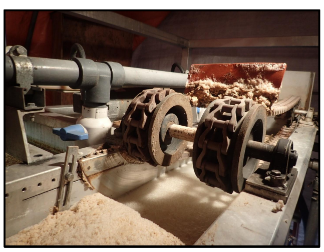
REPORT

Town of Ladysmith

Arbutus Water Treatment Plant Phase 2
Pilot-scale Treatability Study



September 2015

ASSOCIATED ENGINEERING
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Date 4/9/2015
#04-15-078

Executive Summary

The Township of Ladysmith relies on surface water drawn from two intakes: the Chicken Ladder intake and Stocking Lake intake, to provide drinking water to Ladysmith and the Diamond Improvement District. The Township also has a Memorandum of Understanding to provide water to the two Stz'uminus First Nation communities on I.R. 12 and I.R. 13. Water from the two intakes is treated at the Arbutus Water Treatment Plant (WTP). Phase I of the WTP's construction consisted of converging supply mains from the two intakes to a single point of treatment, and chlorine disinfection. Phase II will add pre-treatment and filtration to the WTP, to achieve the following treatment objectives:

- Consistently remove turbidity to drinking water levels as indicated in the Guidelines for Canadian Drinking Water Quality (GCDWQ) Turbidity Technical Document.
- Provide a multi-barrier against micro-biological contaminants and achieve a minimum 3-log (99.9%) removal of *Cryptosporidium parvum* and *Giardia*.
- Reduce true colour to meet the GCDWQ aesthetic objectives.
- Remove organic matter in the raw water and reduce the risk of disinfection byproduct (DBP) formation in the distribution system.

Associated Engineering and Koers & Associates Engineering were retained to evaluate different particulate removal processes for the WTP through bench-scale testing and piloting.

Bench-scale testing was conducted in December of 2014. A significant storm event occurred during this time, allowing for the bench-scale processes to be tested using the most difficult raw water conditions expected to be encountered at the WTP. Coagulation and flocculation followed by either sedimentation or dissolved air flotation (DAF) were tested, using several different combinations of pre-treatment chemicals and doses to create a 'short-list' of chemicals to test at the pilot scale. For the sedimentation clarification process, the three best performing options were polyaluminum chloride (PACl or ClearPAC), aluminum chlorohydrate (ACH or CTI4900) or alum followed by a flocculant aid. For the DAF process, the three best performing options were ACH, PACl, and powdered activated carbon (PAC) followed by alum. The DAF system struggled to lift all of the suspended material in the treated water to the surface for removal, resulting in poorer turbidity removal when compared to the sedimentation process. However, piloting of DAF was still considered for piloting because of its ability to remove organic material and because of the Township's familiarity of DAF that they use at their wastewater treatment plant.

Four different treatment configurations were then piloted:

- Conventional treatment using settling tubes (ST), consisting of coagulation, flocculation, sedimentation and dual-media filtration.
- DAF and media filtration, consisting of coagulation, flocculation, DAF and dual-media filtration.

- DAF and membrane filtration, consisting of coagulation, flocculation, DAF and membrane ultrafiltration.
- Direct membrane filtration, consisting of coagulation, flocculation, and membrane ultrafiltration.

Piloting was conducted from March 2015 to June. Piloting was primarily focused on treating water from Chicken Ladder, which traditionally has greater levels of turbidity and colour than Stocking Lake. Several weeks of piloting, using Stocking Lake, were conducted to verify whether treatment conditions suitable for Chicken Ladder were also effective for Stocking Lake. Pilot testing determined that both conventional treatment and DAF, when followed by dual-media filtration, could not consistently reduce turbidity to meet drinking water objectives and therefore would not be considered able to sufficiently provide protection against viruses and protozoa. Post-treatment aluminum concentrations, caused by the incomplete removal of the dosing chemicals during treatment, also exceeded the GCDWQ Operational Guidelines for drinking water.

Direct membrane filtration was able to consistently reduce turbidity to drinking water objectives and therefore would be awarded disinfection credits for the removal of *Cryptosporidium* and *Giardia*. However, the membranes would experience a rapid rate of fouling, requiring frequent membrane cleanings, unless only low levels of coagulant chemicals were added upstream. At these low doses, direct membrane filtration achieved a poor level of colour and organics removal.

DAF followed by membrane filtration was recommended. This option was able to successfully achieve all of the drinking water treatment objectives, including significantly reducing the potential for DBP formation in the distribution system. The DAF system also protected the membranes from fouling, allowing for much higher doses of pre-treatment chemicals to be added without compromising the membranes. DAF pre-treatment also allowed for a greater margin of error in dosing accuracy, so that if a chemical dose was accidentally increased, it was less likely to impact the membranes then when direct filtration was used.

A conceptual cost for a 125 L/s DAF and membrane filtration plant, with sufficient housing to allow for an expansion to 250 L/s, was developed. These costs were based on layouts prepared in the “Arbutus Water Treatment Plant Phase II – Filtration Pre-Design Report”, dated January 2015, and show an increase in capital costs for the following reasons:

- Included redundant tanks and membranes to allow one component of the WTP to be brought off-line without compromising the WTP’s ability to supply 125 L/s of potable water.
- The extra costs associated with adding DAF, complete with additional structural footprint and residuals management equipment to the original membrane layout.
- A significant change in the US dollar exchange rate since January, increasing the Canadian cost of all process equipment supplied from the US.

The option of building Phase II of the Arbutus WTP as a direct membrane plant first, then adding DAF at a later date was then considered. Cost estimates for these two scenarios are summarized below.

<table>
<tr><th>Process Description</th><th>DAF + Membrane Filtration</th><th>Direct Membrane Filtration</th><th>DAF (Built Afterwards)</th></tr>
<tr><td rowspan="2">Capital Cost</td><td rowspan="2">$13,300,000</td><td>$10,000,000</td><td>$4,100,000</td></tr>
<tr><td colspan="2">$14,100,000 total</td></tr>
<tr><td>Annual Cost</td><td>$343,000 /year</td><td>$349,000 /year</td><td>$343,000 /year</td></tr>
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It is important to note that, if a direct membrane filtration plant is constructed, the following factors will need to be considered:

- The amount of colour removed by the direct filtration plant will be low and treated water may periodically exceed the GCDWQ aesthetic objective for this parameter.
- DBP precursor removal was not significantly impacted by direct membrane filtration. The level of DBPs currently observed in the Ladysmith distribution system will not lower after the membranes are installed.
- Close attention will need to be paid to pre-treatment chemical dosing to avoid rapid fouling of the membranes.
- The rate of chlorine residual decay, due to organics remaining in the treated water, should be considered when determining whether a rechlorination station will be needed at the tie-in location to the Stz'uminus communities.

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List of Abbreviations

ACH	Aluminum chlorohydrate
AO	Aesthetic objective
DAF	Dissolved air flotation
DBP	Disinfection by-product
DBPFP	Disinfection by-product formation potential
DOC	Dissolved organic carbon
GCDWQ	Guidelines for Canadian Drinking Water Quality
HAAFP	Haloacetic acid formation potential
MAC	Maximum acceptable concentration
MC	Maintenance clean
PAC	Powdered activated carbon
PACl	Polyaluminum chloride
ST	Settling tube clarifier
THMFP	Trihalomethane formation potential
TMP	Transmembrane pressure
TOC	Total organic carbon
UVT	Ultraviolet transmittance

1 Introduction

1.1 SCOPE OF WORK

The scope of work for the treatability study involved an evaluation of different treatment process combinations through bench-scale testing and pilot-scale testing.

The objectives of the bench-scale testing were to assess the effectiveness of chemical pre-treatment for colour and organics reduction in the water sources used by the Township of Ladysmith, and to provide initial optimization of the conventional pre-treatment pilot systems.

The objectives of the pilot study were to evaluate the treatment performance and determine optimal operating parameters for different combinations of pre-treatment and filtration options, with the main objective of determining which treatment combination is most suitable for the Arbutus Water Treatment Plant Phase Two expansion.

The pre-treatment options are:
- Coagulation, flocculation and clarification with dissolved air flotation (DAF)
- Coagulation, flocculation and clarification with settling tube clarifier (ST)
- Coagulation and flocculation (used for direct membrane filtration only)

The filtration options are:
- Dual media filtration (sand/anthracite)
- Media filtration (ultrafiltration, GE ZW100)

The information obtained from the treatability study will inform the selection of the full-scale treatment processes, and will be used to estimate process behaviour, challenges, and cost implication at full-scale design.

1.2 EXISTING WATER SYSTEM

Currently, the Township of Ladysmith (Township) relies on surface water as their source of drinking water via two intakes. One intake is located at Stocking Lake. The second intake, called the Chicken Ladder Intake, draws water from Holland Creek. Holland Creek water is fed by Holland Lake, which periodically receives contributions from Bannon Creek. The Township predominantly relies on Stocking Lake from October to April, and switches to Chicken Ladder from April to October. Both intakes lead to the Arbutus Water Treatment Plant (WTP), where water is subjected to chlorine disinfection using chlorine gas.

As detailed in our previous reports, the water quality for these water sources can be characterized to be of relatively low turbidity and low alkalinity. The problems associated with these water sources are related to colour and organics. The colour levels regularly exceed the aesthetic objectives (AO) under the Guidelines for Canadian Drinking Water Quality (GCDWQ). The water contains organic concentrations that could possibly lead to high levels of disinfection by-products (DBP) when chlorinated.

2 Study Design

The bench-scale study protocol and results were detailed in a technical memorandum dated January 2015, appended to this report. A summary of the results is provided below.

