Development of a Large Batch Bench-Scale Dissolved Air Flotation System for Drinking Water Treatability Tests

by

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Abstract

The dissolved air flotation (DAF) has been used in drinking water treatment for its excellent algae and natural organic matter (NOM) removal. DAF drinking water treatability test are often conducted in a DAF jar test apparatus. Although, DAF jar test studies showed that they were able to predict NOM removals at full-scale facilities well, they have not always been successful in predicting the turbidity removals. One possible reason of the DAF jar test inaccuracy results could be associated to the small jar diameter, which may create wall effects. Therefore, the first two objectives of this research are: a) to develop and test a new, larger diameter and larger volume batch bench-scale dissolved air flotation system (LB-DAF) to better simulate turbidity removals in drinking water applications; b) to confirm these results by comparing the LB-DAF and full-scale DAF turbidity removals for two other source waters. The raw water characteristics of the three plants were quite different and the testing was performed at different times of the year. The development/optimization of the LB-DAF evaluated the impact of different variables (i.e., mixing intensity, water depth/tank diameter ratio, impeller shape, saturator pressure and recycle ratio). The results showed that the LB-DAF predicted well the full-scale DAF turbidity removals at three water treatment plants, and these predictions were better than those of DAF jar tests. For the LB-DAF design and operational variables evaluated had a limited impact on the turbidity removals. The LB-DAF predicted well DAF full-scale turbidity removals regardless of water temperature. This is an indication of the robustness of the DAF system.

Ballasted sedimentation (BS) is a compact coagulation/flocculation and sedimentation process combination that has become very popular because it is very compact and because it can handle large variations in raw water turbidity and NOM. The literature survey did not initially identify studies on the BS treatment of algal impacted waters, for which DAF is considered particularly suitable. Thus, the third main objective of this dissertation was to compare the efficiency of BS with that conventional gravity settling (CGS), and that of DAF for the treatment of an algal impacted water via jar tests. These comparisons were performed at the Belleville Water Treatment Plant using Bay of Quinte water, one of the most eutrophic zones of Lake Ontario. Unfortunately, a change of weather prior to the testing resulted in raw water samples with relatively low concentrations of algae and cyanobacteria. The testing showed that DAF and BS had very similar NOM, cyanobacteria/algae (chlorophyll *a* and phycocyanin) removals.; however, the BS required microsand addition, polymer addition and a slightly higher alum dose. Only for turbidity removal the DAF was somewhat superior. It is suggested that these comparison experiments be repeated with waters that are more impacted by algae and cyanobacteria.

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List of Abbreviations

BS	Ballasted sedimentation
C/F	Coagulation and flocculation
C/F/DAF	Coagulation and flocculation followed by dissolved air flotation
C/F/SED	Coagulation, flocculation and sedimentation
CGS	Conventional gravity settling
C/F/CGS	Coagulation, flocculation and conventional gravity settling
DAF	Dissolved air flotation
DI	Digital imaging technique
DBPs	Disinfection by products
DBPFP	Disinfection by-product formation potential
DPA	Dynamic particle analyzer
DOC	Dissolved organic carbon
EOM	Extracellular organic matter
d_{v95}	Maximum floc size expressed on a volume base
FED	Factorial experimental design
G	Velocity gradient
HAAs	Haloacetic acids
HAAFP	Haloacetic acids formation potential
HPO	Hydrophobic NOM fraction
HPI	Hydrophilic NOM fraction
LB-DAF	Large volume bench-scale DAF tank
MF	Microfiltration
NOM	Natural organic matter

ORW	Ottawa River water
PBW	Pre-treated Belleville water
PC:Chla	C-phycocyanin to Chlorophyll *a* ratio
RR	Recycle ratio
SFW	Smiths Falls water
R	Rectangular impeller
SUVA	Specific ultraviolet absorbance
S	Square impeller
SR	Small rectangular impeller
SP	Saturator pressure
Te	Tank equivalent diameter
THMs	Trihalomethanes
TTHMs	Total Trihalomethanes
TTHMFP	Total Trihalomethane formation potential
TOC	Total organic carbon
TPI	Transphilic NOM fraction
UV-254	Ultraviolet absorbance at a wavelength of 254nm
WHO	World Health Organization
WTP	Water Treatment Plant
W/D	Water depth to column diameter ratio
V_1	Total water volume
V_2	Saturated water volume
ZP	Zeta potential

Chapter 1

Introduction

1.1 Background

Turbidity and natural organic matter (NOM) are among the main contaminants to be removed in potable water treatment plants. Turbidity is removed because aesthetic considerations as well as because its relationship with bacteria, *Giardia* cysts, and *Cryptosporidium* oocysts concentrations in water (MWH, 2012). The objective of removing NOM is to reduce formation of harmful disinfection by-products (DBP's), which are formed by the reaction of NOM compounds with chlorine (USEPA, 2012; WHO, 2004).

Coagulation, flocculation and sedimentation (C/F/SED) are the main treatment processes used in the removal of turbidity and NOM, and they can be quite effective and economical. Water treatment plants treating algal-containing surface waters have often used coagulation, flocculation and flotation (C/F/DAF) instead of C/F/SED because dissolved air flotation (DAF) is more effective than conventional settling in removing algae, which are very low-density particles (Zhang et al. 2012; Do Amaral et al. 2013; Teixeira and Rosa 2006; Teixeira et al. 2010). DAF has also been shown to be slightly more effective than C/F/SED in treating moderately humic waters (Heinanen et al. 1995; Chung et al. 2000; Valade et al. 2009; Edzwald, 2010). In addition, Walker and Narbaitz (2016), and Xu and Narbaitz (2016) have shown in bench-scale ultrafiltration tests of waters with a high hydrophobic NOM content, DAF can provide better pre-treatment than sedimentation. Few communities currently have DAF systems, in order to expand the DAF/membrane research to other waters it would be very helpful to have a bench-scale DAF system that produces 20+ liters of water necessary for the membrane tests.

Algae and cyanobacteria create a number of significant problems at water treatment plants including taste and odour problems and the release of cyanobacterial toxins. In August of 2014, there was a large cyanobacteria bloom in western Lake Erie, which contaminated the drinking water distribution system of Toledo, OH with microcystin, a cyanobacterial toxin that can cause liver and kidney damage. As a result, tap water consumption was banned for three days and the residents were supplied with bottled water. As one of the expected impacts of global warming on water treatment plants is increased algal and cyanobacterial problems, the incorporation of DAF in new and upgraded WTPs to remove algae and cyanobacteria cells is expected to increase. As such DAF can be considered as a global-warming impact mitigating technology.

DAF drinking water treatability tests are often conducted using batch DAF jar tests instead of a continuous flow pilot-scale plant tests because they are inexpensive, quick and easy to conduct. Only a limited number of studies have been conducted on the scaling-up DAF batch jar test results to full-scale for water treatment (Bickerton, 2012). The main disadvantages of DAF bench-scale jar tests are: a) the accuracy of the results, which may overpredict or under-predict turbidity removal and b) the relevance of these studies to field conditions (i.e., dynamic and hydraulic factors); (Bickerton, 2012; MacPhee et al., 1996; Gehr & Henry, 1978). Numerous textbooks recommend that type II (flocculent) settling tests be conducted in columns with a minimum diameter of 15 cm, presumably due to minimize wall effects (USEPA, 1996; Droste, 1997). Thus, it was hypothesized that batch DAF test systems may also benefit from larger diameter vessels. Accordingly, to produce more reliable turbidity removal predictions than the conventional DAF jar test, this dissertation concentrates on the development and testing of a larger diameter, larger volume batch dissolved air flotation system, called LB-DAF.

With time water treatment plants need to expand or upgrade their treatment capacity. Often this results in replacing their old separation processes such as sedimentation with a more compact and efficient systems such as DAF or ballasted sedimentation (BS). BS has become very popular water treatment process due to its ability to maintain good turbidity removal performance under raw water quality fluctuations and due to its compactness (Alpert, 2002). However, no direct comparison has been conducted on DAF versus BS for treating algae laden waters. Therefore, it is necessary to conduct studies for comparing the capabilities of these two emerging clarification technologies for the removal of algae and cyanobacteria impacted water.

1.2 Research Objectives

- Build large-volume (~20L), batch bench-scale DAF system (LB-DAF) that has a larger diameter than the DAF jar testers, and to conduct a sensitivity analysis of the LB-DAF characteristics and operational settings to identify the conditions that best mimic the performance of a full-scale DAF unit.

- To confirm the LB-DAF's predictive capabilities for turbidity removal with two other surface waters (i.e., Bay of Quinte, ON and Rideau River, ON water). This will involve a further assessment of the impact of different LB-DAF operational parameters on turbidity and NOM removals.

- To optimize the coagulation for CGS, DAF and BS process in the treatment of an algae impacted water for turbidity removal, and to compare the performance at bench-scale level of these three clarification processes for the removal of algae and cyanobacteria, NOM and disinfection by products formation potential (DBPFP).

1.3 Research Novelty and Contribution

The main novelty of this work is the development and optimization of a large volume laboratory DAF system, which should permit more accurate predictions of full-scale DAF performance. This should reduce the need for pilot-scale testing and reduce design costs. Thus, the LB-DAF could become a very valuable design tool. In addition, it will permit to obtain a bigger volume of water sample than a regular DAF jar test for determining the DAF suitability as a membrane pre-treatment process.

1.4 Research Methodology

This research was divided in three phases.

Phase 1: To test the LB-DAF to optimize its operation

The purpose of this phase was to test the LB-DAF under different operational conditions to: a) assess their impact; and b) determine the values of the variables that yield the best approximation of full-scale DAF performance. The performance was assessed in terms of turbidity and NOM removal. The main LB-DAF design and operational variables to be investigated were tank diameter, water depth/tank diameter ratio, impeller shape, velocity gradients (G), saturator pressure (SP) and recycle ratio (RR). The set of experiments were performed with Ottawa River Water (ORW) because: a) there is a nearby full-scale treatment plant using DAF (Aylmer, QC), which permitted comparisons with a full-scale DAF system and; b) the characteristics of ORW do not change significantly with time. The LB-DAF turbidity removal predictions will also be compared to those generated using a commercial DAF jar test apparatus.

Phase 2: Confirmation of the LB-DAF characteristics by testing other waters and compare their performance with full-scale.

The objective of this phase was to confirm that the optimum LB-DAF parameters arrived for Ottawa River water also apply for other raw waters, this was assessed using other waters treated by DAF at full-scale treatment plants. These include waters from Belleville, ON and Smith Falls, ON. The performance was evaluated in terms of turbidity and NOM.

Phase 3: DAF comparison with CGS and BS for the treatment of an algal impacted water.

The objective of this phase was to compare the performance of DAF, CGS, and BS for treating an algal-impacted water in terms of turbidity, NOM (i.e., DOC, UV-254 and SUVA), disinfection by products formation potential (DBPFP) and algae/cyanobacteria removal at the bench-scale level. The study was performed at the Belleville Water Treatment Plant (Belleville WTP) over a two-day period during the summer of 2018. The experiments were conducted using Bay of Quinte water, which has eutrophic conditions in summer.

1.5 Thesis Layout

This thesis was written in an article-based format. It consists of seven chapters plus a references chapter. Chapters four, five and six were written research articles. The thesis was organized as follows:

- Chapter 1, *General Introduction*, provides a general background on water quality issues in terms of NOM and turbidity. This chapter also presents the novelty of this study, research significance, the research methodology, the research objectives, and the outline of the thesis.

- Chapter 2, *Literature Review,* describes different studies conducted on bench-scale jar test (i.e., coagulation, flocculation and sedimentation process) and their scale-up results, and it compares the turbidity and NOM removals of sedimentation and DAF. This chapter also describes the research on the scale-up of DAF test results. This chapter helped identify the research pursued in this thesis.

- Chapter 3, *Materials and Methods*, the purpose of this chapter is to describe the water sample collection, the materials, the testing equipment and methods, the analytical methods, the experimental plan and the statistical protocols that were utilized for this research.

- Chapter 4, (article 1), *Large batch bench-scale dissolved air flotation system (LB-DAF) for drinking water treatability tests.* It describes the LB-DAF system, the testing procedure and presents the results of the process variable sensitivity tests used to ascertain the optimal LB-DAF testing conditions for scale-up. The assessment was based on comparisons of the turbidity and NOM removals achieved by the LB-DAF and a full-scale DAF unit in the treatment of Ottawa River water. This chapter addresses Phase 1 of the research.

- Chapter 5, (article 2), *Large batch bench-scale dissolved air flotation system (LB-DAF) for simulating full-scale turbidity removal.* This chapter presents the results of LB-DAF process variable sensitivity tests conducted with two different surface waters to confirm the LB-DAF predictive capabilities for turbidity removal. The waters were chosen because their different water quality characteristics and because there are full-scale DAF units with treating them. The two waters were treated by full-scale DAF with different configurations, and the coagulant types and dosages were different. This chapter corresponds to Phase 2 of the research.

- Chapter 6, (article 3), *Comparative study of dissolved air flotation and ballasted sedimentation for an algal impacted water*. Chapter 6 reports on the comparison among three different separation processes at the bench-scale level (i.e., DAF, BS and CGS) for the treatment of Bay of Quinte water, one of the most eutrophic sections of Lake Ontario. Their efficiency was assessed based on turbidity, NOM, algal/cyanobacterial removal, as well as the reduction in disinfection by products formation potential (DBPFP). This chapter corresponds to Phase 3 of the research.

- Chapter 7, General Conclusions, integrates the material presented in previous chapters. It summarizes the findings and conclusions reported in the research articles. In addition, it describes potential areas of future research.

- Chapter 8, References, presents the references used in the chapter 1, 2 and 3 that are complementary to the references consigned in the article chapters.

1.6 Thesis Contribution of Authors

The work conducted in this research has resulted in three scientific manuscripts prepared for publication. In this section the overview of the authors contributions for each paper is presented.

Article 1 (chapter 4):

Gonzalez-Galvis, J. P., Narbaitz, R. M. *Large batch bench-scale dissolved air flotation system (LB-DAF) for drinking water treatability tests.* In preparation for journal submission.

J.P. Gonzalez-Galvis: Conducted the literature review, developed the LB-DAF apparatus, conducted the experiments, analyzed the results and prepared the manuscript.

R.M. Narbaitz: Provided supervision in the development of the experimental procedure, analysis of results and reviewing and revised the manuscript.

Article 2 (chapter 5):

Gonzalez-Galvis, J. P., Narbaitz, R. M. *Large batch bench-scale dissolved air flotation system for simulating full-scale turbidity removal*. In preparation for journal submission.

J.P. Gonzalez-Galvis: Planned and conducted the experiments, analyzed the results and wrote the manuscript.

R.M. Narbaitz: Provided supervision in the development of the experimental procedure, analysis of results and reviewing and revised the manuscript.

Article 3 (chapter 6):

Gonzalez-Galvis, J. P., Hérard, R.M., Berthier, E., Narbaitz, R.M. *Comparative study of dissolved air flotation and ballasted sedimentation for an algal impacted water*. In preparation for journal submission.

J.P. Gonzalez-Galvis: Conducted the literature review, developed the experimental plan, led the execution of the experiments, analyzed the results and prepared the manuscript.

R.M. Hérard: Helped to conduct the laboratory experiments.

E. Berthier: Helped to conduct the laboratory experiments.

R.M. Narbaitz: Provided supervision in the development of the experimental plan, provided help in conducting the experiments, reviewed the analysis of results and reviewed the manuscript.

Chapter 2

2. Literature review

Given that sedimentation and flotation in drinking water treatment have several similarities (i.e., they both require coagulation and flocculation prior to the separation step), the literature review will first focus on coagulation/flocculation/sedimentation (C/F/SED) systems and their scale up. This will be followed by a description of coagulation/flocculation/flotation (C/F/DAF) systems and their scale up and finally the turbidity and organics removal capabilities of C/F/SED and C/F/DAF will be discussed. Finally, the ballasted sedimentation will be discussed.

2.1 Coagulation/flocculation/sedimentation systems and their scale up

The objective of coagulation flocculation within C/F/SED is to create large flocs, so that they settled well. Important design parameters in the coagulation/flocculation (C/F) steps for sedimentation include the mixing intensity (G), detention time, number of stages and the type of flocculation required. The concept of the average hydraulic gradient (G) was developed by Camp and Stein (1943). The G is related to the rotational speed and the configuration of the agitator as well as the geometry of the mixing vessel. Coagulation with alum and iron salts can effectively reduce turbidity, NOM and DBPFPs. Their percent reduction depends on the coagulant type and dose, and the raw water characteristics (Uyak & Toroz, 2007; Matilainen et al., 2010; Sharp et al. 2006; Ritson et al. 2014). NOM removal generally requires substantially larger coagulant doses (~50% larger) than for turbidity removal, thus, coagulation optimized for NOM removal is often called enhanced coagulation.

2.1.1 Conventional (Sedimentation) Jar Tests

The main function of jar tests is to obtain the optimum coagulation conditions in terms of coagulant dose and pH. Five different conditions should be met in order to obtain optimum coagulation: 1) maximise particle removal (turbidity, particles, and pathogens); 2) maximise NOM removal (TOC, UV-254, and DBPs precursors); 3) minimize the residual coagulant concentration; 4) minimize sludge production; and 5) minimize the overall operating cost (Parsons & Jefferson, 2006). Conventional jar test procedures are described in books (e.g., Kawamura (2000) and in standards such as ASTM (2008), and AWWA (2011). The jar test apparatus has six stirring paddles and six jars all of the same size and shape (1000 to 2000 mL). The jar test procedure is as follow: First, 1 or 2 liters of the test water are added to each jar. Second, the test starts with a rapid mix step. It uses a relatively high mixing speed (75, 150, 225, or 300 rpm) and different predetermined dosage of the chemical coagulants are added to the jars. They are allowed to mix for 1 to 2 minutes. The different rotational speeds for conducting the rapid mixing depend on the possible rpm of the motor, the characteristics of the jar test apparatus and the specific water quality characteristics. Third, slow mix period is conducted to simulate the flocculation process. This stage is performed to allow the chemical floc-particle aggregates to grow in size for 20 minutes at (10, 20, 30, or 40 rpm). In many cases, the flocculation step is divided into two periods, in the first period the mixing is relatively intense (~25 - 30 rpm) and in the second period the mixing is less intense (10 - 20 rpm). These two stages are used to simulate the tapered flocculation in full-scale systems, which often include three or more stages of mixing, each of which is at a lower intensity than the previous stage.

For example, the flocculation stages may have velocity gradients of 50, 20 and 10 s^{-1}. Finally, after the slow mix period, the paddles are removed, and the solution is allowed to settle for 30 minutes.

The literature report different rpm, G values and flocculation times for the design of vertical turbine flocculators as a pre-treatment to sedimentation in full-scale typical values are shown in Table 2.1. The typical values of these parameters for conducting conventional jar tests are somewhat different.

Table 2.1 Typical design parameters of a vertical turbine flocculators prior to full-scale sedimentation basins

G (s^{-1})	**Detention Time (min)**	**Stages**	**Flocculation type**	**Reference**
10 - 70	20 - 40	2 - 4	Tapered	Kawamura, (2000)
20 - 75	15 - 25	-	-	AWWA, (1997)
10 - 70	15 - 30	4 - 6	Tapered	Masschelein, (1992)
50 - 75	-	-	-	AWWA, (1991)

Table 2.2 Conventional jar test slow mixing G (flocculation) values and flocculation times

G (s^{-1})	**(rpm)**	**T (min)**	**Reference**
25	30	20	Kan et al. (2002)
30	30	20	Griffith & Williams (1972)
10	20	30	Van Beschoten & Edzwald (1990)
60	30	15	Wang et al. (2014)

As shown before the range of G values used in the design of a full-scale vertical turbine flocculators (10 to 75 s^{-1}) is quite similar to those used in a conventional jar test (10 to 60 s^{-1}). Similarly, the detention time range used for the design of a full-scale vertical turbine flocculators (15 to 40 minutes) is also similar to the flocculation times used in conventional jar tests (15 or 30 minutes). It is also necessary to be aware of some of the limitations of the jar tests. It should be noted that jar tests are used to optimize coagulant doses for mechanical flocculation systems with different impeller/tank geometries as well as for hydraulic flocculation systems. It is also necessary to be precise in specifying what performance parameter is to be scaled-up. For instance, some easily measured parameters are zeta potential, turbidity, color and organics removal after settling (AWWA, 1991). Therefore, some studies conducted on jar test scale-up and parameters impacting their performance are discussed below.

Despite that early studies found a correlation between batch flocculation test results, and continuous flow experiments for full-scale design for flocculation units, Bratby and coworkers recommended not to use a normal jar test apparatus to determine the flocculation characteristics of a particular water because the jar test will over predict flocculation performance (Bratby et al., 1977; Bratby & Lutzow, 1977). One of the difficulties in comparing such data with plant results is the large scale-up in time for settling, in a jar test settling times of 15 to 20 minutes are used while in full-scale facilities settling times maybe up to 240 minutes (Hudson, 1973). Therefore, engineers sometimes choose to perform pilot-scale continuous flow water treatability tests because these results may be extrapolated successfully to full-scale designs (Argaman, 1971). Nevertheless, the high cost and the extensive methodology required for continuous flow pilot plant trials are the main disadvantages for this type of approach (Bratby, 1981). The capacity of jar test to predict full-scale DAF performance will depend on the raw water characteristics, coagulant type and dose.

Bates et al. (1963) evaluated the impact of some of the shape factors on impeller power calculated as power number in a batch bench-scale test. The factors studied were a) different impellers (i.e., flat six-blade disk style; flat, curved, and with blade angles of 25, 45 and 90^o). b) different cylindrical vessels diameters (6, 10, 12, 15 and 24 inches); c) impeller width to impeller diameter ratios (w/D) (0.062 to 0.37); d) impeller diameter to tank diameter ratios (D/T)

(0.25 to 0.50); e) baffles width to tank diameter ratios (wb/T) (7 to 15%); and f) proximity of the impeller to the tank bottom. The study concluded that different impeller shapes have different power requirements in the turbulent range. In addition, the study concluded that the space between turbines in a multi impeller shaft and the impeller proximity to the tank bottom can increase the impeller power consumption. Furthermore, the study did not find a particular critical ratio among the parameters tested. Finally, the study did not conclude if the parameters studied had an impact on turbidity removal.

Lai et al. (1975) conducted a laboratory study for the velocity gradient calibration of conventional jar-test apparatus. This study utilized 2 L square shaped jars. The first set of experiments was configured with a jar without baffles. The second configuration tested involved a fully baffled jar with 4 baffles. Five different impellers shape were tested in the experiments. The study concluded that although flow patterns may be different, impellers of different shapes produce the same G values at different rpm. Finally, the study concluded that the installation of baffles increased the energy input regardless of baffle size or geometry for a given impeller shape and size. However, the study did not make conclusions on the impact of the baffle's configurations installation and impeller shape on the turbidity removals.

Cornwell and Bishop (1983) conducted batch laboratory experiments to define an accurate method for determining G for full-scale systems based on the optimal laboratory values. Five different jar vessels were tested (i.e., square and cylindrical jars with one- and two-liters volume), and different impeller shapes (i.e., axial flow turbine, axial flow propeller, two blade paddle, and radial flow turbine). Based on the results obtained (i.e., the G curves for jar test systems) the authors developed a procedure that allows to scaling-up G values found in the laboratory jar-test to full-scale facilities. The procedure developed involves an equation and scaling-up factors. This methodology was used for comparing two full-scale plants with the G predicted by the jar test. The study concluded that the procedure developed allows for the G value in the plant to be set near the optimal G value found in the laboratory. In addition, the study concluded that the evaluation between full-scale and the jar-test showed similar settled water quality. However, the study does not provide data on what parameters (i.e., turbidity, UV-254, DOC, etc.) were measured for performing the comparison between full-scale and jar test.

2.2 Coagulation/flocculation/dissolved air flotation systems

DAF is a mechanical separation process that can be used for the separation of particles from water; it has been used in drinking water treatment, industrial wastewater treatment and sludge treatment (Krofta & Wang, 1982; Edzwald and Haarhoff, 2012). DAF has many advantages for drinking water applications. DAF has become an established technology for the treatment of algal-laden waters (Edzwald & Haarhoff, 2012; Chu et al., 2011; Jung & Oh, 2018). DAF is also more compact than conventional sedimentation treatment, so DAF is sometimes chosen strictly for this reason. In addition, DAF may perform better than sedimentation in colder waters because low temperatures impact the floc strength and floc settling velocity (Xiao et al., 2010; Lou et al., 2012). DAF has been used in Finland for the treatment of several types of surface waters (Heinanen et al., 1995) including some with significant NOM content. Therefore, DAF can become a prominent technology alternative to C/F/SED for treating low-turbidity water supplies containing aquatic humic substances, and natural color (Malley & Edzwald, 1991) and acid-rain impacted waters (MacPhee et al., 1996). One of the limitations of DAF is that it should not be used with raw waters that have turbidity greater than 50 NTU. Table 2.3 presents a summary with the removal percentage of turbidity and

NOM measured as DOC and UV-254 obtained from different studies conducted on DAF compared with CGS.

According to table 2.3 it is possible to conclude that in general DAF is somewhat superior to conventional sedimentation for turbidity and NOM removal in the treatment of low turbidity, low and intermediate hydrophobicity surface waters as well as algae laden surface waters. The exceptions are Malley & Edzwald, (1991), and Xu & Narbaitz, (2016), which reported the same levels of removal for both DAF and CGS.

Table 2.3 Turbidity, DOC, and UV-254 percentage reductions by C/F/DAF versus C/F/CGS

Water type	Scale	SUVA	C/F/DAF Removal (%)			C/F/CGS Removal (%)			Reference
			Turbidity	DOC	UV- 254	Turbidity	DOC	UV- 254	
Synthetic	Pilot	-	90%	-	-	75%	-	-	Khiadani et al. (2014)
River	Pilot	1 – 3.5	95%	-	-	80%	-	-	Shan-pei et al. (2007)
Lake	Pilot	2.0	-	53%	31%	-	31%	27%	Chu et al. (2011)
Reservoir	Batch	2.8	95%	61%	80%	87%	55%	75%	Zou et al. (2011)
River	Batch	4.7	66%	80%	-	66%	80%	-	Malley & Edzwald (1991)
Reservoir	Batch	2.6	76%	40%	-	76%	40%	-	Malley & Edzwald (1991)
Reservoir	Batch	-	42%	-	-	25%	-	-	Krofta & Wang (1982)
River	Full	4.1	76%	66%	80%	42%	60%	76%	Walker & Narbaitz (2016)
River	Full	3.5†	82%	72%	80%	74%	67%	80%	Xu & Narbaitz (2016)
River	Full	3.9♦	85%	62%	82%	79%	62%	77%	Xu & Narbaitz (2016)

(-) Values no reported
† Summer season
♦ Winter Season

The main characteristics of water treatment DAFs are the generation of air bubbles to which low-density particles become attached, and the rise of these bubble-particle aggregates to the surface of the tank, thus resulting in the separation (Amato et al., 2001; Haarhoff and Edzwald 2001; Han et al., 2001; Edzwald, 2007). DAF clarification relies on the solubility of air in water changing in accordance to system pressure to produce oversaturated conditions, leading to the formation of air bubbles (Edzwald, 2010; Haarhoff & Edzwald, 2001).

Coagulation and flocculation as a DAF pre-treatment provide two essential conditions necessary for favorable particle flotation: 1) particle charge neutralization and 2) particle hydrophobicity (Edzwald, 1993). Particle charge neutralization in a DAF process is necessary to particles to attachment to bubbles. Bubble attachment to the large particles is characterized by contact angle measurements, and the magnitude of the contact angle is related to particle hydrophobicity and adhesion to the bubble. Therefore, hydrophobic particles (those with contact angles of 90 degrees or larger) have good separation by flotation.

In a DAF unit the bubbles either attach to the flocs or enmeshed within the flocs. However, in both mechanisms bubble size is an important factor. As reported by some authors the most efficient performance and particle collision in a DAF unit is achieved when the average floc size is close to the bubble size. (Park et al., 2001; Gorczyca & Klassen, 2008; Gorczyca & Zhang, 2007). Bubble size in a DAF unit is influenced mainly by the following factors: 1) the size of the aperture from which it emerges; 2) the hydrostatic head against which it is compressed; 3) the water surface tension; 4) the speed of emergence, which is related to the volume and pressure of gas behind it; 5) the turbulence of the surrounding nozzle area and; 6) the water temperature (O'Connor et al., 1990; Braul et al., 2001). In general, the bubble size in a DAF system is in the 10–150 μm range (Edzwald, 2010). Ahmed & Jameson (1985) studied bubbles in the range of 75 – 655 μm, and they found that the smallest bubbles (≤ 100 μm) led to the most efficient flotation, and that small bubbles are needed to float fine particles.

Bubble size can decrease due to low surface tension; however, in drinking water treatment surface tension is not affected by adding aluminum-based coagulants (Couto et al., 2009; Ferris & Wubio, 1999). Therefore, bubble size is an important DAF parameter than needs to be studied.

For DAF system to work well the pre-DAF vertical turbine flocculators need to promote the formation of the appropriate size flocs that will readily attached to the bubbles. This is achieved by designing the systems using the appropriate G values and flocculation hydraulic retention time. The typical design parameters of vertical turbine flocculators used for DAF are summarized in table 2.4.

Table 2.4 Typical design parameters of full-scale vertical turbine flocculators preceding DAF systems

G (s^{-1})	T (min)	Stages	Flocculation type	Reference
20 - 90	20	2	-	Kwon et al. (2004)
35 - 65	12	2	Tapered	Bickerton, (2012)
20 - 100	-	2	Tapered	AWWA, (2011)
50 - 100	8 - 16	2	-	Van Beschoten et al. (2002)
50 - 100	10	2	-	Edzwald & Haarhoff, (2012)
22 - 234	10	2	-	Aylmer WTP, QC

Comparing the values in table 2.1 to those in table 2.4 it can be seen that the range of G values used in the design of full-scale vertical turbine flocculators preceding sedimentation basins (10 to 75 s^{-1}) are somewhat lower than those used preceding DAF units (20 to 100 s^{-1}). In addition, the detention time used for the design of a full-scale vertical turbine flocculator preceding sedimentation basins (15 to 40 minutes) are larger than those preceding DAF units (8 to 20 minutes). Therefore, it is possible to conclude that there is a difference in the type of floc produced in each treatment. Mechanical flocculation for sedimentation pre-treatment uses lower G values and large retention times, which promote large flocs sizes, which should settle more readily, In contrast, mechanical flocculation for DAF pre-treatment uses higher G values and shortest detention time than for sedimentation basin, which promotes the formation of smaller flocs that are required for an effective DAF process.

2.2.1 DAF Jar Test Apparatus and Procedures

As one of the main objectives of this research is to investigate the scale-up results from a conventional DAF jar test apparatus to full-scale the following section describes the literature on DAF jar test studies conducted under different operational conditions.

There is no standard DAF jar test procedure; however, some conditions for performing DAF jar test are recommended in the scientific literature. A key difference between DAF jar test and conventional jar test is that in the former, at the end of the flocculation period a volume of pressurized water is introduced at the bottom of the jars to introduce the necessary bubbles. This water simulates the effect of the recycled flow in full-scale DAF systems, and as such its volume is 6 to 12% of the flocculated liquid volume. Edzwald & Haarhoff, (2012) recommend to perform a DAF jar test with a rapid mixing of (200 to 400 rpm) for 1 minute, followed by a slow mixing period of 10 minutes at (50 rpm, or $G= 65\ s^{-1}$). Finally, they recommend a flotation time of 10 minutes. In addition, they recommend that the pressurized water in the DAF jar test be at a constant pressure of 483 to 500 kpa (70 psi) (Edzwald & Haarhoff, 2012). Conventional DAF jar test apparatus have up to six, cylindrical jars with a volume of 1.4 to 2 liters (PJT02 Capital Controls Group, Didcot, GB), or four 2L square jars (Platypus 4G ®, US). The unit is equipped with rotating paddles at adjustable mixing speeds to control velocity gradients within the jars. The units also include a saturated water injection apparatus, which has a nozzle for each jar, which can be controlled independently to allow manipulation of recycle flow. Different studies have used different G values and different flocculation times for conducting DAF jar test. Table 2.5 shows some of the G values and flocculation times used in the DAF jar test for slow mixing.

Table 2.5 Conventional DAF jar test slow mixing G values and flocculation times

G (s^{-1})	(rpm)	T (min)	Jar test used	Reference
10	30	20	Aztec Environmental Control Ltd., U.K.	Malley (1990)
30	60	10	Non specified	Bodo, (1996)
70	-	8	laboratory-made flotation cell	Teixeira et al. (2010)
70	-	10	Non specified	Van Beschoten et al. (2002)
10	30	15	Aztec Environmental Control Ltd., U.K.	MacPhee et al. (1996)
12	30	10	Capital Controls Limited	Technical manual
65	50	10	Non specified	Edzwald and Haarhoff, 2012

As shown in table 2.2 and table 2.5 the flocculation G values used in a conventional jar test are similar that these used in DAF jar test (10 to 60 s^{-1} versus 10 to 70 s^{-1}, respectively). However, the flocculation retention time is different (15 – 30 minutes versus 8 to 20 minutes, respectively). The two different sets of test settings are required to form different types of flocs, big and high-density flocs for sedimentation versus smaller and lower-density flocs for flotation. It is because a low density-flocs contributes to reduce significatively the flocs-bubbles aggregates density, so they are less dense that the density of the water, allowing the flocs-bubbles aggregates to float. In addition, G values for the full-scale DAF units are in a similar range as those used DAF jar tests (20 to 100 s^{-1} for the full-scale versus 10 to 70 s^{-1} for the jar tests). And the flocculation times are also similar (10 to 20 minutes versus 8 to 20 minutes for the DAF jar tests). Therefore, it is possible to conclude that with similar operational conditions in the DAF jar test respect to the full-scale (i.e., G, flocculation time, and coagulant dose), it may be possible to conduct treatability test for simulating full-scale performance. Some studies conducted on DAF jar test compared with full-scale and pilot scale units or compared the performance of DAF pilot-scale and full-scale units, these are presented below.

2.2.2 Comparison of DAF Jar Results with those Larger Scale DAF Systems.

Bickerton (2012) conducted a study for the optimization of DAF for drinking water treatment by comparing the performance of batch flotation test with that at a full-scale facility in Halifax, Nova Scotia, Canada. The batch DAF jar apparatus used consisted of 6 round 2-liter jars. The water tested was classified as a high hydrophobic water with (SUVA>4.0), high colored water, and low alkalinity and turbidity. The study concluded that the optimum removals for turbidity occurred at a coagulant dose between 30 to 35 mg/L as alum (PACl) and a zeta potential (ZP) measurements between -4.6 and 5.8 mV. In addition, the optimum coagulant dose for UV-254 reduction was found to be 35 mg/L as alum with a ZP measurements between -4.7 to 4.5 mV. The study also reports that the DAF jar test over predicted turbidity removal by up to 12% in comparison with the full-scale system. Furthermore, the study found that the variation in the recycle ratio (RR) (12 – 6%) did not affect the DAF performance in the batch system, but when the RR was reduced from 12 to 9% in the full-scale facility this resulted in unstable performance. Therefore, recycle ratio is an important DAF variable, which needs to be investigated.

Van Benschoten et al. (2002), conducted a study on the performance of DAF plus membrane filtration for drinking water treatment by testing four different waters with low (SUVA). The experiments were carried using a batch laboratory DAF jar test apparatus (six-place paddle stirrer) and a continuous flow pilot-scale DAF. DAF jar test were used to determine the optimum polyaluminum chloride (PACl) dose for each water, however for the pilot-scale DAF runs the coagulant dose was based on influent turbidity using a correlation derived from plant historical operating data. Therefore, no direct comparison for scaling up DAF jar test to the pilot plant was performed.

MacPhee et al. (1996) conducted a study on dissolved air flotation coupled with enhanced coagulation for treating typical Eastern Canada surface waters impacted by acid rain. Two coagulants alum, and PACl were used. The experiment was conducted at pH 6.4 ±0.1 with a water temperature of 3°C with both coagulants. The waters tested were collected at four different locations in the province of Nova Scotia. In general, waters tested had low turbidity (i.e., 0.31 – 2.93 NTU), low alkalinity (i.e., <1 – 2 mg/L as $CaCO_3$), and medium SUVA values (i.e., 3.1 – 3.6). The study concluded that PACl coagulant performed better than alum in cold waters. In addition, the PACl coagulant had superior turbidity removals in the pilot plant in comparison with the DAF jar test (88% versus 66%, respectively) at similar coagulant doses (14 mg/L versus 15 mg/L as Al). Therefore, the study concluded that the DAF jar tests tended to slightly under-predict turbidity removal by DAF achieved on the pilot-scale. The study claimed that the removals of DOC and UV-254 achieved in the bench-scale DAF closely approximated those achieved in the pilot DAF testing under similar coagulation conditions. This was true for the UV-254 removals (71% versus 72%), however the DAF pilot plant showed somewhat lower DOC removals (41% versus 48%).

Valade et al. (1996) compared the DAF jar test particle removal to those of pilot-scale DAF. The study tested the impact of coagulant type (alum versus ferric sulphate), flocculation time (5 to 20 minutes), flocculation mixers (gates versus propellers), flocculation stages (two versus three stages), and flocculation mixing intensity (low G (i.e., 30 s^{-1}) versus high G (i.e., 70 s^{-1}) on downstream flotation and filtration performance. The water treated (Gota River in Sweden) had a low turbidity (0.79 to 1.27 NTU), and a TOC concentration of 4.2 mg/L. The study showed that in the flocculation process alum performs slightly better than ferric sulphate for turbidity reduction, and the flocculation time did not impact the performance of both coagulants. Moreover, the study concluded that for DAF the coagulant type did not have differences on turbidity reduction because the value obtained for both coagulants after DAF was 1 NTU. In addition, the effect of flocculation mixing intensity showed that lower DAF turbidity and particle counts were obtained with high G (70 s^{-1}) for 5 minutes of flocculation time. In contrast, no significant difference was observed in

DAF performance comparing gates and propellers with 5 minutes of flocculation.

It should be noted central to DAF performance is the separation of flocs, yet DAF jar tests vessels have a relatively small diameter. For flocculent settling lab tests, standard textbooks, such as Droste (1997), recommend that the column diameter should be at least 14 cm to avoid bridging of the suspension and other wall effects. Analogously, one could expect that DAF lab tests would also be benefit from larger diameter vessels, this needs to be investigated.

