduce the pH, the relatively modest change in pH was likely due to intermediate levels of alkalinity of the raw water (~118 mg/L as CaCO<sub>3</sub>). The near zero zeta potentials imply that charge neutralization/adsorption are important mechanisms. Yan and Jameson [21] explained that charge neutralization/adsorption is an important mechanism for algae and cyanobacteria destabilization because it is an important factor for the attachment of polymer chains to algae cells. However, based on the 4.54 mg Al/L alum dose and a pH of 6.6–7 Amirtharaj and Mills' [22] interpretation of the pC-pH diagram suggest the main removal mechanism would be sweep coagulation, and this application meets the ≥90% turbidity removal criteria used by Choi and Dempsey to identify sweep flocculation [23]. Thus, it seems that both charge neutralization and sweep flocculation may be at play. Also, it should be noted that the performance of DAF systems is also impacted by the generated bubble sizes and bubble concentration, which are a function of the SP and the bubbles release system. The bubble size in a DAF unit is influenced mainly by: (1) the size of the aperture from which it emerges; (2) the hydrostatic head against which it is compressed; (3) the surface tension of the interface formed with the bulk solution as the bubble emerges; (4) the speed of emergence, that is, the volume and pressure of the gas behind it; (5) the turbulence of the surrounding liquid [24]. Bubble size is an important parameter in a DAF unit because DAF performance is affected by bubble size and properties in the contact zone [25]. The bubble-particle interactions (i.e., attachment of a hydrophobic particle to a gas bubble) follows three different steps: (a) collision, (b) attachment and (c) stability [26]. Consequently, the bubble-particle

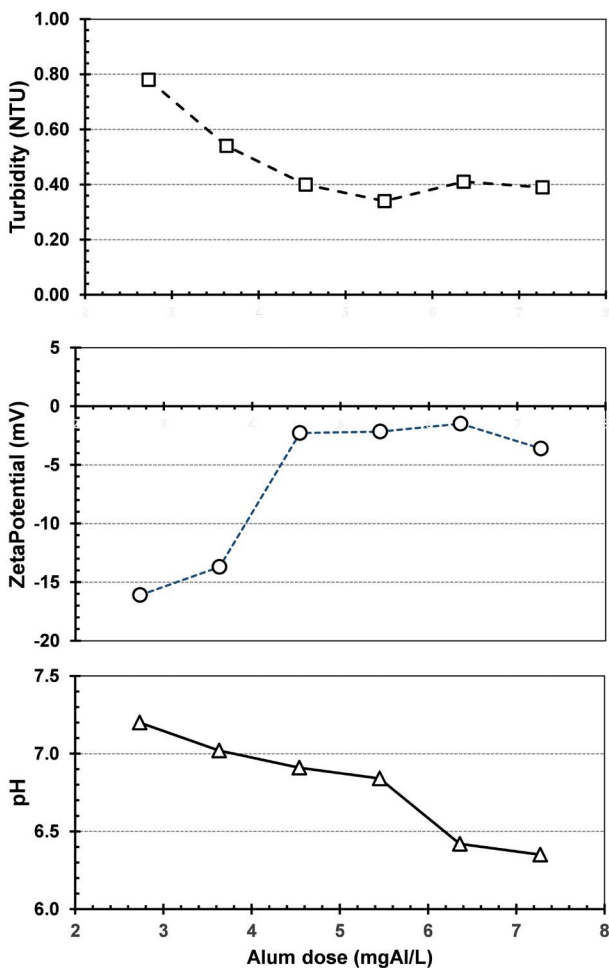


Fig. 2. DAF jar test's final turbidity, ZP and pH vs. coagulant dose.

interactions depend not only on bubble size, but also on different variables such as the floc-particle size and density, number and density of the bubbles, particle–bubble charge and the flotation retention time [27,28].