2.1 BENCH-SCALE TESTING

AE conducted onsite bench-scale testing on December 10-11, 2014. This testing also coincided with a significant storm event that resulted in noticeable change in raw water quality, including increases in turbidity and colour as well as reduction of UVT.

Dissolved air flotation and sedimentation were compared. The bench-scale testing results showed that DAF provided similar water quality to conventional sedimentation in terms of turbidity reduction, and outperformed sedimentation with respect to colour reduction. However, a significant portion of the floc settled to the bottom of the jars. This indicated that DAF may struggle with high turbidity loadings as seen in significant winter storm events.

The bench-scale testing recommended sedimentation with dual media filtration, as well as membranes, for the pilot-scale testing. However, DAF was later re-included in the pilot-scale protocol for a number of reasons:

- The Township already owns and operates a DAF system in a different facility that allows the transfer of operational knowledge.
- DAF may be able to treat raw water from clearer sources, such as from Stocking Lake or Holland Lake, when storm conditions are not impacting source water quality.

2.2 PRE-TREATMENT CHEMICALS

The following chemicals were selected for testing in the pilot study, based on the optimized results from the bench-scale study.

Table 2-1
Pre-treatment Chemicals

Chemical(s)	Pilot to Use Chemicals	Optimized Bench-scale Dose	Desired Dosing Range
ClearPAC (PACl)	Conventional DAF Membrane	20 mg/L	5 – 30 mg/L
CTI4900 (aluminum chlorohydrate; ACH)	Conventional DAF Membrane	8 mg/L	1 – 10 mg/L

Chemical(s)	Pilot to Use Chemicals	Optimized Bench-scale Dose	Desired Dosing Range
Alum	Conventional DAF Membrane	25 mg/L	5 – 30 mg/L
Flocculant aid (CL2410) – to be used with slum	Conventional	5 mg/L	1 – 10 mg/L
Powdered activated carbon (PAC) – to be used with Alum	DAF	7 mg/L	5-10 mg/L

2.3 PILOT TESTING

The pilot study commenced in March 2015 and ran until late June. A pilot process schematic is shown in Figure 2-1, which depicts the four treatment combinations tested:

- ST + media filtration: Coagulation/flocculation/ST sedimentation + dual media filtration
- DAF + media filtration: Coagulation/flocculation/DAF clarification + dual media filtration
- DAF + membrane filtration: Coagulation/flocculation/DAF clarification + UF membranes
- Direct membrane filtration: Coagulation/flocculation + UF membranes

The pilot systems were monitored, operated and maintained primarily by the Township of Ladysmith operators on a daily basis. The membrane pilot was remotely monitored and operated by the membrane supplier. Technical support was provided by AE in the form of bi-weekly visits, phone check-ins and e-mail updates. The pilot schedule, showing the length of testing each option and the chemicals used, is provided as Figure 2-2.

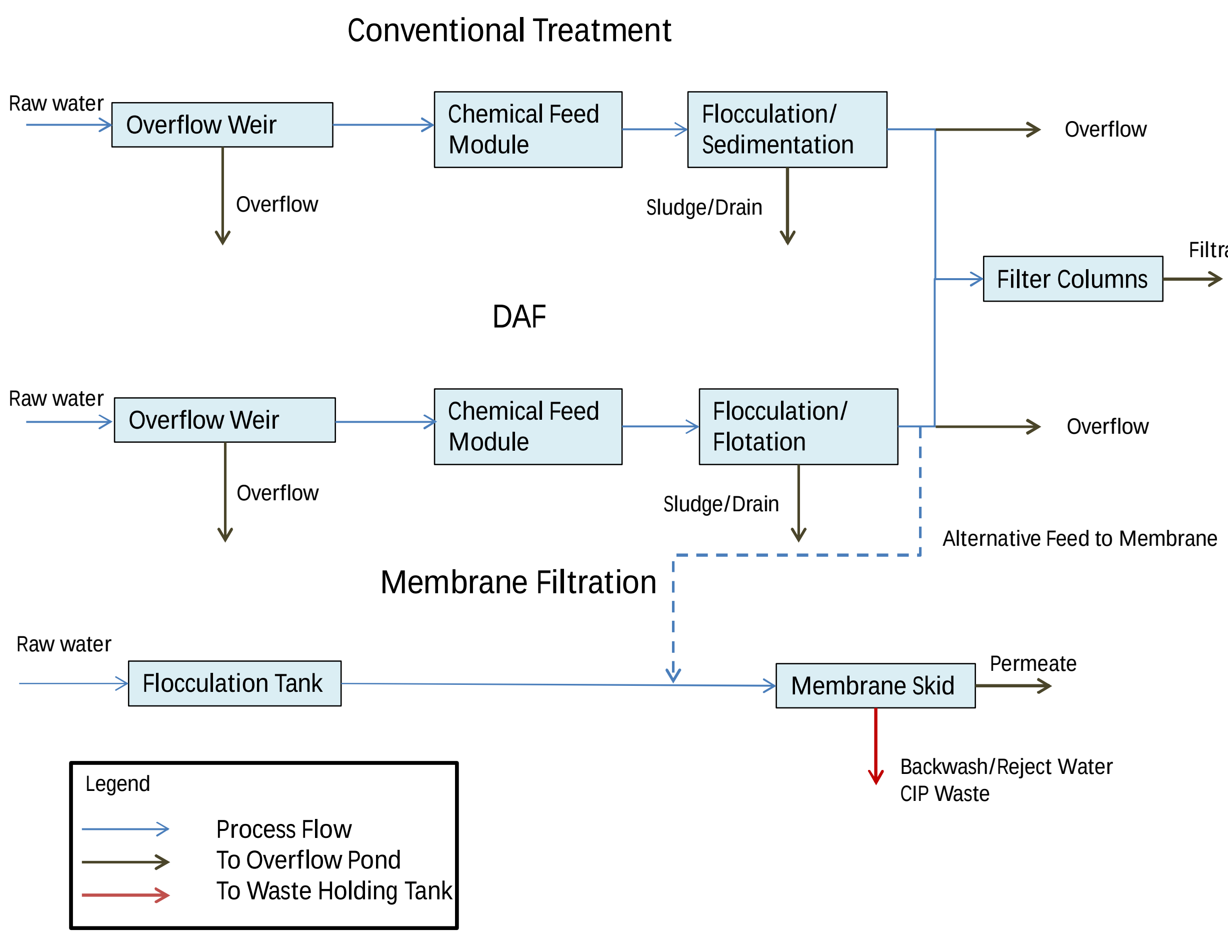


Figure 2-1: Pilot Process Schematic

The pilot schedule is shown in Figure 2-2.

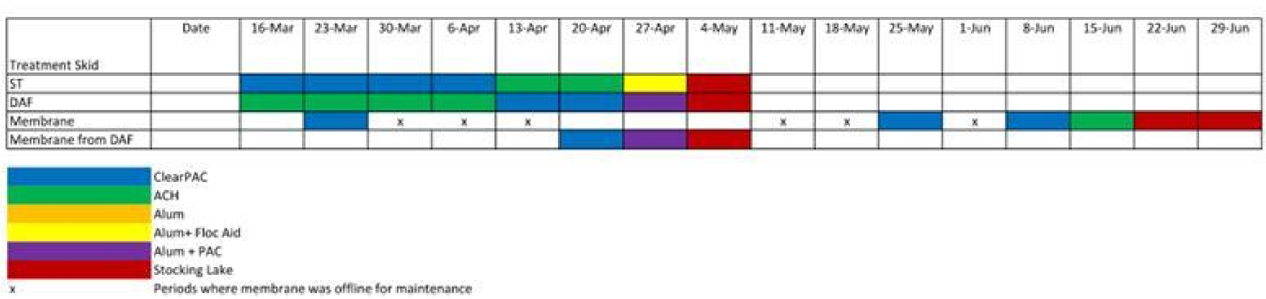


Figure 2-2
Piloting Schedule

2.3.1 Corix Pilot Systems

The DAF, ST and media filtration units were supplied by Corix. The DAF and ST systems were housed in separate heated tents. Heating, lighting and treatment units were powered from the Arbutus WTP. Untreated water was fed to the treatment units from buried, dedicated lines from the Chicken Ladder and Stocking Ladder intakes. The lines were flushed before starting operation to clear the buried lines of any stagnant water.

The DAF unit consisted of a chemical dosing skid and a coagulation/flocculation/flotation skid The ST system consisted of a chemical dosing skid and a coagulation/flocculation/settling skid. Both treatment units led to a media filtration skid that used two parallel filter columns. Each filter column could only process 0.02 L/s of clarified water, so the excess water from the flotation and settling skids was sent to the onsite overflow pond. Sludge from the flotation and settling skids was also sent to the overflow pond.

Chemical Dosing Skid

Settling Tank Skid

DAF Skid

Media Filter Column

2.3.1.1 Operational Parameters and Configuration Details

The Corix pilot units were equipped with online turbidimeters at the raw water feed, downstream of the clarification units, and downstream of the filters. Pre-treatment chemical doses were set manually based on desired dose and inlet flow. A portion of the clarified water from each pilot unit was used to feed two gravity filters, with the remaining portion being diverted to waste. Filter effluent was used for backwash supply.