Gehr et al. (1993) conducted a study on the treatment of an eutrophic reservoir water for trihalomethane formation precursor (THMFP) removal, and the reduction of total trihalomethanes (TTHM). The study compared the results obtained in batch bench-scale DAF jar tests, a pilot-scale continuous flow unit and a full-scale system. The DAF jar test consisted of six-cylinder apparatus similar to the jar test apparatus developed at the Water Research Center (1977). In this study the jars were replaced by conical-bottomed cylinders, 0.1 m diameter and 0.44 m tall. The jar test concluded that highest alum dose, and lower pH (pH = 5-6) were desirable for THMFP reduction. In addition, the polymer dose at the relatively high levels tested (i.e., 0.9 mg/L) did not show a significant difference in the THMFP reduction. In the pilot plant tests the coagulant was switched to ferric chloride, so a direct comparison of the batch test and the pilot-scale could not be made. The full-scale test was conducted in a different time to the pilot-scale test; therefore, the water characteristics may have not been the same as in the pilot-scale. However, the full-scale test was performed at approximately the same operating conditions as the pilot plant, (i.e., with a RR of 10%, and a DAF flotation time of 9 minutes). The full-scale results indicate that the performance in general was not as good as that of the pilot plant. Maximum unfiltered THMFP reductions were approximately 65% compared with over 80% for the pilot plant. In general, the study concluded that DAF has been found capable of removing THMFP from eutrophic waters to below 100 μg/L. In addition, polymer addition would probably be unnecessary for TTHM removal, although it may be required for removal of turbidity. Finally, it was shown that DOC is not a good indicator of precursor's concentration.

Hyde et al. (1977) compared conventional jar tests with DAF jar tests and a pilot-scale DAF unit for the treatment of two different waters. The DAF jar experiments showed that DAF is a technical and feasible technology for floating many types of waters including for heavily algal-laden waters, for highly colored water, and for turbid water with a very low organic content. Interestingly, the study concluded that the optimum coagulant dose for turbidity removal predicted by the regular sedimentation jar test was the optimum dose for flotation in the pilot-scale. In addition, the study concluded that the clarification time was lower in the DAF jar test (i.e. 2 min) in comparison with the settling test (i.e., 15-20 min) to obtain similar turbidity removals. Hyde et al. (1977) also found that the point of air injection and air distribution system inside to a DAF unit can be an important variable that affects DAF effectiveness and; therefore, its impact needs to be investigated. Unfortunately, Hyde et al. (1977) did not report the quality of the DAF jar test turbidity removal predictions.

Some studies presented in this section conclude that DAF jar tests did not always predict well pilot-scale and full-scale DAF turbidity removals. In addition, one study found that DOC and UV-254 removals obtained in a bench-scale DAF were similar than those achieved in the pilot-scale DAF under similar coagulation conditions, (Bickerton, 2012; MacPhee et al. (1996)

2.3 Ballasted Sedimentation as an Alternative Clarification Process

One of the drawbacks of sedimentation (SED) is that it uses a great deal of space because two to four-hour hydraulic retention times are required (Wang et al., 2005). Because the more compact DAF and ballasted sedimentation (BS) have become popular (Borchate et al., 2014; Alpert, 2002). BS, a technology whose trade name is ACTIFLO® attaches high density micro-sand (i.e., 2700 kg/m^3) particles to the flocs making the flocs much heavier, so they settle much more rapidly (Ghanem et al., 2007;

Desjardins et al., 2002). In addition, pilot-scale studies have reported that BS is more effective than SED for waters with large variation in raw water turbidity and natural organic matter (Khiadani et al., 2014; Robinson & Fowler, 2007). DAF is the accepted technology for the treatment of algal-laden waters, but as far as the author was aware there had not been direct comparisons of DAF and BS for the treatment of an algae/cyanobacteria impacted waters. Thus, there is a need to conduct a direct comparison between BS and DAF for such waters.

2.4 Summary

In summary, the literature review main findings were: a) DAF produces slightly better organics removal in comparison with SED; b) bench-scale DAF research for drinking water treatment has been primarily performed using jar tests instead pilot-scale studies; c) there is no recognized standard DAF jar test apparatus, or DAF jar testing procedure for conducting drinking water treatability test; d) DAF jar tests were able to predict full-scale organics removal but they over predicted, or under-predict the turbidity removal of larger DAF units; e) there is a need to evaluate DAF performance for more types of water; f) there is a need to evaluate the capabilities of DAF and BS as an alternative clarification technologies for threating algae-impacted waters.

It is hypothesized that DAF jar test's poor turbidity removal predictions may be linked to the wall effects in the relatively small diameter of the DAF jar tests. Therefore, there is a need to develop and evaluate a larger diameter larger volume bench-scale DAF equipment for drinking water applications. Hopefully, such an apparatus will lead to a more standardized DAF jar tests system. This development needs to consider the numerous process variables such as impeller shape, baffling, velocity gradients, water depth to tank diameter ratio, saturator pressure, recycle ratio and the dissolved air application point, and distribution.

Chapter 3

3. Materials and Methods

The main thrust of this thesis is the development and testing of a large diameter, large volume batch DAF testing apparatus called LB-DAF. The purpose of this chapter is to describe the water sample collection, the materials, the testing equipment and methods, the analytical methods, the experimental plan and the statistical protocols that were utilized for this research.

3.1 Waters tested

As performance data for full-scale DAF systems was critical for the LB-DAF system development, the raw waters of the three nearest WTPs using DAF were selected. These source waters were the Ottawa River (Aylmer WTP, Gatineau, QC), the Rideau River (Smiths Falls WTP, Smiths Falls, ON) and the Bay of Quinte (Belleville WTP, Belleville, ON). Given the 21 L volume of the LB-DAF, the numerous operating conditions tested, as well as the repeat experiments, very large volumes of waters were required for this study and the logistics of obtaining the water were a challenge. ORW was chosen for conducting the Phase I of this study because was the nearest full-scale WTP using a DAF system. Unfortunately, due to space and logistic limitations at the Aylmer WTP (Gatineau, QC) the LB-DAF tests could not be performed on site. Thus, the Phase I tests were performed at the University of Ottawa labs using water samples collected from the Aylmer WTP. The location of this plant (i.e., within our region) greatly facilitated the numerous water collection trips required. The ORW samples were collected during the summer of 2017 and spring of 2018 at the intake of the Aylmer WTP in Aylmer, Quebec. For conducting the confirmatory Phase II tests waters from the Rideau River and the Bay of Quinte were chosen to conduct the LB-DAF turbidity removal comparisons with full-scale DAF systems. Rideau River water (RRW) water samples were collected in the spring and summer of 2018.

Bay of Quinte water (BQW) was collected inside to the Belleville Water Treatment Plant (Belleville WTP) in early winter of 2017 and summer of 2018. Evaluating the LB-DAF with Bay of Quinte water was particularly attractive because of the eutrophic conditions in the Bay of Quinte leading to relatively frequent algal and cyanobacterial blooms in the mid to late-summer (Watson et al., 2005). The water samples were transported to the University of Ottawa in polyethylene buckets or barrels and stored in a 4°C temperature control room (for preservation purposes) until required. Prior to test the containers were brought to the lab and allowed to reach the water temperature at which it was collected.

3.2 Materials

The main materials used in this study were the coagulants, coagulant aids, and chemicals used for the analysis. In the majority of this thesis, the coagulants and coagulant aids used were the same used as the water treatment plant treating the same raw water. The operators of the WTPs kindly provided samples of these chemicals. Aluminum sulfate liquid coagulant (ALS, Kemira, Montreal, QC) with an alum concentration of 4.3±0.1% Al^{3+} (basicity of 0.1±3% and pH of 2.0) was used during the summer at the Aylmer WTP and year around at the Belleville WTP. Poly aluminum sulphate solution (PAS-8, Kemira, Montreal, QC) with an alum concentration of 4.35±0.16% Al^{3+}, (basicity of 20±3% and pH of 4.0) was used at the Smiths Falls WTP. Polyaluminum sulfate silicate (PASS-10, Kemira, Montreal, QC) with an alum concentration of 5.3±0.2% Al^{3+} (basicity of 54±4% and pH of 3.4) was used at the Aylmer WTP during the winter months. Superfloc C-492PWG, a cationic polyacrylamide Kemira, Montreal, QC) polymer was used at Aylmer WTP. The

Smiths Falls WTP used a different cationic polyelectrolyte (Magnafloc LT22S, BASF, Mississauga, ON) for their DAF system. In contrast, the Belleville WTP did not use a flocculation aid. In the ballasted sedimentation tests the ccoagulation/flocculation aids were an anionic polymer (Magnafloc LT27, BASF, Mississauga, ON) and microsand with an effective diameter of 80 µm (Veolia Inc., Montreal, QC,).

Other chemicals used in this research include; potassium hydrogen phthalate (Fisher Scientific Company, Toronto, ON) for making the TOC analyzer standard calibration solutions. Sodium persulfate ($Na_2S_2O_8$, VWR, Mississauga, ON) was used as a reagent for the TOC analysis. An EDTA standard solution 0.020N (HACH company, Loveland, CO, USA), a pH 10.1±0.1 hardness buffer solution (HACH company, Loveland, CO, USA), and a Man Ver ® 2 Hardness Indicator (HACH company, Loveland, CO, USA) were utilized for the water hardness determinations. Ethanol 95% (C_2H_6O, EtOH, Fisher Scientific Company, Toronto, ON) was utilized for conducting the chlorophyll *a* extractions. Sodium phosphate dibasic ACS grade (Na_2HPO_4, ACS grade Sigma-Aldrich Canada Co. Oakville, ON), potassium phosphate monobasic ACS grade (KH_2PO_4, ACS grade Sigma-Aldrich Canada Co. Oakville, ON), a sodium chlorite solution (NaCl, ACS grade Sigma-Aldrich Canada Co. Oakville, ON), potassium chloride (KCl, ACS grade Sigma-Aldrich Canada Co. Oakville, ON), and disodium salt dehydrate, (Na_2EDTA, molecular biology grade Sigma-Aldrich Canada Co. Oakville, ON) were used to prepare the sodium phosphate buffer solution for the phycocyanin extraction.

3.3 Experimental procedures

3.3.1 LB-DAF tank configuration

The LB-DAF tank was designed to be used in a similar fashion as jar tests in that the same vessel was used to sequentially conduct the coagulation, flocculation and flotation steps. The first step in the development of the LB-DAF was to design and build the system, while incorporating as much flexibility as possible, so as to permit the evaluation of many process variables. The LB-DAF was designed to meet some of the essential requirements for a vertical turbine flocculator and at the same time trying to provide satisfactory conditions for flotation in the same vessel (Figure 3.1) (also see Appendix A). A cylindrical tank was chosen because flotation jar test uses cylindrical vessels. The column diameter of 20 cm (~0.65 ft) was chosen to test the hypothesis that a larger diameter vessel would provide better turbidity removal predictions. This vessel should result in smaller wall effects than the 9 cm diameter commercial DAF test apparatus tested. The 1.0 m (3.28 ft) height column was chosen to permit the assessment of the impact of several water depth to tank diameter ratios.

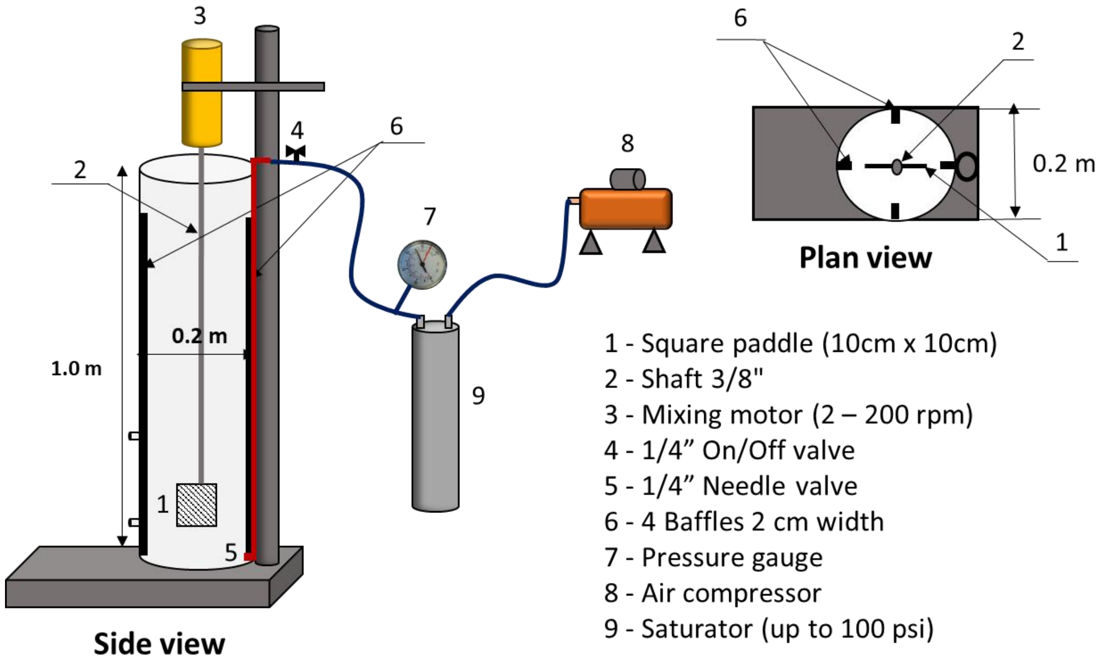

Figure 3.1 Large Volume Bench-scale Dissolved Air Flotation Tank (LB-DAF)

Three different flat impellers with different paddle areas were evaluated; they were designed to meet the minimum requirements for a vertical turbine flocculator (MWH, 2012). Full-scale vertical turbine flocculators should be designed to work with a G between 10 to 80 s^{-1} and the impeller diameter should be between 0.3 to 0.6 times the tank equivalent diameter (Te), with preferred values of 0.4 to 0.5 Te (MWH, 2012). In this research an impeller diameter to Te ratio of 0.5 was chosen. Thus, all the impellers were built with a diameter of 10 cm. The impeller areas were varied by varying the impeller height. Flat impellers were chosen because they are used in jar tests and because their power input (used to calculate mean velocity gradient) can be calculated by the standard power formulas (Lai et al. 1975; Rushton, 1952). The LB-DAF impellers tested are shown in figure 3.2. The small rectangular impeller shown in the figure 3.2 was built to mimic the typical impeller type found in a regular DAF jar test apparatus (Gonzalez-Torres et al. 2014).

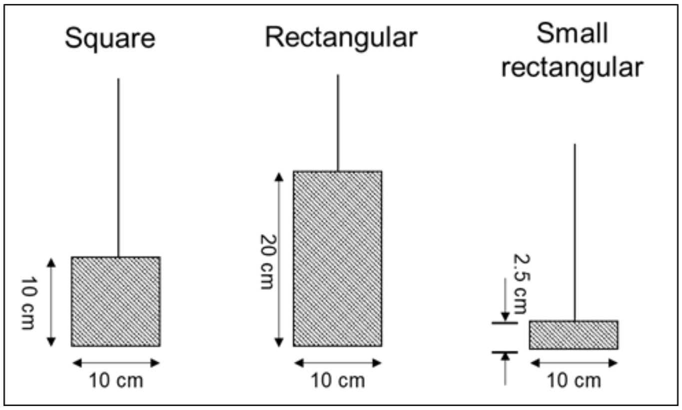

Figure 3.2 Impellers configuration tested in the LB-DAF

The baffle design was based on the recommendations of MWH (2012) (i.e., baffle width to Te ratio of 0.1 to 0.2) in order to prevent vortex from forming around the impeller shaft vortices do not allow the creation of appropriate velocity gradients that promote flocculation. The vessel had four 2 cm wide and 80 cm high stainless-steel baffles, they were aligned vertically along the vessel wall and arranged at 90° from each other.

The bubbles in the LB-DAF were produced by a bubbling device connected to pressure vessel (saturator) and a portable air compressor (TAW-0308, PSI compressors Inc. Ottawa, ON). The pressure vessel (saturator) with a capacity of 8L (2 gallon) and a maximum working pressure of 690 kPa (100 psig). The saturator was connected to the LB-DAF tank by the bubbling device that consisted of connecting tubing an on-off valve and a needle valve (see Appendix D). Low-density polyethylene (LDPE) tubing (6.35 mm or 1/4” OD) with a maximum working pressure of 860 kPa (125 psig) connected the pressure vessel to a 6.35 mm (1/4”) On/Off valve (#4 in figure 3.1) located at the top of the LB-DAF, it controls the saturated water feed. A 6.35 mm OD stainless steel tubing connects the on-off valve to a 6.35 mm (1/4”) needle valve (#5 in figure 3.1). The needle valve was located within the LB-DAF tank, it is approximately 10 cm from the tank bottom. This valve is 1/4” turn open to help in control the bubble size. The creation of a milky white water with many 40 to 80 µm diameter bubbles is critical to performance of DAF systems. In the development of the DAF many different types of orifices and other diffusing devices were evaluated. The above described set-up was the best operating system identified (see Appendix D).

In continuous flow DAF systems, the recycle ratio (RR) is the ratio of the saturated water flowrate to the system flowrate. In the LB-DAF apparatus, which is a batch system, the recycle ratio is defined as the ratio of the saturated water volume (V_2) to the total water volume (V_1). The saturated water is introduced in the LB-DAF by releasing pressurized water to the LB-DAF while maintaining the same pressure on the saturator. The LB-DAF experimental procedure was as follow: a) the LB-DAF tank was filled (e.g., 21 liters) with the water sample to be tested; b) coagulation was conducted at 200 rpm (296 s^{-1}) for 2 minutes; c) flocculation was conducted in a single step for 15 minutes at the preselected rpm or G for the individual experiments; d) then the saturated water was introduced into the vessel to initiate the 15 minutes flotation step; e) at the end of the flotation step clarified water samples were withdrawn for analysis. Preliminary tests showed that for the LB-DAF a two minutes coagulation time yielded better results than a one-minute coagulation period, thus, the former was adopted for all the tests. Given that the LB-DAF tank’s depth to diameter ratios were generally 3 or 4, complete mixing may have been more difficult that in conventional coagulation tanks that have lower depth to diameter ratios. The 15 minutes of flocculation time was chosen because preliminary tests showed that 10 min flocculation periods yield poor flocs. In addition, a single mixing speed flocculation step was used because preliminary tests showed that a two-step flocculation did not change the turbidity removals. The water quality was characterized before and after conducting LB-DAF experiments. The characterization included temperature, pH, turbidity, DOC, and UV-254. LB-DAF experiments were conducted in duplicate.

3.3.2 DAF jar test apparatus

Based on the availability bench-scale DAF jar testing system was used for the LB-DAF comparisons (PJT02 Capital Controls Group, Didcot, GB). The components of this DAF system (figure 3.3) included a pressurization tank (saturator), and two coagulation-flocculation-flotation cells. The clear high- strength acrylic cells (vessels) had an internal diameter of 9 cm and a height of 22 cm. The maximum volume of each cell was 1.4 liters. Each of the DAF units equipped with a removable paddle mixer. The mixers are connected to a speed controller and can be operated at 20, 30, 40, 50, 60, 80, 100, 200, 300 or 400 rpm. Each mixer motor is coupled with a rectangular flat paddle (2 cm width x 6 cm diameter). The velocity gradients (G) were determined by the manufacturer for the paddle mixer as a function of rpm, and this information is available in the apparatus manual (Severn Trent Services, UK). The DAF system included an 8L (2 gal) volume pressurization tank with a maximum working pressure of 690 kPa (100 psig), which serves as an unpacked saturator. The working pressure recommended by the manufacturer was 482 kPa (70 psig), which was adopted in this study. The water in the saturator was pressurized by a portable air compressor cylinder (TAW-0308, PSI Compressors Inc. Ottawa, ON). A high-density polyethylene tube connects the saturator to the bottom side of the flotation cell. To start the flotation step, the On/Off valve in the tube is opened, which allows the pressurized water to pass through a fitting located in the lower parts of the flotation cell's side wall. The fitting contains two orifices in series to help produce appropriate size bubbles.

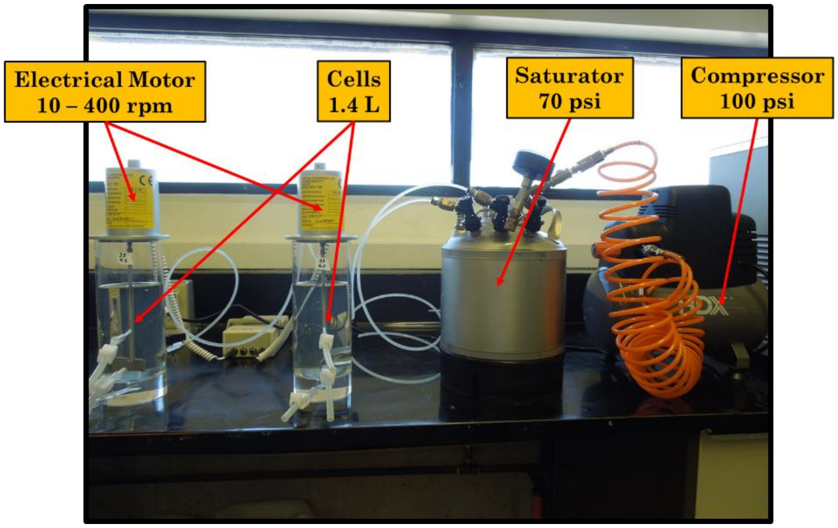

Figure 3.3 DAF jar test apparatus

This study followed DAF jar test testing procedure recommended by the manufacturer (Capital Controls Group, Didcot, GB, 2001). The procedure is as follow: First, one liter of the test water was transferred to the cell (cylinder) of the DAF jar apparatus. Second, the selected coagulant dose was added to the sample at the beginning of the rapid mix step, the rapid mixing step consisted of mixing at 400 rpm (G= 240 s^{-1}) for one minute. Third, this was followed by a 10 minutes slow mixing step at 30 rpm (G= 12 s^{-1}). Fourth, 0.1L (i.e., a 10% recycle ratio) of saturated water was introduced into the cylindrical cell through an opening near the bottom of the cell. Instead of stopping the mixing motor, as suggested by a technical expert Wiley, (2017), the motor speed was reduced to the lowest setting (20 rpm) to ensure that the saturated water/bubbles are distributed throughout the bottom of the jar. Finally, the mixing was stopped, and the floc-bubbles aggregates were allowed to float for 10 minutes. The pH, temperature, turbidity, DOC and UV-254 were monitored before and after conducting DAF jar test. DAF jar test experiments were conducted in duplicate.

3.3.3 Conventional sedimentation jar test

The main focus of this thesis is dissolved air flotation systems, on occasion the DAF jar test turbidity and NOM removals were compared with those of coagulation, flocculation and sedimentation (C/F/SED) jar tests. These bench-scale experiments were conducted using a regular jar test apparatus (Phipps and Bird, Inc. Richmond, VA, US) with six stirring with (2.5 cm width x 7.5 cm diameter) flat paddles with six 2L square beakers.

All the C/F/SED jar test were conducted with the following operational conditions; (a) rapid mix at 100 rpm (G= 70 s^{-1}) for 1 min; (b) slow mixing at 30 rpm (G= 12 s^{-1}) for 15 min and (c) sedimentation for 30 min. These are the usual conditions for C/F/SED jar tests for water treatment applications (Kawamura, 2000; ASTM, 2008; AWWA, 2011). The key water quality parameters were monitored before and after conducting the C/F/SED jar tests. These parameters included turbidity, temperature, pH, DOC, UV-254. C/F/SED jar test experiments were conducted in duplicate.

3.3.4 Ballasted sedimentation jar test

Ballasted sedimentation (BS) jar tests were conducted as part of Phase III of this thesis. The BS performed using a regular jar test apparatus (Phipps and Bird, Inc. Richmond, VA, US). The BS jar test procedures used in this research were adopted from Desjardins et al. (2002). The BS experiments were conducted as follow: a) the sample was placed in the jar and mixing was initiated at 150 rpm (G= 129 s^{-1}); b) 100% of the coagulant was added at the start of the two minute rapid mix step 150 rpm; c) the pre-weighted amount of microsand was introduced 2 min later, along with 70% of the required polymer dosage; d) after two additional minutes of rapid mixing (150 rpm), the remaining (30%) polymer was added; e) the mixing speed was reduced to 100 rpm (G= 70 s^{-1}) and maintained at 100 rpm for six minutes for the flocs to mature; f) the mixing was stopped and the flocs were allowed to settle for three minutes. Finally, the required volume of settled water was collected for analysis. BS experiments were conducted in duplicate.

Preliminary BS jar tests were performed with both Ottawa River water and Bay of Quinte water prior to the Belleville field study (i.e., Phase III) in order to insure reliable results. The Ottawa River water tests permitted comparisons with the Actiflo® unit at the Rockland (ON) water treatment plant, which the tests were able to simulate well. The preliminary experiments also tested three different polymers (Magnafloc LT22S, Magnafloc LT27 and Superfloc C-492 PWG; BASF, Mississauga, ON). Among the more salient findings were that the anionic polymer performed better than the cationic polymers. However, in both cases higher doses (≥0.25 mg/L) were required for obtaining good turbidity removals. In addition, it was observed that square jars do not work well as the microsand tended to accumulate in the corners and the experiments did not work so well. Therefore, the BS experiments were conducted in 1L cylindrical beakers.

3.3.5 Bubble size measurements method

Generating bubbles of sufficiently small size is considered critical to the performance of DAF systems. The size of the bubbles generated in the LB-DAF were quantified using digital image experiments (DI). Bubbles images and bubble size analysis were performed using an apparatus and methodology adapted from (Zhang et al. 2015). The bubble viewing apparatus used in this research consisted of a long plastic tube to transport the water/bubble samples from the bottom of the LB-DAF tank to a rectangular viewing box, located above the water, that permitted digital images of the bubbles to be taken. The viewing chamber was built of transparent Plexiglas (3.175mm = 1/8" wall thickness), its external dimensions were 2.5 cm long, 6.5 cm height and 1.0 cm wide. The bottom of the viewing chamber was connected to a 60 cm long sampling clear tube (6.35mm = 1/4" ID – 9.5mm = 3/8" OD). The top of the viewing chamber was connected to a peristaltic pump via another (6.35mm ID – 9.5mm OD) plastic tube. The suction action of the peristaltic pump MasterFlex® L/S® (Cole-

Parmer Instruments Company, Montreal, QC) (0.40 mL/min) withdraws water and the bubbles from the bottom of the suction tube and carries them to the viewing chamber. During the testing, the bottom of the sampling tube was held 30 cm above the bottom the LB-DAF tank. This distance allowed to have sufficient time to the bubble's formation (i.e., nucleation, growth and coalescence).

Pictures from isolated bubbles in the bubble viewing apparatus were taken with a high-speed high-resolution flare camera model (2M360-CL, IO, Inc. England). The bubble pictures were processed using ImageJ free software (National Institutes of Health, Bethesda, MD, US). A schematic of the bubble viewing apparatus is shown in the left side of figure 3.4, the right side presents a micro bubble image obtained during these bubble measuring tests. This technique can only be used for the measurement of bubbles in clean water solutions because it is not possible to distinguish well between bubbles and flocs with this approach. According to Zhang et al. (2015) this technique is suitable for measuring a mean bubble size range between 20 and 60 µm.

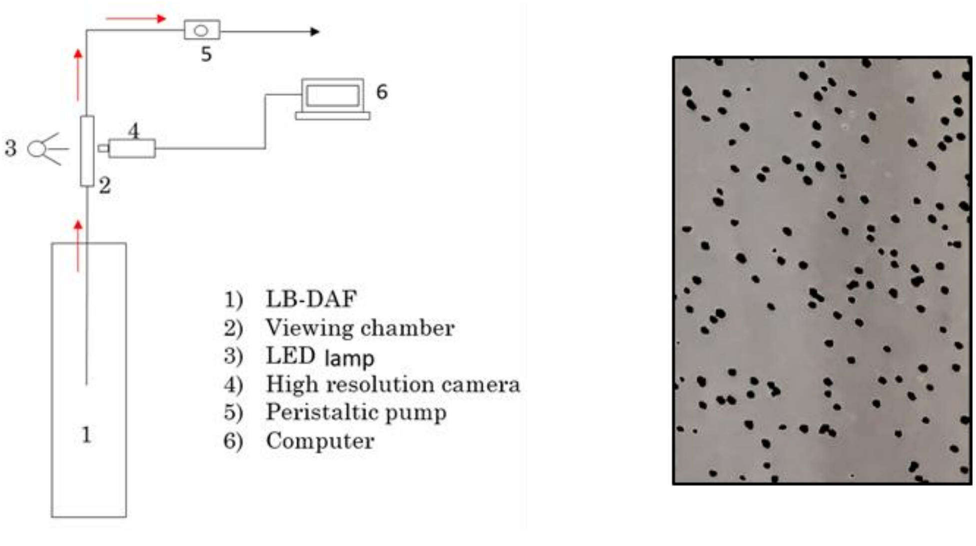

Figure 3.4 Bubble viewing apparatus and micro bubble image obtained

3.3.6 Flocs size measurements

Particles concentration and floc size in the LB-DAF were measured at the end of the flocculation and the flotation steps using a dynamic particle analyzer (DPA) (Bright-

WELL Technologies Inc., Ottawa, ON). The unit is equipped with a high magnification cell (BP-4100-FC-100-U) which has a particle sizing range between 0.75 to 100 μm. Prior to every use, the instrument was calibrated using two polystyrene particles standard solutions (Thermo Fisher Scientific Inc., Fremont, CA) One of the solutions consisted 5 μm particles with a concentration of 10^7 particles per mL, and the second consisted of a solution of 10 μm particles with a concentration of 10^6 particles per mL with a variation of $\leq 2\%$.

3.4 Analytical methods for water characterization

3.4.1 pH

The pH of all of the water samples was measured using a pH meter (Accumet model 910, Fisher Scientific, Hamton, NH). The pH meter was calibrated with pH 4 and 7 buffer solutions every time that the pH was measured.

3.4.2 Ultraviolet Absorbance at 254nm

Ultraviolet absorbance at 254nm (UV-254) was measured by using a UV spectrophotometer (DU-40 Beckman Instruments Inc; Mississauga, ON). The spectrophotometer is equipped with a static mount with a multiple cell holder for 1.0 cm path length quartz cells.

3.4.3 Total Organic Carbon (TOC)

The TOC concentration of the samples was measured using a UV-persulfate oxidation-based TOC analyzer (Phoenix 8000, Tekmar-Dohrmann, Cincinnati, OH). The TOC analysis methodology followed the standard method 5310 C (APHA/AWWA/WEF, 2017). The instrument was calibrated using potassium phthalate solutions with concentrations of 1, 2, 4 and 8 mg C/L. In addition, every 10 samples a blank and standard were analyzed to insure quality control. Samples that were not analyzed within two hours from the time of sampling were acidified (pH # 2) with 0.1N HCl and stored in amber bottles in a refrigerator at a temperature of (4±1

^{o}C). The instrument performed triplicate measurements and the average was reported.

3.4.4 Dissolved Organic Carbon (DOC)

DOC is the dissolved organic fraction of the TOC and this was obtained by filtering water samples through a 0.45 µm nylon membrane filter (47 mm diameter, PALL Sciences Corp, Mississauga, ON). After the vacuum filtration, the TOC concentration of the filtrate is measured as discussed above. DOC samples that were not analyzed within two hours from the time of sampling were acidified (pH # 2) with 0.1N HCl and stored in a refrigerator at a temperature of (4±1 ^{o}C).

3.4.5 Specific UV Absorption (SUVA)

The specific UV was calculated using equation 3.1 based on the UV-254nm with a one cm cell path and DOC measurements.

$$SUVA = \frac{UV_{254}}{DOC} \times 100 \qquad \text{Eq. 3.1}$$

3.4.6 Turbidity

Turbidity was measured by using a Hatch 2100AN Turbidimeter (Loveland, CO). Before measuring the samples, the nephelometric turbidimeter was calibrated with the 0.1 NTU and 20 NTU standards supplied by Hatch.

3.4.7 Trihalomethane Formation Potential (THMFP)

THMFP test was conducted for settled and floated samples as part of Phase III (Belleville) of the study. The THMFP method used was a modified version of Standard Method 5710 (APHA/AWWA/WEF, 2017). The THMFP procedure was as follows; a) the temperature and pH of the samples were recorded before conducting the test; b)

1000 ml of the sample was measured with a graduate cylinder and filtered through a 0.45 µm nylon membrane filter (47 mm diameter, PALL Sciences Corp, Mississauga, ON) to simulate the deep bed filtration at the full-scale WTP; c) a chlorine standard solution with a concentration of 10% was prepared using commercial bleach with a concentration of 4.25% w/v NaOCl; d) six 500 mL clean clear glass bottles were prepared for conducting the test; e) each 500 mL bottle was filled with 200 mL of sample; f) chlorine (NaOCl) solution was added to yield a dose of 4.4 mg/L (i.e., the total chlorine dose applied to the finished water at the Belleville WTP); g) the test bottle then was filled with the water sample until it overflows (in order to avoid having a headspace), the cap was placed on the bottle and it was inverted several times to mix the contents; h) the test bottle was then wrapped in aluminum foil and incubated in the dark at a room temperature ($22\pm1^{o}C$) for 24 hours (i.e., the maximum water age for the Belleville distribution system); i) after 24 hours of incubation time the samples were analyzed for residual free chlorine to guarantee a similar free chlorine residual concentration than this obtained in the Belleville drinking water distribution system. Samples for conducting THM and HAAs were collected in a 40 ml amber glass vials. THM vials were preserved with sodium thiosulfate and the HAAs vials were preserved with 3mg NH_4Cl. Samples were sent to the City of Ottawa drinking water laboratory for THM and HAA analysis. The THM and HAA quantification was conducted using gas chromatography analysis.

3.4.8 Residual free chlorine procedure

The free chlorine test was conducted using the USEPA 8021 N,N-diethyl-p-phenylenediamine (DPD) standard method. The procedure is as follow; a) two sample cells (1" square glass with a 10 mL volume) were prepared, one as the blank and the other one as the sample (i.e., water sample for adding phenylenediamine DPD indicator); b) the spectrophotometer was initiated with the (80 chlorine F&T PP) program, which contains the calibration curve of the measurement wavelength at 530 nm; c) the first cell prepared as a blank was inserted in the cell holder to read zero; d) the second cell filled with sample and the content of one N,N-diethyl-p-phenylenediamine DPD indicator powder pillow was added to it; e) the cell was then swirled for 20 seconds to mix, its contents, after this time a pink color developed because the presence of chlorine in the water sample; n) the cell was placed in the spectrophotometer and a reading with the results of free chlorine in mg/L as Cl_2 were obtained. Free chlorine tests were conducted in duplicate.

3.4.9 Chlorophyll *a* extraction and quantification

Chlorophyll was extracted using ethanol extraction method (Jespersen and Christoffersen, 1981), which is a spectrophotometric method based on the assumption that approximately 1 to 2% of the dry weight of planktonic algae consist of chlorophyll *a*. The chlorophyll *a* extraction and quantification were performed according to the following procedure: a) 500 to 1000 ml of the sample was measured with a graduate cylinder and vacuum filtered through a 0.45 μm nylon membrane filter (47 mm diameter, PALL Sciences Corp, Mississauga, ON); b) the filter was removed from the filtration apparatus using tweezers and folded in half and then placed directly in a plastic test tube (15 ml Fisherbrand); c) the test tube was labeled with the sample data including the volume of the water filtered and stored in a labelled Ziploc bag that was then placed in a refrigerator ($4\pm1^{o}C$) for 24 hours; d) to conduct the extraction, the filter was unfolded as much as possible in the plastic tube, and 15 ml of 95% EtOH was added; e) the test tube was inverted several times and covered with foil to avoid photochemical degradation and then placed in the refrigerator ($4\pm1^{o}C$) to allow the chlorophyll *a* to be extracted for 24 hours; f) after 24 hours, the samples were removed from the refrigerator and centrifuged (Ample Scientific Champion F-33D, Norcross, GA, US) at 3300 rpm for 10 minutes; g) after centrifugation the liquid in the test tube was decanted and placed in a 5 cm path length glass spectrophotometer cuvette (also a second cuvette was filled with only 95% EtOH and used as a blank) h) spectrophotometer absorbance readings were conducted at wavelengths of 665 nm, 750 nm and 649 nm. The chlorophyll_*a* (Chl_*a*) concentrations (in μg/L) were calculated using the equation 3.2.

$$Chl\_a = \frac{[13.7(A_{665} - A_{750}) - 5.76(A_{649} - A_{750})] \times E}{(F \times L)} \qquad \text{Eq. 3.2}$$

Where: A_{665} = Absorbance at 665 nm, A_{750} = Absorbance at 750 nm, A_{649} = Absorbance at 649 nm, E = Extraction volume in mL (e.g. 15 mL), F = Volume of water filtered in L (e.g. 0.5 L), L = Path length of the cuvette in cm (e.g. 5 cm).