The DAF, BS and CGS turbidity removal optimization tests were performed in duplicate, the average results are shown in Fig. 3. The main observations of these test results are as follows. First, the DAF jar test matched the turbidity removals of the full-scale unit. For the same coagulant dose, the DAF jar test turbidity removal was  $96\% \pm 0.8$  while for the full-scale DAF system they were 93%–95%. This was somewhat surprising given the 10%–15% turbidity removal differences between DAF jar test and full-scale DAF results reported in other studies [8,29]. Second, while the CGS jar test's turbidity removal were good (90%), they were among the lowest observed. They were 6%–10% lower than the DAF jar test's turbidity removals at the same coagulant dose. The slightly better DAF turbidity removal agrees with the results reported by others who compared DAF and CGS for the treatment of low turbidity waters (i.e., <20 NTU) [30]. Third, the BS achieved 3% lower turbidity removals than the DAF (92% vs. 95%); given the confidence limits, percentage turbidity removals are statistically identical ( $\alpha = 0.05$ ). However, for optimal turbidity removals BS required a higher coagulant dose (i.e., 7.27 mg Al/L vs. 5.45 mg Al/L for the DAF) in addition to 0.25 mg/L anionic polymer and 4 mg/L microsand. And whereas, the CGS achieved similar turbidity removals to the BS, the BS has a much lower settling time (3.0 vs. 30 min), but it required a higher coagulant dose. It appears that the higher coagulant dose is required to compensate for the more rapid floc formation, and that the dense flocs formed are less effective in trapping (sweeping) turbidity causing particles [29,30]. During the preparation of this manuscript, the authors identified another comparison between BS and DAF for the treatment of algal/cyanobacteria laden waters from a less readily available source [31]. The results in the current study are in agreement with the findings of that AWWARF research report by Knappe et al. [31], that is, that BS and DAF had the same or better turbidity removals than CGS. Their final turbidity values were also below 1.0 NTU.

The similarity of the DAF and BS turbidity removals are likely due to different mechanism. DAF benefits from the superior separation of the light algal/cyanobacterial cells,

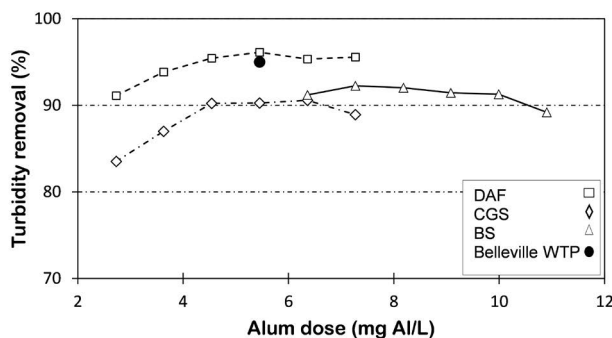


Fig. 3. Impact of alum dose on turbidity removal with three different treatments (DAF, BS and CGS) at the bench-scale level.

while BS benefits from the greater agglomeration achieved by the higher alum dosage and polymer addition. The BS's system higher coagulant dose is necessary to incorporate the high dose of microsand, these higher doses make sweep flocculation the most likely removal mechanism.

### 3.2. Chlorophyll-a and C-phycoerythrin removal by DAF, BS and CGS

Due to the volume of water required for chlorophyll-a and c-phycoerythrin quantification, their removal had to be evaluated in a separate set of jar tests (conducted under the same operational conditions and chemical dose as those used for optimal turbidity removal). Their final chlorophyll-a and c-phycoerythrin concentrations are presented in Fig. 4a and b, respectively. The chlorophyll-a and the c-phycoerythrin percentage removal for each treatment were: DAF 98% and 94%, CGS 87% and 51% and BS 97% and 93%, respectively. Therefore, The DAF and BS had similar chlorophyll-a and c-phycoerythrin removals. These results agree with those reported by other studies by comparing DAF. Knappe et al [31] reported that DAF and BS jar tests had *M. aeruginosa* cells removals that were higher than or equal to those obtained via conventional jar tests. Their study used three different coagulant doses for all the jar tests focusing on the dose for the point of zero charge (PZC); it is