Table 2-2
DAF and ST Operational Parameters

Parameter	Range	Unit
Dissolved air flotation (DAF) unit		
Pre-treatment flow rate	68 - 79	L/min
Flocculation tank volume	1.85	m^3

Parameter	Range	Unit
Flocculation detention time	23 – 27	min
Flotation tank volume	0.61	m^3
Flotation detention time	7 - 9	min
Hydraulic loading rate	9.5 - 11	m/h
Recycle ratio	8 - 15	%
Saturation pressure	66 - 74	psi
Settling tube (ST) unit		
Pre-treatment flow rate	22 – 23.5	L/min
Flocculation tank volume	0.54	m^3
Flocculation detention time	23 - 24	min
Sedimentation tank volume	1.05	m^3
Sedimentation detention time	45 – 48	min
Hydraulic loading rate	2.4 – 2.5	m/h
Dual media filters		
Filter flows	0.9 – 1.2	L/min
Filter column diameter	100	mm
Filtration rates	6 - 9	m/h
Media expansion during backwash	30 - 40	%

2.3.2 Membrane Ultrafiltration

A GE Zeeweed 1000 submerged membrane unit was selected for piloting. Pressurized membranes were considered for piloting, but were not used as they are less tolerant to being dosed with PAC, which was one of the chemicals scheduled to be tested.

pH was adjusted with 36% sulfuric acid to maintain a pH setpoint of 7.0 in the flocculation tank for the majority of the study.

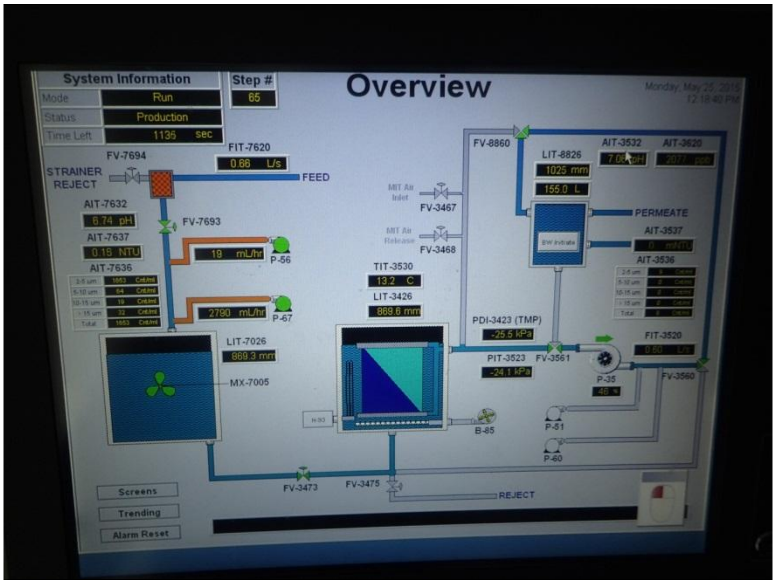
Initially, alkalinity adjustment was conducted via a calcite contactor, which also required pH adjustment (depression with acid) upstream. Due to irreversible membrane fouling and operational issues, the calcite contactor was replaced with 5% soda ash, dosed upstream of the pH adjustment and coagulant dosing points.

The membrane system was operated both on-site by the operators and remotely where possible by the supplier. Various operating parameters were adjusted in order to determine the optimum parameters for full-scale design based on raw water conditions. These are summarized in Table 2-4 and further detailed in Appendix B - GE Pilot Report.

Table 2-4
Membrane Filtration Operating Parameters

Parameter	Values	Unit
Flow rate	34.8 – 38.4	L/min
Instantaneous flux	51.2 – 58.6	Lmh
Percent recovery	95	%
Backwash interval	39	min
Backwash duration	15	seconds
Backwash flux	51.6	Lmh
Maintenance clean interval	Hypo MC: 6 Citric MC: 1	times/week

Membrane Skid in Trailer



Membrane Skid Control Panel

2.4 WATER QUALITY OBJECTIVES

In compliance with the GCDWQ, treatment was considered successful if the following criteria were met after the water had passed through filtration:

- Water that has been treated by ST or DAF and media filtration to have a filtered turbidity of less than 0.3 NTU in 95% of measurements made and never exceed 1.0 NTU.
- Water that had been treated by the membrane to have a permeate turbidity of less than 0.1 NTU in 95% of measurements made and never exceed 0.3 NTU.
- True colour to be less than 15 TCU.
- Aluminum concentrations in treated water shall not rise more than 0.1 mg/L above concentrations observed in raw water.

It was also desired to reduce organic concentrations and lower the risk of disinfection byproduct formation.

2.5 CLEANING PROCEDURES

The dual media filters and the membrane filters required periodic cleaning to remove built-up materials in the filter bed and on the membrane surface and pores, as detailed below.

2.5.1 Dual Media Filter Backwash

Filter backwash was initiated manually by operators when filter head was nearing the overflow point (i.e. terminal headloss reached). This corresponded to roughly once daily. The backwash was conducted using a combined air/water wash (collapse-pulse technique). The backwash duration was based on observations of the clarity of the backwash water. Backwash waste was sent to the overflow pond.

2.5.2 Membrane Cleaning

The following methods were used for cleaning the membranes:

1. Backwash: At the end of each filtration cycle (typically 20 – 60 minutes), a backwash was performed (typically for 15 seconds). During the backwash, the membranes are simultaneously aerated and backpulsed to dislodge solids. Solids are loosened from the surface of the membranes and suspended in the process tank due to the aeration. The tank is then drained and refilled.
2. Maintenance cleaning (MC): During maintenance cleans, the process tank is drained and then filled with permeate. Sodium hypochlorite or citric acid is added to achieve a desired concentration in the process tank. Once the tank is full, the membranes are soaked in the chemical solution for 15 minutes and then the solution is drained from the tank. In the present study, a sodium hypochlorite MC was conducted 6 times per week at a dose of 250 mg/L. Additionally, a citric acid MC was conducted once per week at a concentration of 2,000 mg/L (pH of 2.1).

3. Recovery clean: Also called clean-in-place (CIP), recovery cleans are required to restore the permeability of the membrane once the membrane becomes fouled. A fouled membrane condition occurs if the transmembrane pressure (TMP), a measure of headloss through the membrane, approaches and does not stabilize at values of approximately 12 to 13 psi (terminal vacuum). The cleaning chemicals that are typically used are sodium hypochlorite for the removal of organic foulants and citric acid for the removal of inorganic contaminants. The typical procedure for cleaning ZeeWeed® 1000 membranes consists of soaking them in a 500 mg/L sodium hypochlorite solution for 4-6 hours. This procedure is then repeated with a citric acid solution, for which the concentration is usually 2 g/L. Variations upon this practice can include only using one of the cleaning chemicals, changing chemical concentrations and/or durations, and heating the cleaning solution. A mineral acid such as hydrochloric or sulphuric acid may also be added during the citric acid recovery clean to achieve the target pH of 2.1. In between chemical soaks, the membranes are flushed with potable water to ensure no chemical residual remains in the membranes or membrane tank. The standard interval for a CIP is every thirty days; in the present study, this interval varied depending on the pilot conditions.

Waste from the membrane cleanings was sent to a waste holding tank and trucked offsite for disposal.

2.6 DATA COLLECTION

For the Corix units, turbidity was measured via online HACH probes and recorded once daily by operators. For the GE membrane unit, turbidity and TOC were measured online and logged in the pilot PLC. Samples were collected and analyzed at an external laboratory for a number of other parameters: colour (true and apparent, UV transmittance (UVT), pH, alkalinity, disinfection by-product formation potential (DBPFP), and total metals.

3 Results

Tables 3-1 and 3-2 provide a summary of the water quality and performance data obtained in the pilot study. Specific parameters are discussed in greater detail in the following subsections.

3.1 TURBIDITY

Table 3-3 summarizes the performance of the different tested treatment conditions with respect to turbidity removal. Numbers in parentheses indicate the average value observed.

Table 3-3
Turbidity Results

Pre-treatment	Filter	Chemical	Treated Water Turbidity (NTU)		Conclusion
			Chicken Ladder	Stocking Lake	
Raw Water	-	-	0.20 – 0.65 (0.36)	0.43 – 0.68 (0.47)	-
DAF	Media Filter	10 mg/L PACL	0.08-0.25 (0.13)	0.34 – 0.44 (0.39)	FAIL
DAF	Media Filter	15 mg/L PACl	-	0.09 – 0.62 (0.39)	FAIL
DAF	Media Filter	15 mg/L alum 8 mg/L PAC	0.18 – 1.23 (0.68)	-	FAIL
DAF	Media Filter	4 mg/L ACH	0.14 – 1.45 (0.42)	-	FAIL
DAF	Membrane	10-15 mg/L PACl	< 0.004	< 0.004	PASS
DAF	Membrane	15 mg/L alum 8 mg/L PAC	< 0.004	-	PASS
-	Membrane	Calcite contactor (no coagulant)	< 0.003	-	PASS
-	Membrane	0.7-5.0 mg/L PACl 60 mg/L soda ash	<0.004	-	PASS
-	Membrane	0.6-2.4 mg/L ACH 60 mg/L soda ash	<0.003	< 0.003	PASS
ST	Media Filter	10 mg/L PACl	0.85-1.45 (1.06)	-	FAIL

Pre-treatment	Filter	Chemical	Treated Water Turbidity (NTU)		Conclusion
			Chicken Ladder	Stocking Lake	
ST	Media Filter	15 mg/L PACl 0.2 mg/L Praestol	0.38 – 1.03 (0.66)	-	FAIL
ST	Media Filter	12 mg/L ACH 0.2 mg/L Praestol	0.08 – 0.47 (0.34)	0.49 – 0.69 (0.62)	FAIL
ST	Media Filter	25 mg/L alum 10 mg/L floc aid	0.43 – 0.62 (0.53)	-	FAIL

For the pre-treatment and filtration processes to be awarded disinfection/removal credits for viruses, *Cryptosporidium* and *Giardia*, the process must meet the turbidity objectives listed in Section 2.4. None of the combinations of ST followed by media filtration satisfied these objectives. One combination of DAF and media filtration met the turbidity objective when treating Chicken Ladder water (10 mg/L PACL), but could not meet this objective when treating Stocking Lake water. This indicates that ST or DAF followed by media filtration cannot reliably protect consumers from microbiological contaminants in Chicken Ladder or Stocking Lake water.