3.4.10 C-Phycocyanin extraction and quantification

C-phycocyanin extraction procedure was adapted from (Horváth et al., 2013; Dianursanti & Indraputri, 2018). C-phycocyanin extraction was conducted with sodium phosphate buffer solution (pH = 6.8). The buffer solution was prepared as follow; a) one liter of distilled water was measured with a graduate cylinder and poured into a rinse bottle; b) 8.77 g of NaCl (final concentration 0.15 mol/L), 2.01 g of KCl (final concentration 27 mmol/L), 11.36 g of Na_2HPO_4 (final concentration 80 mmol/L), 2.72g of KH_2PO_4 (final concentration 20 mmol/L) and 3.72 g of Na_2EDTA (final concentration 10 mmol/L) were added to the bottle; c) the pH of the buffer solution was adjusted to 7.45-7.50 using 3-4 mL of 5 mol/L NaOH. The buffer solution was stored in a refrigerator at $4\pm1^{o}C$. The extraction procedure involved the following steps; a) 500 to 1000 ml of the sample was measured with a graduate cylinder and vacuum filtered through a 0.45 μm membrane filter (47 mm diameter, PALL Sciences Corp, Mississauga, ON); b) The filter was removed from the filtration apparatus using tweezers and folded in half and then placed directly in a plastic test tube (15 ml Fisherbrand); c) the test tube was labeled with the sample data including the volume of the water filtered and stored in a labelled Ziploc bag that was then placed in a refrigerator (temperature $=4\pm1^{o}C$); d) the filter was unfolded as much as possible within the plastic tube, and 10 ml of the sodium phosphate buffer solution was added; d) the test tube sealed and inverted several times, then it was covered with foil to avoid photochemical degradation; e) the test tube was then shaken using a vortex mixer at about 1000 rpm for 15 minutes; f) the test tube was then placed for 24 hours in a refrigerator (temperature = $4\pm1^{o}C$) to allow the C-Phycocyanin to be extracted;

g) after the 24 hours extraction the sample was centrifuged (Ample Scientific Champion F-33D, Norcross, GA, US) at 3300 rpm for 15 minutes to remove the cell debris; h) the supernatant was collected for spectrophotometric analysis; i) the precipitate in the test tube was discarded; and j) supernatant spectrophotometer absorbance readings were performed at wavelengths of 620nm and 652nm. The C-Phycocyanin concentration (C-PC) in mg/mL was calculated using the equation 3.3 (Bennett and Bogorad, 1973).

$$C - PC = \frac{(A_{620} - 0.474 \times A_{652})}{5.34} \qquad \text{Eq. 3.3}$$

Where: A_{620} = Absorbance at 620 nm, A_{652} = Absorbance at 652 nm

3.5 Experimental plan

As discussed in section 1.4 this thesis is divided in three phases, the subsections bellow describes the experiments conducted as part of this thesis.

3.5.1 Phase I. LB-DAF development

Phase I experiments consisted of LB-DAF tank tests using Ottawa River water under different operational conditions. The different conditions were intended a) to assess the impact of the LB-DAF design/operational variables; and b) to determine the values of the variables that yield the best approximation of Aylmer WTP's for turbidity and NOM removal. The main LB-DAF tank design and operational variables that were investigated in Phase I included five different recycle ratios (RR) (i.e., 6, 8, 10, 12 and 15%), three different saturator pressures (SP) 482, 550 and 620 kPa (70, 80 and 90 psig), four different water depth to tank diameter (W/D) ratios (2.5, 3.0, 3.5 and 4.0 m/m) and six different G values in the flocculation step (8, 16, 34, 41, 64 and 92 s^{-1}). The Phase I experiments were conducted using water samples collected in different dates, the coagulant type, coagulant dose and polymer dose used in the testing of these samples matched those used at the full-scale WTP at the time the water samples were collected. The Aylmer WTP treats raw ORW using aluminum-based coagulants and a cationic polyacrylamide (Superfloc C-492PWG, Kemira, Montreal, QC) polymer. During the summer they use alum (i.e., ALS Kemira, Montreal, QC) as a coagulant and during the winter they use a polymerized aluminum coagulant (PAS 8, Kemira, Montreal, QC). Their dose was between 30 - 35 mg/L as Al_2O_3 (2.73 – 3.18 mg Al/L). The dose of polymer was generally between 0.07 - 0.08 mg/L. The experimentation also involved bubble size measurements using distilled water within the LB-DAF apparatus at the different operating pressures (482, 550 and 620 kPa, or 70, 80 and 90 psig). To ascertain that the LB-DAF performed better than the DAF jar tests a number of DAF jar tests were also performed as part of Phase I. The sample collection in different dates was necessary due to the large volumes of water required and to see if the seasonal variation in water quality/coagulant type had an impact on performance. Experiments were conducted in duplicate.

3.5.2 Phase II. LB-DAF confirmation

The objective was to confirm the optimum LB-DAF design/operational conditions identified in Phase I by conducting comparisons with the DAF systems at two other full-scale WTPs (Belleville, ON WTP and Smiths Falls WTP, ON). Again, the comparisons were in terms of turbidity and NOM removals. In Phase I it was identified that based on the turbidity removal the best simulations of full-scale performance were obtained when the LB-DAF was operated with a water volume of 21 liters, G=50 s^{-1}, RR of 10% and SP of 482 kPa (70 psig). Therefore, they were considered as the standard test conditions for conducting LB-DAF experiments. It should be noted that in the Phase I the LB-DAF turbidity removals were not very sensitive to changes in the values of many of the operational values. Accordingly, the sensitivity test in Phase II were limited to the impact of the flocculation mixing G's (i.e., 10, 20, 30, 50, 79 and 113 s^{-1}), four different RR (6, 8, 10, and 15%), three different SP 482, 550 and 620 kPa (70, 80 and 90 psig) and four different W/D ratio (2.5, 3.0, 3.5 and 4.0 m/m). The testing procedure was that outlined in section 3.3.1.

The LB-DAF experiments with raw Smiths Falls water were conducted using PAS-8 as coagulant with a dose of 80 mg/L as Al_2O_3 (7.3 mg Al/L) and 0.07 mg/L of Magnafloc LT22S (Cationic polyelectrolyte, BASF company, Mississauga, ON) polymer. These were the same concentrations used at the Smiths Falls WTP at the time of sampling. These tests were conducted with water collected in June 2018. The Belleville WTP has a pre-oxidation step within the intake (1.25 mg/L $KMnO_4$ and & 2-4 mg/L chlorine) for taste, odor, zebra and quagga mussel control and to oxidize iron. The water samples were collected after the pre-oxidation step in November 2017 and early summer June 2018. This water was then treated with coagulation/flocculation (C/F) units as DAF pre-treatment using alum (60 mg/L as Al_2O_3 (4.9 mg Al/L)). Like Belleville WTP the related LB-DAF experiments were performed using 60 mg/L as Al_2O_3 (4.9 mg Al/L) (ALS, Kemira, Montreal, QC) and no polymer. Phase II experiments were conducted in duplicate.

3.5.3 Phase III. DAF and Ballasted Sedimentation Comparison for the Treatment of an Algal-laden Water.

Phase III used jar tests to compare the performance of dissolved air flotation, conventional gravity settling, and ballasted sedimentation for the treatment of an algal impacted water. DAF is generally considered the separation of choice for algal-impacted waters, however ballasted sedimentation is currently a very popular separation process. The key objective is to determine if BS can perform as well as DAF for such waters. The experiments followed the procedures outlined in sections 3.3.2, 3.3.3 and 3.3.4. DAF jar test and C/F/SED jar test were conducted in, the Phase III jar tests comparison were in terms of their reduction of for turbidity, algae (measured as chlorophyll *a)*, cyanobacteria (quantified in terms of c-phycocyanin), THMFP and NOM reduction. One week prior to the field-testing preliminary BS jar test were conducted with Belleville WTP water to find the suitable testing conditions for turbidity removal. These tests evaluated six different aluminum sulfate coagulant (ALS, Kemira, Montreal, QC) doses (i.e., 70, 80, 90, 100 and 110 mg/L as Al_2O_3 or 6.4, 7.3, 8.2, 9.1 and 10 mg Al/L), six different Magnafloc LT27 (Anionic polyelectrolyte, BASF, Mississauga, ON) polymer 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). The characteristics of the raw and ballasted settled water were quantified in terms of a number of water quality parameters including temperature, pH and turbidity. During the Belleville field testing the impact of the coagulant dose was reassessed (in duplicate) but the polymer dose, sand dose and settling time were kept constant at the values identified in the preliminary testing. BS results were compared with DAF jar test and CGS for turbidity, chlorophyll *a*, phycocyanin, THMFP, UV-254 and DOC removal. The BS procedure was described in the section 3.3.4.

3.6 Statistical Analysis

3.6.1 Factorial experimental design

The objective of conducting factorial experimental design (FED) in this research was to determine which LB-DAF variables (i.e., G, RR, SP) have a significant impact on the LB-DAF performance for turbidity removal. Some of the advantages in conducting FED in research are that it allows one to reduce the number of experiments, it permits the evaluation of interactions among the variables and it identifies the significant effects of each variable from the insignificants ones (Tarley et al., 2009; Abdel-Ghani et al., 2007). In this study, three different variables: velocity gradient [G] (s^{-1}), saturator pressure [SP] (psig) and recycle ratio [RR] (%) were studied to assess their impact on the LB-DAF tank performance for turbidity removal. These three variables were each investigated at two levels. Thus, this is a two-level, three factors experimental design 2^k with $k = 3$. Three factors at two levels gives a total of eight experimental conditions $2^3 = 8$. The experimental design model was conducted with one centre point and six centre point runs. Each test was conducted using replicate runs for the purpose of obtaining an internal estimate of the error variance that can be used to identify the statistically significant effects from the experiments.

Therefore, a total of 22 runs were carried out. Factorial design analysis was conducted using Minitab 18 statistical software (Minitab Inc. Global Headquarter, PA, US).

Chapter 4

Large Batch Bench-scale Dissolved Air Flotation System (LB-DAF) for Drinking Water Treatability Tests

Authors: J. P. Gonzalez-Galvis, R. M. Narbaitz

4.1 Abstract

The feasibility of dissolved air flotation (DAF) for water treatment is frequently assessed by bench-scale tests using commercially available 1-2 L volume DAF jar test apparatus. However, they can over predict or under predict turbidity removals (Bickerton, 2012; MacPhee et al., 1996). It is hypothesized that, similarly to flocculent settling tests, larger diameter vessels will improve the DAF batch test predictions. Thus, the main objective of this research was to develop a larger diameter/larger volume (~21L) batch bench-scale DAF system (LB-DAF) to better simulate DAF full-scale units at water treatment plants. A sensitivity analysis of the impact of LB-DAF key design/operational variables was conducted to identify the values that yielded the best simulations of a full-scale DAF system. These variables included saturator pressure (SP), recycle ratio (RR), water depth to tank diameter ratio (D/W), impeller type and velocity gradients (G's). For the low turbidity, high organics river water tested, the LB-DAF system simulated the full-scale DAF turbidity removals much better than the DAF jar tests. This was in part due to the LB-DAF's saturated water delivery system and its larger vessel diameter. The values of the LB-DAF design/operational parameters had a relatively small impact on turbidity and natural

organic matter (NOM) removals. NOM removal in the LB-DAF, the DAF jar test and the full-scale DAF were very similar

4.2 Introduction

Coagulation, flocculation and sedimentation (C/F/SED) are the main treatment processes used in removal of turbidity and natural organic matter (NOM) at water treatment plants (WTPs), they are quite effective and economical (Matilainen et al., 2010; Edzwald, 1993). However, for the treatment of surface waters containing algae dissolved air flotation (DAF) has often been used as the separation process. This is because DAF is more effective than conventional settling in removing algae, which are very low-density particles (Zhang et al. 2012; Do Amaral et al. 2013). While some studies have found that the NOM removals by DAF were very similar than those by sedimentation (Heinanen et al. 1995; Valade et al. 2009; Malley and Edzwald, 1991). Yet, others recommend DAF for the separation of highly hydrophobic NOM waters (Zheng et al., 2015; Haarhoff, 2018). In addition, the higher hydrophobic NOM removals achieved by DAF resulted in lower membrane fouling (Walker and Narbaitz, 2016; Xu and Narbaitz, 2016). However, only a limited number of WTPs use DAF. To expand our group's research on the impact of DAF as a membrane pre-treatment process to other source waters, it was desirable to have batch bench-scale DAF unit that produces at least 20 L of floated water to conduct week-long membrane tests. Commercially available DAF test units, which are used for preliminary assessment of DAF have volumes of up to 2L. DAF jar tests apparatus are able to predict NOM removals achieved in pilot-scale and full-scale DAF units (MacPhee et al. 1996; Zou et al. 2011). However, one of the drawbacks of some DAF jar test apparatus is that they do not necessarily simulate well the turbidity removals in full-scale DAF units. For example, Bickerton, 2012, found that jar tests over-predicted full-scale DAF turbidity removals by up to 12%. In addition, other studies found that DAF jar test trend to under-predict turbidity removals (MacPhee et al., 1996). Possible reasons for the DAF jar test turbidity predictions deviations may be the combination of the saturated water delivery system, the saturated water application point and the wall effects in the small diameter jars. In a sedimentation process a particle tends to rotate and equilibrate to an orientation when it is settling in a stagnant fluid in the absence of walls (Fan et al., 2004; Hazzab et al., 2008). When the wall effects become significant, the equilibrium particle orientation changes. The change in particle orientation leads to a different projected area and drag coefficient (Lau et al., 2010). These changes in the particles projected area and drag coefficient may also impact the flotation performance in a flotation column. The 9 cm jars in DAF tester used in this study allows particles to attach to the jar walls, which are resuspended in the clarification step. Numerous textbooks recommend that type II (flocculent) settling tests be conducted in columns with a minimum diameter of 15 cm, to minimize wall effects (Droste, 1997), so possibly the DAF jar tests also require higher diameter vessels. In addition, the saturated water/bubble delivery system located near the base of the jar creates an area of high turbulence, this possibly leads to floc breakage and cause particle resuspension in the clarification process (Hyde et al., 1977). Therefore, a lab-scale DAF with a bigger diameter tank may result in more realistic full-scale DAF turbidity removal predictions. Some larger size batch bench-scale DAF systems have been developed for conducting wastewater and sludge treatability tests (Mulbarger and Huffman, 1970; Wood and Dick, 1973; Bratby, 1983). However, none have been evaluated for drinking water applications, and according to a DAF equipment manufacturer, scale-up of water treatment applications are more challenging than wastewater and sludge treatment applications (Liu, 2017). Therefore, the main objectives of this research are to build a larger diameter and a large-volume (~21L) batch bench-scale DAF tank (LB-DAF), and to optimize the LB-DAF characteristics such as, saturator pressure (SP), recycle ratio (RR), water depth to diameter ratio (W/D) and mixing conditions, so that its performance approaches that of a full-scale DAF. This manuscript describes the LB-DAF evaluation for a river water with low turbidity and a relatively high NOM content; the testing was performed at different times of the year as a form of verification.

4.3 Materials and Methods

4.3.1 Water Tested

The experiments were conducted using raw Ottawa River water (ORW). Given the 21L volume of the LB-DAF, the numerous operating conditions tested, as well as the repeat experiments, very large volumes of waters were required for this study and the logistics of obtaining the water were a challenge. ORW was chosen because there was nearby full-scale WTP using a DAF system (Aylmer WTP, Gatineau, QC), which would facilitate full-scale/lab-scale comparisons. ORW is typical of Northern Canadian river water with low turbidity, high color and low alkalinity; b) it has a high NOM content and a large hydrophobic (HPO) fraction (Zheng et al., 2015; Xu & Narbaitz, 2016), which make this water suitable for treating with DAF (Zou et al., 2011; Haarhoff, 2008). The Aylmer WTP operates three AquaDAF ® units. DAF treatment was chosen for the Aylmer WTP because its compactness, it has a design hydraulic loading rate of 38 m/h, which is in the range of high rate DAF systems (Edzwald et al., 1999) and a flocculation basin hydraulic retention time of 10 min. The mixing speed of the rapid mix tank and two stage-flocculation system were 34, 15 and 6.9 rpm, respectively. Under average flow conditions their mixing mean velocity gradient (G) values are 234, 67 and 22 s^{-1}, respectively. To maintain good performance the plant operates with a constant recycle flowrate, this impacted both the saturator pressure and the percent recycle ratio. The ORW samples were collected during the summer of 2017 and spring of 2018 from the influent line of the Aylmer WTP. Water samples were stored at ($4\pm1^{o}C$) until testing.

4.3.2 Large Volume Bench-scale Dissolved Air Flotation Tank (LB-DAF) Configuration

The LB-DAF was designed to sequentially conduct the coagulation, flocculation and flotation steps in the same vessel. The first step in the development of the LB-DAF was to design and build the system, while incorporating as much flexibility as possible, so as to be able to assess the impact of many process variables. The LB-DAF system (figure 4.1) was designed to meet some of the essential requirements for a vertical turbine flocculator in the Coagulation/Flocculation process, but at the same time trying to provide satisfactory conditions for flotation in the same vessel. A cylindrical tank was chosen because the commercial flotation jar test in our lab uses cylindrical vessels. The 20 cm diameter column was chosen to provide a larger diameter than our DAF jar tester DAF jar tester (9 cm), which will likely result in smaller wall effects (USEPA, 1996). The 1.0 m column height was chosen to evaluate the impact of several water depth to tank diameter ratios. Three different flat impellers with different areas were tested in the LB-DAF; they were designed to meet the minimum requirements for a vertical turbine flocculator (MWH, 2012). The impeller configurations were as follows: a square impeller (10 cm x 10 cm); a rectangular impeller (R) (10 cm x 20 cm); and a small rectangular impeller (SR) (10 cm x 2.5 cm). The latter was built to mimic the typical impeller type found in a regular DAF jar test apparatus (Gonzalez-Torres et al. 2014). The impellers were attached to a 3/8" shaft (#2 in figure 4.1), which was secured with a bearing at the bottom of the tank to eliminate vibrations. This study used flat impellers because the power input (necessary to calculate G) of the flat impellers could be calculated using the Rushton correlations (Rushton, 1952). The LB-DAF has four 2 cm wide, 80 cm tall stainless-steel baffles arranged at 90^o from each other along the vessel wall. The mixing was provided by a motor with an operating speed range between 3-200 rpm (VAC SKU 5000810, Servo Dyne, Cole-Parmer, Montreal, QC). The saturated water is produced in a pressure vessel (saturator) with a capacity of 8L (2 gallon), which is connected to portable air compressor (TAW-0308, PSI compressors Inc. Ottawa, ON) that helps maintain a constant pressure in the saturator. The saturator was connected to the tank through a low-density polyethylene (LDPE) tubing (6.35 mm or 1/4" OD) and a 6.35 mm OD stainless steel pipe. The LB-DAF bubble delivery tubing incorporates a 6.35 mm (1/4") On/Off valve (#4 in figure 4.1) and a 6.35 mm (1/4") needle valve (#5 in figure 4.1). The On/Off valve controls the saturated water feed, while the partially open needle valve, located to approximately 10 cm from the LB-DAF tank bottom, helps control the bubble size (Appendix D). In continuous flow DAF systems, the recycle ratio (RR) is the ratio of the saturated water flowrate to the system flowrate. In the LB-DAF apparatus, which is a batch system, the recycle ratio was defined as the ratio of the saturated water volume (V_2) to the total water volume (V_1).

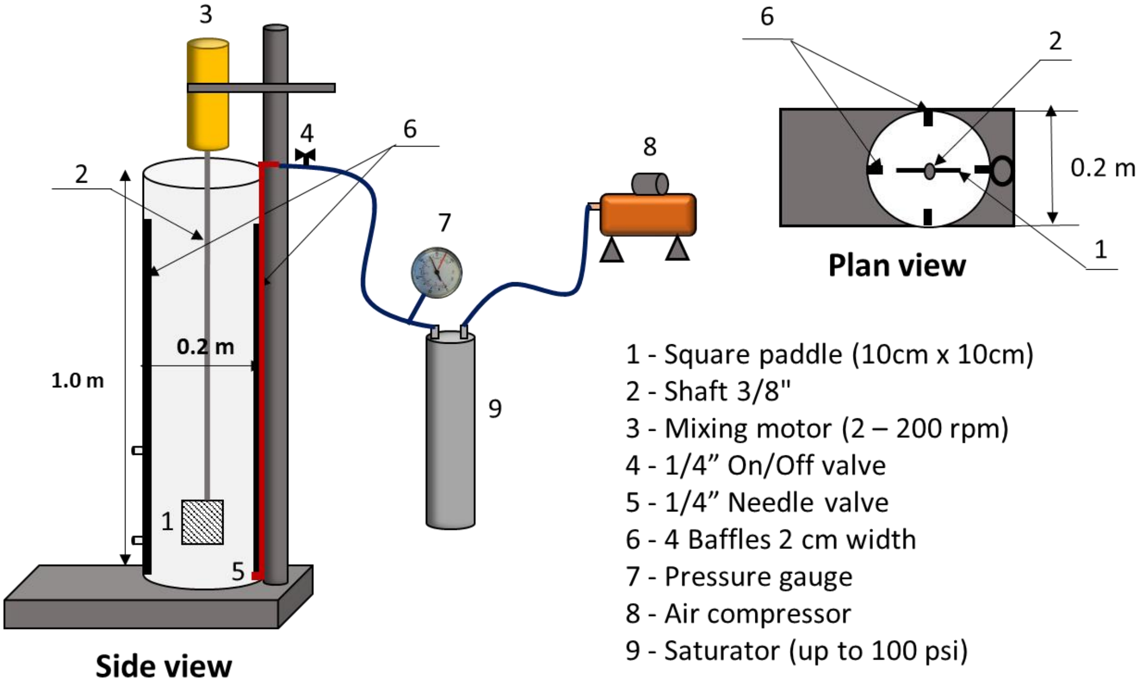

Figure 4.1 Large Volume Bench-scale Dissolved Air Flotation Apparatus (LB-DAF)

4.3.3 Experimental Plan

4.3.3.1 DAF jar test experiments

C/F/DAF jar test experiments were conducted in a commercial DAF jar test bench-scale apparatus (PJT02 Capital Controls Group, Didcot, GB). The components of the DAF jar test apparatus include a coagulation-flocculation-flotation cell with a mixer and a water saturator. The high strength acrylic cell (jar) has an internal diameter of 9 cm and a height of 22 cm. The maximum volume of the cell is 1.4 liters. The unit is equipped with a rotating flat paddle connected to a motor with adjustable mixing speeds to control velocity gradients within the jars. The unit also includes a saturated water injection apparatus, which has a nozzle. The nozzle apparatus is connected to an 8L (2 gal) volume pressurized saturator tank (Capital Controls Inc, England), which was pressurized by a compressor (TAW-0308, PSI Compressors Inc. Ottawa, ON). As per the manufacturer's instructions the saturator tank was manually shaken to ensure a reasonable saturation efficiency. The DAF jar test manufacturer's recommended operating conditions were followed, they were; a) coagulation at 400 rpm (G= 240 s^{-1}) for one minute; b) flocculation at 30 rpm (G= 12 s^{-1}) for 10 minutes; c) flotation was conducted for 10 min with a SP of 482 kPa (70 psig) and a RR of 10%. The chemicals, chemical doses and water temperature were the same as that of the matching LB-DAF tests. The C/F/DAF experiments were conducted in duplicate.

4.3.3.2 LB-DAF experiments

These experiments tested the LB-DAF tank under different operational conditions to: a) assess their impact; and b) determine the values of the variables that yield the best approximation to the Aylmer WTP's DAF system in terms of turbidity removals. The main LB-DAF tank design and operational variables that were investigated include five different recycle ratios (RR), three different saturator pressures (SP), four different water depth to diameter ratios (W/D) and six different flocculation step G's values. The chemical dose in the LB-DAF experiments were the same used by the Aylmer WTP at the time the raw water samples were collected. The Aylmer WTP used aluminum sulfate (ALS, Kemira, Montreal, QC: 4.3±0.1% Al^{3+}) during the summer of 2017 and poly hydroxide aluminum sulphate (PAS-8, Kemira, Montreal, QC: 4.35±0.16% Al^{3+}) during the winter and spring of 2018. The coagulant doses varied between 30 and 35 mg/L as Al_2O_3 (2.73 – 3.18 mg Al/L) according to the season and the raw water turbidity. In addition, 0.07 to 0.08 mg/L cationic polyacrylamide polymer (Superfloc C-492PWG, Kemira, Montreal, QC) was used by Aylmer WTP as a flocculation aid. The majority of the LB-DAF tests were performed using a set of base conditions (i.e., W/D=3.0, RR=10%, square mixer, SP=480 kPa) and these base conditions were varied for the W/D, RR, SP, and impeller shape sensitivity tests.

The procedure was as follows: a) the coagulation was conducted at 200 rpm (G = 296 s^{-1}) for 2 minutes; b) the flocculation was performed for 15 minutes at a constant mixing speed; c) preliminary tests showed that using distilled water and floated water as the pressurized water yielded very similar results, thus to simplify the testing distilled water was used as the pressurized water in the experiments presented; d) flotation was started by introducing the saturated water (RR=10% except for the RR sensitivity tests); e) once the saturated water entered the LB-DAF tank the On/Off valve was closed and a flotation time of 15 minutes was allowed; and f) after that water samples were collected for analysis.

The 15 minutes of flocculation time was chosen because preliminary tests showed that 10 min flocculation periods yielded poor flocs. In addition, a single mixing speed flocculation step was used because preliminary tests showed that a two-step flocculation did not change the turbidity removals. The flocculation G's of 8, 16, 24, 41, 64 and 92 s^{-1}, correspond to mixer speeds of 21, 33, 43, 61, 83 and 105 rpm, respectively. The flowrate of saturated water delivery system was recalibrated before each LB-DAF test. The LB-DAF laboratory experiments were conducted at 20 ± 2.0 ^{o}C to simulate summer of 2017 water temperatures, 6 ± 1.0 ^{o}C to simulate early spring of 2018 water temperatures and 1.2 ± 0.5 ^{o}C to simulate winter 2018 water temperatures for conducting factorial design experiments. All experiments were performed in duplicate and their water quality samples were analyzed in triplicate.

4.3.3.3 Bubble size measurements method

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 as it emerges; 4) the speed of emergence, the volume and pressure of the gas behind it; and 5) the turbulence of the surrounding liquid (O'Connor et al. 1990; Braul et al. 2001). The size of the bubbles generated by the LB-DAF system were quantified using a digital imaging technique (DI). Bubbles images were captured and analyzed using a modified version of the apparatus and the methodology developed by Zhang et al. (2015). The apparatus consists of a 60 cm long ¼" (6.35 mm) ID Plexiglas sampling tube that is connected to the bottom of a viewing chamber, a second tube that connects the top of the chamber to the peristaltic pump MasterFlex® L/S® (Cole-Parmer Instruments Company, Montreal, QC) that created suction. Water with bubbles were withdrawn by the suction into the bottom of the sampling tube, located 30 cm above the bottom of the LB-DAF tank, up the tube and into the viewing chamber. The pump flow rate was 0.45 ml/min. The bubble viewing chamber, that is located above the water, consisted of a 2.5 cm long, 6.5 cm high and 1.0 cm wide clear Plexiglas box, it had a 3.175mm (1/8") wall thickness. A high-speed high-resolution flare camera model (2M360-CL, IO, Inc., England) was used to photograph individual bubbles in the viewing chamber. The bubble pictures were processed using ImageJ software (National Institutes of Health, Bethesda, MD). The bubble size measurement experiments were conducted in triplicate at room temperature (~20 ± 2 ^{o}C). In each bubble diameter measurement test, the diameter of approximately 1100 bubbles were measured. It should be noted that these measurements were performed with tap water as opposed to flocculated water, this was because chemical flocs interfere with the bubble measurements.

4.3.4 Analytical Methods

The pH of all the water samples was measured using a pH meter (Accumet model 910, Fisher Scientific, Hampton, NH). Turbidity was determined using a Hatch 2100AN Turbidimeter (Loveland, CO). NOM removal was measured by subrogate NOM parameters: UV-254 absorbance and the dissolved organic carbon (DOC) concentrations. The DOC is the dissolved organic fraction of the total organic carbon (TOC) concentration and the DOC was obtained by vacuum filtering the water samples through a 0.45 µm nylon membrane filter (PALL Sciences Corp; Pensacola, FL) and then performing the 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 methodology follows the standard method 5310 C (APHA/AWWA/WEF, 2017). Ultraviolet absorbance at 254nm (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 multiplying the UV-254 nm by 100 and dividing it by the DOC concentration. The alkalinity and the total hardness of the raw water were determined according to Standard Methods 2320 and 8226 (2340), respectively (APHA/AWWA/WEF, 2017). Flocs/particles concentration and size measurements after the LB-DAF flocculation step were performed using a dynamic particle analyzer (DPA) (Bright-WELL Technologies Inc., Ottawa, ON) equipped with a high magnification cell BP-4100-FC-100-U with a particle sizing range between 0.75 to 100 µm. The instrument was calibrated using two polystyrene particles standard solutions (Thermo Fisher Scientific Inc., Fremont, CA). The 5 µm size particle standard had a concentration of 10^7 particles per mL, the 10 µm particle standard solution had a concentration of 10^6 particles per mL. Water temperature was measured using a waterproof thermocouple (Digi-Sense RK-91100-00, Cole-Parmer, Montreal, QC). Zeta potential measurements of the coagulated ORW were conducted using a Zetasizer Nano Particle Analyzer (Nano ZS, Malvern Instruments Ltd., Worcestershire, UK).

4.4 Results and discussion

4.4.1 Water quality

Table 4.1 shows the characterization of the raw ORW in summer of 2017, winter and spring of 2018.

Table 4.1 Raw ORW characterization, summer 2017, winter and spring 2018

Parameter	Raw ORW (Summer 2017)	Raw ORW (Winter 2018)	Raw ORW (Spring 2018)
pH	6.79±0.01	7.14±0.02	6.91±0.29
Turbidity (NTU)	2.71±0.02	3.79±0.11	6.55±0.33
Alkalinity (mg/L as $CaCO_3$)	40.0 ±1.20	38.3 ± 3.27	30.8 ±1.44
UV-254 (cm^{-1})	0.27±0.007	0.29±0.001	0.29±0.008
DOC (mg/L)	5.90±0.04	6.45±0.03	6.64±0.012
SUVA ($L\ mg^{-1}\ m^{-1}$)	4.57±0.01	4.49±0.02	4.37±0.10
True Color (Pt-Co)	44.3±1.3	47.3±1.30	42.3±1.5
Total Hardness (mg/L)	38.0±1.8	31.3±1.30	25.0±1.7

(Values are average ± one standard deviation) (n = 3)

The ORW characteristics include a yellowish color, relatively high NOM content, low turbidity and low alkalinity. The values of these parameters are consistent with those reported by Zheng et al., 2015, and Xu and Narbaitz, 2016. An analysis of the particle zeta potential (ZP) conducted on coagulated ORW samples with a coagulant dose of 30 and 35 mg/L as Al_2O_3 (2.73 – 3.18 mg Al/L), yielded particles ZP values of -10 and -0.93 mV, respectively. These ZP values are sufficient to achieve particle destabilization and those values are close to the range recommended by the literature (MHW, 2012). The turbidity, UV-254 and DOC removals achieved by Aylmer WTP's DAF in summer of 2017 and spring of 2018 were as follows: turbidity (86% and 93%), UV-254 (78% and 83%) and DOC (60% and 63%), respectively. However, during the summer period of 2017 the raw ORW turbidity varied significantly (between 2.71 and 5.21 NTU). As the LB-DAF experiments were conducted with different batches of raw ORW, the samples had different feed turbidity, so the results are reported in terms of turbidity removals. The raw water DOC concentrations did not change significantly from one sampling batch to the next.

4.4.2 Bubble size measurements

Bubble size is an important parameter in a DAF unit because DAF performance is affected by the bubble size and properties in the contact zone (Edzwald, 2010). The bubble-particle interactions (i.e., attachment of a hydrophobic particle to a gas bubble) follow three different steps: a) collision, b) attachment and c) stability (Dai et al., 1999). Consequently, the bubble-particle interactions not only depend on bubble size, but also on different variables such as floc-particle size and density, number and density of the bubbles, particle-bubbles charge and the flotation retention time (Lepinnen & Dalziel, 2004; Han et al., 2001). The particle collection by bubbles in the contact zone of a DAF unit has been studied using a conceptual model (Edzwald et al. 1990; Malley and Edzwald 1991; Edzwald, 1995). This model is based on the single collector efficiency concept that is used to describe particle–bubble collision and attachment for a batch system. In the same model four transport mechanisms of bubbles-particles are considered: Brownian diffusion, interception, differential settling, and inertia. For DAF water treatment applications where the typical particle size is of the order of 10 µm the interception term is the most significant term in the total single collector efficiency (Edzwald, 1995). Based on this conceptual model, it was found in the LB-DAF that as the mean floc size increases close to the mean bubble size the collision efficiency increases. As part of this research the impact of three different saturator pressure 482, 551 and 620 kPa (70, 80 and 90 psig) on the mean bubble size diameter was investigated. Figure 4.2 shows the bubble size frequency (number based) distribution found at 482 kPa (70 psig) saturator pressure in the LB-DAF.

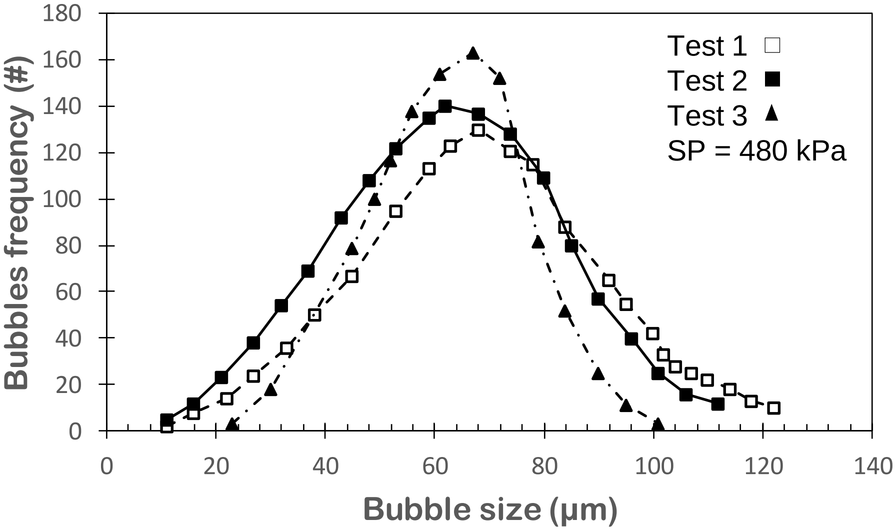

Figure 4.2 Bubble size distribution in the LB-DAF at saturator pressure of 482 kPa (70 psig)

The three bubble measurements at 482 kPa (70 psig) showed fairly similar results (figure 4.2). There was a relatively wide range of bubbles sizes (i.e., 11 to 122 µm) produced and there is an insignificant number of bubbles beyond this range. In addition, there is a narrower range of maximum frequency (45 to 80 µm). The average diameter for this set of tests was 66.5±31.3 µm. The tests at the other two saturator pressures showed similarly shaped bubble size patterns. Table 4.2 shows that the average bubble size and standard deviation of the bubble size decreased as the saturator pressure increased. The decrease in the LB-DAF mean bubble size with increasing saturator pressures was expected based on previous studies (O'Connor et al., 1990; Grau and Heiskanen, 2005). However, as the bubble size distributions are rather wide, there is considerable overlap in the bubble sizes generated at the three pressures tested. In fact, as the confidence limits overlap they are statistically the same. Thus, the saturator pressure may not significantly impact the DAF performance.

Table 4.2 Mean bubble size in the LB-DAF at different SP (kPa)

SP (kPa)	Mean bubble size (µm)
482	66.5±31.3
551	54.4±24.1
620	47.7±19.6

(mean bubble size ± one standard deviation) (n = 3)

The bubble size distribution found in the LB-DAF at different SP's agree with those reported by other studies conducted with similar bubble size measurement technique (i.e., bubbles with diameter smaller than 150 µm) (Yamashita et al. 1979; Grau and Heiskanen, 2005; Bailey, et al. 2005). In addition, the highest percentage of bubbles obtained in the LB-DAF for the three different SP is in the same range found in DAF full-scale systems (40 to 80 µm). (Edzwald, 2010).

4.4.3 Factorial design experiments for evaluating the LB-DAF variables impacting its performance for turbidity removal.

Factorial design experiments were conducted using raw ORW in winter of 2018 with the same coagulant and polymer type and dose used at the Aylmer WTP. The statistical analysis was conducted based on the final turbidity values as the response. The floated water turbidity values obtained in the LB-DAF factorial design experiments were very similar to those reported by the Aylmer WTP at the time the floated water samples were collected (0.93 to 1.93 NTU). These turbidity values are significantly higher than those obtained during the summer, it is presumably associated with the fragility of alum flocs in cold water. From the LB-DAF factorial design results a Pareto chart of the effects (main effects and interactions) was prepared to provide a visual representation of the analysis of variance decomposition (figure 4.3).

Figure 4.3 shows that at the α=0.05 level the main variables that impact the LB-DAF turbidity final turbidity values (factors beyond the dashed line set up by the analysis) from the greatest to the lowest were: velocity gradient [G] (s-1) and recycle ratio (RR-%). Although, the LB-DAF factorial design experiments for ORW showed that the G values and the RR values had a statistically significant impact on the final turbidity, the range of turbidity values (0.93 to 1.93 NTU) was relatively small. It is suspected that the analysis showed that G had a very large impact on the final turbidities because of the quite low G, low recycle ratio and low saturator pressure point. Given the limited range in these values the impact of these variables (G and RR) as well as other variables (i.e., SP, W/D ratio) were studied in greater detail.

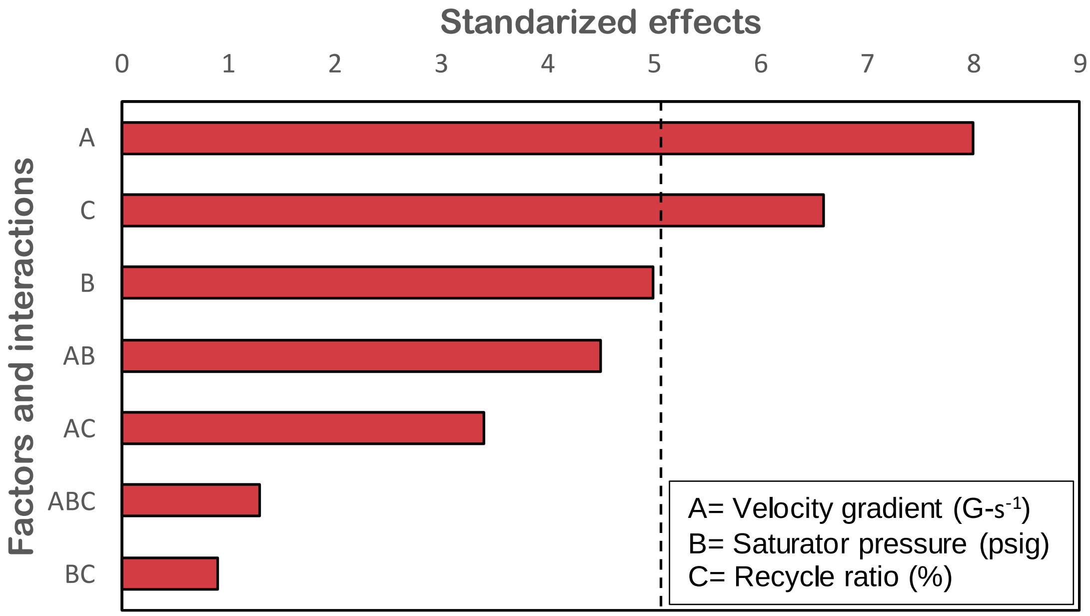

Figure 4.3 Pareto chart main variables and interactions impact on the LB-DAF final turbidity for the winter 2018 tests.