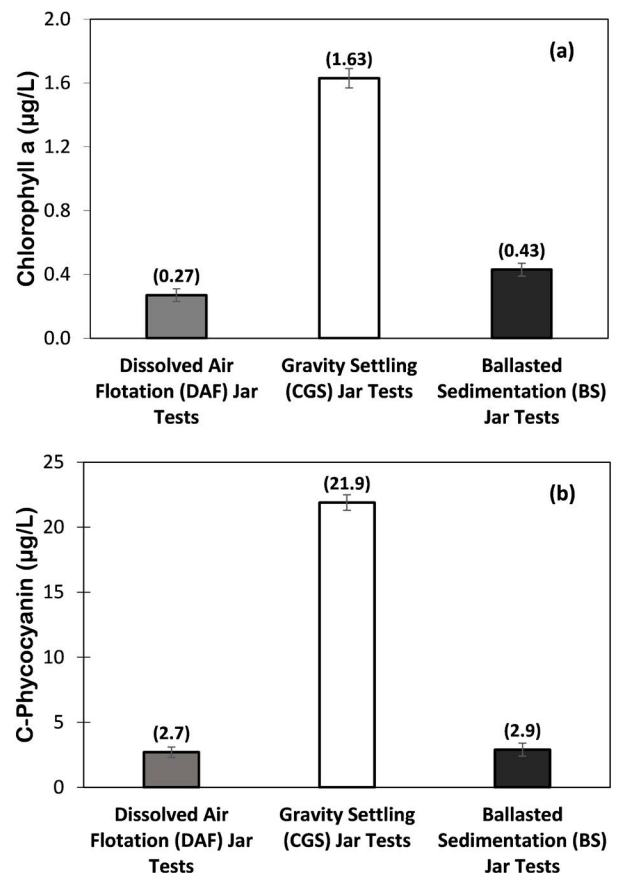


Fig. 4. DAF, CGS and BS final concentrations of (a) chlorophyll-a and (b) c-phycoerythrin (error bars indicate one standard deviation).

not clear whether these doses were optimal for BS. Based on the turbidity removals achieved in the current study, optimal performance by BS may require higher coagulant doses. It is speculated that if Knappe et al [31] had optimized the BS coagulant dose for cyanobacterial removals they may have obtained consistently better cyanobacterial removals than achieved by CGS. Further studies are required to ascertain this. In their pilot-scale BS study Robinson and Fowler [4] reported higher percentage phytoplankton and cyanobacteria removals than the current study. However, this was for a different water and they used higher coagulant and polymer doses (i.e., 95 and 0.45 mg/L, respectively).

The similar performance achieved by DAF and BS for the removal of algae and cyanobacteria may have been impacted by two possible factors. First, the combined use of  $\text{KMnO}_4$  and chlorine applied as a pre-oxidation step at the intake of Belleville WTP may help inactivate algal cells thereby allowing hydrous manganese dioxide ( $\text{MnO}_2$ ) to adsorb on algal cells increasing the specific gravity and settling velocity [32]. This could improve the BS and the CGS performance, but at the same time it should negatively impact the DAF. Second, low  $\text{KMnO}_4$  doses (i.e., 1.25 mg/L) reduce the quantity of algal-derived extracellular organic matter and therefore facilitate coagulation [33].

In this study, CGS was not as effective as DAF for the removal of algae and cyanobacteria, measured as chlorophyll-a and c-phycoerythrin. This could be associated to the following factors: (a) the low density algal/cyanobacterial cells more readily float than settle, (b) coagulation, flocculation and DAF is less influenced by cell aggregation and therefore, DAF is able to better remove small algae and cyanobacteria flocs than sedimentation [34]. Based on these results, it is suggested that more comparison between DAF and BS be conducted for waters with higher levels of algae and cyanobacteria and without a pre-oxidation step.