All combinations of membranes, either with coagulation/flocculation or with DAF as pre-treatment, were able to meet the turbidity objectives.

3.2 COLOUR

Apparent colour is the measurement of dissolved and suspended particulates that cause water discolouration. True colour is a measure of dissolved particulates, typically organic in nature. The GCDWQ stipulates an aesthetic objective for true colour, as it is more difficult to remove and is a rough indicator of the presence of organics and precursors for disinfection byproducts. For this particular piloting program, true colour measurements were consistently greater than apparent colour, when in reality apparent colour must always be greater than or equal to true colour. The laboratory responsible for colour analysis, Maxxam Analytics in Victoria, stated that apparent colour and true colour are measured using two different analytical methods, with significantly greater inaccuracy in the apparent colour method. The difference in true colour and apparent colour measurements shown in Tables 3-1 and 3-2 therefore reflects the level of inaccuracy in apparent colour measurements by this particular laboratory.

Table 3-4 summarizes the ability of the treatment configurations involving membranes to reduce colour from the incoming water. One of the piloted scenarios involving ST and DAF were included for comparison.

Table 3-4
True Colour Removal Results

Pre-treatment	Filter	Chemical	Treated True Colour (NTU)		Conclusion
			Chicken Ladder	Stocking Lake	
Raw Water	-	-	19-42 (27)	14 – 29 (17)	-
DAF	Media Filter	10-15 mg/L PACL	5-15 (7)	5-10 (9)	PASS
DAF	Membrane	10 mg/L PACl	5-5 (5)	10-12 (11)	PASS
DAF	Membrane	15 mg/L PACl	-	5-5 (5)	PASS
DAF	Membrane	15 mg/L alum 8 mg/L PAC	5-21 (9)	-	FAIL
-	Membrane	Calcite contactor (no coagulant)	19-31 (24)	-	FAIL
-	Membrane	0.7-3.3 mg/L PACl 60 mg/L soda ash	8-16 (11)	-	FAIL
-	Membrane	5.0 mg/L PACl 60 mg/L soda ash	7-19 (14)	-	FAIL
-	Membrane	1.8 mg/L ACH 60 mg/L soda ash	-	7-9[1] (7)	PASS
ST	Media Filter	12 mg/L ACH 0.2 mg/L Praestol	18-36 (27)	5-12 (6)	FAIL

Note: [1] – Raw water colour was 14-15 TCU during this testing period.

The DAF clarification process was effective at reducing true colour to aesthetic objective levels, regardless of whether a media column or membrane was used downstream for filtration. Using PACl during clarification was the most effective coagulant used, while the combination of alum and PAC was not sufficient to always meet the aesthetic objective.

Without DAF, the membrane skid was able to achieve some level of colour removal with just coagulation and flocculation as pre-treatment, was not enough to consistently meet the aesthetic objective of 15 TCU. Water that was treated with ACH before the membrane resulted in treated water colour levels of 7-9 TCU, but as the raw water levels were only 14-15 TCU at that time, it is uncertain whether ACH would have been sufficient if raw water colour levels were greater. ST achieved little to no removal of colour from Chicken

Ladder water, although some removal was observed when treating Stocking Lake water. The ST process would not be suitable for reducing colour levels in both water sources.

3.3 UVT AND ORGANICS

UVT and TOC are not currently governed under the GCDWQ. However, the improvement of UVT and a reduction of TOC can be roughly correlated with the removal of potential disinfection byproduct precursors. UVT is also used to size ultraviolet (UV) reactor, which should be installed downstream of media filtration systems to ensure that *Cryptosporidium* and *Giardia* have been sufficiently removed or inactivated. Tables 3-5 and 3-6 show the UVT and TOC concentrations measured before treatment and after the different tested membrane scenarios. One of the piloted scenarios involving DAF or ST, followed by media filtration, was included for comparison. A higher UVT value is desirable as it indicates that more light passes through the water and is essentially clearer. A lower TOC concentration is desirable as it indicates that there is less organic material available to potentially react with chlorine to form disinfection byproducts.

Table 3-5
UVT Improvement Results

Pre-treatment	Filter	Chemical	UVT (%)		Conclusion
			Chicken Ladder	Stocking Lake	
Raw Water	-	-	68.0 – 83.2 (79.0)	80.8 – 87.0 (84.0)	-
DAF	Media Filter	10-15 mg/L PACL	84.6 – 96.0 (92.4)	84.6 – 96.9 (88.1)	Improvement
DAF	Membrane	10 mg/L PACl	95.2 – 97.1 (96.1)	87.3 – 89.0 (88.2)	Improvement in CL only
DAF	Membrane	15 mg/L PACl	-	96.2 – 97.1 (96.7)	Improvement
DAF	Membrane	15 mg/L alum 8 mg/L PAC	82.0 – 97.5 (94.3)	-	Improvement
-	Membrane	Calcite contactor (no coagulant)	76.1 – 82.2 (79.0)	-	No change
-	Membrane	0.7-3.3 mg/L PACl 60 mg/L soda ash	86.5 – 91.5 (89.2)	-	Improvement
-	Membrane	5.0 mg/L PACl 60 mg/L soda ash	85.6 – 92.5 (88.3)	-	Improvement
-	Membrane	1.8 mg/L ACH	-	89.8 – 92.0	Improvement

Pre-treatment	Filter	Chemical	UVT (%)		Conclusion
			Chicken Ladder	Stocking Lake	
		60 mg/L soda ash		(91.1)	
ST	Media Filter	12 mg/L ACH 0.2 mg/L Praestol	78.8 – 81.8 (80.2)	82.7 – 85.0 (83.8)	No change

ST followed by media filtration had little effect on UVT. DAF followed by media filtration improved UVT in both Chicken Ladder and Stocking Lake water when PACl was added, with even greater improvements achieved when a membrane was used instead of the media filter. Without any pre-treatment, membranes had no impact on UVT. The addition of PACl and soda ash followed by direct membrane filtration improved UVT but not to the same extent as when DAF was included. The addition of ACH and soda ash achieved a small level of improvement to UVT, but less than when PACl was used.

Table 3-6
TOC Removal Results

Pre-treatment	Filter	Chemical	TOC (mg/L)		Conclusion
			Chicken Ladder	Stocking Lake	
Raw Water	-	-	3.0	2.5	-
DAF	Media Filter	10-15 mg/L PACL	-	1.9	Improvement.
DAF	Membrane	10 mg/L PACl	1.0 – 2.4 (1.2)	2.2 – 2.3 (2.3)	Improvement in CL only
DAF	Membrane	15 mg/L PACl	-	1.0 – 1.3 (1.1)	Improvement
DAF	Membrane	15 mg/L alum 8 mg/L PAC	0.9 – 1.8 (1.1)	-	Improvement
-	Membrane	Calcite contactor (no coagulant)	2.7 – 2.8 (2.8)	-	No change
-	Membrane	0.7-3.3 mg/L PACl 60 mg/L soda ash	1.6 – 2.2 (1.8)	-	Improvement
-	Membrane	5.0 mg/L PACl 60 mg/L soda ash	2.0 – 2.1 (1.8)	-	Improvement
	Membrane	0.6 mg/L ACH 60 mg/L soda ash	2.4-2.9 (2.4).	-	Slight Improvement

Pre-treatment	Filter	Chemical	TOC (mg/L)		Conclusion
			Chicken Ladder	Stocking Lake	
-	Membrane	1.8 mg/L ACH 60 mg/L soda ash	-	1.8-2.4 (2.0)	Slight Improvement
ST	Media Filter	12 mg/L ACH 0.2 mg/L Praestol	-	2.4	No change

When treating Chicken Ladder water, the only treatment option that did not show at least some removal of TOC is when membranes were run with only the calcite contactor in operation, showing that membrane filtration needs some form of pre-treatment or coagulant to achieve any level organics removal. One of the tested doses of PACl (10 mg/L) used in combination with DAF and membrane filtration did not significantly reduce colour in Stocking Lake water. However, increasing the dose to 15 mg/L significantly improved treatment, indicating that some adjustment of dose will be required when switching from Chicken Ladder to Stocking Lake as a raw water source.

When looking at the UVT and TOC results combined, the following conclusions can be drawn:

- Membranes with no chemical pre-treatment have little impact on UVT and organic concentrations.
- DAF followed by either media filtration or membrane filtration significantly improved UVT and organic concentrations.
- When PACl was used in combination with DAF and membranes, the optimal dose changes depending on whether Chicken Ladder or Stocking Lake water is being treated.
- Direct membrane filtration (coagulation and flocculation only) effectively improved UVT and organic concentrations. PACl appears to be an effective coagulant for improving these particular parameters. ACH was not as effective as PACl, but also achieved some level of improvement to UVT and TOC.
- ST had no effect on UVT or TOC concentrations.

3.4 DISINFECTION BY-PRODUCT FORMATION POTENTIAL

Disinfection by-product formation potential (DBPFP) was measured for select raw and treated water samples. The results are summarized in Table 3-7.