4.4.4 DAF jar test and LB-DAF prediction capabilities for turbidity removal.

The main function of a jar test is to obtain the optimum coagulation conditions in terms of coagulant dose and pH. Preliminary tests conducted in different dates showed that the DAF jar test did not achieved the same percentage turbidity removal as the LB-DAF. It was suspected that this may be due to the smaller DAF jar diameter and the dissolved air delivery system application point (figure 4.4).

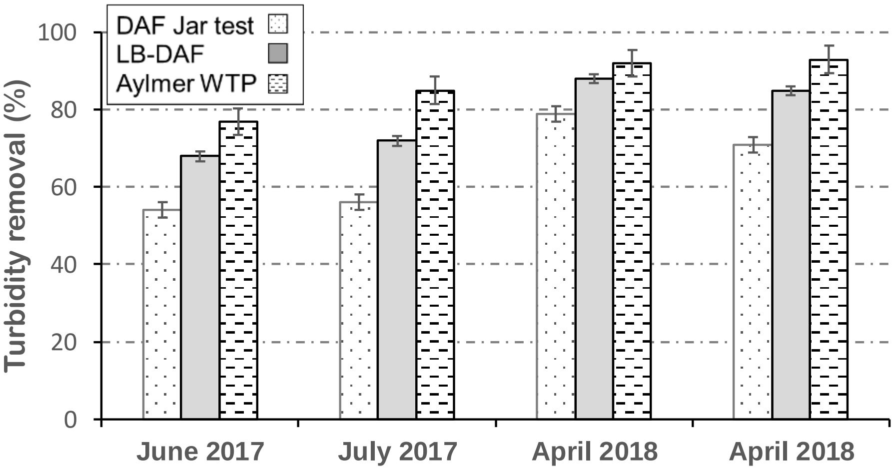

Figure 4.4 Turbidity removal predictions using DAF jar test apparatus versus the LB-DAF and Aylmer WTP (error bars indicate one standard deviation)

However, a comparison between the DAF jar test bubbles size and the bubbles size obtained in the LB-DAF showed that the DAF jar test bubbles device produces a larger mean bubble size (78 μm±13) than the LB-DAF (66±31 μm) with the same saturator pressure 482 kPa (70 psig). Accordingly, a turbidity removal comparison was conducted using: a) the LB-DAF; b) the "as is" DAF jar test apparatus; and c) the DAF jar test using the LB-DAF's pressurized water delivery system/bubble device. The tests were conducted in summer of 2017 and spring of 2018. Figure 4.5 shows that the LB-DAF bubble device placed in the DAF jar test improved the predicted turbidity removal by approximately 10%. While the full-scale DAF turbidity removal was 92% for summer of 2017, the LB-DAF predicted 91%, which is only 1% lower. In contrast, the "as is" DAF jar test predicted 78%, which is 15% lower than the DAF full-scale and the DAF jar tester with the LB-DAF's pressurized water delivery system achieved 86% turbidity removal for the summer of 2017.

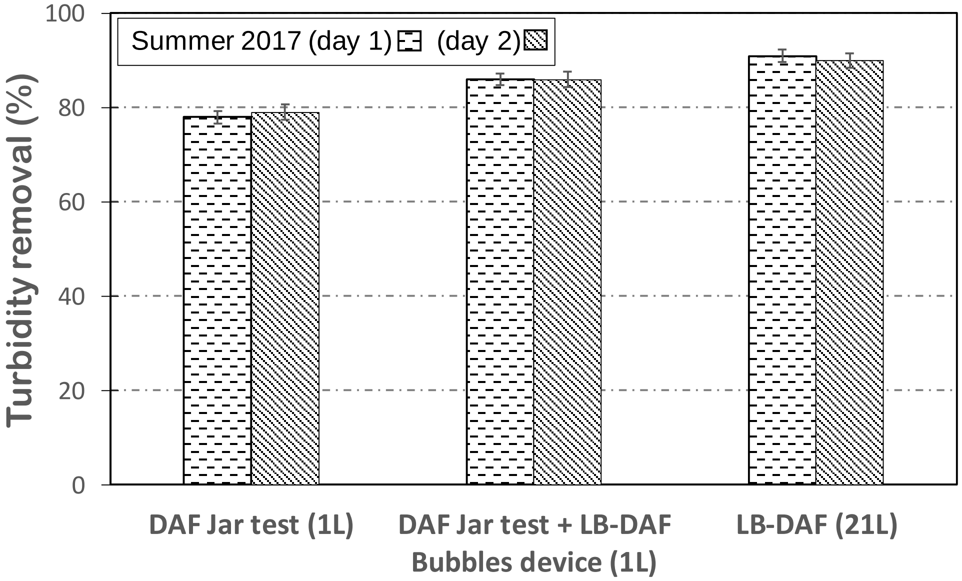

Figure 4.5 Turbidity removal predictions using DAF jar test apparatus (with and without the LB-DAF bubbles release device) versus the LB-DAF (error bars indicate one standard deviation)

The differences in the final turbidity predictions between the regular DAF jar test and the LB-DAF were not only associated with the difference of the saturated water release system but likely also due in part to the impact of the smaller DAF jar test diameter, which may result in greater wall effects. In addition, the DAF jar test bubbles device is located in the side of the jar close to the bottom, thus when the saturated water is released it generates a strong turbulent flow that may cause flocs break-up and particle resuspension.

4.4.5 Impact of impeller size on LB-DAF performance

Three different flat impellers with different impeller areas were tested in the LB-DAF to assess their impact on turbidity reduction. Three different rotational speeds 45, 50 and 55 rpm were used to obtain the same velocity gradient G=37 s^{-1} in the flocculation step for each impeller. This G value was chosen because preliminary LB-DAF tests showed that at this G value good turbidity removals were obtained. The DPA analysis of the flocs-particles showed that the rectangular impeller produced bigger flocs than the square and the small rectangular. The mean floc sizes (on a volume averaged basis) were 39, 49 and 33µm, for the square, rectangular and small rectangular, respectively. Turbidity removal performance achieved in the LB-DAF using different impellers are presented in figure 4.6.

A DPA analysis of the LB-DAF floated water showed that the particles with sizes higher than 2.25 µm and 9.25 µm were completely removed when flocculation was conducted with the square (S) and the rectangular (R) impellers, respectively. In contrast, the particle analysis showed that for the small rectangular (SR) impeller a big portion of particles bigger than 9.25 µm still were not removed. The lower turbidity removals achieved by the SR impeller in the LB-DAF may also potentially be caused by different patterns in the fluid motion of the particles close to the vessel wall, deficiencies in the top-to-bottom turnover particles, or by the different sweep area covered by the SR impeller in the LB-DAF (Harnby et al., 2007; Spicer and Pratsinis, 1996). Given that this testing of the three flat impellers were performed at the same G values, G did not describe well the level of mixing in the jars, or because the Rushton equation used to calculate G was not so accurate (figure 4.6).

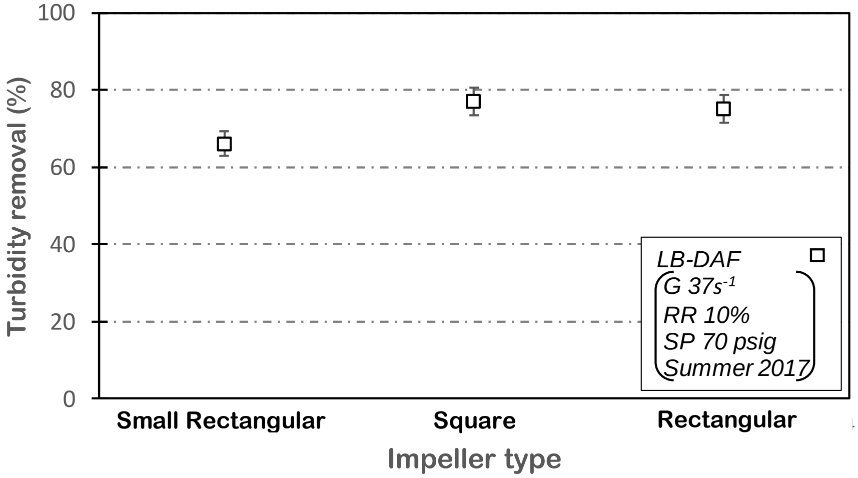

Figure 4.6 LB-DAF impeller type impact on turbidity removal (error bars indicate standard deviation) (n=2)

The turbidity removal differences between the Aylmer WTP DAF and the LB-DAF using the S and the R impellers were 10 and 13%, respectively. Additional reasons for this difference are probably associated to: first, the static nature of the batch test create more quiescent conditions leading to better separation; and second, the more turbulent flow conditions in the influent section of the full-scale continuous flow DAF may be more conductive to floc-bubble aggregation and turbidity removal. An estimate of the frequency of exposure of the flocs to the high shear impeller zone can be obtained from the circulation time (Spicer et al., 1996). In the current study the circulation time was calculated for the three impellers tested. The small rectangular impeller had the highest circulation time, which decreases the frequency of exposure to the high intensity shear in the impeller zone, were turbulent energy dissipation rates are much lower than in the bulk zone (Yong & Glasgow, 1987). Therefore, it is hypothesized that due to the lower frequency of exposure to the high shear zone the small rectangular impeller produces larger and less compact flocs than the square and the rectangular impellers, which may impact the floc-particles separation by flotation in the LB-DAF. Subsequent experiments using the square impeller yielded closer approximations to the full-scale turbidity removals. Therefore, the other LB-DAF sensitivity tests were conducted using the square impeller.

4.4.6 Impact of the flocculation velocity gradient on LB-DAF performance.

The flocs-particles size distributions obtained in the LB-DAF with the DPA technique for three different mixing speeds 21, 61 and 105 rpm, or G's of 8, 41 and 92 s^{-1} are presented in figure 4.7 (a), (b) and (c), respectively. This DPA technique measures the number of particle within different size bins, the smallest bin is 0.75 to 1.75 µm particles (mean bin particle size = 1.25 µm). In all the tests conducted the largest number of particles was in this bin, for example in figure 4.7 this bin contains 66% of the particles. This figure also shows that as the particle size increases the number of particles decreases. This also suggest that there may be many particles smaller than

0.75 µm in the solution, which this apparatus cannot measure (Bodo, 1996; Valade et al., 1996).

Based on figure 4.7 the number average floc sizes were approximately 1.0 µm for the three values of G. The literature often describes floc sizes on a volume averaged basis (Morris & Knocke, 1984; Jarvis et al., 2006). The mean floc size (volume average basis) for the G= 8, 41 and 92 s-1 runs were 20, 15 and 20 µm, respectively. Thus, for this type of application the volume averaged particle size shows a biased to the larger size particles. The different mean floc sizes and the size distribution found in the LB-DAF at the different G's tested are similar to those reported in other studies conducted with a similar particle size distribution measurement technique (Edzwald & Walsh, 1992; Van Gelder et al., 1999). In addition, in those studies the authors also concluded that different raw water particles were flocculated to sizes (diameters) between 10 and 100 µm, which lead to a good turbidity removals.

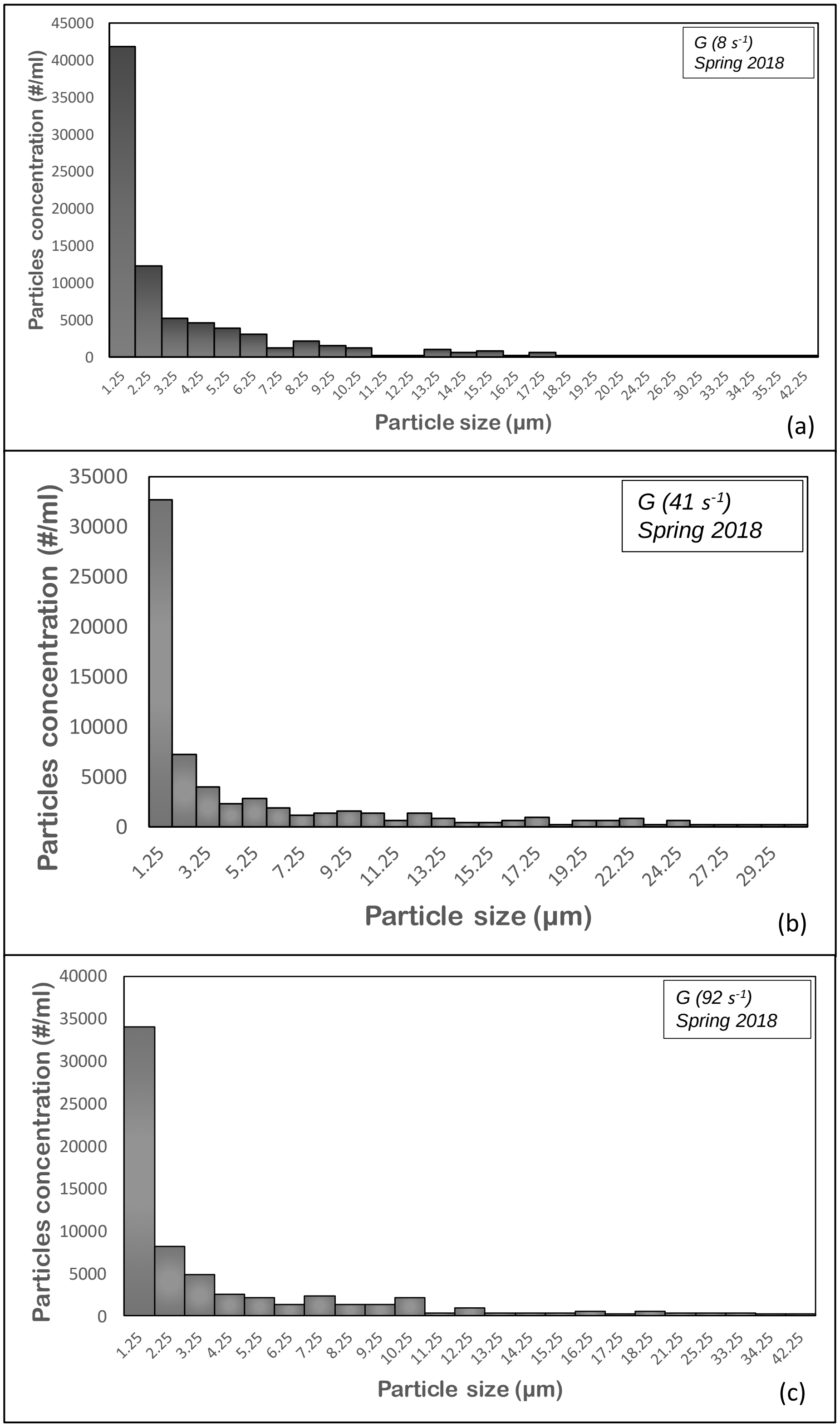

Figure 4.7 DPA measured particle-floc size distributions obtained in the LB-DAF after flocculation for three different G's (a) 8 s^{-1}, (b) 41 s^{-1} and (c) 92 s^{-1}.

Increasing values of G should result in higher rates of sharing and thus smaller floc-particles, which should facilitate the flotation. In addition, as the particle diameter increases the particle volume increases, which increases the gravitational force and the buoyance force of the particles. However, these two forces are expected to be similar in magnitude, but opposite in direction. Floc alum density has been reported to be 1010 kg/m^3, Shawwa & Smith (2000), thus the floc-bubble agglomerates should have a lower density than the flocs. Thus, the gravitational force should be comparable to the buoyancy forces, and the particle rise velocity should be significantly affected by the drag force. The drag force is expected to be higher for large flocs and smaller for the smaller flocs, thus smaller flocs are expected to lead to better flotation.

Figure 4.8 shows that the flocculation step's G has a small impact on the turbidity removal in the Spring 2018 tests. From figure 4.8 turbidity removals increased as the G increased up to 25 s^{-1} and appeared to be fairly constant for higher G values. The results presented in the figure 4.8 were generated using the same raw water samples.

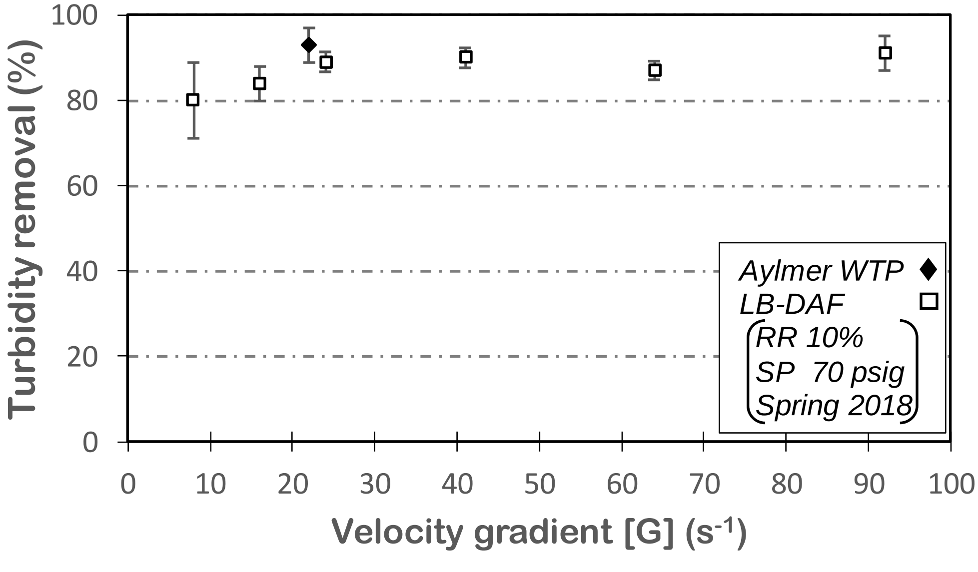

Figure 4.8 LB-DAF turbidity removal at different velocity gradients [G] (s^{-1}) (square impeller) (error bars indicate standard deviation) (n=2)

The linear model generated from the winter 2018 factorial design experiments predicted a similar relatively small increase in turbidity removals with increasing G. Because of the different of the raw water characteristics and the much lower water temperature of the winter 2018 factorial design experiments, the resulting linear model cannot be used to simulate the impact of G for these spring 2018 test results. However, the model was used to predict the change in the percentage removal as G increased from 8 s^{-1} to 92 s^{-1}, respectively. The percentage turbidity removal predicted by the factorial experiments in winter of 2018 improved 14% from the lowest (G=37 s^{-1}) to the highest (G=193 s^{-1}), respectively. In contrast, the turbidity removal obtained in the LB-DAF in spring of 2018 improved 12% from the lowest (G= 8 s^{-1}) respect to the highest (G= 92 s^{-1}). Thus, the increases in the two data sets are consistent, thus, while the impact of G may be statistically significant, the magnitude of the impact is rather moderate.

This figure also shows that the LB-DAF had very similar turbidity removals to the full-scale DAF at the Aylmer WTP. The standard deviation showed by Aylmer WTP (rhombus in figure 4.8) correspond to the range of values for the three units at the plant at the time of sampling. The results obtained agree with those reported by other studies, that variations in physical flocculation characteristics (detention time, number of mixing stages, mixer type and mixing intensity) had only slight effects on DAF performance (Valade et al., 1996; Dahlquist et al., 1996; Edzwald et al., 1994).

4.4.7 Impact of saturator pressures on LB-DAF turbidity reduction

Figure 4.9 shows that as expected increasing the saturator pressure results in a decrease in the mean bubble size. However, as discussed earlier, given the broad range of bubble sizes measured the confidence limits of the bubble sizes overlap, so they were statistically the same. Therefore, it is not entirely surprising that the mean turbidity percent removals for the three saturator pressures were very similar and their confidence limits also overlap (i.e., they are statistically the same).

Many different variables are important to obtain good particle removal in a DAF unit. For example, in the separation zone of a DAF unit flotation occurs when the bubbles number exceed the floc concentration, which means that at least one bubble is attached to every floc (Edzwald, 2007). So, the concentration of bubbles is also critical, that is why it is necessary to create a solution that has so many bubbles so that it is milky white. In addition, variables such as bubble particle interactions, particle size and density, particle-bubbles charges and the flotation retention time may impact the flotation performance in a DAF full-scale unit (Lepinnen & Dalziel, 2004; Han et al., 2001).

The LB-DAF turbidity removals for all the three saturator pressures ranged between 79 and 82%. However, due to the variability of the three units at the Aylmer WTP at the time of sampling (rhombus in figure 4.9) it is considered that the turbidity removal performance obtained in the LB-DAF at the different SP tested is very similar to this reported by Aylmer WTP. The saturators of most full-scale WTPs operate in the 480 to 620 kPa (70 – 90 psig) range. It should be noted that at the Aylmer plant the saturator pressure was frequently 380 kPa (55 psig), this was required in order to maintain the high recycle flowrate necessary to efficiently contact the incoming water with the pressurized recycle flow.

Therefore, Aylmer WTP performance for turbidity removal could be approximated for all the three different SP used in the LB-DAF tests. Previous studies have reported that the most efficient performance and particle collision in a DAF unit is achieved when the average floc size (30 to 50 µm) is close to the mean bubble size (Gorczyca and Klassen, 2008; Gorczyca and Zhang, 2007). In the current study, the mean (volume averaged) bubble size for the 482 kPa (70 psig) run was determined to be 70.4 µm, which is consistent with figure 4.2.

Accordingly, on a volume averaged basis mean bubble diameter was 3.5 to 4.6 times larger than the mean floc sizes (i.e., 20, 15 and 20 µm). Therefore, the most probably mechanism for the particles removal in the LB-DAF could be as a result of several flocs attached to a single bubble forming bubbles-particle agglomerates (Lepinnen & Dalziel, 2004).

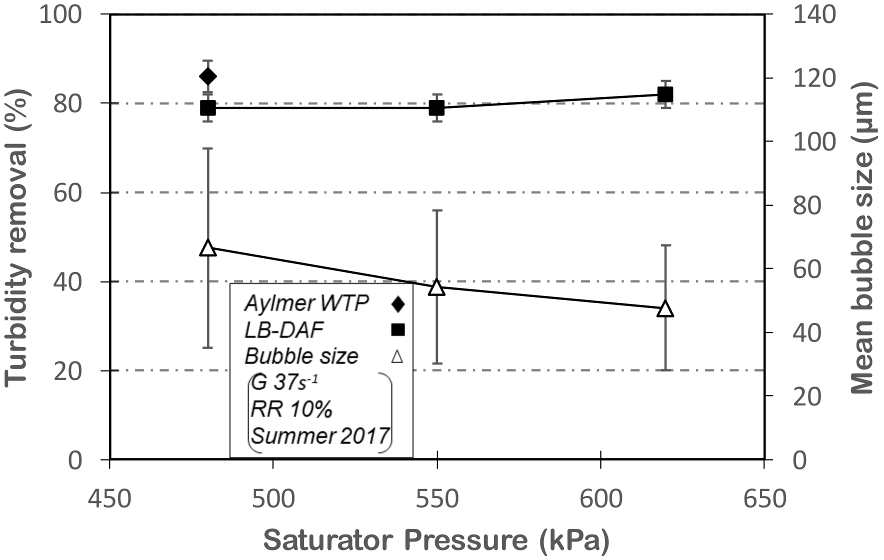

Figure 4.9 LB-DAF saturator pressure impact on turbidity removal and mean bubble size (error bars indicate standard deviation) (n=2) for turbidity and (n=3) for bubble size

4.4.8 Impact of recycle ratios on LB-DAF turbidity reduction

The LB-DAF recycle ratio experiments were conducted in the summer of 2017 and spring of 2018. Results showed that increasing the recycle ratio did not have a significant difference on turbidity removal (figure 4.10). The linear regression of this data yielded a slope with (α=0.05) confidence limits that included a value of zero, thus indicating that statistically the RR did not have an effect. Due to the variability of the three units at the plant at the time of sampling (rhombus in figure 4.10) it is considered that the turbidity removal performance obtained in the LB-DAF at the different RR tested is very similar to this reported by Aylmer WTP.

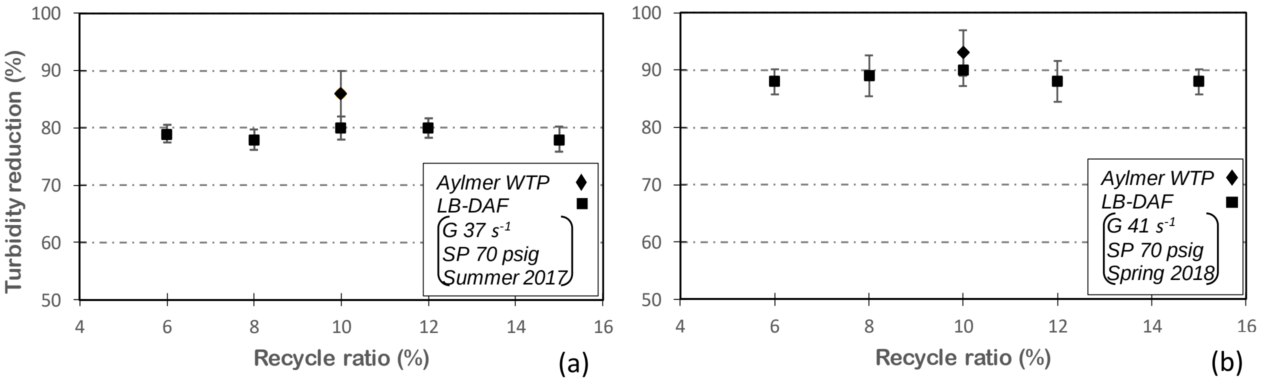

Figure 4.10 LB-DAF recycle ratio impact on turbidity reduction (error bars indicate standard deviation) (n=2)

These results seem to contradict the results of the factorial design experiment conducted during the winter of 2018 and presented in section 4.4.3, which showed that RR was the second significant variable that impact the LB-DAF turbidity removal. While the impact of this variable may be more significant in cold water conditions, it seems do not have a significant impact in summer of 2017 and spring of 2018. The differences in the percentage turbidity removals during the two sets of tests are 9% and that of the model predictions are 14% likely related to the differences in the quantity and characteristics of the particles in the raw water.

The higher turbidity removals by the full-scale DAF units were unexpected in that the non-flow LB-DAF was expected to have more ideal conditions for the separation given its more static nature. Thus, the flow and flow patterns of the full-scale DAF system seem to have a role in the efficiency of the separation that is not replicated by the LB-DAF. Although, changing the RR in the LB-DAF did not significantly impact the observed turbidity removals, one cannot scale up the impact of this operating variable because of the flow patterns within continuous flow full-scale units and the need of a minimum recycle flow to completely cover the contact zone with saturated (white) water. Thus, the impact of recycle ratio should be studied at the pilot-scale tests or in the full-scale unit.

4.4.9 Impact of LB-DAF water depth to tank diameter ratio.

DAF full-scale facilities are designed to operate with a basin depth between 2.0 and 3.5 m (Edzwald, 2010). Continuous flow DAF units require such a water depth to allow the bubbles to be in contact with the floc-particles to produce floc/particles/bubbles aggregates as they rise to the top of the tank. However, due to lack of flow in batch DAF units such depths may not be necessary for them, so the minimum required depth needs to be determined. Figure 4.11 shows that the LB-DAF W/D ratio has a very small impact on turbidity removal for both the summer and spring test runs. The linear regression of this data yielded a slope with (α=0.05) confidence limits that included a value of zero, thus indicating that statistically the W/D ratio did not have an effect. In addition, the turbidity removal performance among the three DAF units at the Aylmer WTP was 80±3% for the summer of 2017 and 93±4% for the spring of 2018. Thus, the LB-DAF turbidity removals for both seasons were very similar to those achieved by the full-scale units at the Aylmer WTP.

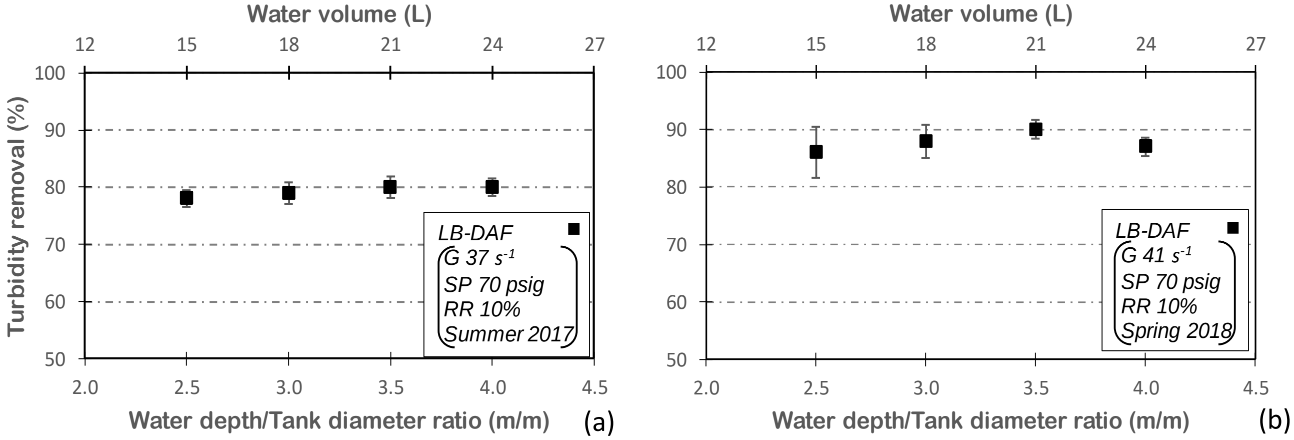

Figure 4.11 LB-DAF water depth to tank diameter (W/D) ratio impact on turbidity reduction (error bars indicate standard deviation) (n=2).

The velocity gradient varies in the flocculation step as the water volume varies in the LB-DAF. However, in this research the mixing speed was adjusted to obtain the same velocity gradient for the different W/D ratio tested. The small impact of the water depth to tank diameter ratio should be confirmed in future research using different waters and evaluating lower water depth to diameter ratios. The results showed that if one wants to minimize the volume of water required for the testing, the above results show that 15 liters (W/D = 2.5 and water depth 0.5 m) will yield good results.

4.5 LB-DAF different operational parameters impact on NOM removal

A comparison between the LB-DAF and Aylmer WTP for NOM removal was also conducted in this research. The different variables tested in the LB-DAF (i.e., G's, RR, SP and W/D), did not show a significant impact on the LB-DAF NOM removal measured as DOC (figure 4.12 (a) summer 2017 and (b) spring 2018, respectively). In addition, the UV-254 removals had the same trend as the DOC for all the variables tested.

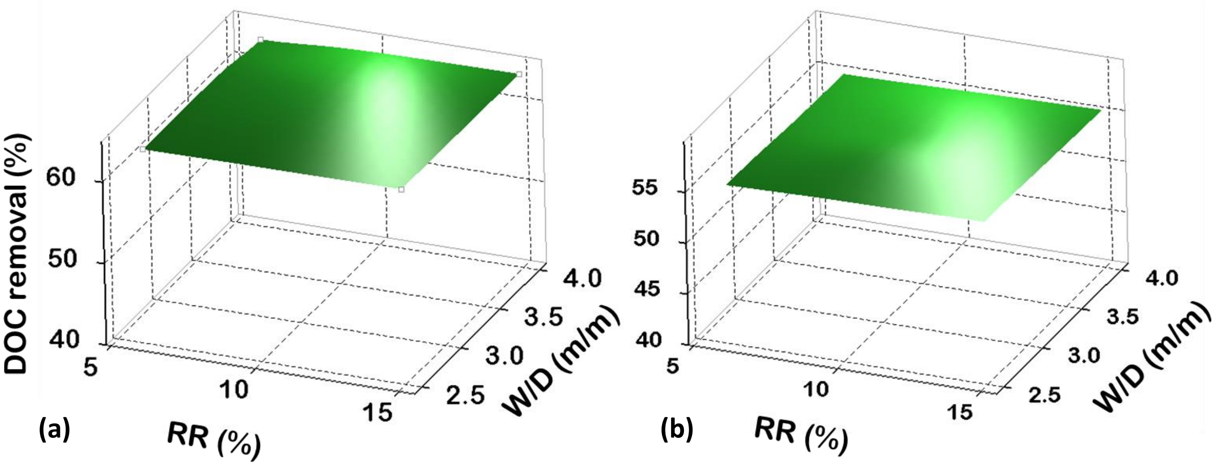

Figure 4.12 LB-DAF DOC removal summer 2017 (a) and spring 2018 (b)

The low impact of the different variables tested in the LB-DAF on DOC and UV-254 removal is likely because the NOM removal is primarily dependent on the coagulation (i.e., pH, coagulant type, and dose) (Malley, 1990; Matilainen et al., 2010; Yan et al., 2008). The UV-254 removals obtained in the LB-DAF for the summer and spring experiments (77 – 84%) had only a difference of approximately 5% from those measured at the Aylmer WTP. In addition, the DOC removals in the LB-DAF (56 – 65%) were differed by only 10% from those at Aylmer WTP. The DAF jar test DOC removal (65%) and UV-254 removal (82%) were also very similar than Aylmer WTP and the LB-DAF. These findings confirm the result reported by others (Zou et al. 2011; Malley & Edzwald, 1991).

4.6 Impact of coagulant dose

Batch tests such as jar tests are primarily used to determine the optimal coagulant dose, ideally the optimal coagulant dose capabilities should be assessed conducting a dose-impact comparison with a full-scale DAF system. Full-scale plants generally operate using a nearly constant coagulant dose, so such dose impact studies are generally not possible. As an alternative, one could conduct dose impact comparisons with pilot-scale DAF system. Unfortunately, we were unable to participate in a pilot-scale study to conduct such a direct comparison. Therefore, as a substitute a parallel coagulant-dose sensitivity tests were performed with the commercial DAF jar tests apparatus and the LB-DAF (figure 4.13).

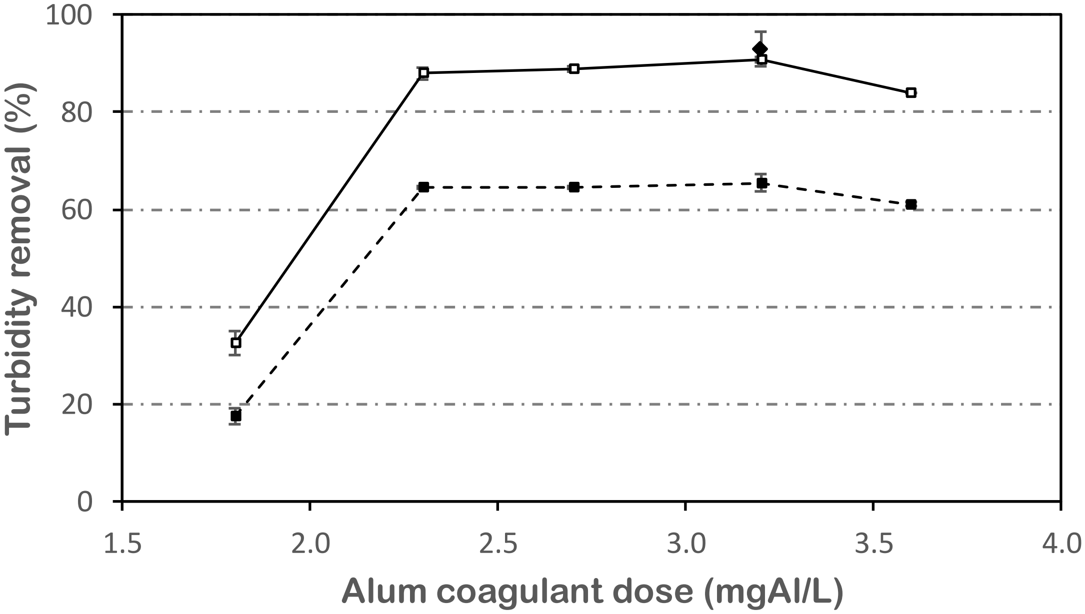

Figure 4.13 Optimum alum coagulant dose predictive comparisons between the LB-DAF and DAF jar test apparatus (error bars indicate standard deviation) (n=2)

The sensitivity tests conducted for different coagulant doses treating ORW showed that the LB-DAF exhibited the same turbidity removal pattern as the DAF jar tester, however they were higher. In this specific case, the DAF jar test under predicted the turbidity removal by 28%, this difference was significantly larger than those in other data sets. It is suspected to be related to a few factors. First, the raw water of this set of tests had an initial turbidity of 1.5 NTU and it was much more difficult to treat. However due to the Aylmer WTP variability (rhombus in figure 4.13), it was considered that the LB-DAF had very similar turbidity removals than Aylmer WTP. Secondly, the DAF jar test results in figure 4.13 were obtained with the flocculation velocity gradient (G) recommended in the manufacture DAF jar test manual, (i.e., 12 s^{-1}), while the flocculation in the LB-DAF tests was 41 s^{-1}, one of the base values used in our testing. Thus, it is suspected that if the LB-DAF G would had been matched with the DAF jar test, the turbidity removal dereferences would had been lower.

4.7 Optimal LB-DAF testing conditions

The above results showed that the LB-DAF system was not particularly sensitive to changes in the variables studied, these findings should be confirmed with tests with other challenge waters. Based on the above studies it is unnecessary to study further the impact of impeller shape. In addition, the water depth to column diameter tests suggest that using a ratio of 2.5 (15 liters) is satisfactory. Further testing should include even lower water depth to diameter ratios, as this will reduce the volume of water required per test and simplify the system construction. To conduct LB-DAF treatability studies the following set of conditions are recommended: (a) a minimum water volume of 15 liters (or 21 liters to obtain sufficient floated water for membrane treatability tests); b) square impeller; c) conduct flocculation with a G in the range of 30 s^{-1} to 70 s^{-1} for 15 min; (d) use a saturator pressure of 482 kPa (70 psig); (e) a recycle ratio of 10%; and (f) a flotation time of 15 min. It should be noted that due to the batch characteristics of the LB-DAF it is not suited to simulate the impact of the recycle flowrate which may be critical to full-scale continuous flow DAF operation.