### 3.3. DAF, BS and CGS comparison for the removal of NOM

This study also compared the NOM removals of the optimal turbidity removal DAF, CGS and BS tests (Fig. 5). Some studies have concluded that NOM removal is dependent on coagulation (i.e., pH, coagulant type, and dose), and not a function of the solid-liquid separation process [35]. However, other studies treating reservoir waters observed by up to 10% higher DOC and UV-254 absorbance removals by DAF than those by CGS [36].

In the current study, the DAF jar tests showed a somewhat higher average DOC removal than the CGS (38% vs. 30%), while the UV-254 removals were closer (59% and 57%) (Fig. 5). However, due to the overlapping confidence intervals, the differences do not appear to be statistically significant. The BS jar tests had slightly higher average UV-254 removals and slightly lower average DOC removals than the DAF jar tests. However, the confidence intervals also overlap, and thus the DOC and the UV-254 removals are considered statistically the same for all the treatments. Given the 33% higher alum dose used in the BS tests compared to that of the alternatives, slightly higher NOM removals were expected. In addition, Belleville WTP had slightly higher average UV-254 removals (62%) than the different jar tests treatments. However, this small difference

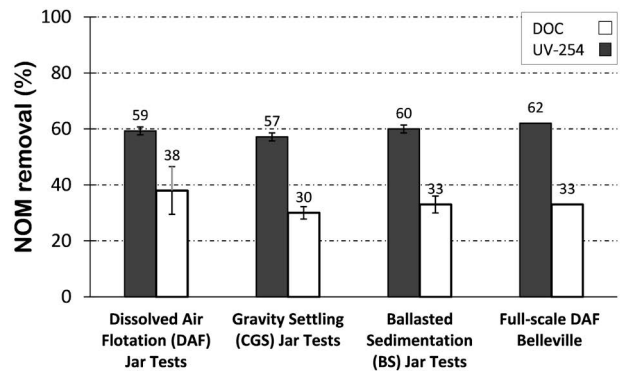


Fig. 5. DAF, CGS and BS comparison for NOM removal (error bars indicate one standard deviation,  $n = 2$ ).

was not statistically significant ( $\alpha = 0.05$ ). The similar results found in this study for NOM removal using DAF, BS and CGS agree with those reported by Knappe et al. [31].

The THMs generated in the disinfection by-product formation potential tests after clarification (i.e., DAF, CGS and BS) were similar, however the THM levels were very low, presumably due to experimental and/or analytical problems. Unfortunately, the results of the THM analysis were obtained in mid-September, and by then the levels of algae in the Bay of Quinte were much lower. In addition, two of the research assistants were no longer available, so it was decided not to attempt to repeat the experimental program.

UVA is a better predictor of THM and HA production than DOC because the UVA of NOM is generally attributed to the aromatic chromophores associated with DBP formation [37]. Thus, given the similar UVA removals the HA formation potentials (HAAFP) were expected to be similar for the three separation processes. Fig. 6 shows that the HAAFP values differed somewhat, but since their concentrations differ by less than 10% from the mean, the three treatments can be considered to achieve similar reductions in the HAAFP. If these differences are actually significant, a possible explanation for the differences is that (a) the various NOM fractions have different yields of HAAs; (b) that UVA is not sufficiently precise descriptors of the HAA formation potential for this water; and (c) the three separation processes remove the HAA forming fractions to somewhat different extent. These HAA concentrations were below the maximum allowable by the Canadian drinking water regulations, that is, 80  $\mu\text{g/L}$  [38], and they fall within the range reported by the City of Belleville for their HAA distribution system values [39].