Table 3-7
Disinfection By-Product Formation Potential Results

Pre-treatment	Filter	Chemical	THMFP / HAAFP (ug/L)		Average Percent Reduction
			Chicken Ladder	Stocking Lake	
Raw Water	-	-	220 / 166	270 / 175	-
DAF	Media Filter	4 mg/L ACH	100 / 76	-	55% / 54%
DAF	Media Filter	15 mg/L PACl	-	160 / 31	41% / 82%
DAF	Membrane	10 - 15 mg/L PACl	66 / 24	73 / 21	71% / 87%
-	Membrane	1.8 mg/L ACH 60 mg/L soda ash	-	200 / 164	25% / 6%
ST	Media Filter	15 mg/L PACl 0.2 mg/L Praestol	220 / 166	-	0%

The raw water samples collected from Chicken Ladder and Stocking Lake contained similar levels of precursors for HAA formation, while Stocking Lake had greater concentrations of THM precursors available. This was surprising in that Stocking Lake is traditionally viewed as the cleaner water source.

As described in previous sections, the formation potential for DBPs does not mean that these are the levels of DBPs anticipated to form after chlorination, but the maximum amount of DBPs that could form if all of the precursors reacted with the disinfectant. What is important from this assessment is to review the percent removal achieved by the different piloted treatment processes.

Treatment involving ST achieved no noticeable level of reduction in DBPFP, which agrees with the process's inability to remove organics or colour from the water. Conversely, DAF followed by media filtration, which was able to remove organics and improve colour, was able to remove approximately half of the precursors present in Chicken Ladder and Stocking Lake water. Similarly DAF followed by membrane filtration removed more than three-quarters of precursors present in the raw water. Direct membrane filtration was able to remove THM precursors, albeit far less effectively than when DAF was employed, but was unable to significantly reduce the amount of HAA precursors available. These results correlate with the reduced TOC removal observed when treating Chicken Ladder water and the small amount of TOC removal when subjecting Stocking Lake water to direct membrane filtration.

Table 3-8 relates the demonstrated reduction in formation potential to observed levels of THMs and HAAs in the Ladysmith distribution system, in order to estimate the level of actual DBPs that would be anticipated in the distribution system if full scale versions of the pilot systems were installed at the Arbutus WTP.

Table 3-8
Anticipated DBP Levels in Distribution System after Treatment

Treatment	% Removal		Anticipated Concentrations in Distribution System (ug/L)	
	THM	HAA	THM	HAA
None [1]	0%	0%	51 – 63 (55)	70 – 100 (79)
ST + Media Filtration	0%	0%	51 – 63 (55)	70 – 100 (79)
DAF + Media Filtration	55%	82%	23 – 28 (25)	13 – 18 (14)
DAF + Membranes	71%	87%	15 – 18 (16)	9 – 13 (10)
Membranes	25%	6%	38 – 47 (41)	66 – 94 (74)

Note: [1] THM and HAA concentrations as measured in the distribution system in 2014.

3.5 METALS

Total metal analyses were conducted for Chicken Ladder and Stocking Lake water. Table 3-9 focuses on aluminum before and after treatment. The GCDWQ has an operating guideline for aluminum to not increase during treatment by more than 0.1 mg/L.

Table 3-9
Aluminum Concentrations

Pre-treatment	Filter	Chemical	Aluminum (mg/L)		Conclusion
			Chicken Ladder	Stocking Lake	
Raw Water	-	-	0.09	0.04	-
DAF	Media Filter	4 mg/L ACH	3.77	-	FAIL
DAF	Media Filter	15 mg/L PACl	-	0.3	FAIL
DAF	Membrane	10 mg/L PACl	0.01	-	PASS
DAF	Membrane	15 mg/L PACl	-	0.01	PASS
-	Membrane	5.0 mg/L PACl 60 mg/L soda ash	0.06	-	FAIL
ST	Media Filter	12 mg/L ACH 0.2 mg/L Praestol	-	4.0	FAIL

DAF and ST followed by media filtration had aluminum concentrations in the treated water that were much greater than the levels observed in the raw water. This indicates that the coagulants are not fully removed during settling and flotation, and are passing through the filters into the treated water. ACH seemed to produce higher concentrations of alum in the treated water than PACl. In contrast, the membranes were able to reduce or keep aluminum concentrations at the same concentrations as present in the raw water.

In addition to aluminum, some metals were observed to increase slightly through the DAF, ST and media filter skids when treating Chicken Ladder water, specifically: copper, iron, lead and zinc. We postulate that these metals are being leached from the piping in the pilot units. In all cases, the concentrations of these metals are below the applicable GCDWQ MACs or AOs. No other unexpected changes to metal concentrations were observed.

3.6 FOULING

A successful membrane system is one that removes the target water quality parameters with a low level of interruption and maintenance. The GE pilot was unfortunately plagued with a high frequency of maintenance problems, ranging from clogged chemical metering pumps to air compressor failure to pH meter calibration issues. These issues can be attributed to damage to the pilot system that occurs during shipping, and oversight by the technical vendors during the pilot set-up. Many of these issues would not be prevalent in a full scale version of the treatment facility. However, the membrane rapidly fouled when used with certain combinations of treatment, requiring that the pilot shut down for a full CIP far more frequently than the targeted interval of once every month.

Table 3-10 quantifies the fouling rate for the different tests involving the membranes. When newly cleaned, the membrane would typically start running at a transmembrane pressure (TMP) of 30 kPa. During operation, the TMP would rise until a CIP is triggered at 80 kPa. Using the rate of TMP increase observed for the different piloted tests, the length of time that the membrane is anticipated to run before a CIP is required was estimated.

Table 3-10
Transmembrane Pressure and CIP Cleaning Intervals

Source Water	Pre-Treatment	Chemical Dose	TMP Increase (kPa/day)	Operating Time Before CIP Required (days)
Chicken Ladder	-	Calcite contactor	13	5
	-	PACL: 0.7 mg/L Soda Ash: 60 mg/L	3	20
	-	PACL: 3.5 mg/L Soda Ash: 60 mg/L	4	15

Source Water	Pre-Treatment	Chemical Dose	TMP Increase (kPa/day)	Operating Time Before CIP Required (days)
Stocking Lake	-	PACL: 5 mg/L Soda Ash: 60 mg/L	20	3
	-	ACH: 0.6 mg/L Soda Ash: 60 mg/L	3	20
	DAF	PACl: 10 mg/L	1.2	50
	DAF	Alum: 15 mg/L PAC: 8 mg/L	13	5
	-	ACH: 1.8 mg/L Soda Ash: 60 mg/L	1.2	50
	-	ACH: 2.4 mg/L Soda Ash: 60 mg/L	5	12
	DAF	PACl: 10 - 15 mg/L	1.5 - 22[1]	40 - 3

Note: [1] Fouling rate for DAF + membrane treatment on Stocking Lake confounded by accidental shock dosing of alum during test period.

Direct membrane filtration, in combination of a coagulant, led to rapid fouling of the membrane except when low doses of ACH were used. Small increases to ACH rapidly accelerated fouling rates. Including DAF upstream of the membranes significantly reduced the fouling rate of the membranes when using PACl. Dosing the water with alum and PAC led to rapid fouling of the membranes, even when DAF was used as pre-treatment. A high dose of alum was accidentally added during DAF and membranes pilot runs using Stocking Lake water; however, performance before the alum dose indicated a slow fouling rate.

4 Discussion

4.1 TREATMENT PROCESS SELECTION

Several combinations of dosing chemicals, pre-treatment, and filtration processes were piloted to determine their effectiveness and ultimately recommend a system that could effectively treat Chicken Ladder and Stocking Lake water.

Conventional treatment using ST struggled to improve water quality along any of the parameters monitored. ST requires particulates to be large enough that they will settle out of the water before filtration, but under typical conditions the particulates in Chicken Ladder and Stocking Lake water are fine and in low concentrations such that not enough particulates could aggregate during treatment to form settleable floc. This can be contrasted to the bench-scale testing that showed that ST was effective when high turbidity events occurred, since a larger amount of sediment was available in the water to form floc. As these high turbidity events are relatively uncommon, ST is not recommended for the Arbutus WTP.

DAF followed by media filtration was able to effectively reduce true colour, organic concentrations and DBP precursor levels, but could not meet the turbidity removal objectives that must be met in order for this treatment technology to be awarded the treatment “credits” for the *Cryptosporidium* and *Giardia* removal. This difficulty with turbidity removal was also observed when DAF bench-scale testing was performed during the December storm event. In addition, the dosed coagulant was not being properly removed during DAF and media filtration, resulting in elevated levels of aluminum in the treated water that exceeded the GCDWQ operational guideline. DAF followed by media filtration is not recommended for the Arbutus WTP.

Direct membrane filtration was able to consistently remove turbidity to meet the drinking water objectives and to be granted treatment “credits” for *Cryptosporidium* and *Giardia*. Membranes would also be able to consistently remove turbidity during the type of storm and turbidity events typical for Holland Creek and Stocking Lake. However, the membranes could not effectively remove colour and organics unless a coagulant was added upstream, and even then colour was not always removed to aesthetic objective from the GCDWQ. More importantly, the membranes experienced rapid fouling unless very low doses of ACH were added. Even small increases in ACH doses led to rapid fouling. It is believed that a combination of organic material in the raw water and the coagulants themselves contributed to the accelerated fouling rates. In other words, a direct membrane filtration system could potentially be optimized to meet the Ladysmith treatment objectives, but would lead to rapid fouling of the membranes that would result in frequent membrane cleanings and shorter membrane life, increasing operation and maintenance costs unless careful monitoring of the optimal coagulant dose was implemented.

Adding a DAF system upstream of the membranes was found to significantly reduce the fouling rate of the membranes. The DAF unit allowed for some of the organic material and coagulant to be removed via flotation before coming into contact with the membrane. Adding DAF upstream of the membranes allowed for greater coagulant doses to be safely used without compromising the membranes, which improved the removal of colour, organics, and DBP precursors. It is recommended that the Arbutus WTP be upgraded with a treatment system consisting of coagulation, flocculation, DAF, and membrane filtration. It is recommended that soda ash and PACl be used as pre-treatment chemicals during coagulation.