While there was not one set of operational/design parameter values that we could be considered optimal, this lack of sensitivity demonstrates the robustness of the DAF process. This was indirectly demonstrated by the full-scale DAF system used for the comparisons, it performed well even though the recycled water pressure varied from 380 kPa to 480 kPa and the recycle ratio varied from 8 to 10%.

4.8 Conclusions

(1) The LB-DAF apparatus had better prediction capabilities for turbidity removal than the commercial DAF jar test apparatus tested in the treatment of raw Ottawa River water. This appears to be due to a combination of reduced wall effects due to the bigger LB-DAF diameter and the improved saturated water release system of the LB-DAF.

(2) The LB-DAF had very similar percent turbidity removals in comparison with Aylmer WTP's in both during summer of 2017 and spring of 2018.

(3) The LB-DAF recycle ratio, saturator pressure and water depth to diameter ratio did not have a significant impact on turbidity removal.

(4) The flocculation G's had a statistically significant, yet slight impact on the LB-DAF turbidity removals.

(5) NOM removal by the LB-DAF and DAF jar tests were very similar to that achieved at the Aylmer WTP. In addition, the different LB-DAF variables tested did not impact the NOM removals. This was expected based on the findings of a several researchers who found that NOM removal is a primarily function of the coagulation process.

(6) It is necessary to conduct additional confirmatory experiments with different waters. In addition, the turbidity removals of the LB-DAF system should be compared again other commercially available DAF jar testers. Then, it will be possible to assess if

the LB-DAF is superior to all commercial jar test systems and yields the most reliable turbidity removal predictions.

4.9 Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council (NSERC), Canada. The authors would like to thank the Universidad Santo Tomas Tunja – Colombia, COLCIENCIAS and COLFUTURO for their partial financial support of the lead author through their international doctoral scholarships. We thank the operators and management of the Aylmer WTP in Gatineau, Quebec, for providing water, coagulant samples and plant information.

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Chapter 5

Large Batch Bench-scale Dissolved Air Flotation System for Simulating Full-scale Turbidity Removal

Authors: J. P. Gonzalez-Galvis, R. M. Narbaitz

5.1 Abstract

As dissolved air flotation (DAF) jar tests are not particularly good at predicting full-scale DAF turbidity removals, our group has developed a more reliable larger diameter/larger volume batch apparatus (LB-DAF) which was optimized by comparison with a full-scale DAF treating a low turbidity, highly coloured river water (SUVA ~ 4.3). The objective of this study was to verify that the LB-DAF was capable of simulating well full-scale DAF systems treating two significantly different waters. One was water from a large eutrophic Bay in Lake Ontario (SUVA ~2.6) and the second river water (SUVA ~3.5). The turbidity removals of full-scale DAF treating these waters were compared with those for the LB-DAF operated with different flocculation Gs, saturated water pressures, recycle ratios and water depth to diameter ratios. The LB-DAF tests turbidity removals differed by less than 6% from the best performing full-scale DAF, thus they are good predictors of turbidity removals. The LB-DAF NOM removals for both waters differed by less than 1% from that measured at the corresponding treatment plants. In addition, as in the previous LB-DAF study, the different LB-DAF operational variable values tested did not have a significant impact on its turbidity and NOM removals.

5.2 Introduction

Dissolved air flotation (DAF) has been shown to be a compact water treatment separation process in the treatment of algal-laden waters, acid rain impacted waters, and waters with a high natural organic matter (NOM) content (Zou et al., 2011; Shanpei et al., 2007; MacPhee et al., 1996). The feasibility of DAF for a given water treatment application and the chemical dosage requirements are often assessed by bench-scale tests. 1 and 2L DAF jar tests have been shown to be good predictors of full-scale DAF NOM removal (Malley and Edzwald, 1991; Chu et al., 2011). However, while DAF jar tests are useful to identify the optimal chemical dosage for turbidity removal, the turbidity removals in these tests are different from those in full-scale plants (Bickerton, 2012; MacPhee et al., 1996). In an attempt to overcome these deficiencies, Gonzalez-Galvis & Narbaitz (2019a) developed a larger diameter large volume batch DAF testing apparatus, the called LB-DAF. They evaluated the unit for the treatment of a low-alkalinity, low turbidity, relatively high colour and natural organic matter water and found that the LB-DAF was able to predict full-scale DAF turbidity removals better than their commercial DAF jar tester. They conducted LB-DAF tests with water collected during the summer of 2017, winter and spring of 2018 and found that the turbidity removals were not significantly impacted by changing the values of the LB-DAF operational variables. Accordingly, they recommended a set of testing conditions, however there was not a distinct set of operating conditions that were clearly optimal. Therefore, the objectives of this study are: a) to confirm the LB-DAF's predictive capabilities for turbidity removal with two other surface waters with different characteristics; b) to further assess the impact of different LB-DAF operational parameters on turbidity removals so as to confirm the earlier results; c) to assess the impact of raw water quality; and d) to possibly identify a set of optimal LB-DAF testing conditions.

5.3 Materials and Methods

5.3.1 Water Tested

The experiments were conducted using: a) Bay of Quinte water (Belleville WTP, Belleville, ON, Canada) after pre-oxidation (PBW) and b) Rideau River water collected at the town of Smiths Falls, ON, Canada (SFW). These two waters were chosen because of logistic reasons and because the Belleville and Smiths Falls WTPs incorporate DAF units, so they permit LB-DAF versus full-scale DAF performance comparisons. The Belleville WTP has a pre-oxidation step within the intake (1.25 mg/L $KMnO_4$ and & 2-4 mg/L chlorine) for taste, odor, zebra mussel and quagga mussel control and to oxidize iron before coagulation. The Belleville water samples were collected in Winter of 2017, and Summer of 2018. Coagulation was conducted using 60 mg/L alum (as Al_2O_3, or 4.9 mg Al/L) (ALS, Kemira, Montreal, QC: 4.30±0.1% Al^{3+}) and no polymer. This process is carried out in two rapid mix cells in series with a hydraulic retention time of ~1.5 min. Tapered flocculation is conducted in three hydraulic flocculation cells in series, they have a helicoidal flow pattern. The velocity gradient in these stages are approximately: 50, 34 and 15 s^{-1}, respectively. Flotation is conducted in two separate two-cell DAF tanks and the operational design conditions are: hydraulic loading rate of 30 m/h; saturated water pressure (SP) of ~517 kPa (75 psig) and 550 kPa (80psig) and recycle ratio (RR) between 8 and 12%. At the time of the testing the Belleville WTP's saturation pressures oscillated between ~517 kPa (75 psig) and 550 kPa (80psig) and the RR varied between 8 and 10%.

The Smiths Falls WTP uses poly aluminum sulphate solution (PAS-8, Kemira, Montreal, QC: 4.35±0.16% Al^{3+}) as coagulant with a dose of 80 mg/L as Al_2O_3 (7.3 mg Al/L) and 0.07 mg/L Magnafloc LT22S (Cationic polyelectrolyte, BASF, Mississauga, ON) as a flocculation aid. This plant conducts coagulation in a mechanical mixing unit with a hydraulic detention time of 1.7 minutes. Flocculation is conducted with 2-stage tapered energy flocculation using mechanical mixers. The flocculation basins provide a total hydraulic retention time of approximately 12 minutes and the velocity gradient in the chambers are 41 and 14 s^{-1}, respectively. Flotation is conducted in an AquaDAF ® high-rate clarification unit (15 to 30 m/h). At the time that water samples were collected the saturator pressure was 620 kPa (90 psig), and the recycle ratio varied between 8 and 12%. Raw SFW samples were collected in the spring of 2018. Water samples from both WTP's were stored at ($4\pm1^{o}C$) until testing.

5.3.2 LB-DAF characteristics and operational conditions

The LB-DAF designed, build and tested in previous studies Gonzalez-Galvis & Narbaitz (2019a) was developed for treating a maximum water volume of 24 liters with a diameter of 20 cm and a height of 1.0 m, respectively. The LB-DAF incorporates a square paddle and a motor to conduct mechanical coagulation and flocculation. Coagulation, flocculation and flotation (C/F/DAF) procedures in the LB-DAF were as follow: a) coagulation was conducted at 200 rpm (296 s^{-1}) for 2 minutes; b) flocculation for 15 minutes at a constant mixing speed (the actual rpm was dictated by the chosen flocculation G for the experiment); c) the saturator vessel was filled with distilled water and operated at a constant pressure 482 (70 psig) except for the SP sensitivity experiments; d) the flotation step duration was 15 minutes (after of introducing the required recycle flow); e) RR of 10% except for the RR sensitivity experiments.

In the development of the LB-DAF using a different water, Gonzalez-Galvis & Narbaitz (2019a) found that the LB-DAF was not very sensitive to values of flocculation G, recycle ratio, saturator pressure and water depth to diameter ratio. The overall objectives of this study were to find a set of parameters that better matches DAF full-scale performance for turbidity removal and to confirm which of these variables have the biggest impact on the LB-DAF performance.

5.3.2.1 Factorial design experiments for evaluating the LB-DAF variables impacting its performance for turbidity removal

Factorial design experiments were conducted using raw SFW with the same coagulant and polymer type and dose used at the Smiths Falls WTP. The statistical analysis was conducted based on the final turbidity values as the response. The variables tested in the factorial design experiments were: a) velocity gradient in the flocculation step (10 and 113 s^{-1}); saturator pressure 482 and 620 kPa (70 and 90 psig) and recycle ratio (6 and 15%).

5.3.2.2 LB-DAF experiments

The LB-DAF experiments were conducted at the same temperature as the water when it was collected, this was achieved by keeping the water samples stored in a fridge (4 ± 1^{o}C) and allowing to achieve the specific sampling temperature for each test before conducting it. For simulating summer temperature, the water sample was kept at room temperature (~22ºC) overnight. When collected during the Spring of 2018 the Rideau River water (Smith Falls) water temperatures was 16 ± 1.0 ºC. The PBW collected in the November of 2017 had a temperature of 3.2 ± 1.0 ºC, and the PBW collected during late July of 2018 was 24 ± 1.0 ºC. Parameters such as temperature, pH and turbidity were measured before and after conducting LB-DAF experiments. All experiments were performed in duplicate and their water quality samples were analyzed in triplicate.

5.3.3 Analytical Methods

The pH of all the water samples was measured using a pH meter (Accumet model 910, Fisher Scientific, Hampton, NH). Turbidity was determined using a Hatch 2100AN Turbidimeter (Loveland, CO). Total organic carbon (TOC) analysis was conducted using a UV-persulfate oxidation-based TOC analyzer (Phoenix 8000, Tekmar-Dohrmann, Cincinnati, OH). The TOC analysis methodology followed the standard method 5310 C (APHA/AWWA/WEF, 2017). The DOC is the dissolved organic fraction of the TOC concentration, it was obtained by vacuum filtering the water samples through a 0.45 μm nylon membrane filter (PALL Sciences Corp; Pensacola, FL) and then performing the TOC analysis of the filtrate. Ultraviolet absorbance at 254nm (UV-254) was measured 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 multiplying the UV-254 nm by 100 and dividing it by the DOC concentration. The alkalinity and the total hardness of the raw water were determined according to standard methods 2320 and 8226 (2340), respectively (APHA/AWWA/WEF, 2017). Flocs/particles concentration and size measurements after the flocculation step were performed using a dynamic particle analyzer (DPA) (Bright-WELL Technologies Inc., Ottawa, ON) equipped with a high magnification cell BP-4100-FC-100-U, it quantifies particles between 0.75 to 100 µm in size. It was calibrated using two standards: a 5 µm polystyrene particles standard solutions (Thermo Fisher Scientific Inc., Fremont, CA) with a concentration of 10^7 particles per mL; and a 10 µm polystyrene particle solution with a concentration of 10^6 particles. Water temperature was measured using a waterproof thermocouple (Digi-Sense RK-91100-00, Cole-Parmer, Montreal, QC). NOM fractionation was conducted using XAD-4 and XAD-8 resins (Fisher Scientific, Hampton, NH). In this approach the NOM was quantified in terms of the TOC concentrations. The NOM fractionation procedure used in this study was adopted from Thurman and Malcom (1981).

5.4 Results and discussion

5.4.1 Water quality

Table 5.1 shows the characterization of the PBW water samples collected in the early winter of 2017 and the summer of 2018, and the characteristics of the raw SFW water samples collected in the spring of 2018. The SFW was very clear (turbidity<1 NTU), while the PBW turbidities were higher, yet still considered relatively low.

Initial water turbidity for the PBW varied between seasons, it was 80% higher in the summer test period. The difference in the turbidity concentrations in the PBW between winter and summer could be probably because the oxidized iron, an increase of particles contributed by runoff to the Bay of Quinte, in which there was a storm two days before sample collection (St-Hilaire et al., 2015; Parsons & Jefferson, 2006). It should be noted that there is also significant variability in the phosphorous concentrations in the Bay of Quinte, characterized by relatively low levels (10 – 15 µg TP/L) in spring and fall, and high summer concentrations (>50 µgTP/L). This leads to quite eutrophic conditions resulting in increasing picoplankton and solids in the water (Nicholls et al., 2002; Nicholls & Carney, 2011; Shimoda et al., 2016).

Table 5.1 Pre-treated Belleville and raw Smiths Falls water characterization

Parameter	Pre-treated Belleville water (November 2017)	Pre-treated Belleville water (Summer 2018)	Raw SFW (Spring 2018)
pH	6.67±0.2	8.32±0.14	6.96±0.05
Turbidity (NTU)	1.51±0.06	8 -12 ±0.15	0.92±0.06
Alkalinity (mg/L as $CaCO_3$)	96.7 ±13	116.7±6.5	108.3±2.88
UV-254 (cm^{-1})	0.15±0.001	0.14±0.001	0.23±0.001
DOC (mg/L)	5.58±0.01	5.49±0.02	6.55±0.010
SUVA (L mg^{-1} m^{-1})	2.69±0.01	2.55±0.01	3.51±0.005
True Color (Pt-Co)	20.3±1.7	6.7±0.65	26.7±1.5
Total Hardness (mg/L)	120±2.3	119±2.6	97.0±1.2

(Values are average ± one standard deviation) (n = 3)

The NOM concentration of SFW water was a bit higher than the PBW. Based on the SUVA, SFW (3.63 L/mg/m) has a more hydrophobic character than PBW (SUVA =2.58 L/mg/m). The hydrophobic NOM characteristic of the SFW was confirmed by conducting NOM fractionation. The results showed that the NOM hydrophobic (HPO), hydrophilic (HPI) and transphilic (TPI) composition of the SFW was 58, 35 and 7%, respectively. Given its higher SUVA value, SFW is expected to yield better UV-254 and DOC removals than PBW (Edzwald & Van Benschoten, 1990; Edzwald & Haarhoff, 2012). The Bay of Quinte water fractionation was not presented because it yielded unreasonable results, accordingly it was repeated and again it produced unreasonable results.

5.4.2 Factorial design experiments for evaluating the LB-DAF variables impacting its performance for turbidity removal

The final turbidity values obtained in the LB-DAF factorial design experiments were very similar to those reported by the Smiths Falls WTP at the time the water samples were collected (0.23 to 0.33 NTU).

Table 5.2 shows the analysis of variance at the α=0.05 level for the factorial design experiments. The main variables that impact the LB-DAF turbidity removal (P-value≤0.05) from the greatest to the lowest were: velocity gradient [G] (s^{-1}), recycle ratio (RR-%) and the interaction between the G and the RR. Although, the LB-DAF factorial design experiments for SFW showed that the G values, the RR values and their interactions had a statistically significant impact on the final turbidity, the range of turbidity values (0.21 to 0.54 NTU) was relatively small. Given the limited range in these values the impact of these variables (G and RR) as well as other variables (i.e., SP, W/D ratio) were studied in greater detail.

Table 5.2 LB-DAF Analysis of variance factorial design experiments SFW

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	0.210436	0.026304	12.17	0.000
Linear	3	0.150469	0.050156	23.20	0.000
Gs	1	0.097656	0.097656	45.18	0.000
SP	1	0.007656	0.007656	3.54	0.089
RR	1	0.045156	0.045156	20.89	0.001
2-Way Interactions	3	0.041119	0.013706	6.34	0.011
Gs*SP	1	0.001056	0.001056	0.49	0.500
Gs*RR	1	0.031506	0.031506	14.57	0.003
SP*RR	1	0.008556	0.008556	3.96	0.075
3-Way Interactions	1	0.002256	0.002256	1.04	0.331
Gs*SP*RR	1	0.002256	0.002256	1.04	0.331

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Curvature	1	0.016592	0.016592	7.68	0.020
Error	10	0.021617	0.002162		
Total	18	0.232053			

5.4.3 Impact of velocity gradient on floc size and turbidity removal in the LB-DAF.

The figure 5.1 (a), (b) and (c) shows the flocs-particles size distribution in the LB-DAF after flocculation of SFW with a G of 8, 41 and 92 s^{-1}, respectively measured with the DPA technique. In all the tests conducted the largest number of particles were in the 1.25 μm particle size box (i.e., range between 0.75 to 1.75 μm). For example, in figure 5.1 (a), (b) and (c) the number of flocs particles in this size range comprise 58, 63 and 60% of the total number, respectively. The number-based concentration distributions for all the G's tested in the LB-DAF and for both waters (i.e., SFW and PBW) were very similar. The floc size distribution at different G's found in the LB-DAF agrees with the floc size distributions found in other studies using a different particle counter (Bodo, 1996).

The mean floc size range (on a volume average basis) obtained in the LB-DAF for all the G's tested treating PBW and SFW was similar (25 - 34μm). The volume-based mean floc size found in the LB-DAF tests agree with the mean floc size (on a volume average) reported by others Edzwald & Walsh, (1992). These values are significantly higher than one would expect from figure 5.1; this difference occurs because these graphs represent the total number of particles and the larger size particles contribute a disproportionally higher fraction of the overall volume.

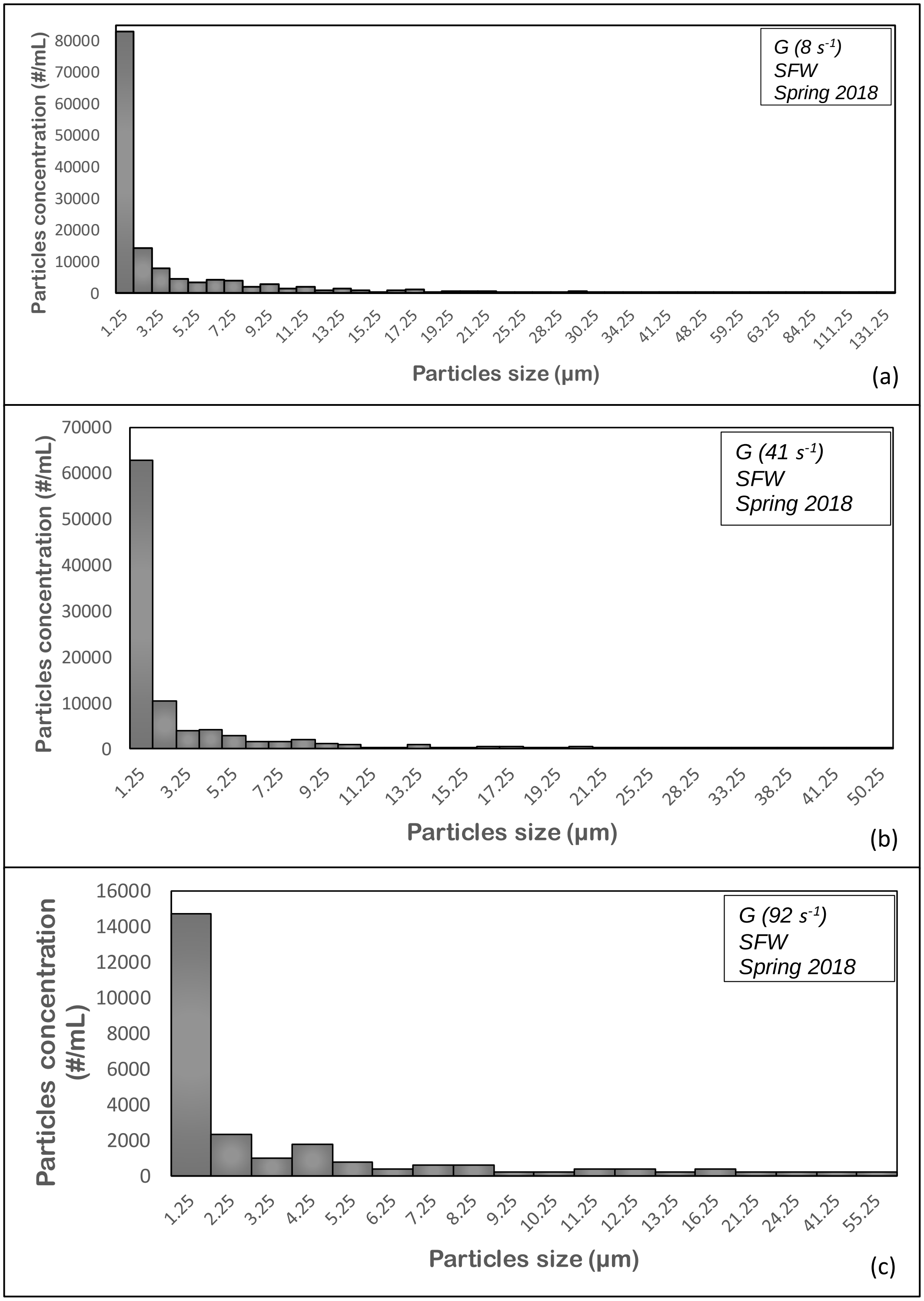

Figure 5.1 DPA measured particle-floc size distributions obtained in the treatment of SFW with different velocity gradients (a) 8 s^{-1}, (b) 41 s^{-1} and (c) 92 s^{-1}.

Some operators consider that DAF units should be fed “large” flocs, while others consider that it should be “small” (Bache and Rasool, 2001). However, there is no consensus as to how “large” and “small” flocs are defined. Edzwald & Walsh, (1992) reported that flocs found in DAF pilot and bench-scale studies treating different source waters have sizes in the range of 10 to 100 µm leading to a good flotation performance in terms of turbidity removal. In contrast, it is well known that good turbidity removal using sedimentation requires larger flocs. For example, Van Leussen & Cornelisse (1993) found an optimal clarification process by sedimentation with floc sizes of 200 to 500µm. Therefore, 10 to 100 µm flocs obtained in the LB-DAF treating PBW and SFW are significantly smaller than those for optimal sedimentation, and they result in good DAF turbidity removals.

One of the shortcomings of the DPA analysis is that they do not detect particles smaller than 0.75 µm (Bushell et al., 2002), but comparisons with other methods have shown that DPA technique is a reliable method to quantify the floc size distribution (Govoreanu et al., 2004). The floc/particle sizes distribution obtained in the LB-DAF in the flocculation step treating PBW and SFW agree with the floc/particles size range reported by other studies using the similar measurement technique (Edzwald & Walsh, 1992).

The impact of the different G’s on turbidity removal in the LB-DAF treating PBW and SFW is shown in figure 5.2 (a) and (b), respectively. The turbidity removals achieved for the two waters were different presumably due to the differences in the raw water characteristics. The LB-DAF results were very similar to those of the full-scale DAF (i.e., Belleville and Smiths Falls WTP’s, white rhombus in figure 5.2).

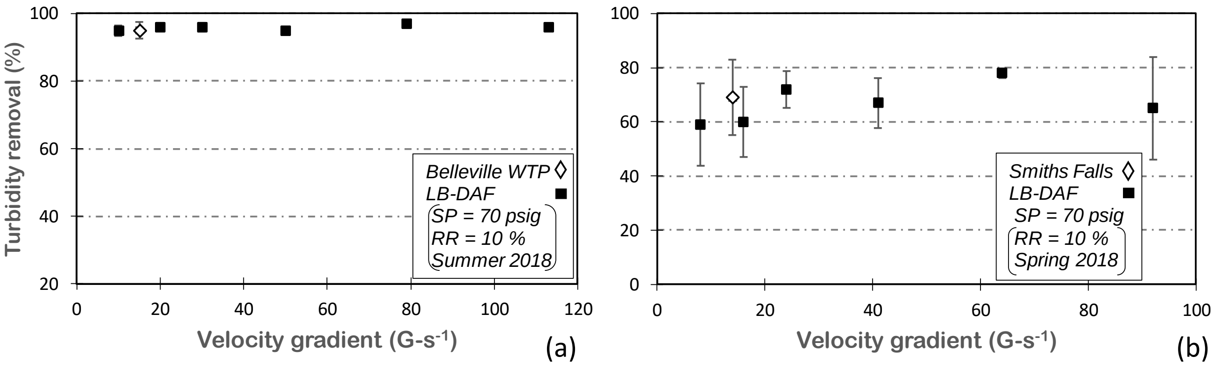

Figure 5.2 LB-DAF velocity gradient [G] (s^{-1}) impact on turbidity reduction (a) PBW and (b) SFW. (error bars indicate one standard deviation) (n=2)

The PBW LB-DAF tests (figure 5.2-a) yielded very similar turbidity removals for all the G values tested. In contrast, the SFW LB-DAF tests (figure 5.2-b) showed higher velocity gradients resulted in slightly higher turbidity removals than the lower G values, this slightly increasing removal trend is in agreement with the results reported in other studies (Valade et al., 1996; Edzwald et al., 1994). Despite that the lower G's <20 s^{-1} tested for SFW (figure 5.2b) showed a lower turbidity removal than the highest ones, a linear regression analysis confirmed that the impact of the different G's on turbidity removal for SFW is not statistically significant ($\alpha=0.05$) as the confidence limits of the slopes included zero. Gonzalez-Galvis & Narbaitz (2019a) observed that the turbidity removals were slightly smaller for low G values (G<37 s^{-1}). However, if the same statistical approach is used with their data set, G also has a statistically insignificant impact on turbidity removals. Given the limited impact of G on the floc sizes, the limited impact on turbidity removals seems logical. Overall, the full-scale turbidity removal predictions were very good as the ranges of the full-scale and LB-DAF turbidity removals overlapped. Although, the factorial design experiment showed that the G had a significant impact on the LB-DAF turbidity removal, the improvement of the turbidity removal by increasing the G in the factorial experiments was very similar to the turbidity removal in the latest LB-DAF experiments 8% versus 9%, respectively. It should be noted that while the no G impact PBW data is inconsistent with SFW results, others in the literature have also reported cases where G has no apparent impact on turbidity removals (Dahlquist et al., 1996). The inconsistency is likely due to the differences in the raw water quality.

5.4.4 LB-DAF recycle ratio impact on turbidity reduction

As the factorial design experiments identified RR as a significant factor that impact turbidity removal, a set of LB-DAF experiments were conducted with PBW and SFW using a larger number of RR values (figure 5.3 a and b). The turbidity removals achieved for the two waters were different presumably due to the differences in the raw water characteristics.

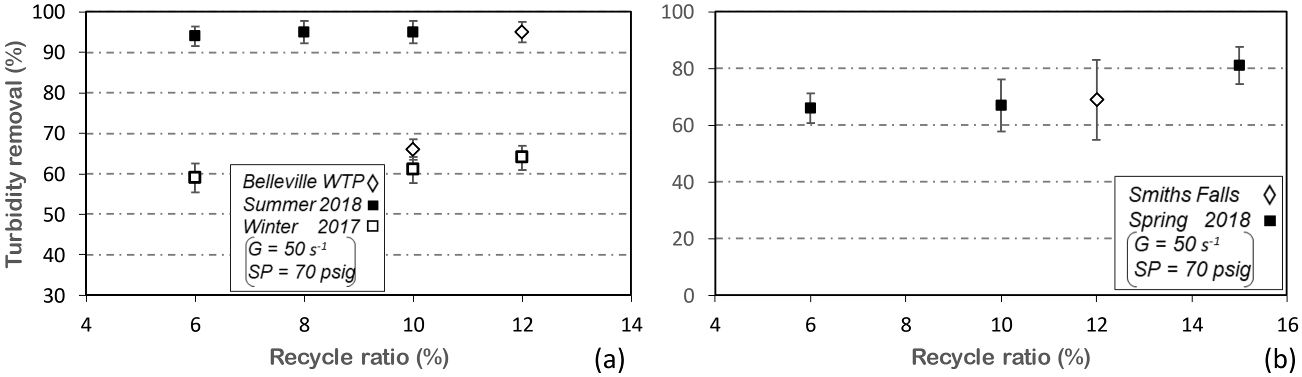

Figure 5.3 Final turbidity removal obtained at different RR in the LB-DAF treating (a) PBW and (b) SFW (error bars indicate ± one standard deviation) (n=2)

Although, the table 2 showed that the RR had the second most important impact on turbidity removal in the LB-DAF, different recycle ratios had a slight impact on the LB-DAF performance for turbidity removal in the treatment of the winter of 2017 PBW water and the spring of 2018 SFW water, while there was no apparent impact for the summer PBW water. A linear regression analysis of the PBW results showed that the RR impact is not statistically significant (α=0.05) since the confidence limits of the slope included zero for the experiments conducted in summer of 2018. However, the linear regression analysis conducted on PBW results in winter of 2017 (figure 5.3a) showed that the turbidity removal predictions are statistically significant. These turbidity removal differences could be due to low initial water turbidity concentration, which make flocs aggregation more difficult and thus more difficult to treat. Based on the earlier LB-DAF Ottawa River water tests, the turbidity removals were not expected to be impacted by changes in the recycle ratio (Gonzalez Galvis & Narbaitz, 2019a).

In addition, the lower LB-DAF turbidity removals for PBW in winter of 2017 compared with summer of 2018 could be associated for the following reasons: a) Cold water temperatures (i.e., 2-3^{0}C), which impact the coagulation process by decreasing the flocs aggregation rate, flocs structure (i.e., fewer compact flocs) and zeta potential particles reduction (Xiao et al., 2009; Braul et al., 2001); b) Cold water temperatures also impact water viscosity, which impacts the flotation performance due to a higher resistance to bubble/particles attachment and reducing the bubbles rise velocity (Edzwald, 2006; Edzwald and Walsh, 1992).

In general, the LB-DAF had good full-scale turbidity removal predictions for all the RR tested. However, this study recommends conducting LB-DAF experiments using a RR of 10% for obtaining a more stable, compact and thicker layer of sludge than this obtained with a RR of 6% and avoid possible particle resuspension after flotation. It should be noted that Bickerton (2012) found that for a full-scale DAF unit a small reduction in the RR from 12 to 11% did not affect its turbidity removal, but when the RR was lowered to 9%, this resulted in unstable water turbidities. In addition, the lower turbidity removals observed in DAF full-scale facilities when the RR was reduced could be associated with low bubbles volume concentration in the contact zone (Edzwald, 2010; Edzwald and Haarhoff, 2012). Therefore, the RR may not impact the performance of batch systems that are static in nature, but it does in DAF full-scale facilities. Therefore, the recycle ratio in DAF process is a variable whose impact should be evaluated in a dynamic, continuous flow DAF units that better simulate the real operational conditions (i.e., hydraulic loading rates and flow patterns).

5.4.5 Different saturator pressures impact on turbidity reduction in the LB-DAF

Gonzalez-Galvis & Narbaitz (2019a) conducted bubble size photographic measurements in the LB-DAF using tap water at room temperature (~20 ± 2 °C). They showed that as expected the mean bubble size decreased with increasing saturator pressure; however, there was significant overlap in the bubble sizes. These differences in bubbles size did not impact the turbidity removal in either treating PBW in the summer of 2018, or SFW in the spring of 2018 (figure 5.4 a and b). These results are similar to those obtained by Gonzalez-Galvis & Narbaitz (2019a) for Ottawa River water (ORW).

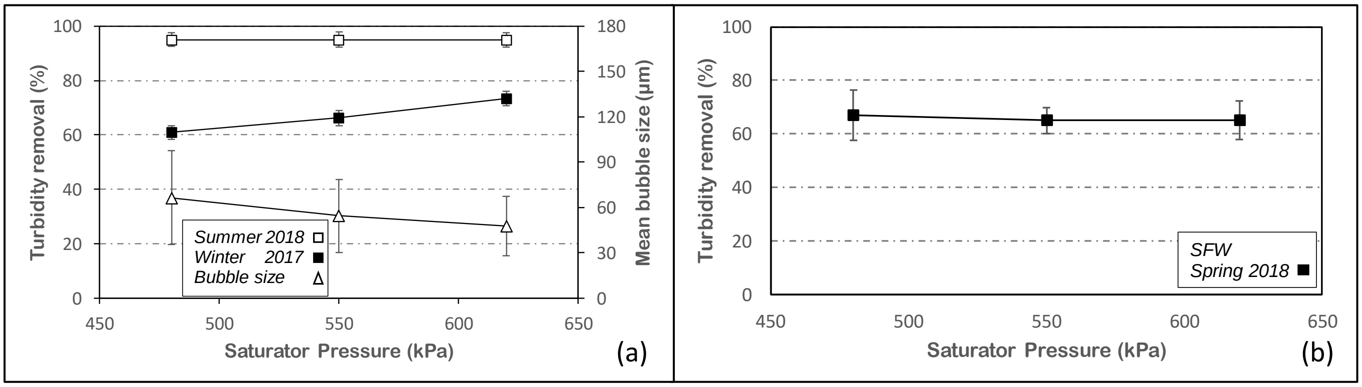

Figure 5.4 Final turbidity removal obtained at different SP in the LB-DAF treating (a) PBW and (b) SFW.

The LB-DAF saturator pressure sensitivity experiments with PBW in the winter of 2017 showed a slight turbidity removal improvement as the SP increases (figure 5.4-a). Linear regression analysis showed that the (α=0.05) confidence limits of the slope did not include zero, thus the impact of the saturator pressure was statistically significant. Given the limited number of runs and the differences with the results with the other waters further winter testing should be performed. As there were small changes in the raw water turbidities during storage, the observed turbidity removal differences could be associated with these small changes in the initial turbidity values, However, the final turbidity values were very similar for all the three SP tested (i.e., 0.59, 0.51 and 0.40 NTU), which is considered as satisfactory performance for flotation.

In summary, the different SP tested in the LB-DAF yielded similar turbidity removals in comparison with full-scale units: LB-DAF treating PBW during the winter of 2017 61% vs. 66% for Belleville WTP DAF; LB-DAF treating PBW during the summer of 2018 95% vs. 93 to 95% for Belleville WTP DAF; and 67% removal by the LB-DAF treating SFW in the spring of 2018 vs.55 to 69% for the Smiths Falls WTP's DAF, respectively. Since the results for a SP of 482 kPa (70 psig) were particularly consistent, 482 kPa (70 psig) was adopted as a standard SP in the LB-DAF tests.

Previous studies have reported that the most efficient performance and particle collision in a DAF unit is achieved when the number average floc size (30 to 50 μm) was close to the mean bubble size (Gorczyca & Klassen, 2008; Gorczyca and Zhang, 2007). Gorczyca & Klassen, (2008) noted that their larger mean floc size (i.e. 30 to 50 μm) could be due to that many particles in the water were algal filaments as their particle counter reported. Gonzalez-Galvis & Narbaitz (2019a) reported that the mean (volume averaged) bubble size for the 70 psi in the LB-DAF was determined to be 70.4 μm. Consequently, on a volume averaged basis the mean bubble diameter was 2.0 to 2.8 times larger than the mean floc sizes measured at the different G's (i.e. 25 to 34 μm) for both waters PBW and SFW. Therefore, the most probably mechanism for the particles removal in the LB-DAF could be as a result of several flocs attached to a single bubble forming bubbles-particle agglomerates (Lepinnen & Dalziel, 2004).

5.4.6 Impact of different LB-DAF water depth to tank diameter ratio on turbidity removals

Different water depth to column diameter ratios were evaluated in order to assess if smaller water volumes could be used in this type of testing. In these experiments the velocity gradient values were kept constant by changing the mixing speed (rpm) according to the water volume in each test. The LB-DAF turbidity removals for

Belleville summer samples and the Smiths Falls spring samples are shown in figure 5.5 (a) and (b), respectively. In the treatment of PWB, the different W/D ratios tested in the LB-DAF showed no significant impact on turbidity removal, the LB-DAF predictions were close to the 93 to 95% turbidity removals observed at the Belleville WTP (figure 5.5-a). Furthermore, this trend was very similar to the previous Ottawa

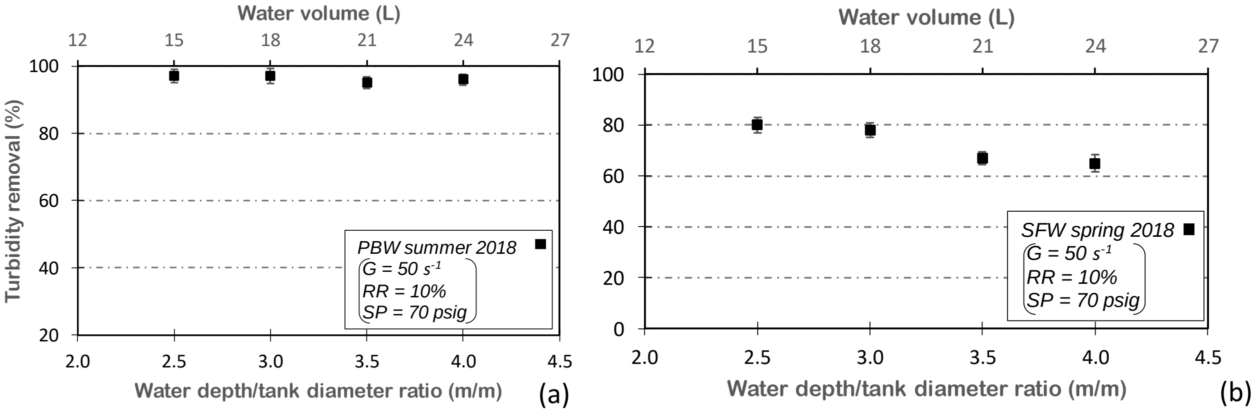

Figure 5.5 Final turbidity removal obtained at different W/D in the LB-DAF treating (a) PBW and (b) SFW (error bars indicate one standard deviation) (n=2)

In contrast, SFW experiments showed lower turbidity removals for the 3.5 and 4.0 D/W ratios, it is hypothesized that the SFW samples used for these tests had substantially lower raw water turbidities (<0.8 NTU) which makes treatment more difficult. This lower turbidity was probably due to particle sedimentation during the water storage time in barrels in the laboratory, retesting is recommended.