## 4. Practical applications and future research perspectives

In this research, we were able to simulate BS in a jar test based on an existing procedure developed by Desjardins et al. [9]. This work provides new and detailed information on the challenges one encounters conducting a BS jar test (i.e., polymer type, shape of the jar, etc.), which could be useful for personnel conducting treatability studies and possibly operators. However, it is acknowledged that in most situations operators address feed water quality fluctuations by direct coagulant dosage adjustment of the

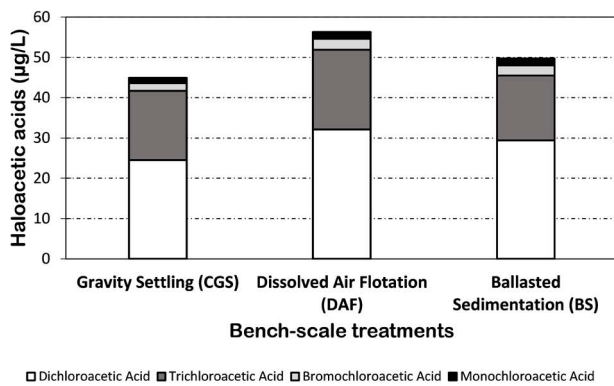


Fig. 6. HAAFP for the DAF, CGS and BS effluents.

full-scale BS system based on their experience of the raw water source. This is because due to their short hydraulic residence time (circa 20 minutes), the full-scale system's response is slightly shorter than the time required to conduct BS jar tests. It should be acknowledged that while the BS systems have higher chemical costs, DAF systems have the additional energy cost of pressuring the recycled water. Accordingly, a comparative full-cost evaluation should be conducted.

This study's key finding is that BS performs just as well as DAF, which is considered the standard technology for algal removal. These results need to be verified with other algal/cyanobacteria-impacted waters. This important because with global warming more WTPs will experience algal/cyanobacterial problems, and designers need to be aware that BS may perform well under such conditions. Based on these results the authors propose the following research. First, conduct similar DAF-BS comparisons with different source algal-laden waters, and if possible, to do so in pilot-plants, or full-scale systems. Second, expand the testing to incorporate downstream filtration because of differences in the turbidity removals of DAF and BS. It is suggested that such studies incorporate particle size distribution analysis. Third, conduct a full-cost evaluation of treatment systems incorporating BS and DAF units as well as the downstream filtration.

## 5. Conclusions

The novelty of this bench-scale study is that it presents a direct comparison of DAF and BS for the treatment of an algal-impacted water. It is acknowledged that in 2004, Knappe et al. [31] conducted a similar study but its results were not very widely distributed, we were unaware of its existence and that led us to undertake the current study. The current study showed that for an algal/cyanobacteria impacted water both DAF and BS were superior to CGS. These results are consistent with the findings of Knappe et al. [31]. The algal and cyanobacterial pigment removal, the DOC removal and the HAAFP of both DAF and BS were very similar.

Thus, the key finding was that for the increased algal/cyanobacterial growth scenario BS performs just as well as DAF, which is considered the standard technology for

algal removal. These results need to be verified with other algal-impacted waters and hopefully using pilot or full-scale tests. Given that global warming is expected to increase algal/cyanobacterial problems at water treatment plants, the universality of the results is very important to engineers designing sustainable WTPs.

## Acknowledgements

This manuscript is based on part of the lead author's doctoral thesis (J.P. Gonzalez-Galvis. Development of a large batch bench-scale dissolved air flotation system (LB-DAF) for drinking water treatability tests. PhD Thesis, Dept. of Civil Eng., Univ. of Ottawa, Ottawa, ON, Canada, 2019. dx.doi.org/10.20381/ruor-23583). The research was supported by the Natural Sciences and Engineering Research Council (NSERC), Canada. The authors would like to thank the Universidad Santo Tomás Tunja – Colombia, COLCIENCIAS and COLFUTURO for their partial financial support of the lead author through their international doctoral scholarships. The author would like to thank the operators and management of the Belleville WTP for their extensive cooperation.

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