4.2 SEASONAL OPERATION

Based on the results of the piloting program DAF followed by membrane filtration offers the Township reactor best balance of effective treatment, and operation and maintenance requirements. However, with water from Stocking Lake historically being of better quality than Chicken Ladder, the Township is always looking for opportunities to shut down some of the treatment processes when treating Stocking Lake water in order to reduce operating costs.

Therefore, the option of shutting down DAF when treating Stocking Lake water was considered. Membrane filtration will always be required to comply with surface water treatment regulation. Of the different pre-treatment chemicals used, only ACH at low doses in combination with soda ash allowed direct filtration to run without rapid fouling of the membranes. The period of testing for this scenario was short, but the limited data available suggests that colour levels can be reduced with a low dose of ACH. Close attention will be required for dose optimization, as it was determined that increasing the ACH dose by only 0.6 mg/L led to rapid membrane fouling.

As shown in Table 3-1, ACH was not as effective in combination with DAF as PACl, therefore the use of PACl is recommended whenever DAF is used. In other words, if DAF is turned off when treating Stocking Lake water ACH should be used. However, when the DAF process is brought back online PACl should be used instead of ACH.

4.3 PHASED CONSTRUCTION

If the Township cannot finance the construction of a DAF and membrane facility in a single stage, it is recommended that Phase II of the Arbutus WTP consist only of coagulation, flocculation and membrane filtration. DAF would be added at a later date as Phase III. The priority would be the construction of the membrane system as it would combine with the existing Phase I disinfection system to provide adequate protection from viruses, *Cryptosporidium* and *Giardia*, which are acute risks to human health. Addition of DAF could be delayed because its benefits are not as critical to human health, specifically:

- DAF would improve colour removal. This is an aesthetic objective and does not have a direct impact on human health, and therefore not as critical as the membrane system.
- DAF would improve the removal of organics and DBP precursors. While the DBP formation can impact human health, the impacts are long term and require a lifetime exposure to DBPs at levels exceeding the MACs. Reducing long term risk is needed but is not as immediately critical as the acute health risks of viruses and protozoa, addressed by the membrane system.
- DAF will significantly reduce membrane fouling rates, which will have a direct beneficial impact on operation and maintenance costs of the membrane system .

4.4 ULTRAVIOLET IRRADIATION

A treatment system consisting of DAF and membrane filtration or direct membrane filtration should be sufficient to adequately protect consumers from microbiological contaminants without the need of additional disinfection beyond chlorination. The addition of ultraviolet (UV) reactors to inactivate *Cryptosporidium* and *Giardia* are not required.

4.5 MEMBRANE SELECTION

While a GE submerged membrane was used for piloting, this is not the only viable option available to Ladysmith for a full-scale membrane facility. Now that piloting has confirmed that PAC will not be used upstream of the membrane, a pressurized membrane configuration should be considered as they may offer similar performance in a smaller footprint. Other membrane vendors should be taken into consideration.

As an early step in preliminary design, it is recommended that a bid document be prepared and sent to invited vendors for the procurement of the membrane system. As there is no standard design criterion for membranes, the sizing and support piping for each membrane brand can vary significantly. By pre-selecting a specific brand and model, the rest of the Arbutus WTP expansion can be accurately laid out. In addition, the procurement process will also provide accurate estimates for power requirements and the amount of waste generated as part of the membrane maintenance and cleaning operations. In the absence of a sewer line near the Arbutus WTP waste residuals management will be an important consideration in development the next stage of the facility.

4.6 COST ESTIMATE

The results of the piloting report were used to refine the layouts and construction cost estimates developed as part of the "Arbutus Water Treatment Plant Phase II – Filtration Pre-Design Report" dated January 2015, focusing on two options: the first layout involved constructing a DAF and membrane filtration plant in a single stage. The second option involved construction of a direct membrane filtration as a first stage, with DAF added as a second stage at a later date. A summary of the design assumptions are provided in Table 4-1.

Table 4-1
Arbutus WTP Phase II Design Parameters

Process / Treatment Plant Feature	Design Assumptions
General	• Flocculation, DAF and membrane processes include 50% redundancy to allow partial shut-down of plant for maintenance without interrupting treatment capacity. • Treatment plant sized to treat 125 L/s, with space available in building for expansion to 250 L/s.
Coagulation	• Coagulant introduced using flash mixer or in-line jet mixer. • A second, parallel coagulant injection point included to act as contingency should the first coagulation point need to be temporarily taken off-line. • Coagulation for DAF and membrane facility consists of soda ash addition followed by PACl dosing. • Coagulation for direct membrane filtration facility consists of soda ash addition followed by ACH dosing.
Flocculation	• Three flocculation trains in parallel (one redundant train). • Each train consists of two flocculation tanks in series. • Minimum 30 minute flocculation time. • For 250 L/s design capacity, add two more flocculation trains.
DAF	• Three DAF tanks in parallel (one redundant tank). • 25 m/hr loading rate.

Process / Treatment Plant Feature	Design Assumptions
	• 10% treated water recycled and pressurized to 60-90 psi before being blended with unclarified water entering flotation tank. • For 250 L/s design capacity, add two more flotation trains.
Membranes	• Three trains of ultrafiltration membranes in parallel (one redundant unit). • Average raw water turbidity < 1 NTU, maximum 50 NTU. • Average true colour 25 TCU, maximum 90 TCU. • Water temperature range: 3 – 17°C • Average TOC 3 mg/L, maximum 5 mg/L. • For 250 L/s design capacity, add two more membrane trains.
Disinfection	• Provide chlorination using existing chlorine gas system from Phase I WTP.
Other Facilities / Rooms	• Each chemical and dosing system housed in separate storage rooms. • Dedicated electrical room and building mechanical room. • DAF sludge dewatering equipment housed in room separate from main treatment process equipment. • Neutralized membrane cleaning waste sent to engineered wetland on site. • Neutralized overflow sent to stormwater retention pond.

A detailed cost estimate was developed for the two variations of the membrane plant. Details are provided in Appendix C and are summarized in Table 4-2.

Table 4-2
Treatment Plant Capital Cost Estimate

Process Description	Capital Cost[1]	
DAF and Membrane Filtration		$13,300,000
Direct Membrane Filtration	$10,000,000	
DAF (Installed at a later date)	$4,100,000	
Total		$14,100,000

Note: [1] Includes management and engineering costs, and a 20% contingency allowance.

Operation and maintenance cost estimates are provided in Table 4-3, based on an annual average day demand of 50 L/s. In the absence of DAF, the membranes will require additional maintenance and greater chemical consumption for the following reasons:

- Without DAF more frequent cleaning and CIP will likely be needed, leading to an increase in cleaning chemical consumption and a higher volume of generated waste.
- Direct membrane filtration will have a small impact on organic removal and therefore the natural chlorine demand of Stocking Lake and Chicken Ladder will remain relatively high, in the range of 3.0 mg/L. Greater chlorine dosing will be required to achieve a free chlorine residual until DAF pre-treatment is installed.

Table 4-3
Treatment Plant Annual Cost Estimate

Process Description	Chemical Consumption	Power	Labour	Maintenance and Part Replacement	Total
DAF and Membrane Filtration	$165,000 /year[1]	$27,000 / year	$100,000 /year[2]	$51,000	$343,000 /year
Direct Membrane Filtration	$168,000 /year[1]	$21,000 /year	$100,000 /year[2]	$60,000	$349,000 /year

Notes: [1] Majority of chemical cost is due to soda ash. Elimination of soda ash would reduce annual chemical use costs by $120,000.
[2] Labour costs assume a Senior Operator and two Shift Operators each spend an average of two days a week on site.

At this stage of evaluation, the operation and maintenance cost savings for the membranes when combined with DAF pre-treatment are offset by the operating costs of the DAF system itself and maintenance of a larger treatment facility to house both treatment processes. The cost estimates do not take into account reduction in operation and maintenance requirements at the reservoir and along the distribution system if DAF is included in the initial construction. In the long term, organic material that passes through the direct membrane filtration system may eventually become soluble and accumulate in the distribution system and reservoir. Reducing organic concentrations with DAF would decrease the amount of accumulated material and thereby decrease the frequency of required pipe flushings and reservoir cleanings.

In addition, removing organic material through DAF may reduce the chlorine residual rate of decay. This will become significant when the connection between the Ladysmith distribution system to the Stz'uminus First Nation communities on I.R. 12 and 13 are completed, as the travel distance from the Arbutus reservoir to I.R. 13 is over 5 km. Improving the rate of decay may avoid the need for a rechlorination station near the connection point to the Stz'uminus communities.

5 Recommendations

5.1 TREATMENT RECOMMENDATION

It is recommended that the Phase II construction at the Arbutus WTP consist of coagulation, flocculation, DAF and membrane filtration. The optimal coagulant doses were determined to be 60 mg/L of soda ash with 10-15 mg/L of PACl, although adjustment to the chemical doses should be made as raw water quality conditions change. UV disinfection would not be required.

5.2 NEXT STEPS

The following tasks are recommended to move forward with the implementation of filtration at the Arbutus WTP:

- Confirm design flow and the level of redundancy desired for the Phase II construction.
- Prepare bid document for procurement of the membrane system to determine footprint, power requirements, waste generation, and pipe connection requirements. It is recommended that bidding process be by invite only.
- Update VIHA on the proposed future treatment at the Arbutus WTP.

Certification Page

This report presents our findings regarding the Town of Ladysmith, Arbutus Water Treatment Plant Phase 2 Pilot-scale Treatability Study.