5.5 LB-DAF different operational parameters impact on NOM removal

The LB-DAF was also assessed tested for NOM reduction in terms of UV-254 absorbance and DOC. As shown in figure 5.6 (a) and (b), the LB-DAF tests with the different operating conditions (i.e., G's, and RR) yielded only small variations in the DOC removals. The LB-DAF DOC removals obtained in the winter of 2017 treating PBW (46±3%) was higher than the removal obtained in the summer of 2018 (37±4%), but similar to those reported by Belleville WTP (47 and 33%, respectively). In addition, the UV-254 absorbance removal obtained in the LB-DAF in winter of 2017 (66±1%) was slightly higher than in the summer of 2018 (62±1%) and close to those reported by the Belleville WTP (64% for the winter of 2017 and 62% for the summer of 2018 sampling days).

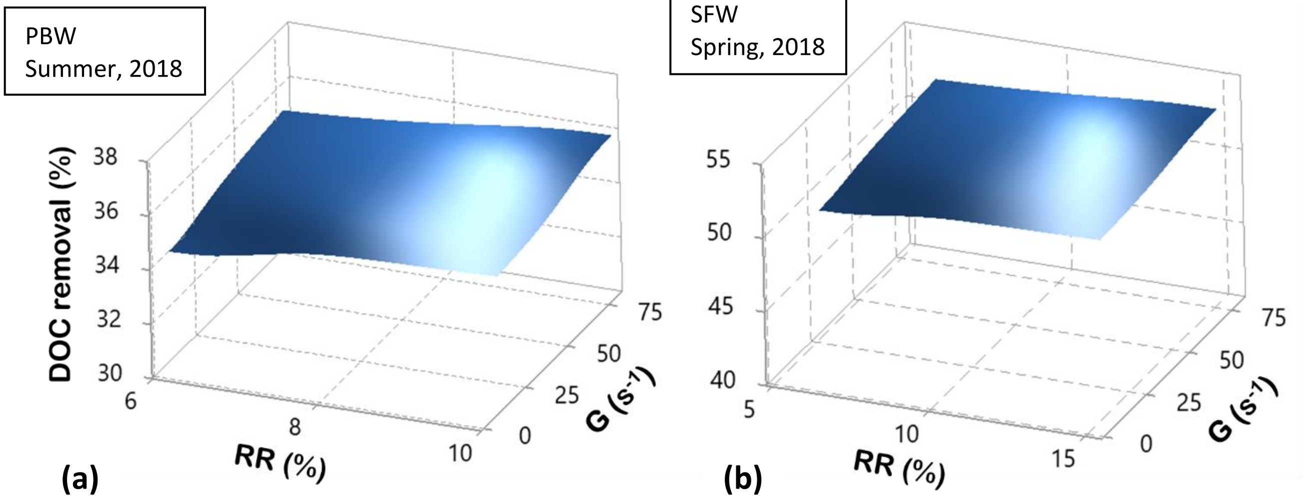

Figure 5.6 Velocity gradient and recycle ratio impact on DOC removal in the LB-DAF treating (a) PBW and (b) SFW.

The differences in the NOM removals between seasons treating PBW can be attributed to the nature of the NOM, and the plant operating conditions as well as the different sources that contribute to the NOM composition in the Bay of Quinte (i.e., humic substances, carbohydrates, amino acids, peptides, enzymes and toxins) (Sillanpaa et al., 2018; Her et al., 2004; Amy, 2008).

In addition, the LB-DAF DOC and UV-254 absorbance removals treating SFW (53±2% seen in figure 5.7b and 73±1%) also were very similar than those reported by the Smiths Falls WTP (51 and 76%, respectively). The UV-254 removals were significantly higher than the DOC removals for both waters. This indicates that, as expected, coagulation/flocculation/DAF favours the removal of hydrophobic fraction of the NOM (Mao et al., 2013; Chu et al., 2011; Zou et al., 2011). The higher NOM removals for SFW than for PBW could also attributed to the more hydrophobic character of the SFW NOM (SUVA of 3.51 and HPO fraction of 58%). These results agree with other studies in that coagulation and flocculation coupled with DAF effectively removed NOM (Chu et al., 2011; Zou et al., 2011; Malley and Edzwald, 1991).

5.6 Discussion

As confirmed with these two additional waters it is possible to predict full-scale DAF turbidity removals and conduct DAF treatability tests with the LB-DAF unit. According to the results of this study it is recommended to conduct LB-DAF treatability studies with the following set of conditions: (a) minimum water volume of 15 liters, which is the lowest water level tested in the LB-DAF (or 21 liters to obtain sufficient floated water for membrane treatability tests); b) conduct flocculation with a G in the range of 30 s^{-1} to 70 s^{-1} for 15 min; (c) use a saturator pressure of 480 kPa (70 psig) to reduce energy consumption by the air compressor; (d) a recycle ratio of 10% for obtaining a more stable, compact and thicker layer of sludge and avoid possible particle resuspension after flotation; and (e) a flotation time of 15 min. The impact of recycle ratio and water depth to diameter ratio should be tested in a continuous flow DAF pilot-scale plants because hydrodynamic conditions that may impact the system are not possible to mimic in a batch bench-scale DAF system.

5.7 Conclusions

(1) This study using two significantly different surface waters confirmed that the LB-DAF predicted turbidity and NOM removals well. Therefore, the LB-DAF can be considered as a useful tool for conducting drinking water treatability tests.

(2) Although the SFW factorial design experiments showed that velocity gradient, recycle ratio and their interactions have an impact on the LB-DAF turbidity removal, additional laboratory test showed that the impact of these variables was small, and this did not significantly affect the LB-DAF predicted capabilities for turbidity removal. In addition, the different parameters tested in the LB-DAF (i.e., G's, SP, and

W/D) did not have a significant impact on turbidity removal for the treatment of either pre-oxidized Bay of Quinte water, or raw SFW.

(3) The experiments conducted with PBW in winter and summer also showed that the LB-DAF predicts turbidity and NOM removal well even treating cold waters.

(4) As expected based on earlier research, the different LB-DAF operational parameter values did not have a significant impact on NOM removal either treating PBW, or SFW.

(5) The study also confirmed that coagulation, flocculation and flotation is a suitable technology for removing the NOM hydrophobic fraction in waters with SUVA higher than 3.5. It was showed by the higher UV-254 removals treating SFW 73% in comparison with PBW 66 and 62%, respectively.

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Chapter 6

Comparative Study of Dissolved Air Flotation and Ballasted Sedimentation for an Algal Impacted Water

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6.1 Abstract

Dissolved air flotation (DAF) is considered the best technology for the treatment of algal laden waters. Ballasted sedimentation (BS) is an alternative separation process that has become popular for the treatment of many types of waters. The objective of this bench-scale study was to compare DAF with BS for the treatment of water from a eutrophic waterway (Bay of Quinte, ON) in the summer. The comparison also included conventional gravity settling (CGS) jar tests. The study was performed at the Belleville Water Treatment Plant (Belleville WTP) over a two-day period during late July 2018, unfortunately a storm two days prior to the testing reduced the algal/cyanobacterial concentrations from the source water. The BS optimization required many runs to optimize the alum dose, the polymer type, the polymer dose and the microsand dose. The optimized BS jar tests had slightly lower turbidity removal than the DAF jar tests, and they required 33% more coagulant, 0.25 mg/L anionic polymer and microsand additions. The removal of cyanobacteria and algae (quantified using chlorophyll *a* and c-phycocyanin concentrations) by DAF and BS were very similar. The DOC removals and the disinfection by products formation potential (DBPFP) of DAF and BS treated water were also similar. Thus, BS and DAF

performed equally well, and both were superior to conventional sedimentation. Retesting during more intense algal bloom conditions is recommended.

6.2 Introduction

Water treatment plants (WTPs) assess their coagulation, flocculation and separation process efficiency based on their turbidity and natural organic matter (NOM) removals. In addition to its visual impact, turbidity may reflect the presence of suspended solids including bacteria, Giardia cysts and Cryptosporidium oocysts (MWH, 2012). Turbidity may also contribute to color, taste and odor in many surface waters (Constantine, 1982; Kwon et al., 2004; Khiadani et al., 2014). NOM in surface waters can arise from runoff that carries the breakdown products of terrestrial organisms, or by biological activities in the water environment, mainly algal and microbial activity (Sillanpaa et al., 2018). NOM in natural waters is a mixture of complex organic compounds, such as humic and fulvic acids, soluble extracellular and intracellular macromolecules (i.e., carbohydrates, amino acids, peptides, enzymes and toxins) (Amy, 2008; Hua et al., 2017). NOM removal at WTPs is important because the NOM-chemical disinfectant reactions produce harmful disinfection by-products (DBPs) in the distribution system (Goslan et al., 2017; Delpla and Rodriguez, 2017). Accordingly, NOM is often referred to as DBP precursors. Coagulation using metal ions, such as aluminium, followed by flocculation and conventional gravity settling (C/F/CGS) is the main approach used for removing NOM and therefore reduce DBPs concentrations in waters. (Matilainen, 2010; Yan et al., 2008; Golea et al., 2017). Coagulation, flocculation and dissolved air flotation (C/F/DAF) is considered the standard technology for the removal of algae and cyanobacteria cells (Jung & Je Oh, 2018; Edzwald & Haarhoff, 2012). This technology has also been shown to provide somewhat better NOM removals than C/F/CGS (Chu et al., 2011; Maeng et al., 2018; Gehr et al., 1993; Malley, 1990; Jeon et al., 2015; Gough et al., 2014). In recent years, ballasted sedimentation (BS) has become a very popular separation process due to its compactness and its ability to handle large raw water quality fluctuations (Borchate et al., 2014; Alpert, 2002). In their original literature search, the authors did not identify studies directly comparing BS and DAF for the treatment of algal-laden waters. Therefore, the objectives of this bench-scale study were: a) to optimize the coagulation for CGS, DAF and BS process in the treatment of Bay of Quinte water for turbidity removal; and b) to 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.

6.3 Materials and Methods

6.3.1 Water Tested

The experiments were conducted using water collected at Belleville WTP, which treats Bay of Quinte water (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 the mid to late-summer (Watson et al., 2008; Yakobowski, 2008). Belleville WTP has a pre-oxidation step within the intake (1.25 mg/L $KMnO_4$ and & 2-4 mg/L chlorine) for taste, odor plus zebra mussel and quagga mussel control and to oxidize iron before the coagulation, flocculation (C/F), and DAF processes. The water samples for conducting CGS, DAF and BS jar test comparisons were collected after the pre-oxidation step in late July of 2018. Coagulation at the Belleville WTP used alum (ALS, Kemira, Montreal, QC: 4.30±0.1% Al^{3+}) with a dose of 60 mg/L as Al_2O_3 (5.45 mg Al/L) year around.

6.3.2 Bench-scale experiments

6.3.2.1 Dissolved air flotation jar test

C/F/DAF jar test experiments were conducted in a DAF jar test apparatus (PJT02 Capital Controls Group, Didcot, GB). The components of the DAF jar test apparatus include one coagulation-flocculation-flotation cell. The high strength acrylic cell (jar) has an internal diameter of 9 cm, a height of 22 cm, and a maximum volume of 1.4 liters. The unit is equipped with rotating flat paddle 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 8L (2 gal) volume pressurized saturator tank (Capital Controls Inc/ Trent Severn Ltd, England), which is pressurized by 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), they were: a) a 1000 ml of water sample was added to the flotation jar; b) the jar content was mixed at 400 rpm (G= 240 s^{-1}) for one minute; c) the coagulant was added to the liquid and mixed for 1 minute (coagulation); d) the liquid was then mixed at 30 rpm (G= 12 s^{-1}) for 10 minutes (flocculation); d) the mixing was then stopped and 110 ml of saturated water was transferred through the connecting tubing to initiate the floatation step; and f) 10 min flotation period was used for the bubble-floc aggregates to form and float that results in the clarification. The saturator pressure (SP) used was 482 kPa (70 psig). These experiments used a 10% recycle ratio (RR), which was achieved by introducing 110mL of saturated water. Earlier testing with this jar test apparatus showed that the turbidity removal predictions could be improved by an alternative pressurized water delivery system (Gonzalez Galvis & Narbaitz, 2019a), in the current study this bubbling system was used for the DAF jar tests instead of the jar tester's pressured water delivery system. The optimum coagulant dose was chosen in terms of particle destabilization measured through the zeta potential (ZP) and the turbidity removal. The experiments 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*, C-Phycocyanin and trihalomethanes formation potential (THMFP) removals.

6.3.2.2 Ballasted sedimentation jar test

Ballasted sedimentation (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 procedures used in this research were adopted from Desjardins et al., (2002). The BS experiments were conducted as follow: a) the water sample was placed in the jar and mixing was initiated at 150 rpm (G= 129 s^{-1}); b) 100% of the coagulant was added at the start of the two minute rapid mix step (150 rpm); c) the pre-weighted amount of microsand with an effective diameter of 80 µm (Veolia Inc., Montreal, QC,) was introduced 2 min later, along with 70% of the required polymer dosage; d) after two further minutes of (150 rpm) rapid mixing, the remaining polymer (30%) was added; e) the mixing speed was reduced and maintained at 100 rpm (G= 70 s^{-1}) for six minutes for the flocs to mature; f) the mixing was stopped and the flocs allowed to settle for three minutes.

Preliminary tests with conventional square jars led to significant sand deposition in the corners even when the mixer paddles were lowered within 3 mm of 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 had to be optimized. It should be noted that like most BS systems, these BS tests used an anionic polymer as a flocculation aid. Therefore, the BS preliminary optimization experiments with Bay of Quinte water were conducted in our lab, they included testing six different aluminum sulfate coagulant (ALS, Kemira, Montreal, QC) doses, six different Magnafloc LT27 (Anionic polyelectrolyte, BASF, Mississauga, ON) polymer 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 dose 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 ≥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 flocs density sufficiently to produce 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 remained in the jar bottom. 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 measured through ZP and turbidity removal, 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 experiments were conducted in duplicate.

6.3.2.3 Conventional sedimentation jar test

CGS experiments were conducted using a regular bench-scale jar test apparatus with six stirring paddles with six 2L square beakers (Phipps and 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 s^{-1}) for 1 min; (b) slow mixing at 30 rpm (G= 12 s^{-1}) for 15 min and (c) sedimentation for 30 min. These are the usual conditions for C/F/CGS jar test in water treatment treatability test (Kawamura, 2000; ASTM, 2008; AWWA, 2011). 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 were collected for conducting DOC, UV-254, Chlorophyll *a*, C-Phycocyanin and THMFP analysis. The C/F/CGS experiments were conducted in duplicate.

6.3.3 Analytical Methods

The pH of all the water samples was measured using a pH meter and electrode (HQ40D, HACH, Loveland, CO). Turbidity was determined using a turbidimeter (2100AN, Hatch, Loveland, CO). Total organic carbon (TOC) analysis was conducted using a UV-persulfate oxidation-based TOC analyzer (Phoenix 8000, Tekmar-Dohrmann, Cincinnati, OH). The TOC analysis methodology follows the standard method 5310 C (APHA/AWWA/WEF, 2017). The DOC is the dissolved organic concentration, and this was obtained by vacuum filtering the water samples through a 0.45 µm nylon membrane filter (PALL Sciences Corp; Pensacola, FL) and then performing TOC analysis on the filtrate. Ultraviolet absorbance at 254nm (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 multiplying the UV-254 nm by 100 and dividing it by the DOC concentration. The alkalinity and the total hardness of the raw water were determined according to Standard Methods 2320 and 8226 (2340), respectively (APHA/AWWA/WEF, 2017). Zeta potential measurements of the coagulated Belleville 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-phycocyanin, a common freshwater cyanobacterial pigment. Chlorophyll_*a* was extracted using ethanol extraction method (Jespersen & Christoffersen, 1981) and quantified spectrophotometrically. C-Phycocyanin is used to quantify cyanobacteria blooms as it is a freshwater cyanobacteria specific pigment (Ahn et al., 2007; Parésys et al., 2005). C-phycocyanin extraction was conducted using 10 mL sodium phosphate buffer solution (pH = 6.8). The C-Phycocyanin spectrophotometric analytical procedure was adopted from (Horváth et al., 2013; Dianursanti & Indraputri, 2018). The DBPFP quantification were conducted on a modified version of Standard Methods 5710, of the trihalomethane formation potential test (THMFP) (APHA/AWWA/WEF, 2017). 1000 ml of sample were measured with a graduate cylinder and filtered through a 0.45 µm 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 THMFP tests used a 4.4 mg/L chlorine (NaOCl) dose, which is the total chlorine dose applied to the finished water at the Belleville WTP. A 24 hours chlorine contact (incubation) time was chosen to simulate the maximum water age found in the Belleville drinking water distribution system. The DBPs formed in these tests were measured in terms of the THM's and HAA's formed, they were quantified by gas chromatography analysis.

6.4 Results and Discussion

Water quality characterization of pre-treated Belleville water (PBW) in early summer 2018 is presented in table 6.1.

Table 6.1 Pre-treated Belleville water characterization summer 2018

Parameter	Pre-treated Belleville water
pH	8.32±0.14
Turbidity (NTU)	8 - 12 ±0.15
Alkalinity (mg/L as $CaCO_3$)	116.7±6.5
UV-254 (cm^{-1})	0.14±0.001
DOC (mg/L)	5.49±0.02
SUVA (L mg^{-1} m^{-1})	2.55±0.01
True Color (Pt-Co)	6.7±0.65
Total Hardness (mg/L)	119.3±2.6
Chlorophyll *a* (µg/L)	12.9±2.95
C-phycocyanin (µg/L)	44.3±5.14

*(average ± one standard deviation) (n = 3)

PBW water characteristics shows a water with a slightly above neutral pH, relatively low turbidity, moderate hardness, intermediate alkalinity and intermediate SUVA (table 6.1). The SUVA water is between 2.0 and 4.0; therefore, the most probably composition of the NOM is a mixture of aquatic humics, hydrophobic and hydrophilic NOM and a mixture of molecular weights (Edzwald & Van Benschoten, 1990). The C-phycocyanin (cyanobacterial) levels found in the PBW has a concentration close to the range reported by previous studies (Yakobowski, 2008). The late July dates of the testing were restricted by the logistics of the field testing, the extensive preparation required, the plant and personnel availability. Unfortunately, due to a severe storm two days prior to our testing the water characteristics changed, and the algal/cyanobacterial concentrations were much lower than the reported by previous studies in the same period (i.e., cyanobacterial concentrations quantified as Chlorophyll *a* 12 – 25 µg/L) (Yakobowski, 2008). However, based on the World Health

Organization criteria for cyanobacteria bloom at the first level alert (i.e., cyanobacteria concentrations higher that 2000 cells/mL, or 1 µg/L chlorophyll *a*) (WHO, 1997), the Bay of Quinte water still could be characterized as moderate algal bloom.

6.4.1 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 DAF units at the Belleville WTP. As shown in figure 6.1, based on the zeta potential 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). These dosages corresponded to near zero ZP measurement (-2.28 and -2.17 mV, respectively). ZP values close to the neutrality has been reported as the optimum for the removal of cyanobacterial cells, NOM and extracellular organic matter (EOM) (Henderson et al., 2008; Chekli et al., 2017). The DAF jar test and full-scale DAF particle destabilization were confirmed by their 94 and 95% turbidity percentage removal, respectively. Thus, the DAF jar tests simulated the DAF full-scale turbidity removals well. However, this is not always the case because DAF jar test may either over, or under predict turbidity removals (Bickerton, 2012; MacPhee, 1996). Particles destabilization in water can be achieved by different mechanism including double-layer compression, absorption and charge neutralization, entrapment of particles into a precipitate and adsorption and bridging between particles (MWH, 2012). These particle destabilization mechanisms allow particles agglomeration, which lead to particles and turbidity removal. Also, it should be noted that DAF systems performance are also impacted by the bubble size generated and bubble concentration which are a function of the saturator pressure and the bubbles release system. In addition, it should be noted that there is not a standard DAF jar tester, there are several commercial jar test apparatus available in the market but there has been no direct comparison between these units to ascertain how well they predict full-scale turbidity removals.

Figure 6.1 also shows that for coagulant doses greater than 4.54 mg Al/L the changes in the particles ZP with increasing coagulant dose were relatively small. Possible reasons for this are: a) fine colloid particles are not satisfactorily destabilized by the coagulant, and b) that the pre-chlorination step applied in the Belleville WTP make colloids to become more resistant to the coagulation process (Bean et al., 1964).

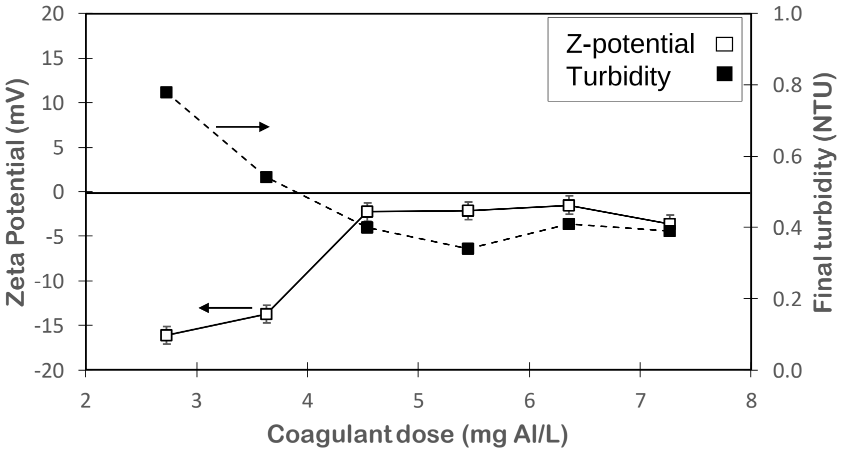

Figure 6.1 DAF jar test zeta potential versus final turbidity at different coagulant doses (error bars indicate ZP standard error).

The DAF, BS and CGS optimization results are shown in figure 6.2, from it the following can be observed. First, the DAF jar test matched the turbidity removals of the full-scale unit which was surprising given earlier results (Gonzalez-Galvis & Narbaitz, 2019b). However, one possible explanation is that these DAF jar test experiments were conducted with a different bubble device release system, which was placed vertically with a space of 5 cm above the jar bottom. Second, the turbidity removals by the DAF jar tests were 6 - 10% higher than the conventional jar test at the same coagulant dose. Third, the BS achieved slightly lower turbidity removals than the DAF, however it required a higher coagulant dose (i.e., 7.27 mg Al/L) plus 0.25 mg/L anionic polymer plus the microsand (4 g/L). In addition, the BS and CGS achieved similar turbidity removal results, but the BS has a much lower settling time (3.0 versus 30 minutes).

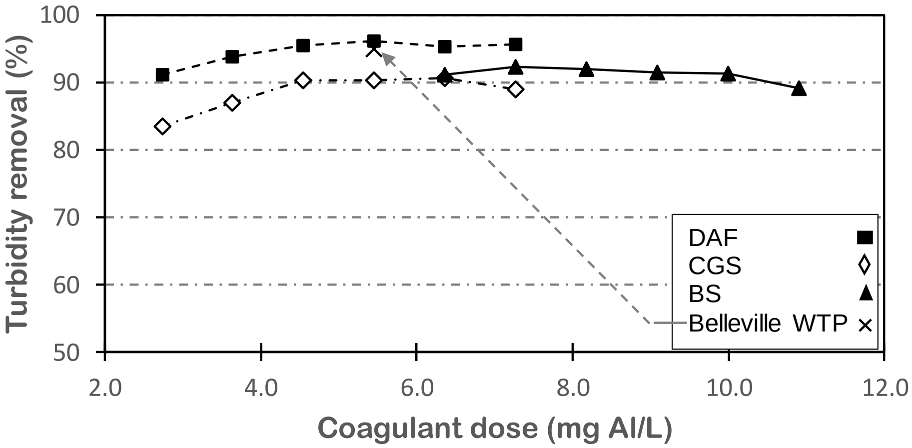

Figure 6.2 Impact of coagulant dose on turbidity removal with three different treatments (DAF, BS and CGS) at the bench-scale level

As the turbidity removal by BS did not improve after a coagulant dose of 7.27 mg Al/L, so this dose was considered as the optimum for BS. The higher coagulant doses used for BS tests were determined to be necessary in preliminary tests. Note that in the comparisons in figure 6.3 are for the best performing dose for each of the alternatives, the DAF and CGS turbidity removals experiments correspond to an alum dose of 5.45 mg Al/L while the BS experiments use an alum dose of 7.27 mg Al/L. Figure 6.3 also presents the turbidity removal of the full-scale DAF systems at the Belleville WTP.

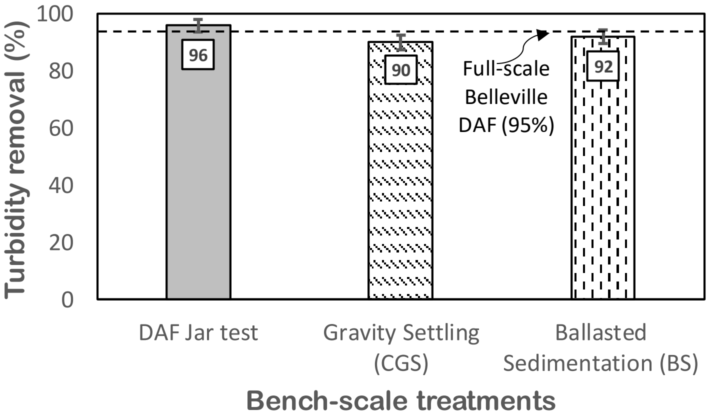

Figure 6.3 Optimized BS jar test turbidity removal comparison with DAF, CGS jar test and Belleville WTP (error bars indicate one standard deviation)

The turbidity removal obtained in the DAF jar test (96%) was similar that reported by the full-scale DAF at the Belleville WTP (93 - 95%) using the same coagulant type and dose. The optimized BS procedure achieved good turbidity removal percentage (92%), that only differs by 3% from that of the full-scale DAF. The CGS jar test had the lowest turbidity removal (90%) among the treatments using the same coagulant dose as the DAF. 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) (Khiadani et al., 2014). During the preparation of this manuscript the authors became aware of other comparisons between BS and DAF (Alvarez et. al, 1999; Knappe et al., 2004). The results in the current study are in agreement with the findings of Alvarez et al. (1999) that BS and DAF did not show big differences in turbidity removal and the final turbidity values obtained in all the treatments were below 1.0 NTU.

6.4.2 Chlorophyll *a* and c-phycocyanin removal by DAF, BS and CGS

Due to the volumes of water required for chlorophyll *a* and c-phycocyanin quantification, their removal had to be evaluated in separate jar tests (conducted under the same operational jar test and chemical dose conditions as those used for turbidity removal). Their final chlorophyll *a* and c-phycocyanin concentrations are presented in figure 6.4 (a) and (b), respectively. The chlorophyll *a* and the c-phycocyanin percentage removal for each treatment were: DAF 98-94%, CGS 87-51% and BS 97-93%, respectively. Therefore, The DAF and BS had similar removal performance for chlorophyll *a* and c-phycocyanin, respectively. These results agree with those reported by other studies by comparing DAF and BS for the removal of M. aeruginosa cells via jar test (Knappe et al., 2004), and with the results reported by BS pilot-scale studies in the removal of phytoplankton and cyanobacteria cells (Robinson & Fowler, 2007). However, 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 $KMnO_4$ and chlorine applied as a pre-oxidation at the intake of Belleville WTP, which may help inactivate alga cells and, therefore; hydrous manganese dioxide (MnO_2) could adsorb on algal cells to increase the specific gravity and settling velocity (Henga et al., 2008). This could improve the BS and the CGS performance, but at the same time it should negatively impact the DAF. Second, low $KMnO_4$ doses (i.e., 1.25 mg/L) reduces the quantity of algal derived extracellular organic matter and therefore, facilitating coagulation (Wang, et al., 2013). In this study, CGS was not as effective for the removal of algae and cyanobacteria, measured as chlorophyll *a* and c-phycocyanin, as DAF, this was expected based on the work of Do Amaral et al. (2013) and Teixeira & Rosa, (2006). 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 no pre-oxidation step.

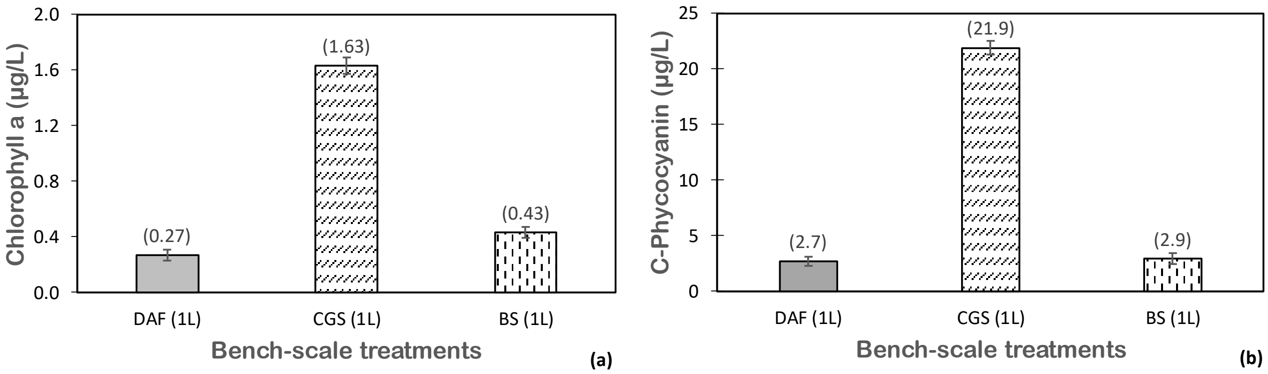

Figure 6.4. DAF, CGS and BS final concentrations of (a) chlorophyll *a* and (b) c-phycocyanin (error bars indicate one standard deviation).

6.4.3 DAF, BS and CGS comparison for the removal of NOM

This study also compared the performance of DAF, CGS and BS for NOM removal (figure 6.5). Some studies have concluded that the NOM removal is dependent on coagulation (i.e., pH, coagulant type, and dose), and not a function of the solid-liquid separation process (Malley, 1990; Matilainen et al., 2010; Yan et al., 2008). However, other studies have found that DAF improves the NOM removal up to 10% in terms of

DOC and UV-254 absorbance treating reservoir waters in comparison with CGS (Chu et al., 2011; Zou et al., 2011).

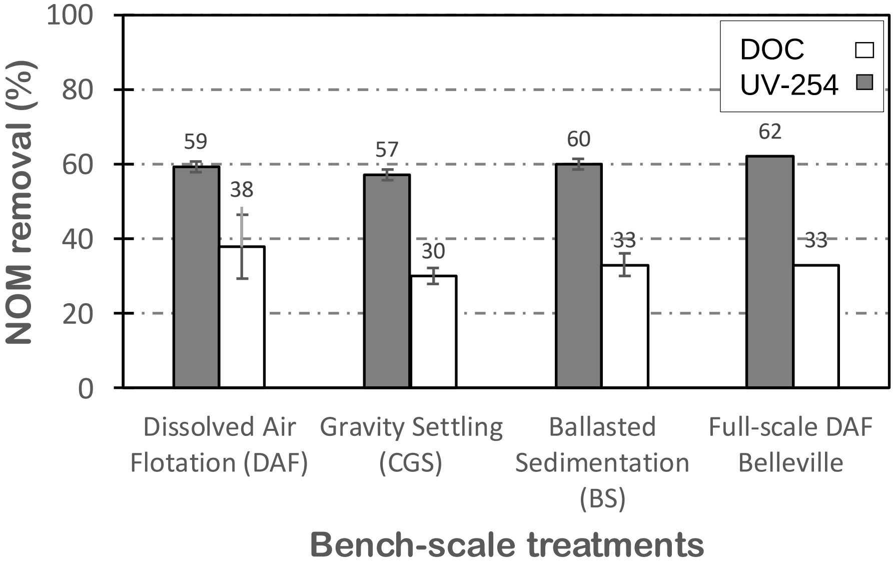

Figure 6.5. DAF, CGS and BS comparison for NOM removal (error bars indicate one standard deviation, n=2)

In the current study, the DAF jar tests showed somewhat higher average DOC removal than the CGS (38 versus 30%), while the UV-254 removals were closer (59 and 57%) (figure 6.5). However, due to the overlapping confidence intervals the differences do not appear to be statistically significant. The BS jar test had slightly higher average UV-254 removals and slightly lower average DOC removals than the DAF jar tests. However, the confidence intervals overlap and thus the DOC and the UV-254 removals are considered statistically the same for all the treatments. In addition, Belleville WTP had slightly higher UV-254 removals (62%) than all the different jar tests treatments. However, this small difference was not statistically significant (α=0.05). The similar results found in this study for NOM removal using DAF, BS and CGS agree with those reported by other authors (Knappe et al., 2004).

The TTHM's generated in the disinfection by-product formation potential tests (DBPFPT) after clarification (i.e., DAF, CGS and BS) were similar, however the TTHM levels were very low presumably due to experimental and/or analytical problems. The haloacetic acids formation potentials (HAAFP) of the DAF, CGS and BS effluents are presented in figure 6.6. These concentrations correspond to a total percentage reduction of 34, 47 and 42% (with respect to the HAAs concentrations formed from the raw water), respectively. These concentrations were within the maximum allowable by the Canadian drinking water regulations 80 µg/L (Health Canada, 2012). The predominant HAAs after DAF, BS and CGS treating PBW from the highest to the lowest were: dichloroacetic acid 55-71%, trichloroacetic acid 36-44%, bromochloroacetic acid 4-6% and monochloroacetic acid 3-4%, respectively. HAAs formation in surface waters has been linked with humic acids and NOM hydrophobic neutral fractions (Reckhow et al., 1990; Marhaba & Van, 2000).

As our attempts to fractionate the raw water NOM with XAD columns failed, it is not possible to link the production of the HAAFP to a particular NOM fraction. The hydrophobic NOM fraction is indirectly quantified by UV-254 absorbance (Hua et al., 2015; Golea et al., 2017), using this criteria and the findings of the above researchers the DAF treatment would be expected to have the lowest HAA formation and the CGS the highest HAA formation. Our data showed the opposite trend. However, other studies have suggested that the hydrophilic fraction of NOM produces greater HAA's concentrations than THM's (Sinha et al., 1997; Hwang et al., 2001), and this may be the case in this study. Given the HAA concentration vary ±10% from the mean, the three treatment can consider to achieve similar reductions in the HAAFP.

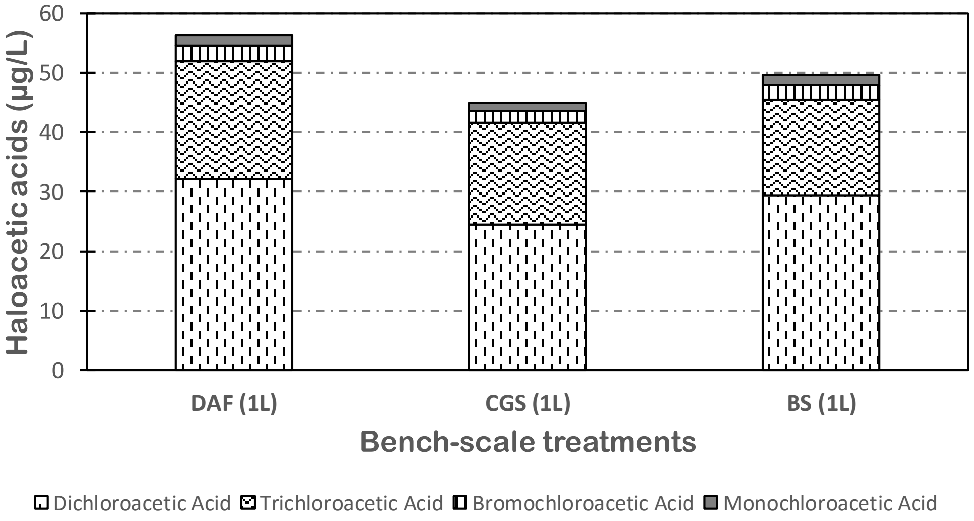

Figure 6.6. HAAFP for the DAF, CGS and BS effluents

6.5 Conclusions

The main conclusions of this bench-scale study were as follows: First, DAF jar tests predicted the turbidity removals of the full-scale DAF relatively well. This was somewhat surprising because earlier studies suggest that turbidity removals in DAF jar tests do not always predict full-scale DAFs. Second, given that in the literature DAF is considered the technology of choice for algal laden waters, it was somewhat surprising that BS performed similarly to DAF in the treatment of these algal laden waters. These results confirm the findings of Alvarez et al. (1999) and Knappe et al. (2004). Both DAF and BS were superior to CGS. The algal and cyanobacterial pigment removal, the DOC removal and the TTHMFP and HAAFP of both DAF and BS were very similar. The similarity in the performance may have resulted from the unfortunate timing of the testing, that is because of weather conditions the algal and cyanobacteria concentrations were lower than the hoped-for bloom conditions. Because of this, it is recommended that the testing be repeated during algal/cyanobacterial bloom conditions. The only significant difference in BS effluent quality was a somewhat higher turbidity levels than the DAF, which may result in somewhat shorter filter runs, and the higher chemical requirements.

6.6 Acknowledgements

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Chapter 7

General Conclusions

7.1 Overview

The overall objective of this thesis was to develop a bench-scale system that yielded more accurate predictions of full-scale dissolved air flotation (DAF) turbidity removals at water treatment plants. A large diameter, large volume batch bench-scale DAF system (LB-DAF) was designed, built and tested with different surface waters. This development evaluated the impact of several LB-DAF design and operational variables on the quality of the turbidity and NOM removal predictions by conducting comparisons with full-scale DAF units. Given accepted superiority of DAF for the treatment of algal-laden waters and the current popularity of ballasted sedimentation systems, this thesis also conducted a bench-scale comparison of these two processes for the treatment of an algal-laden water. The following is a summary of the main conclusions derived from the three phases of this work.

7.2 LB-DAF development and testing

The LB-DAF was designed, built and tested with Ottawa River water, that permitted a comparison with a DAF full-scale facility (Aylmer WTP, Gatineau, QC). The main conclusion of the development of the LB-DAF system are the following:

1. For ORW, the turbidity removals predicted by the LB-DAF were closer to the full-scale values than those obtained using the commercial DAF jar apparatus

tested. LB-DAF yielded turbidity removals similar to those of the full-scale DAF at the Aylmer WTP regardless of the season/water temperature.

2. The inferior DAF jar test turbidity predictions were due, in part, to its bubble generation system, which yielded larger bubbles than that of the LB-DAF. It also appears that improved LB-DAF turbidity removals were also associated with the larger vessel diameter.
3. The NOM removal in both the LB-DAF and the DAF jar test was similar and predicted well the full-scale DAF NOM removals.
4. The LB-DAF tests turbidity removals appear to increase slightly as the G values increase up to 25-37 s^{-1} and remain constant for higher G values.
5. Although increasing the LB-DAF saturator pressure decreased the mean bubble diameter, the distribution of the bubble sizes at the three pressures tested showed a substantial overlap. This likely contributed to the limited impact of saturator pressure on the turbidity removals.
6. The different parameters tested in the LB-DAF (i.e., G's, RR, SP, and W/D) did not show to have a significant impact on turbidity and NOM removal.
7. Different recycle ratio had a small impact on the LB-DAF for turbidity removal. Therefore, a 10% recycle ratio was chosen as a standard for conducting LB-DAF experiments.
8. Based on the LB-DAF experiments treating Ottawa River water, it is recommended that future LB-DAF treatability studies utilize the following set of conditions: (a) minimum water volume of 15 liters (or 21 liters to obtain sufficient floated water for membrane treatability tests); b) square impeller; c) conduct flocculation with a G in the range of 30 s^{-1} to 70 s^{-1} for 15 min; (d) use a saturator pressure of 482 kPa (70 psig); (e) a recycle ratio of 10%; and (f) a flotation time of 15 min.

7.3 Phase II: LB-DAF turbidity and NOM removal predicted capabilities treating different surface source waters

To confirm the LB-DAF capabilities it was tested using two different surface waters that treated with full-scale DAF systems (Belleville WTP and Smiths Falls WTP). The main conclusions of the confirmation LB-DAF tests are as follows:

1. The LB-DAF can predict the full-scale DAF turbidity and NOM removals well for the two different waters tested during different seasons.
2. Factorial design experiments showed that velocity gradient, recycle ratio and their interactions had an impact on the LB-DAF turbidity removal performance. However, additional laboratory experiments confirmed that the impact of these variables was not statistically significant. This suggests the low G experiments in chapter 4 should be repeated.
3. In the treatment of Bay of Quinte water and Rideau River water, again the different values of the LB-DAF's saturator pressure and depth to diameter ratios did not have a significant impact on the turbidity removals.
4. This research confirmed that the recommended LB-DAF operating conditions are: (a) minimum water volume of 15 liters; b) conduct flocculation with a G in the range of 30 s^{-1} to 70 s^{-1} for 15 min; (d) use a saturator pressure of 482 kPa (70 psig); and (e) a recycle ratio of 10%.

7.4 Phase III : DAF, BS and CGS jar test optimization for the treatment of an algal-laden water.

The jar test bench-scale experiments conducted for comparing three different clarification processes for algae laden waters. The main conclusions of this comparison are:

1. DAF and BS jar tests had slightly better turbidity removal than CGS. However, the BS required higher coagulant dose plus the polymer and required the addition of microsand.
2. The turbidity removal obtained in the DAF jar tests was very close to that observed at Belleville WTP DAF system.
3. NOM removal in terms of DOC and UV-254 was similar for DAF, BS and CGS, and their performance was similar to that of the full-scale DAF unit at the Belleville WTP.
4. The removal of disinfection by-products formation potential was similar by DAF, BS and CGS.
5. Unexpectedly, the cyanobacteria and algae removal in the BS jar tests were very similar to those in the DAF jar tests, and these removals were higher than those observed in CGS jar tests. Therefore, this study confirmed that CGS is not the most appropriate technology for treating algae laden waters.

7.5 Recommendations for future research

Based on the findings of this research during the LB-DAF experiments, the following future research is recommended:

1. The predicted capabilities of the LB-DAF system for turbidity removal should be compared again other commercially available DAF jar testers. Then, it will permit to standardize a set of optimum DAF batch bench-scale procedures for obtaining reliable scale-up results.
2. Due to that some DAF jar test and full-scale DAF facilities use square and rectangular shapes in their units (i.e., beakers and coagulation, flocculation and DAF tanks); therefore, it is recommended to build a LB-DAF square tank to assess the impact shape in terms of turbidity and NOM removal. These results should also be compared with the already developed LB-DAF and with regular DAF jar test and full-scale.

3. As some studies claim that DAF improves the NOM removal, it could be of interest to know if DAF helps to remove a specific fraction of the NOM (i.e., hydrophobic, hydrophilic or transphilic), or if their removals is exclusively a function of the coagulation process.
4. It is necessary to conduct more floc size characterization and its impact on DAF turbidity, so it will be possible to advice DAF water treatment facilities on turbidity removal optimization. .

Chapter 8

8. References

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Appendix A

LB-DAF General Configuration and Shaft Calculations: Supplementary Material

A.1 LB-DAF general configuration.

The LB-DAF tank consists of a cylinder made from impact-resistant transparent polycarbonate with 8” OD and 7-3/4” ID with a 1/8” wall thick, and a total high of 3.28 ft. The tank has two sampling ports located from a distance of 3” and 6” respectively from the base. The base of the tank was made from 1” thick impact-resistant polycarbonate. In addition, the tank is baffled with four removable baffles made of 1/8” thick stainless-steel with a width of 2 cm and a height of 0.80 m. The baffles are located at 90^{o} from each other along the cylinder wall. The main objective of the baffles is to prevent the vortexing around the impeller shaft in the coagulation/flocculation steps. The tank has a stainless-steel mixer shaft with a 3/8” diameter with a threated end, so that different impellers can be attached to it. To help produce the DAF bubbles the system includes a pressure vessel (saturator) with a capacity of 8L (2 gallon) and a maximum working pressure of 690 kPa (100 psig), which is connected to a one-gallon capacity portable air compressor (TAW-0308, PSI compressors Inc. Ottawa, ON). The saturator was connected to the tank by low-density polyethylene (LDPE) tubing (6.35 mm or 1/4” OD) with a maximum working pressure of 860 kPa (125 psig) and a 6.35 mm OD stainless steel pipe. The LB-DAF bubble delivery tubing incorporates a 6.35 mm (1/4”) On/Off valve (#4 in figure A.1) and a 6.35 mm (1/4”) needle valve (#5 in figure A.1). The On/Off valve controls the saturated water feed, while the partially open needle valve, located to approximately 10 cm from the LB-DAF tank bottom, helps control the bubble size. While in continuous flow DAF systems the recycle ratio

(RR) is the ratio of the saturated water flowrate to the system flowrate. In the LB-DAF apparatus, which is a batch system, the recycle ratio is defined as the ratio of the saturated water volume (V_2) to the total water volume (V_1). The saturated water volume was measured with a mark (previously calibrated with a graduate cylinder) in the LB-DAF wall. The saturated water is introduced in the LB-DAF tank by opening the on-off valve, while maintaining the same pressure in the saturator.

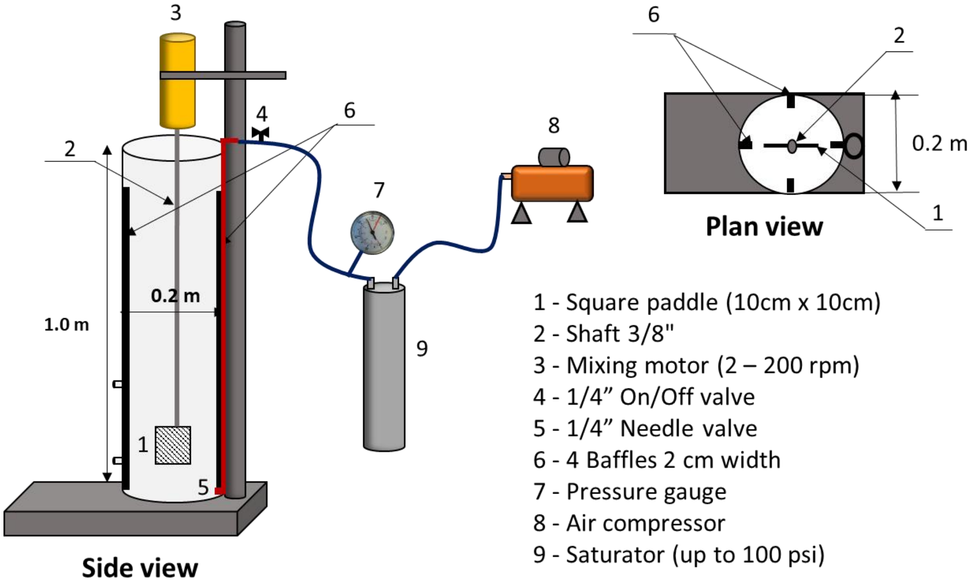

Figure A-1 Large Volume Bench-scale Dissolved Air Flotation Apparatus (LB-DAF)

A.2 Torque, Momentum and Shaft Diameter Calculations

The EEUA shaft sizing method was used for conducting the shaft diameter calculations (Harnby et al., 2007). The theoretical design bases of this method are based on the assumption that the impeller will probably become jammed, causing the motor to stall. Therefore, the shaft is then designed, so that yield stress of the shaft material in shear is not exceeded by such an event. The procedure conducted for the shaft calculations was as follows:

a) Initial assumptions

The mechanical mixing calculations were done upon the flocculation speed requirements because a low speed is equivalent to a high torque. The initial parameters from the design were based on the main factors influencing power input such as liquid viscosity and density, tank diameter, water depth, diameter and width of the impeller. The forces that act on an agitator shaft according to the EEUA method are showing in the figure A-2.

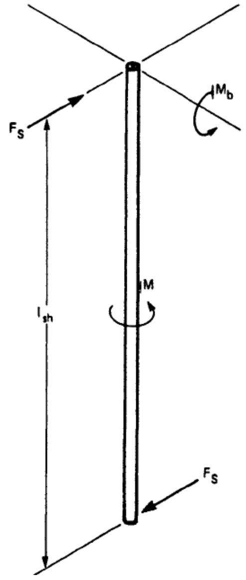

Figure A-2 Forces on an agitator shaft (Harnby et al., 1997)

The literature reports different mixed speed ranges for flocculation. The table A-1 shows a summary of the mixing speed as well as velocity gradient used in the flocculation processes as a pre-treatment for DAF in pilot and bench scale.

Table A-1 Mixing speed ranges for flocculation in a pilot and DAF bench scale

Velocity Gradient G (s^{-1})	Speed (RPM)	Hydraulic retention time T (min)	Reference
-	50	10	Edzwal & Haarhoff et al. (2011)
30 - 70	-	5 - 20	Valade et al. (1996)*
-	15 - 20	10	Krofta et al. (1982)
2 - 100	-	20	Dolejs, (1983)
50 - 100	-	8 - 16	Van Beschoten et al. (2002)*
11 - 45	-	20	Chu et al. (2011)*
70	-	8	Teixeira et al. (2010)
25	-	10	Amaral et al. (2013)
-	25	18	Shan-pei et al. (2007)*
70	-	8	Teixeira et al. (2006)

*Pilot scale

Therefore, the low speed chosen for the shaft calculation purposes was 20 rpm and for all the calculations water temperature was assumed to be 20 ^{0}C. All the impeller utilized in this study had a 10 cm diameter.

b) Reynolds number calculation

The Reynolds number is calculated for the low mixing speed (i.e. flocculation step), and this can be calculated from equation A-1.

$$R_e = \frac{D^2 N \rho}{\mu} \qquad \text{Eq. (A-1)}$$

Where: Re = Reynolds number; D = Impeller diameter, m; N = characteristic velocity, rps; ρ = density of water, kg/m^3; μ = dynamic viscosity of the water, N.s/m^2

$$R_e = \frac{(0.1m)^2 \times \left(20\frac{rev}{min} \times \frac{1\,min}{60s}\right) \times \left(998.2\,{}^{kg}/_{m^3}\right)}{\left(1.002 \times 10^{-3}\,{}^{kg}/_{m\,s}\right)} = 3320.7$$

According to Rushton (1952), a laminar flow for power characteristics of a mixing impeller correspond to a Reynolds number in a range of 1.0 to 100. After this value the flow is considered as transitional for Reynolds number between 100 and 10000 and therefore, turbulent flows are considered for Reynolds number higher than 10000. Therefore, in this case a transitional flow is produced for the flocculation step.

c) Power expenditure

The power expenditure for turbulent flow can be calculated by the equation A-2:

$$P = K_t n^3 D^5 \rho \qquad \text{Eq. (A-2)}$$

Where: P = Power expenditure, watts; Kt = constant that depends on the kind of impeller; n = rps of the impeller; ρ = fluid density; D = Impeller diameter, m.

Therefore, the power expenditure will be:

$$P = (33) \times \left(20 \frac{rev}{min} \times \frac{1\,min}{60s}\right)^3 \times (0.1\,m)^5 \times \left(998.2\, {}^{kg}/{}_{m^3}\right) = 0.0122\,W$$

The table A-2 shows a summary of the main shaft design parameters.

Table A-2 Shaft design summary parameters

Parameter	Value
Tank diameter (T)	0.2 m
Impeller diameter (D)	0.1 m
Length of impeller shaft (l_{sh})	0.9 m
Reynolds number (Re)	3320,7
Power expenditure (P)	0.0122 W
Motor power (P')	0.066 hp
Motor speed (N)	20 rpm

In general, it can be assumed that the pull-out torque for design purposes is between 1.5 and 2.5 time, the rated motor torque depending upon the nature of the mixing duty (i.e. F_{pt} = 1.5 for simple blending and 2.5 for more rigorous high viscosity or solids settling operations). The shaft in the LB-DAF will be used for mixing water, so F_{pt} = 1.5 (natural surface water plus small concentrations of a chemical coagulant).

d) Torque calculation (M_r – Nm)

The torque (M_r) can be calculated using the equation A-3.

$$M_r = P'/2\pi N \qquad \text{Eq. (A-3)}$$

Where: P' = motor power, w; N = motor speed, rps

$$M_r = \frac{0.0122\,w}{2 \times \pi \times 20\frac{rev}{min} \times \frac{1min}{60\,s}} = 5.82 \times 10^{-3}\,Nm$$

e) Pull – out torque of the motor (M_{pt} – Nm)

The pull-out of torque (M_{pt}) can be calculated using the equation A-4

$$M_{pt} = F_{pt} \times M_r \qquad \text{Eq. (A-4)}$$

$$M_{pt} = 1.5 \times 5.82 \times 10^{-3} Nm = 7.5 \times 10^{-3}\,Nm$$

f) Side force on impeller or stalling (F_s - N)

The side force on impeller (F_s) can be calculated using the equation A-5

$$F_s = 8M_{pt}/3D \qquad \text{Eq. (A-5)}$$

Where: D = Impeller diameter in (m)

$$F_s = \frac{8 \times (7.5 \times 10^{-3}\,Nm)}{3 \times 0.1m} = 0.2N$$

Therefore, the maximum side force on impeller of staling (F_{max}) will be:

$$F_s = F_{max} = 0.2N$$

e) Bending moment due to stalling forces (M_b - Nm)

The bending moment due to stalling forces (M_b) can be calculated by equation A-6.

$$M_b = F_{max} \times l_{sh} \qquad \text{Eq. (A-6)}$$

Where:

l_{sh}= length of impeller shaft (m) = 0.9 m

$$M_b = 0.2N \times 0.9m = 0.18\, Nm$$

f) Equivalent bending moment due to stalling forces (M_{be} – Nm)

The equivalent bending moment due to stalling forces (M_{be}) can be calculated by the equation A-7.

$$M_{be} = \left[M_b^2 + 0.75M_{pt}^2\right]^{1/2} \qquad \text{Eq. (A-7)}$$

$$M_{be} = [(0.18)^2 + 0.75 \times (7.5 \times 10^{-3}\ Nm)^2]^{1/2} = 0.18\, Nm$$

The shaft was constructed of stainless steel, so assuming the yield coefficient of this steal is:

$\boldsymbol{\sigma_y = 400 \times 10^6 Nm^{-2}}$

Choosing a shaft diameter of Dsh = 3/8" or 9.525x10^{-3} m

The direct stress due to the mass of the impeller must now be considered, and for very long shafts the direct stress due to the mass of the shaft. For safe operation, this combined stress must be less than yield stress as is showed in the equation A-8.

$$\frac{32M_{be}}{\pi D_{sh}^3}+\frac{4m_p g}{\pi D_{sh}^2}+l_{sh}\rho_s g<\sigma_y \qquad \text{Eq. (A-8)}$$

Where: ρ_s = shaft density = 8 x 10^3 kg/m^3; m_p = Mass of agitator = 120 kg

$$\frac{32\times 0.18Nm}{\pi(9.525\times 10^{-3}m)^3}+\frac{4\times 120kg\times 9.81\,m/s^2}{\pi(9.525\times 10^{-3}m)^2}+0.9m\times(8\times 10^3\,kg/m^3)\times 9.81\,m/s^2<\sigma_y$$

$$=2349661.5\ Nm^{-2}$$

Therefore, 2349661.5 < $\sigma_y = 400\times 10^6 Nm^{-2}$.Thus, the 3/8" shaft diameter is appropriate for the LB-DAF.

g) Yield strength of material in pure torsion (Ty – Nm^{-2})

The yield strength of material (Ty) is calculated by the equation A-9.

$$T_y = 0.577\sigma_y \qquad \text{Eq. (A-9)}$$

$$T_y = 0.577\times\ (400\times 10^6\,N/m^2)$$

$$T_y = 231\times 10^6\,N/m^2$$

h) Peak torsional shear stress in shaft due to 2.5 times T$_{pk}$ motor torque rate (Nm^{-2})

The peak torsional shear stress in the shaft is calculate by the equation A-10.

$$\tau_{pk}\neq 16\frac{(2.5M_{t\prime})}{\pi D_{sh}^3} \qquad \text{Eq. (A-10)}$$

$$\tau_{pk}\neq\frac{16\times 2.5\times(5.82\times 10^{-3}Nm)}{\pi\times(9.525\times 10^{-3}m)^3}=85750.79\,N/m^2$$

As the $\boldsymbol{\tau_{pk}}$ should be lower than the $\boldsymbol{T_y}$; therefore, the 3/8" shaft diameter is appropriate for the LB-DAF.

Appendix B

Velocity Gradient [G] (s^{-1}) Calculations: Supplementary Material

Important design parameters in the coagulation/flocculation (C/F) steps before a clarification process (i.e. sedimentation and flotation) include the mean velocity gradient (G), the detention time, the number of stages and the type of flocculation required. The concept of the mean velocity gradient (G) was developed by Camp and Stein (1943). The value of G is related to the rotational speed and the configuration of the agitator as well as the geometry of the mixing vessel. In this appendix the methodology used for calculating the impeller power number (Np) and the G for flocculation (before flotation) in the LB-DAF is presented. The Np and the G calculations were performed for three different impeller shape (i.e., square, rectangular and small rectangular). Figure B-1 shows the three different impeller configurations.

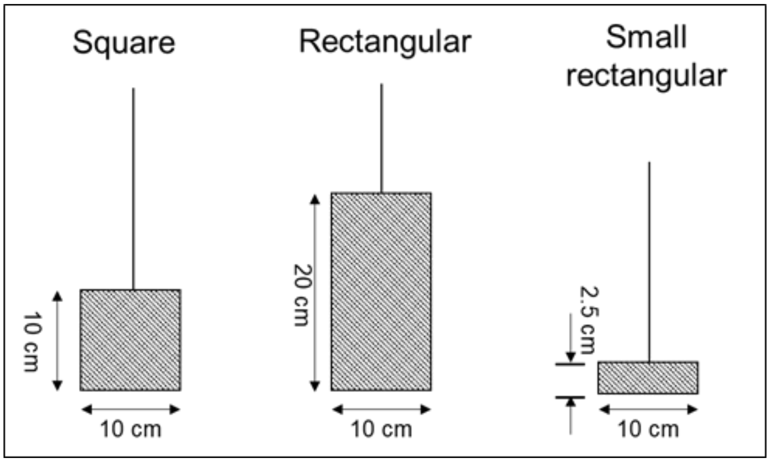

Figure B-1. Impeller configurations tested in the LB-DAF tank

B.1 Velocity gradient [G] (s^{-1}) calculated by Rushton, 1952 approach (square impeller)

A study on mixing of liquids in chemical processing conducted by Rushton, 1952 developed equations for calculating the number power (Np) of different impeller shapes in the viscous and turbulent range. These Np for calculating the G have been used for the design of vertical turbine flocculators in water treatment facilities. Although, these equations were developed in 1952 they are still published in current water treatment design books (Harnby et al., 2007; Wang et al., 2005). In base to the different impeller area tested in the LB-DAF the following Np were chosen for conducting the velocity gradient calculations.

Square impeller Np = 49
Rectangular impeller Np = 71
Small Rectangular (SR) Np = 36.5

B.1.1 Power expenditure (P) is obtained by using Rushton equation (B-1)

$$P = \frac{N_p}{g} n^3 D^5 \rho \qquad \text{Eq. (B-1)}$$

Where: P = Power expenditure, (W); N_p = Impeller power number; n = Impeller rotational speed, (rps); ρ = Water density, (kg/m^3); D = Impeller diameter, (m); g = Gravity constant, (m/s^2).

So, for the square impeller operated at 10 rpm and a water temperature of 20°C (ρ= 998.2 kg/m^3) P will be:

$$P = \frac{49}{9.8\, m/s^2} \times \left(10 \frac{rev}{min} \times \frac{1\, min}{60 s}\right)^3 \times (0.10\, m)^5 \times \left(998.2\, {}^{kg}\!/_{m^3}\right) = 2.3 \times 10^{-4}\, W$$

$$\boxed{\boldsymbol{P = 2.3 \times 10^{-4}\, W}}$$

B.1.2 Velocity gradient [G] (s^{-1})

The velocity gradient can be calculated by using the equation (B-2).

$$G = \sqrt{\frac{P}{\mu V}} \qquad \text{Eq. (B-2)}$$

Where: G = velocity gradient, s^{-1}; P = power expenditure, (W), (note 1 W = 1 $kg \cdot m^2/s^3$) μ = dynamic viscosity of the water, ($kg/m \cdot s$); V= volume of flocculation basin, (m^3).

So, for the LB-DAF filled with 21L of water at 20°C, then:

$$G = \sqrt{\frac{2.3 \times 10^{-4}\ kg \cdot m^2/s^3}{\left(1.002 \times 10^{-3}\, {}^{kg}\!/_{m \cdot s}\right) \times (0.021\, m^3)}} = 3.0\, s^{-1}$$

$$\boxed{\boldsymbol{G = 3.0\, s^{-1}}}$$

A summary of the Reynolds number (Re), P and G values for all the three impellers (i.e., square, rectangular and two-blades) using Rushton approach are shown in the table B-1.

Table B-1. Velocity gradient calculations summary different impellers (10 – 970 rpm).

Speed control	Mixing speed (rpm)	G-1 Square (s^{-1})	G-2 Rectangular (s^{-1})	G-3 SR (s^{-1})	Re-1 Square	Re-2 Rectangular	Re-3 SR	P-1 Square (W)	P-2 Rectangular (W)	P-3 SR (W)
0.5	**10**	3	4	3	1660	1660	1660	2.3E-04	3.3E-04	1.7E-04
1.0	**50**	37	45	32	8302	8302	8302	2.9E-02	4.2E-02	2.2E-02
1.5	**100**	105	126	90	16603	16603	16603	2.3E-01	3.3E-01	1.7E-01
2.0	**150**	193	232	166	24905	24905	24905	7.8E-01	1.1E+00	5.8E-01
2.5	**200**	296	357	256	33207	33207	33207	1.8E+00	2.7E+00	1.4E+00
3.0	**240**	390	469	336	39848	39848	39848	3.2E+00	4.6E+00	2.4E+00
3.5	**280**	491	591	424	46490	46490	46490	5.1E+00	7.3E+00	3.8E+00
4.0	**330**	628	756	542	54791	54791	54791	8.3E+00	1.2E+01	6.2E+00
4.5	**380**	776	934	670	63093	63093	63093	1.3E+01	1.8E+01	9.4E+00
5.0	**440**	967	1164	835	73055	73055	73055	2.0E+01	2.9E+01	1.5E+01
5.5	**500**	1172	1410	1011	83017	83017	83017	2.9E+01	4.2E+01	2.2E+01
6.0	**540**	1315	1583	1135	89659	89659	89659	3.6E+01	5.3E+01	2.7E+01
6.5	**600**	1540	1854	1329	99621	99621	99621	5.0E+01	7.2E+01	3.7E+01
7.0	**650**	1737	2090	1499	107922.5	107922	107922	6.3E+01	9.2E+01	4.7E+01
7.5	**710**	1982	2386	1711	117884.6	117885	117885	8.3E+01	1.2E+02	6.2E+01
8.0	**780**	2283	2748	1970	129507	129507	129507	1.1E+02	1.6E+02	8.2E+01
8.5	**830**	2506	3016	2163	137808.7	137809	137809	1.3E+02	1.9E+02	9.8E+01
9.0	**880**	2736	3293	2361	146110.4	146110	146110	1.6E+02	2.3E+02	1.2E+02
9.5	**930**	2972	3577	2565	154412.2	154412	154412	1.9E+02	2.7E+02	1.4E+02
10.0	**970**	3166	3811	2732	161053.6	161054	161054	2.1E+02	3.1E+02	1.6E+02

Note: The above velocity gradients were calculated in the LB-DAF using a high-torque, low-speed mixer 20 – 900 rpm (VAC SKU 5000820, Servo Dyne).

Table B-2. Velocity gradient calculations summary different impellers (2 – 200 rpm).

Speed control	Mixing speed (rpm)	G-1 Square (s^{-1})	G-2 Rectangular (s^{-1})	G-3 SR (s^{-1})	Re-1 Square	Re-2 Rectangular	Re-3 SR	P-1 Square (W)	P-2 Rectangular (W)	P-3 SR (W)
0.5	**2**	0	0	0	332	332	332	1.8E-06	2.7E-06	1.4E-06
1.0	**12**	4	5	4	1992	1992	1992	4.0E-04	5.8E-04	3.0E-04
1.5	**21**	10	12	9	3487	3487	3487	2.1E-03	3.1E-03	1.6E-03
2.0	**33**	20	24	17	5479	5479	5479	8.3E-03	1.2E-02	6.2E-03
2.5	**43**	30	36	26	7139	7139	7139	1.8E-02	2.7E-02	1.4E-02
3.0	**50**	37	45	32	8302	8302	8302	2.9E-02	4.2E-02	2.2E-02
3.5	**61**	50	60	43	10128	10128	10128	5.2E-02	7.6E-02	3.9E-02
4.0	**72**	64	77	55	11954	11954	11954	8.6E-02	1.2E-01	6.4E-02
4.5	**83**	79	95	68	13781	13781	13781	1.3E-01	1.9E-01	9.8E-02
5.0	**94**	96	115	82	15607	15607	15607	1.9E-01	2.8E-01	1.4E-01
5.5	**105**	113	136	97	17434	17434	17434	2.7E-01	3.9E-01	2.0E-01
6.0	**115**	129	156	112	19094	19094	19094	3.5E-01	5.1E-01	2.6E-01
6.5	**126**	148	178	128	20920	20920	20920	4.6E-01	6.7E-01	3.4E-01
7.0	**138**	170	204	147	22912	22913	22913	6.1E-01	8.8E-01	4.5E-01
7.5	**150**	193	232	166	24905	24905	24905	7.8E-01	1.1E+00	5.8E-01
8.0	**160**	212	255	183	26565	26566	26566	9.5E-01	1.4E+00	7.1E-01
8.5	**172**	236	285	204	28557	28558	28558	1.2E+00	1.7E+00	8.8E-01
9.0	**183**	259	312	224	30384	30384	30384	1.4E+00	2.1E+00	1.1E+00
9.5	**193**	281	338	242	32044	32045	32045	1.7E+00	2.4E+00	1.2E+00
10.0	**200**	296	357	256	33206	33207	33207	1.8E+00	2.7E+00	1.4E+00

Note: The above velocity gradients were calculated in the LB-DAF using a high-torque, low-speed mixer 2 – 200 rpm (VAC SKU 5000810, Servo Dyne).

Appendix C

Preliminary Work

The preliminary work of this research included:

1) Design of the LB-DAF: The design of the LB-DAF was made according to recommended parameters in the scientific literature for vertical turbine flocculators and dissolved air flotation units. The system was described and presented in chapter 3 and 4 and Appendix A.

2) Collection and characterization of different surface waters: This characterization was performed to help select waters with appropriate levels of hydrophobic NOM content (i.e., high SUVA values). The characterization was conducted in terms of turbidity, true Color, UV-254, TOC, DOC, SUVA, and Chlorophyll_*a*. Water from different locations in Ontario and Quebec were characterized. These waters include those that were tested further within this program (Belleville, ON and Smith Falls, ON) as these treatment plants include full-scale DAF units. Table C-1 shows the water characterization from the different locations. The water treatment facilities were chosen based on TOC information (Ontario Ministry of the Environment) (website: https://www.ontario.ca/environment-and-energy/ministry-environment-and-climate-change-resources). Table C-1 shows the water characterization from the different locations.

Table C-1 Raw water characterization from different locations

Parameter	Smiths* Falls ON 27/07/2016	Belleville* ON 24/08/2016	Aylmer* QC 27/07/2016	Casselman ON 27/07/2016	Perth ON 27/07/2016	Alexandria ON 27/07/2016
pH	7.53	7.40	7.06	7.32	7.47	7.43
Turbidity (NTU)	0.86	1.77	3.43	7.10	1.60	1.34
UV-254 (cm^{-1})†	1.42	1.17	2.20	2.17	1.23	2.49
TOC (mg/L)	5.08	5.21	NM	5.25	4.57	7.16
DOC (mg/L)	4.34	5.02	5.83	5.07	4.53	6.92
SUVA (L mg^{-1} m^{-1})	3.26	2.34	3.76	4.29	2.72	3.60
True Color (Pt-Co)	41	13	35	27	34	53
Chlorophyll_*a* (µg/L)	2,1	NM	NM	0.8	1.7	2.4

*Water treatment plants with DAF treatment

† The UV-254 cm^{-1} was measured by using a 10 cm path length quartz cell.

NM: not measured

The water characterisation showed that the water collected in Casselman, ON had a high SUVA>4.0, which according to Edzwald and Van Benschoten, (1990) this water can be classified like a water composed mostly from aquatic humics with high hydrophobicity characteristics. In contrast, the other samples showed a water with a medium SUVA values between 2 and 4, which can be described as water with a mixture of aquatic humics and other NOM, and a mixture of hydrophobic and hydrophilic NOM.

3) Preliminary jar tests: Numerous sets of conventional jar test for simulating conventional gravity settling (CGS) and dissolved air flotation (DAF) jar tests (DAF-jar test) were conducted using Ottawa River water (ORW) to build a data base on the differences between these two treatments for turbidity and organics reduction, and for comparing the performance of DAF-jar test with the Aylmer DAF water treatment plant (Aylmer, WTP). The jar tests were conducted from May to July of 2016. The main findings of this work were:

a) CGS and DAF jar tests conducted with different target pH (i.e., 5.0, 5.5, 6.0, and 6.5) did not impact the performance of both processes in terms of turbidity removals. However, CGS was superior to DAF for turbidity reduction for all the pH values with a removal percentage of 86% and

74%, respectively. In addition, natural organic matter NOM removal was slightly better by DAF than for CGS.

b) The DAF jar test did not predict turbidity removals well when it was compared with Aylmer WTP using the same coagulant type and dose and the same aid. The final turbidity for the DAF jar test was 1.36 NTU and the final turbidity reported by Aylmer WTP was 0.44 NTU, respectively. In addition, the NOM removals measured as UV-254 and DOC were similar in the DAF jar test and in Aylmer WTP.

c) The polymer addition for conducting DAF jar tests did not improve the turbidity removal treating ORW in comparison with alum alone. The turbidity removals were 83% and 77%, respectively. In addition, the NOM removal did not improve with the polymer addition and the removals were similar to those obtained with alum alone.

In summary, preliminary DAF jar test for Ottawa River water showed that DAF had slightly better NOM removals than CGS for UV-254. Note that this confirms the full-scale info from (Walker and Xu, 2016). In addition, DAF jar test comparisons with Aylmer WTP using the same coagulant type and dose showed that the DAF jar test under predict turbidity removals by 22%. The findings in this preliminary work are in agreement with some results found in previous studies cited in the literature review in relation to that DAF is superior to CGS for the removal of dissolved organic species DOC and UV-254 (Chu et al. 2011; Zou et al. 2011), and that DAF requires less time than CGS for obtaining similar results for organics reductions.

Appendix D

Different Bubble Devices Tested in the LB-DAF: Supplementary Material

With the objective to produce an obtain an adequate size and bubbles volume three different bubble devices were designed, built and tested in the LB-DAF. They are described as follows:

D.1 Plastic Disk with Small Center Orifice (Device I)

This device incorporated 1 cm diameter plastic disk with a small perforation in the center (1 mm diameter). This small disk is enclosed in a PVDF fitting connecting to the recycle ratio feed system (figure D-1). The main purpose of this device was that the pressurized saturated water hits the disk and at the same time generate a turbulence through the small orifice to generate the bubbles. However, this system had only a small volume of big size of bubbles. Therefore, it was discarded.

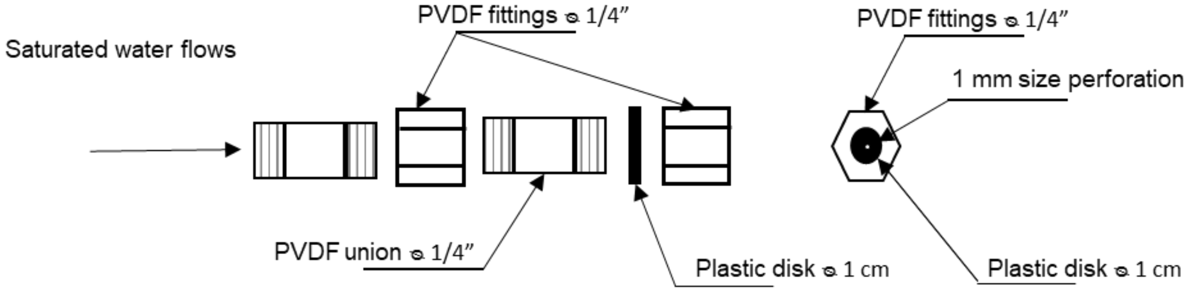

Figure D-1 Plastic Disk with Small Center Orifice (Device I)

D.2 Stainless-steel Nozzle (Device II)

This device was designed and constructed to simulate the DAF jar test nozzle. This device consists of a solid stainless-steel cylinder with a 1-1/2" diameter and a length of 4.0 cm. The cylinder has a ½" threaded hole in the center with a depth of 2cm. Then, the ½" hole diameter is reduced to a 1/8" diameter to the bottom. The device also has a solid stainless-steel disk, which was placed 3 mm in from of the cylinder (figure D-2). It was expected that once the pressurized water passes through the nozzle and it will hit the disk and flow outwards. This creates turbulence and bubbles. However, this nozzle also yielded a small volume of big size of bubbles. Therefore, this device also was discarded.

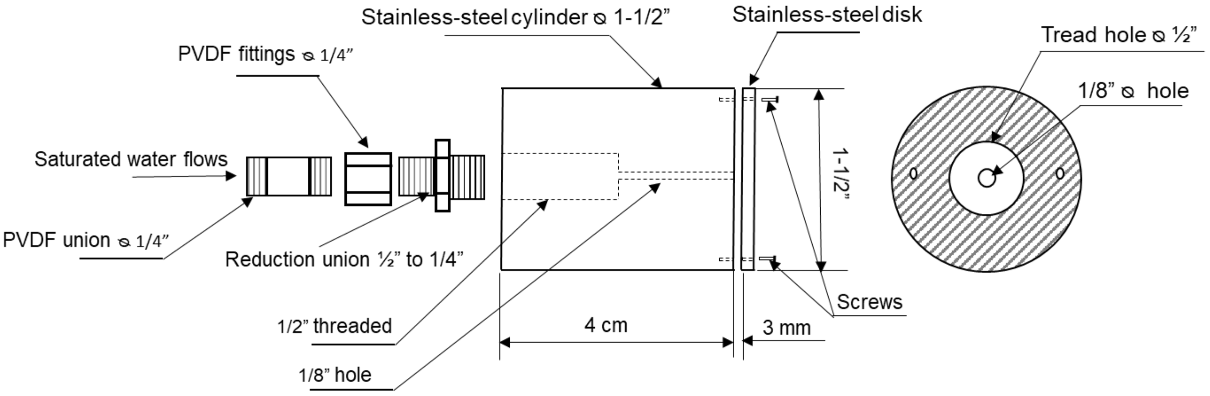

Figure D-2 Stainless-steel Nozzle (Device II)

D.3 Polyethylene Ring (Device III)

This device consists of a ring made of low-density polyethylene (LDPE) tubing (6.35 mm or 1/4" OD) and 19 cm diameter. The main purpose of this device was to generate an uniform bubble distribution a long the periphery of the LB-DAF. The device has small holes made with a heated regular sewing needle (figure D-3). The holes were placed 1 cm apart. This device provides much more bubbles volume than the device I and II, respectively. However, the bubble size obtained was bigger that the necessary to obtain good flotation results.