Respectfully submitted,

Prepared by:

Sabrina Diemart, M.A.Sc., E.I.T.
Process Engineer

Reviewed by:

Sutha Suthaker, Ph.D., P.Eng.
Water Specialist

PROFESSIONAL
PROVINCE OF
K. D. KOHUT
33863
BRITISH COLUMBIA
ENGINEER
Sep 4/15

Keith Kohut, M.A.Sc., P.Eng.
Project Manager

SD/SS/KK/lp

Appendix A – Bench-Scale Study

Associated Engineering GLOBAL PERSPECTIVE. LOCAL FOCUS.

Date:	January 28, 2015 **File:** 2014-2829.00.E.04.00
To:	John Manson, Town of Ladysmith; Matt Palmer, Koers & Associates Engineering Ltd.
From:	Sabrina Diemert, M.A.Sc., E.I.T.
Project:	Ladysmith Arbutus WTP
Subject:	Bench-scale Treatability Assessment

MEMO

1 BACKGROUND

The Township of Ladysmith (Township) relies on surface water as their source of drinking water via two intakes. One intake is located at Stocking Lake. The second intake, called the Chicken Ladder Intake, draws water from Holland Creek. Holland Creek water is fed by Holland Lake, which periodically received contributions from Bannon Creek. The Township predominantly relies on Stocking Lake from October to April, and switches to Chicken Ladder from April to October. Both intakes lead to the Arbutus Water Treatment Plant (WTP), where water is subjected to chlorine disinfection using chlorine gas.

As detailed in our previous reports, the water quality for these water sources can be characterized to be of relatively low turbidity and low alkalinity. The colour levels regularly exceed the aesthetic objectives under the Guidelines for Canadian Drinking Water Quality (GCDWQ). The water contains organic concentrations that could possibly lead to high levels of disinfection by-products (DBP) when chlorinated.

The Township is planning to expand the Arbutus WTP as part of Phase Two construction to include a filtration process. As part of the design for the expansion, a bench-scale treatability assessment was conducted by Associated Engineering. The bench-scale studies aimed to identify a treatment scheme (to be further tested during pilot-scale studies) which can meet the following treatment objectives that were previously developed for the Arbutus WTP source waters:

- Turbidity <0.3 NTU for conventional process and <0.1 for membrane process.
- Organics less than a level that chlorination would not produce excessive DBPs greater than the allowable GCDWQ limits (<0.1 mg/L total trihalomethanes, <0.08 mg/L haloacetic acids).
- True Colour to be less than 15 TCU.

As such, AE conducted onsite bench-scale testing during the period of December 10-11, 2014. This testing also coincided with a subtropical storm event with heavy rain (>50 mm/day) that resulted in noticeable change in raw water quality. The tests were primarily conducted on water from the Chicken Ladder intake, as this water has greater levels of colour, organic concentrations and during the storm event, turbidity. Additional tests were conducted with the optimized treatment processes to confirm their performance using the alternative water sources (Stocking Lake and Holland Lake). Raw water quality was also reviewed (but not tested) for Bannon Creek, as it contributes to Holland Lake. Key raw water quality parameters are listed in Table 1-1. The raw water data is based on samples collected on Dec. 9, unless otherwise noted.

Selected water quality parameters from the December 2014 storm event are compared to 2013 average conditions for Chicken Ladder, Stocking Lake and Holland Lake in Table 1-2. Turbidity, colour, total iron and total aluminum concentrations (where measured) were higher in all waters under storm conditions when compared to average values. Dissolved organic carbon (DOC) remained consistent with average values for Chicken Ladder and Stocking Lake, despite a significant drop in the dissolved ultraviolet transmittance (UVT) in Chicken Ladder water (80% average, 55.3% under storm conditions).

Table 1-1: Raw water quality parameters under heavy rain conditions

Parameter		Water Source				
		Chicken Ladder (Dec. 9)	Chicken Ladder (Dec 10)	Stocking Lake	Holland Lake	Bannon Lake
Unfiltered	pH	6.9	6.9	7	7	6.7
	Turbidity (NTU)	10.9	13.8	1.6	1.8	0.3
	Apparent Colour (TCU)	160	184	41	63	97
	UVT	50.9%	55.3%	83.8%	79.2%	56.2%
	Alkalinity (mg/L $CaCO_3$)	3[a]	≤20[b]	10[a]	30[b]	≤20[b]
Dissolved (filtered with a 0.45 µm filter)	Turbidity (NTU)	0.7	0.9	0.4	0.7	0.3
	True colour (TCU)	83	70	30	40	20
	UVT	55.3%	63.1%	83.8%	81.2%	56.4%
	Dissolved organic carbon, DOC (mg/L)	4.7	4.5	2.9[c]	N/A	N/A

[a] Alkalinity test conducted by Maxxam using titration method (detection limit of 0.5 mg/L as $CaCO_3$)
[b] Alkalinity test conducted by AE using colorimetric reader (detection limit of 20 mg/L as $CaCO_3$)
[c] Average of duplicate analyses
N/A = not analyzed

Table 1-2: Average and storm event raw water quality parameters

Parameter	Chicken Ladder		Holland Lake		Stocking Lake	
	Average (2013)	Storm event (Dec. 10, 2014)	Average (2013)	Storm event (Dec. 9, 2014)	Average (2013)	Storm event (Dec. 9, 2014)
Turbidity (NTU)	0.41	13.8	0.9	1.8	0.30	1.6
True Colour (TCU)	13	70	10	40	10	30
DOC (mg/L)	4.5	4.5	2.6	N/A	2.3	2.9
Dissolved UVT	80.0%	55.3%	76.6%	79.2%	84.8%	83.8%
Total Iron (mg/L)	0.05	1.20	0.19	N/A	0.07	0.12
Total Aluminum (mg/L)	0.053	1.12	0.059	N/A	0.038	1.20

N/A = not analyzed

2 OBJECTIVES

Specific objectives of this study were to:

- Conduct bench-scale dissolved air flotation (DAF) and sedimentation tests to establish optimum pre-treatment conditions for the pilot program including the assessment of:
    - Optimum coagulant dose
    - Effects of alternate coagulants
    - Effects of alkalinity addition and coagulant aid (polymeric)
    - Effects of powdered activated carbon (PAC)
    - Effects of DAF operating parameters such as recycle rate and flocculation time
- Use optimized conditions to determined disinfection by-product formation potential (DBPFP) in treated and untreated water.

3 EQUIPMENT DESCRIPTION

All experiments were conducted using the ECE DBT6 dissolved air flotation jar tester system. Figures 1-1 through 1-3 show the bench-scale DAF tester/saturator assembly, typical fine bubbles released to float the flocs and a typical float observed. For sedimentation tests, the recycle water injector manifold was removed and flocs were allowed to settle (see Figure 1-4). For sample analysis of filtered or dissolved components (including true colour), water was filtered through a 0.45 µm syringe-tip membrane.

Figure 1-1: Bench Scale Jar Tester/Saturator

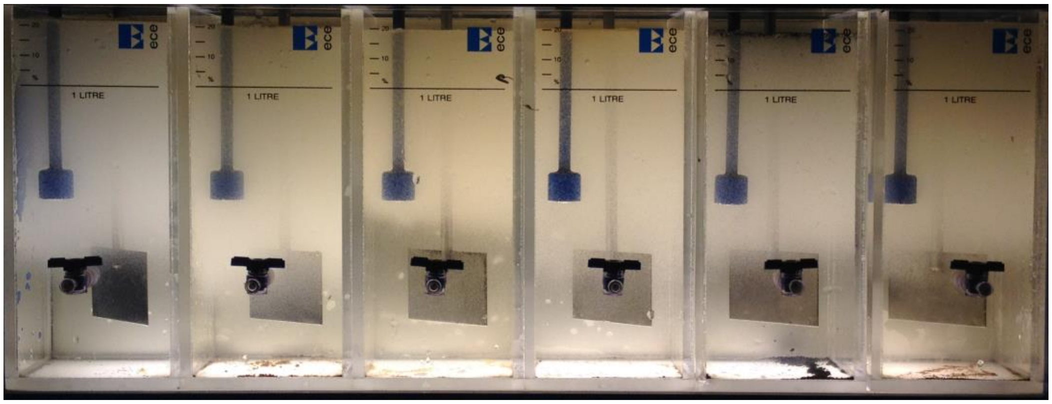


Figure 1-2: Bubbles being released during DAF

Figure 1-3 and 1-4: Typical float (ClearPAC, 15 mg/L) and settled floc (alum + PAC)

4 RESULTS: DAF TESTS

DAF tests were conducted on December 10th, using Chicken Ladder water collected on December 9th. All data sheets from the bench scale tests, as well as detailed water quality results from an external laboratory, are appended to this memo.

4.1 Alum Optimization

DAF was simulated with a range of alum doses. Trends for various water quality indicators as functions of alum dose are shown in Figures 4-1 and 4-2.

Clarified water turbidity corresponds to how well the flocs float during the DAF treatment, while filtered water turbidity is linked with the filterability of the flocs through a 0.45 μm filter (comparable to full scale media filtration processes). UV transmittance (UVT) usually correlates with the removal of organics from the raw water; that is, higher UVT values are linked with lower organic levels. Colour is measured in units of “TCU” (true colour units): higher values indicate that water samples have a higher intensity of yellow colour.