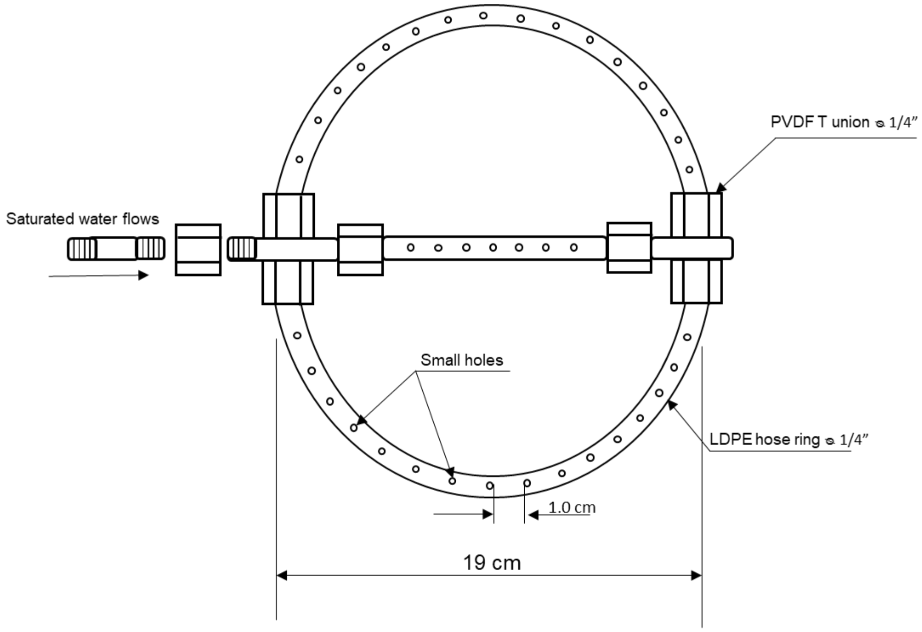

Figure D-3 Polyethylene O-ring Plan View (Device III)

D.4 Stainless-steel pipe plus needle valve (Device IV)

The last bubbles device tested in the LB-DAF consisted of a 6.35 mm OD stainless steel pipe. The LB-DAF bubble delivery pipe incorporates a 6.35 mm (1/4”) On/Off valve and a 6.35 mm (1/4”) needle valve (figure D.4). The On/Off valve controls the saturated water feed, while the partially open needle valve, located to approximately 10 cm from the LB-DAF tank bottom, helped control the bubble size. This device produced big volume of small size of bubbles necessary to obtain good flotation results. Therefore, this device was used to conduct the experiments in the LB-DAF tank.

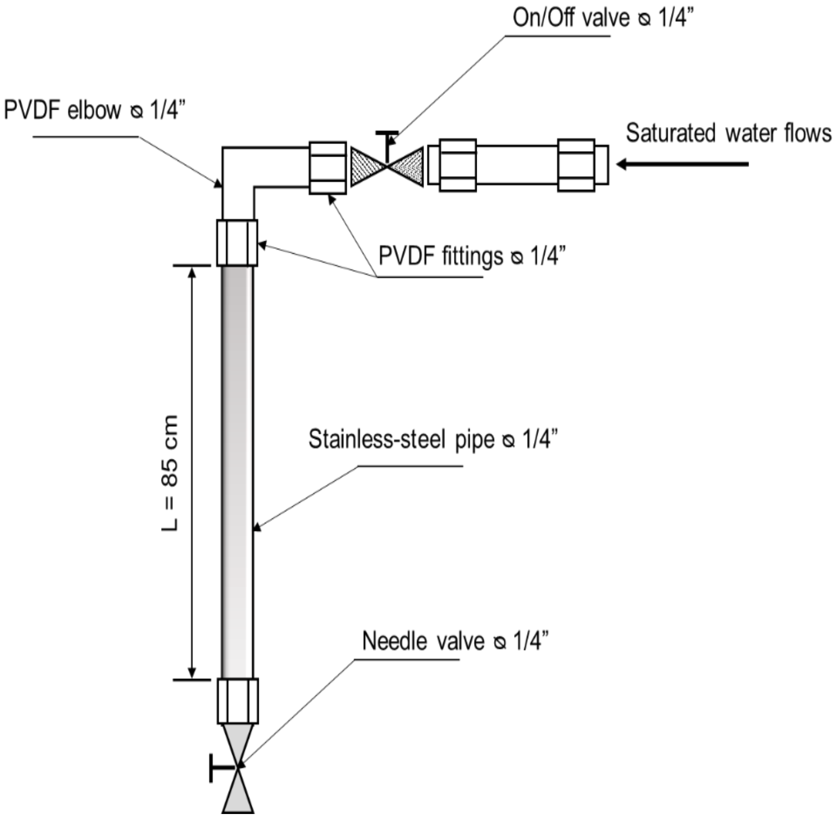

Figure D-4 Stainless-steel pipe plus needle valve (Device IV)

Appendix E

LB-DAF Laboratory Experiments Raw Data: Supplementary Material

This appendix contains the raw data obtained in the LB-DAF conducting laboratory experiments. The data is recorded for the turbidity sensitivity analysis test for all the variables tested. In addition, it is also presented the raw data obtained for the UV-254 absorbance and dissolved organic carbon (DOC) for Ottawa River water (Table E-1 to E-7), Belleville water and Smiths Falls (i.e., Rideau River) water experiments (Table E-8 to E-13), respectively.

E.1 LB-DAF Ottawa river water experiments raw data

The LB-DAF raw data experiments treating ORW are presented in table E-1 to E-5. In addition, the raw data from UV-254 and DOC final concentrations are introduced in tables E-6 and E-7, respectively. These data were presented in the chapter 4 and the dates of collection were June 30, July 19 and August 11 of 2017. In addition, a new set of experiments were conducted with ORW collected on May 11 of 2018.

Table E-1 Final turbidity values obtained in the LB-DAF at different [G] (s^{-1}) in the treatment of Ottawa River water in spring of 2018.

Mixing Speed (rpm)	G (s^{-1})	Final turbidity test 1 (NTU)	Final turbidity test 2 (NTU)	Average final turbidity (NTU)	Turbidity reduction (%)
21	8	0.97	1.04	1.01±0.04	80±6.0
33	16	1.25	1.05	1.15±0.10	84±4.0
43	24	0.63	0.54	0.59±0.04	89±1.3
61	41	0.48	0.45	0.47±0.02	90±0.6
83	64	0.49	0.53	0.51±0.02	87±1.2
105	92	0.44	0.48	0.46±0.02	91±4.0

Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table E-2 Final turbidity values obtained in the LB-DAF using different impeller types in the treatment of Ottawa River water in summer of 2017.

Impeller type	Final Turbidity Test 1 (NTU)	Final Turbidity Test 2 (NTU)	Average Final Turbidity (NTU)	Turbidity Reduction (%)
S	0.39	0.38	0.39±0.005	77±1.0
R	0.42	0.44	0.43±0.010	75±1.0
SR	0.67	0.66	0.67±0.005	66±1.0

Samples collected on summer of 2017 (June); water temperature 20±2°C; Turbidity = 4.6 NTU
(S) square, (R) rectangular and (SR) small rectangular

Table E-3 Final turbidity values obtained in the LB-DAF at different saturator pressures in the treatment of Ottawa River water in summer of 2017.

Saturator Pressure (PSI)	Final Turbidity Test 1 (NTU)	Final Turbidity Test 2 (NTU)	Average Final Turbidity (NTU)	Turbidity Reduction (%)
70	0.34	0.36	0.35±0.010	79±1.0
80	0.38	0.35	0.36±0.010	82±1.0
90	0.35	0.36	0.36±0.005	79±1.0

Samples collected on summer of 2017 (July); water temperature 20±2°C; Turbidity = 5.2 NTU

Table E-4 Turbidity reduction in the LB-DAF using different recycle ratio (RR) in the treatment of Ottawa River water in summer of 2017 and spring of 2018.

	Summer, 2017		Spring, 2018	
RR (%)	**Average Final Turbidity (NTU)**	**Turbidity Reduction (%)**	**Average Final Turbidity (NTU)**	**Turbidity Reduction (%)**
6	0.36±0.01	79±0.6	0.50±0.04	88±0.4
8	0.45±0.01	78±1.7	0.49±0.03	89±3.5
10	0.29±0.02	80±0.3	0.47±0.02	88±3.6
12	0.41±0.02	80±0.3	0.50±0.03	88±2.2
15	0.44±0.01	78±1.0	0.47±0.01	90±0.6

Samples collected on summer of 2017 (July); water temperature 20±2°C; Turbidity = 5.2 NTU
Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table E-5 Turbidity reduction in the LB-DAF using different water depth to tank diameter ratios (D/W) in the treatment of Ottawa River water in summer of 2017 and spring of 2018.

	Summer, 2017		Spring, 2018	
(D/W) (m/m)	**Average Final Turbidity (NTU)**	**Turbidity Reduction (%)**	**Average Final Turbidity (NTU)**	**Turbidity Reduction (%)**
2.5	0.38±0.01	78±1.0	0.50±0.04	86±0.5
3.0	0.41±0.01	79±1.9	0.49±0.03	88±2.9
3.5	0.37±0.01	80±1.9	0.47±0.02	90±0.7
4.0	0.69±0.03	80±0.6	0.50±0.03	84±0.5

Samples collected on summer of 2017 (August); water temperature 20±2°C; Turbidity = 3.4 NTU
Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table E-6 UV-254, DOC and SUVA reduction in the LB-DAF treating summer 2017 raw ORW

Parameter	Value	UV-254 (cm^{-1})	UV-254 Reduction (%)	DOC (mg/L)	DOC Reduction (%)	SUVA (L/mg/m)	SUVA Reduction (%)
G (s^{-1})	37	0.055±0.001	80±0.5	2.39±0.01	65±0.2	2.30±0.05	43±1.5
SP (psig)	70	0.069±0.001	73±0.5	2.97±0.01	50±0.2	2.33±0.05	47±1.6
	80	0.060±0.001	79±0.3	2.15±0.02	63±1.0	2.78±0.04	43±0.5
	90	0.067±0.003	74±1.6	2.97±0.04	50±0.5	2.22±0.04	48±1.3
RR (%)	6	0.065±0.002	77±1.1	2.56±0.08	63±2.0	2.25±0.01	45±0.3
	8	0.055±0.002	80±0.5	2.11±0.02	64±2.0	2.61±0.01	36±1.6
	10	0.053±0.001	81±0.5	2.46±0.01	64±2.2	2.46±0.05	40±1.4
	12	0.051±0.001	82±0.5	2.05±0.02	65±2.1	2.47±0.02	39±1.2
	15	0.054±0.000	81±0.5	2.12±0.09	64±2.3	2.55±0.05	37±1.6
D/W (m/m)	4.0	0.066±0.001	76±0.3	2.42±0.09	58±0.1	2.72±0.03	38±0.8
	3.5	0.053±0.000	81±0.3	2.41±0.00	65±1.7	2.44±0.08	45±2.7
	3.0	0.061±0.001	77±0.3	2.62±0.03	56±0.8	2.34±0.06	47±1.9
	2.5	0.059±0.001	77±0.5	2.52±0.01	57±0.2	2.34±0.06	47±1.8

Table E-7 UV-254, DOC and SUVA reduction in the LB-DAF treating spring 2018 raw ORW

Parameter	Value	UV-254 (cm^{-1})	UV-254 Reduction (%)	DOC (mg/L)	DOC Reduction (%)	SUVA (L/mg/m)	SUVA Reduction (%)
G (s^{-1})	8	0.059±0.002	80±0.1	2.60±0.11	61±0.4	2.25±0.02	48±0.7
	16	0.059±0.002	80±0.8	2.81±0.11	58±2.3	2.10±0.02	52±0.7
	24	0.053±0.001	82±0.5	2.67±0.03	60±0.6	2.00±0.07	53±1.2
	41	0.052±0.001	82±0.4	2.63±0.07	60±1.5	2.00±0.07	53±1.0
	64	0.057±0.001	82±0.4	2.73±0.06	60±1.3	2.09±0.04	52±1.3
	92	0.056±0.001	81±0.5	2.53±0.06	62±1.3	2.20±0.01	49±0.5
RR (%)	6	0.045±0.001	84±0.1	2.37±0.03	54±2.2	2.00±0.02	54±1.0
	8	0.047±0.001	84±0.1	2.40±0.05	55±1.2	2.00±0.03	54±1.2
	10	0.052±0.001	82±0.4	2.63±0.07	60±1.5	2.00±0.07	54±1.0
	12	0.046±0.002	84±0.3	2.39±0.06	56±2.0	2.00±0.03	54±1.0
	15	0.046±0.002	84±0.3	2.39±0.06	56±1.9	2.00±0.03	54±1.0
D/W (m/m)	4.0	0.056±0.001	81±0.7	2.63±0.02	60±0.3	2.14±0.04	51±1.2
	3.5	0.052±0.001	82±0.4	2.63±0.07	60±1.5	2.00±0.07	54±1.0
	3.0	0.052±0.001	82±0.3	2.46±0.02	63±0.4	2.11±0.04	51±1.4
	2.5	0.054±0.001	82±0.6	2.43±0.01	63±0.3	2.20±0.03	49±1.1

E.2 LB-DAF Belleville and Rideau river water experiments raw data

The LB-DAF raw data experiments for turbidity removal treating Belleville and Rideau River water are presented in table (E-8 to E-11). In addition, the raw data from UV-254 and DOC final concentrations are listed in tables (E-12 and E-13), respectively. These data were presented in the chapter 5 and 6. The dates of collection were June of 2018 for Smiths Falls. The Belleville water samples were collected in November 29 of 2017 and July 26 of 2018.

Table E-8 Final turbidity values obtained in the LB-DAF at different [G] (s^{-1}) treating Belleville and Rideau River water

	Belleville water [1]		**Rideau River water [2]**	
G (s^{-1})	**Average Final Turbidity (NTU)**	**Turbidity reduction (%)**	**Average Final Turbidity (NTU)**	**Turbidity reduction (%)**
10	0.44±0.09	95±1.6	0.34±0.02	59±15.1
20	0.37±0.07	96±1.2	0.35±0.02	60±12.9
30	0.37±0.08	96±1.3	0.25±0.02	72±6.8
50	0.44±0.01	95±0.4	0.37±0.05	67±9.3
79	0.31±0.03	97±0.3	0.19±0.03	78±1.8
113	0.34±0.05	96±0.8	0.27±0.09	65±18.8

[1] Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

[2] Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table E-9 Final turbidity values obtained in the LB-DAF at different saturator pressure treating Belleville and Rideau River water

	Belleville water [1]		**Rideau River water [2]**	
Saturator Pressure (psig)	**Average final turbidity (NTU)**	**Turbidity Reduction (%)**	**Average final turbidity (NTU)**	**Turbidity Reduction (%)**
70	0.59±0.01	61±1.2	0.37±0.05	67±9.3
80	0.51±0.06	66±1.0	0.26±0.03	65±4.9
90	0.40±0.04	74±1.0	0.30±0.04	65±7.2

[1] Samples collected on winter of 2017; water temperature 3.2±1°C; Turbidity = 1.51 NTU.

[2] Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table E-10 Final turbidity values obtained in the LB-DAF at different recycle ratio treating Belleville and Rideau River water

	Belleville water [1]		**Rideau River water [2]**	
Recycle Ratio (%)	**Average final turbidity (NTU)**	**Turbidity Reduction (%)**	**Average final turbidity (NTU)**	**Turbidity Reduction (%)**
6	0.50±0.02	94±0.3	0.28±0.01	66±5.1
8	0.40±0.05	95±0.8	ND	ND
10	0.44±0.01	95±0.4	0.37±0.05	67±9.3
15	ND	ND	0.25±0.01	55±6.5

[1] Samples collected on winter of 2017; water temperature 3.2±1°C; Turbidity = 1.51 NTU.

[2] Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

ND= no determined

Table E-11 Final turbidity values obtained in the LB-DAF at different water depth to tank diameter ratios (D/W) treating Belleville and Rideau River water

	Belleville water		**Rideau River water**	
(D/W) (m/m)	**Average Final Turbidity (NTU)**	**Turbidity Reduction (%)**	**Average Final Turbidity (NTU)**	**Turbidity Reduction (%)**
2.5	0.27±0.06	97±0.8	0.20±0.01	80±2.1
3.0	0.30±0.06	97±0.9	0.23±0.01	78±0.6
3.5	0.44±0.01	95±0.4	0.37±0.05	67±1.5
4.0	0.38±0.03	96±0.4	0.40±0.09	65±3.5

[1] Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

[2] Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table E-12 UV-254, DOC and SUVA reduction in the LB-DAF treating summer 2018 Belleville water

Parameter	Value	UV-254 (cm^{-1})	UV-254 Reduction (%)	DOC (mg/L)	DOC Reduction (%)	SUVA (L/mg/m)	SUVA Reduction (%)
G (s^{-1})	10	0.060±0.001	57	3.62±0.02	34	1.65±0.02	39
	20	0.061±0.001	56	3.52±0.01	36	1.73±0.01	36
	30	0.058±0.001	58	3.67±0.01	33	1.59±0.01	41
	50	0.059±0.001	58	3.65±0.02	34	1.61±0.02	40
	79	0.055±0.001	61	3.32±0.02	39	1.65±0.02	39
	113	0.056±0.001	60	3.43±0.01	38	1.63±0.02	39
RR (%)	6	0.059±0.001	58	3.58±0.02	35	1.65±0.01	39
	8	0.058±0.001	59	3.53±0.02	36	1.64±0.01	39
	10	0.059±0.001	58	3.65±0.02	34	1.61±0.01	40
SP (psig)	70	0.059±0.001	58	3.65±0.02	34	1.61±0.01	40
	80	0.055±0.001	61	3.49±0.02	36	1.57±0.01	42
	90	0.053±0.002	62	3.40±0.02	38	1.57±0.01	42
D/W (m/m)	4.0	0.053±0.001	62	3.25±0.02	41	1.62±0.01	40
	3.5	0.053±0.000	62	3.33±0.02	39	1.60±0.01	40
	3.0	0.059±0.001	58	3.65±0.02	34	1.61±0.01	40
	2.5	0.055±0.001	61	3.45±0.02	37	1.58±0.01	41

Table E-13 UV-254, DOC and SUVA reduction in the LB-DAF treating spring 2018 Rideau river water

Parameter	Value	UV-254 (cm^{-1})	UV-254 Reduction (%)	DOC (mg/L)	DOC Reduction (%)	SUVA (L/mg/m)	SUVA Reduction (%)
G (s^{-1})	10	0.064±0.001	72	3.03±0.01	54	2.09±0.03	40
	20	0.062±0.001	73	3.05±0.04	53	2.03±0.01	42
	30	0.063±0.001	73	3.00±0.06	54	2.09±0.03	40
	50	0.063±0.001	73	3.19±0.01	51	1.98±0.02	44
	79	0.063±0.001	73	2.98±0.03	54	2.11±0.02	40
	113	0.060±0.001	74	2.96±0.06	55	2.02±0.04	42
RR (%)	6	0.063±0.001	72	2.99±0.03	54	2.12±0.03	40
	10	0.063±0.001	73	3.19±0.01	51	1.98±0.02	42
	15	0.058±0.002	75	2.76±0.03	58	2.10±0.04	40
SP (psig)	70	0.063±0.001	73	3.19±0.01	51	1.98±0.02	40
	80	0.065±0.001	72	3.20±0.04	51	2.02±0.05	42
	90	0.065±0.002	72	3.18±0.04	51	2.03±0.02	40
D/W (m/m)	4.0	0.064±0.002	74	3.01±0.05	56	2.10±0.01	40
	3.5	0.063±0.001	73	3.19±0.01	51	1.98±0.02	42
	3.0	0.058±0.003	73	2.95±0.02	51	1.98±0.01	40
	2.5	0.061±0.001	72	2.87±0.04	54	2.11±0.01	44

Appendix F

LB-DAF Floc Size Characterization Using DPA Technique Raw Data: Supplementary Material

This appendix contains the raw data obtained in the LB-DAF treating different waters. The floc-particle size characterization was conducted using dynamic particle analysis (DPA) technique. The floc size characteristics for each velocity gradient (G) are presented as follows: Ottawa River water ORW (Table F-1 to F-6), Pre-treated Belleville water (PBW) (Table F-7 to F-12) and Rideau River water (RRW) (Table F-13 to F-18), respectively.

F.1 Ottawa River water floc size characteristics.

This floc size characterization was presented and analyzed in chapter 4.

Table F-1 Floc size and particle concentration ORW [G] (8 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	41867
2	1.75-2.75	2.25	12235
3	2.75-3.75	3.25	5162
4	3.75-4.75	4.25	4588
5	4.75-5.75	5.25	3824
6	5.75-6.75	6.25	3059
7	6.75-7.75	7.25	1147
8	7.75-8.75	8.25	2103
9	8.75-9.75	9.25	1529
10	9.75-10.75	10.25	1147

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
11	10.75-11.75	11.25	191
12	11.75-12.75	12.25	191
13	12.75-13.75	13.25	956
14	13.75-14.75	14.25	574
15	14.75-15.75	15.25	765
16	15.75-16.75	16.25	191
17	16.75-17.75	17.25	574
18	17.75-18.75	18.25	191
19	18.75-19.75	19.25	191
20	19.75-20.75	20.25	191
21	23.75-24.75	24.25	191
22	25.75-26.75	26.25	191
23	29.75-30.75	30.25	191
24	32.75-33.75	33.25	191
25	33.75-34.75	34.25	191
26	34.75-35.75	35.25	191
27	41.75-42.75	42.25	191

Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table F-2 Floc size and particle concentration ORW [G] (16 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	13495
2	1.75-2.75	2.25	570
3	2.75-3.75	3.25	570
4	3.75-4.75	4.25	760
5	4.75-5.75	5.25	190
6	6.75-7.75	7.25	190
7	7.75-8.75	8.25	380
8	8.75-9.75	9.25	380
9	9.75-10.75	10.25	190
10	10.75-11.75	11.25	760
11	11.75-12.75	12.25	190
12	12.75-13.75	13.25	190
13	13.75-14.75	14.25	190
14	14.75-15.75	15.25	190
15	15.75-16.75	16.25	570
16	16.75-17.75	17.25	570

No	**ECD_Range (µm)**	**ECD_Center (µm)**	**Particle_Concentration (#/ml)**
17	17.75-18.75	18.25	190
18	19.75-20.75	20.25	570
19	21.75-22.75	22.25	190
20	22.75-23.75	23.25	380
21	23.75-24.75	24.25	190

Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table F-3 Floc size and particle concentration ORW [G] (24 s^{-1})

No	**ECD_Range (µm)**	**ECD_Center (µm)**	**Particle_Concentration (#/ml)**
1	0.75-1.75	1.25	38235
2	1.75-2.75	2.25	8029
3	2.75-3.75	3.25	6691
4	3.75-4.75	4.25	3250
5	4.75-5.75	5.25	3441
6	5.75-6.75	6.25	1912
7	6.75-7.75	7.25	1912
8	7.75-8.75	8.25	2103
9	8.75-9.75	9.25	574
10	9.75-10.75	10.25	1721
11	10.75-11.75	11.25	574
12	11.75-12.75	12.25	191
13	13.75-14.75	14.25	956
14	14.75-15.75	15.25	574
15	15.75-16.75	16.25	382
16	16.75-17.75	17.25	765
17	17.75-18.75	18.25	382
18	18.75-19.75	19.25	382
19	19.75-20.75	20.25	191
20	23.75-24.75	24.25	191
21	26.75-27.75	27.25	191
22	27.75-28.75	28.25	382
23	28.75-29.75	29.25	191
24	35.75-36.75	36.25	191
25	36.75-37.75	37.25	191

Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table F-4 Floc size and particle concentration ORW [G] (41 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	32691
2	1.75-2.75	2.25	7222
3	2.75-3.75	3.25	3991
4	3.75-4.75	4.25	2281
5	4.75-5.75	5.25	2851
6	5.75-6.75	6.25	1901
7	6.75-7.75	7.25	1140
8	7.75-8.75	8.25	1330
9	8.75-9.75	9.25	1521
10	9.75-10.75	10.25	1330
11	10.75-11.75	11.25	570
12	11.75-12.75	12.25	1330
13	12.75-13.75	13.25	760
14	13.75-14.75	14.25	380
15	14.75-15.75	15.25	380
16	15.75-16.75	16.25	570
17	16.75-17.75	17.25	950
18	17.75-18.75	18.25	190
19	18.75-19.75	19.25	570
20	20.75-21.75	21.25	570
21	21.75-22.75	22.25	760
22	22.75-23.75	23.25	190
23	23.75-24.75	24.25	570
24	24.75-25.75	25.25	190
25	26.75-27.75	27.25	190
26	27.75-28.75	28.25	190
27	28.75-29.75	29.25	190
28	29.75-30.75	30.25	190

Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table F-5 Floc size and particle concentration ORW [G] (64 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	55517
2	1.75-2.75	2.25	14121
3	2.75-3.75	3.25	8511
4	3.75-4.75	4.25	7738
5	4.75-5.75	5.25	5997
6	5.75-6.75	6.25	4256
7	6.75-7.75	7.25	5803
8	7.75-8.75	8.25	2902
9	8.75-9.75	9.25	2128
10	9.75-10.75	10.25	2515
11	10.75-11.75	11.25	1741
12	11.75-12.75	12.25	774
13	12.75-13.75	13.25	1161
14	13.75-14.75	14.25	967
15	14.75-15.75	15.25	774
16	15.75-16.75	16.25	967
17	16.75-17.75	17.25	774
18	17.75-18.75	18.25	193
19	18.75-19.75	19.25	967
20	19.75-20.75	20.25	193
21	20.75-21.75	21.25	580
22	21.75-22.75	22.25	387
23	22.75-23.75	23.25	387
24	23.75-24.75	24.25	193
25	24.75-25.75	25.25	387
26	26.75-27.75	27.25	387
27	29.75-30.75	30.25	193
28	30.75-31.75	31.25	387
29	31.75-32.75	32.25	193
30	32.75-33.75	33.25	193
31	33.75-34.75	34.25	387
32	37.75-38.75	38.25	193
33	39.75-40.75	40.25	193
34	40.75-41.75	41.25	193

Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

Table F-6 Floc size and particle concentration ORW [G] (92 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	34061
2	1.75-2.75	2.25	8222
3	2.75-3.75	3.25	4894
4	3.75-4.75	4.25	2545
5	4.75-5.75	5.25	2153
6	5.75-6.75	6.25	1370
7	6.75-7.75	7.25	2349
8	7.75-8.75	8.25	1370
9	8.75-9.75	9.25	1370
10	9.75-10.75	10.25	2153
11	10.75-11.75	11.25	392
12	11.75-12.75	12.25	979
13	12.75-13.75	13.25	392
14	13.75-14.75	14.25	392
15	14.75-15.75	15.25	392
16	15.75-16.75	16.25	587
17	16.75-17.75	17.25	196
18	17.75-18.75	18.25	587
19	20.75-21.75	21.25	392
20	24.75-25.75	25.25	392
21	32.75-33.75	33.25	392
22	33.75-34.75	34.25	196
23	41.75-42.75	42.25	196

Samples collected on early spring of 2018; water temperature 6±1°C; Turbidity = 4 – 7 NTU.

F.2 Belleville water floc size characteristics.

This floc size characterization was presented and analyzed in chapter 5.

Table F-7 Floc size and particle concentration PWB [G] (10 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	27939
2	1.75-2.75	2.25	760
3	3.75-4.75	4.25	950
4	4.75-5.75	5.25	570
5	5.75-6.75	6.25	380
6	7.75-8.75	8.25	190
7	8.75-9.75	9.25	190
8	10.75-11.75	11.25	380
9	11.75-12.75	12.25	190
10	15.75-16.75	16.25	190
11	18.75-19.75	19.25	190
12	20.75-21.75	21.25	190
13	23.75-24.75	24.25	190
14	29.75-30.75	30.25	380
15	49.75-50.75	50.25	190

Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

Table F-8 Floc size and particle concentration PWB [G] (20 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	22254
2	1.75-2.75	2.25	1182
3	2.75-3.75	3.25	394
4	3.75-4.75	4.25	197
5	4.75-5.75	5.25	197
6	6.75-7.75	7.25	197
7	7.75-8.75	8.25	394
8	9.75-10.75	10.25	394
9	10.75-11.75	11.25	197
10	11.75-12.75	12.25	394
11	12.75-13.75	13.25	394

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
12	13.75-14.75	14.25	591
13	18.75-19.75	19.25	197
14	20.75-21.75	21.25	394
15	22.75-23.75	23.25	197
16	23.75-24.75	24.25	197
17	24.75-25.75	25.25	197
18	36.75-37.75	37.25	197
19	48.75-49.75	49.25	197
20	49.75-50.75	50.25	197
21	52.75-53.75	53.25	197
22	54.75-55.75	55.25	197

Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

Table F-9 Floc size and particle concentration PWB [G] (30 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	44297
2	1.75-2.75	2.25	1354
3	2.75-3.75	3.25	1354
4	3.75-4.75	4.25	774
5	5.75-6.75	6.25	193
6	6.75-7.75	7.25	193
7	9.75-10.75	10.25	387
8	11.75-12.75	12.25	580
9	13.75-14.75	14.25	193
10	14.75-15.75	15.25	193
11	15.75-16.75	16.25	387
12	20.75-21.75	21.25	193
13	22.75-23.75	23.25	580
14	26.75-27.75	27.25	193
15	31.75-32.75	32.25	193
16	42.75-43.75	43.25	193
17	43.75-44.75	44.25	193
18	45.75-46.75	46.25	193
19	60.75-61.75	61.25	193

Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

Table F-10 Floc size and particle concentration PWB [G] (50 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	33647
2	1.75-2.75	2.25	1338
3	2.75-3.75	3.25	1721
4	3.75-4.75	4.25	765
5	4.75-5.75	5.25	191
6	5.75-6.75	6.25	191
7	7.75-8.75	8.25	382
8	8.75-9.75	9.25	382
9	9.75-10.75	10.25	191
10	10.75-11.75	11.25	956
11	11.75-12.75	12.25	382
12	12.75-13.75	13.25	574
13	18.75-19.75	19.25	191
14	20.75-21.75	21.25	191
15	24.75-25.75	25.25	191
16	26.75-27.75	27.25	191
17	28.75-29.75	29.25	191
18	46.75-47.75	47.25	191
19	48.75-49.75	49.25	191
20	54.75-55.75	55.25	191

Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

Table F-11 Floc size and particle concentration PWB [G] (79 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	110480
2	1.75-2.75	2.25	2560
3	2.75-3.75	3.25	788
4	3.75-4.75	4.25	591
5	4.75-5.75	5.25	197
6	5.75-6.75	6.25	197
7	6.75-7.75	7.25	197
8	8.75-9.75	9.25	788
9	9.75-10.75	10.25	394
10	23.75-24.75	24.25	197
11	45.75-46.75	46.25	197

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
12	49.75-50.75	50.25	197
13	53.75-54.75	54.25	197
14	61.75-62.75	62.25	197
15	67.75-68.75	68.25	197

Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

Table F-12 Floc size and particle concentration PWB [G] (113 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	55767
2	1.75-2.75	2.25	2692.2
3	2.75-3.75	3.25	1346.1
4	3.75-4.75	4.25	961.5
5	4.75-5.75	5.25	192.3
6	6.75-7.75	7.25	192.3
7	7.75-8.75	8.25	576.9
8	8.75-9.75	9.25	384.6
9	9.75-10.75	10.25	384.6
10	10.75-11.75	11.25	576.9
11	11.75-12.75	12.25	192.3
12	12.75-13.75	13.25	192.3
13	15.75-16.75	16.25	384.6
14	17.75-18.75	18.25	192.3
15	18.75-19.75	19.25	384.6
16	22.75-23.75	23.25	384.6
17	25.75-26.75	26.25	192.3
18	26.75-27.75	27.25	192.3
19	27.75-28.75	28.25	192.3
20	37.75-38.75	38.25	192.3
21	49.75-50.75	50.25	192.3
22	52.75-53.75	53.25	192.3

Samples collected on summer of 2018; water temperature 24±1°C; Turbidity = 8 – 12 NTU.

F.3 Rideau River water floc size characteristics.

This floc size characterization was presented and analyzed in chapter 5.

Table F-13 Floc size and particle concentration RRW [G] (10 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	82970
2	1.75-2.75	2.25	14338
3	2.75-3.75	3.25	7838
4	3.75-4.75	4.25	4588
5	4.75-5.75	5.25	3441
6	5.75-6.75	6.25	4205
7	6.75-7.75	7.25	4014
8	7.75-8.75	8.25	1911
9	8.75-9.75	9.25	2676
10	9.75-10.75	10.25	1529
11	10.75-11.75	11.25	1911
12	11.75-12.75	12.25	764
13	12.75-13.75	13.25	1338
14	13.75-14.75	14.25	764
15	14.75-15.75	15.25	382
16	15.75-16.75	16.25	955
17	16.75-17.75	17.25	1147
18	17.75-18.75	18.25	191
19	18.75-19.75	19.25	573
20	19.75-20.75	20.25	573
21	20.75-21.75	21.25	573
22	22.75-23.75	23.25	191
23	24.75-25.75	25.25	191
24	25.75-26.75	26.25	191
25	27.75-28.75	28.25	191
26	28.75-29.75	29.25	573
27	29.75-30.75	30.25	191
28	31.75-32.75	32.25	382
29	33.75-34.75	34.25	191
30	39.75-40.75	40.25	382
31	40.75-41.75	41.25	382
32	43.75-44.75	44.25	382
33	47.75-48.75	48.25	191
34	50.75-51.75	51.25	191

No	ECD_Range (μm)	ECD_Center (μm)	Particle_Concentration (#/ml)
35	58.75-59.75	59.25	191
36	60.75-61.75	61.25	191
37	62.75-63.75	63.25	191
38	64.75-65.75	65.25	191
39	83.75-84.75	84.25	191
40	94.75-95.75	95.25	191
41	110.75-111.75	111.25	191
42	116.75-117.75	117.25	191
43	130.75-131.75	131.25	191

Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table F-14 Floc size and particle concentration RRW [G] (20 s^{-1})

No	ECD_Range (μm)	ECD_Center (μm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	34021
2	1.75-2.75	2.25	3801
3	2.75-3.75	3.25	3991
4	3.75-4.75	4.25	1711
5	4.75-5.75	5.25	1330
6	5.75-6.75	6.25	1521
7	6.75-7.75	7.25	380
8	7.75-8.75	8.25	570
9	8.75-9.75	9.25	380
10	9.75-10.75	10.25	1140
11	10.75-11.75	11.25	380
12	11.75-12.75	12.25	190
13	12.75-13.75	13.25	760
14	13.75-14.75	14.25	190
15	14.75-15.75	15.25	190
16	15.75-16.75	16.25	190
17	16.75-17.75	17.25	190
18	18.75-19.75	19.25	190
19	20.75-21.75	21.25	380
20	22.75-23.75	23.25	380
21	23.75-24.75	24.25	190
22	25.75-26.75	26.25	190
23	27.75-28.75	28.25	190
24	29.75-30.75	30.25	190
25	31.75-32.75	32.25	190

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
26	34.75-35.75	35.25	190
27	36.75-37.75	37.25	190
28	42.75-43.75	43.25	190
29	43.75-44.75	44.25	190
30	45.75-46.75	46.25	190
31	50.75-51.75	51.25	190
32	63.75-64.75	64.25	190

Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table F-15 Floc size and particle concentration RRW [G] (30 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	20504
2	1.75-2.75	2.25	2708
3	2.75-3.75	3.25	2128
4	3.75-4.75	4.25	580
5	4.75-5.75	5.25	1161
6	5.75-6.75	6.25	774
7	6.75-7.75	7.25	967
8	7.75-8.75	8.25	1161
9	8.75-9.75	9.25	387
10	9.75-10.75	10.25	387
11	10.75-11.75	11.25	387
12	11.75-12.75	12.25	580
13	12.75-13.75	13.25	193
14	13.75-14.75	14.25	193
15	15.75-16.75	16.25	193
16	20.75-21.75	21.25	387
17	21.75-22.75	22.25	193
18	43.75-44.75	44.25	193
19	60.75-61.75	61.25	193
20	64.75-65.75	65.25	193

Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table F-16 Floc size and particle concentration RRW [G] (50 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	62897
2	1.75-2.75	2.25	10323
3	2.75-3.75	3.25	4015
4	3.75-4.75	4.25	4206
5	4.75-5.75	5.25	2868
6	5.75-6.75	6.25	1529
7	6.75-7.75	7.25	1529
8	7.75-8.75	8.25	2103
9	8.75-9.75	9.25	1147
10	9.75-10.75	10.25	956
11	10.75-11.75	11.25	191
12	11.75-12.75	12.25	382
13	12.75-13.75	13.25	956
14	13.75-14.75	14.25	382
15	14.75-15.75	15.25	191
16	15.75-16.75	16.25	574
17	16.75-17.75	17.25	574
18	17.75-18.75	18.25	382
19	18.75-19.75	19.25	382
20	19.75-20.75	20.25	574
21	20.75-21.75	21.25	382
22	23.75-24.75	24.25	191
23	24.75-25.75	25.25	191
24	26.75-27.75	27.25	191
25	27.75-28.75	28.25	191
26	28.75-29.75	29.25	191
27	32.75-33.75	33.25	191
28	33.75-34.75	34.25	191
29	37.75-38.75	38.25	382
30	38.75-39.75	39.25	191
31	40.75-41.75	41.25	191
32	48.75-49.75	49.25	191
33	49.75-50.75	50.25	191

Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table F-17 Floc size and particle concentration RRW [G] (79 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	7264.7
2	1.75-2.75	2.25	955.9
3	2.75-3.75	3.25	764.7
4	3.75-4.75	4.25	764.7
5	4.75-5.75	5.25	764.7
6	5.75-6.75	6.25	382.4
7	6.75-7.75	7.25	191.2
8	7.75-8.75	8.25	573.5
9	10.75-11.75	11.25	191.2
10	13.75-14.75	14.25	191.2
11	15.75-16.75	16.25	191.2
12	18.75-19.75	19.25	191.2
13	25.75-26.75	26.25	191.2
14	49.75-50.75	50.25	191.2

Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.

Table F-18 Floc size and particle concentration RRW [G] (113 s^{-1})

No	ECD_Range (µm)	ECD_Center (µm)	Particle_Concentration (#/ml)
1	0.75-1.75	1.25	14701
2	1.75-2.75	2.25	2321
3	2.75-3.75	3.25	967
4	3.75-4.75	4.25	1741
5	4.75-5.75	5.25	774
6	5.75-6.75	6.25	387
7	6.75-7.75	7.25	580
8	7.75-8.75	8.25	580
9	8.75-9.75	9.25	193
10	9.75-10.75	10.25	193
11	10.75-11.75	11.25	387
12	11.75-12.75	12.25	387
13	12.75-13.75	13.25	193
14	15.75-16.75	16.25	387
15	20.75-21.75	21.25	193
16	23.75-24.75	24.25	193
17	40.75-41.75	41.25	193
18	54.75-55.75	55.25	193

Samples collected on spring of 2018; water temperature 16±1°C; Turbidity = 0.92 NTU.