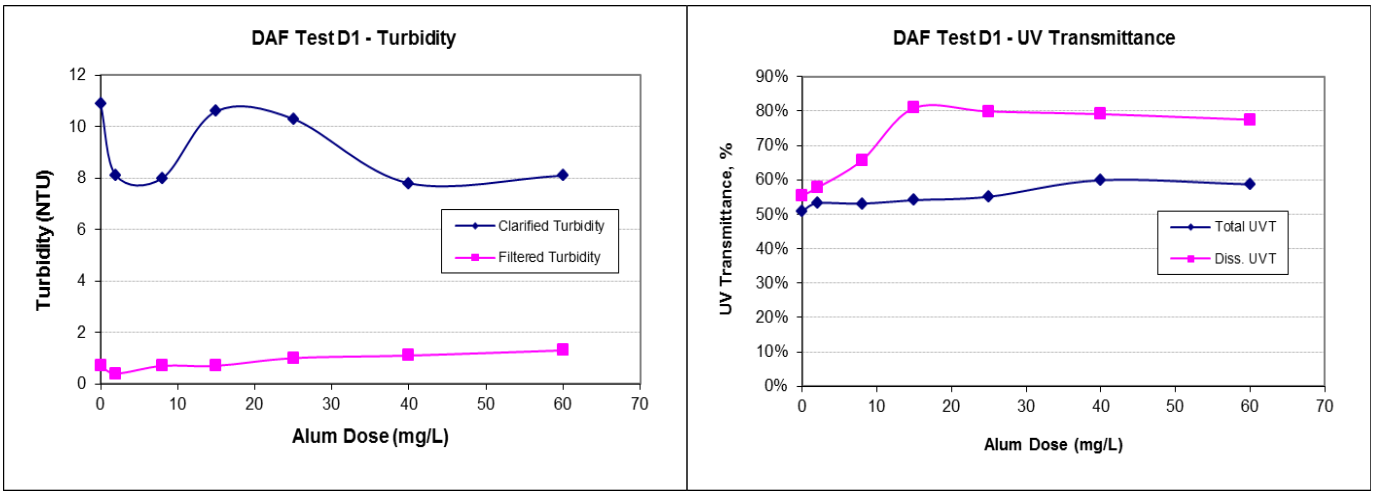


Figure 4-1: Turbidity and UVT for alum-DAF jar tests

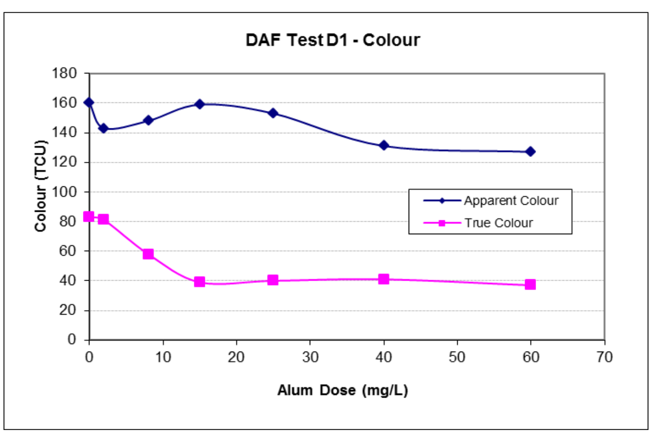


Figure 4-2: Colour measurements for alum DAF jar tests

Over the range of doses tested (2 mg/L to 60 mg/L), 25 mg/L alum was determined to be the optimum dose with respect to UV transmittance improvements and reductions in colour.

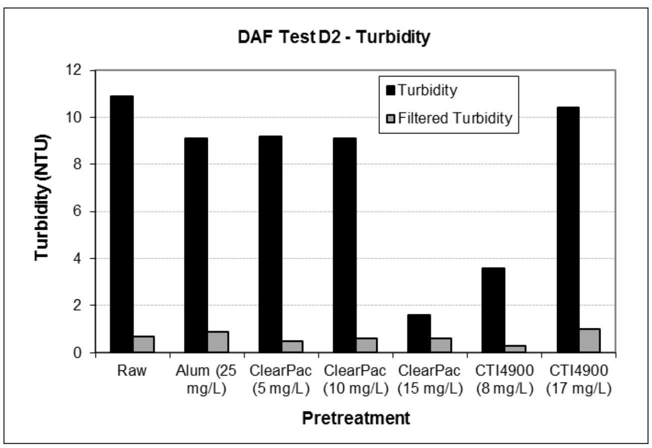
Alum did not improve filtered water turbidity. Alum doses of more than 10 mg/L resulted in increased clarified water turbidity.

Alum was not considered a good candidate for coagulation with DAF as sediment was noted to have settled to the bottoms of the jars during the flotation period. Any floc which settles during DAF can end up in the treated water stream.

Alum typically requires alkalinity to perform effectively. As illustrated in this test, the low alkalinity of the raw water may be preventing alum dosing alone from producing a noticeable improvement in water quality. Additional tests were later conducted to assess the effectiveness of alkalinity addition.

4.2 Alternate Coagulants

In test D2, ClearPAC (a poly-aluminum chloride (PACl) coagulant) and CTI4900 (an aluminum chlorohydrate coagulant also known as ACH) were compared with the optimized alum condition (25 mg/L) at similar doses on a dry coagulant basis. Neither PACl nor ACH is anticipated to rely on alkalinity to the same extent as alum to effectively aggregate particles, and are therefore worth testing for naturally low alkalinity waters. ClearPAC (at 15 mg/L) and CTI4900 (at 8 mg/L) provided improved turbidity reductions and increased UVT, in comparison to alum (refer to Figure 4-3). Colour was also further reduced below 20 TCU for the alternative coagulants. Some sediment was noted at the bottoms of the jars after the flotation period. ClearPAC at 15 mg/L is preferred due to its superior reduction of turbidity.



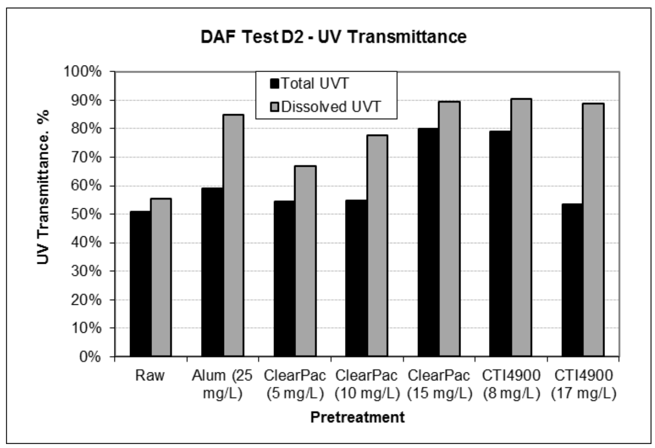


Figure 4-3: Turbidity and UVT measurements for alternate coagulants DAF jar tests

4.3 Effect of Alkalinity Addition and Flocculant Aid

The option to improve alum performance (at the optimized dose of 25 mg/L) was tested in Test D3 with two alternatives: increasing the alkalinity in the water through the addition of soda ash, and improving the agglomeration of particles by adding a flocculant aid (CL2410, a cationic polymer). These tests were conducted at the optimized alum dose. It should be noted that adding a polymer would likely make the flocs heavier and could favour settling instead of flotation.

The lower dose of soda ash tested (10 mg/L) produced water with improved UVT and clarified water turbidity. A higher dose of soda ash (20 mg/L) yielded poorer floc formation: the float had a foamy appearance and a lot of sediment settled to the bottoms of the jars. Similarly poor flotation was observed when the flocculant aid was added at two different doses: 5 mg/L and 10 mg/L. Soda ash addition at 10 mg/L (with 25 mg/L alum) produced similar quality water to 15 mg/L

ClearPAC, and could be considered for pre-treatment. Flocculant aid did not improve water quality when used in conjunction with DAF and is not recommended.

No noticeable increase in alkalinity was detected using the bench-scale measurement equipment available at the time of testing, which has a detection limit of 20 mg/L (lower than the normal alkalinity range of Ladysmith source waters).

4.4 Effect of Flocculation Time

The standard DAF test involves 13 minutes of flocculation time (5 minutes at 60 rpm, 5 minutes at 36 rpm and 3 minutes at 20 rpm for saturation/observations, followed by 7 minutes of flotation time before sampling). Newer DAF facilities are often constructed to provide fairly short retention time through flocculation (20 minutes and shorter); however, pilot testing at other locations on Vancouver Island had suggested longer flocculation periods (30-45 minutes) may improve DAF performance.

To test if a longer flocculation time could be beneficial for the DAF, test D4 employed a 30 minute flocculation time (10 minutes at 60 rpm, 10 minutes at 36 rpm, and 10 minutes at 20rpm for saturation/observations), followed by 10 min flotation time before sampling. UVT and colour did not appear significantly affected for most chemical conditions when compared to the shorter (13 minute) flocculation tests. Some turbidity values appeared to reduce slightly at the longer flocculation time condition (for example, filtered turbidity went from 0.6 NTU to 0.2 NTU for 15 mg/L ClearPAC), but otherwise extending flocculation time did not significantly improve water quality.

4.5 Effect of DAF Recycle Rates

Most DAF jar tests were conducted with recycle rates between 10-14%. Test D5 assessed the effect of increasing the DAF recycle rates up to 22%. No significant improvement on turbidity, UVT and colour was seen upon increasing the DAF recycle rate.

4.6 Effect of adsorbent

Two doses of powdered activated carbon (PAC) were tested (8 and 17 mg/L) with the optimized alum dose, both of which produced water with low turbidity, improved UVT (85-87%, compared to alum at 81%) and visibly decreased colour. However, in all trials, sediment and a portion of the PAC settled to the bottom of the jars during the flotation period. Therefore, PAC is not considered an option for DAF process.

4.7 Dissolved organic carbon (DOC) results

DOC samples were collected from the best performing jars (in terms of colour, turbidity and UVT) for a number of chemical conditions (Figure 4-4).

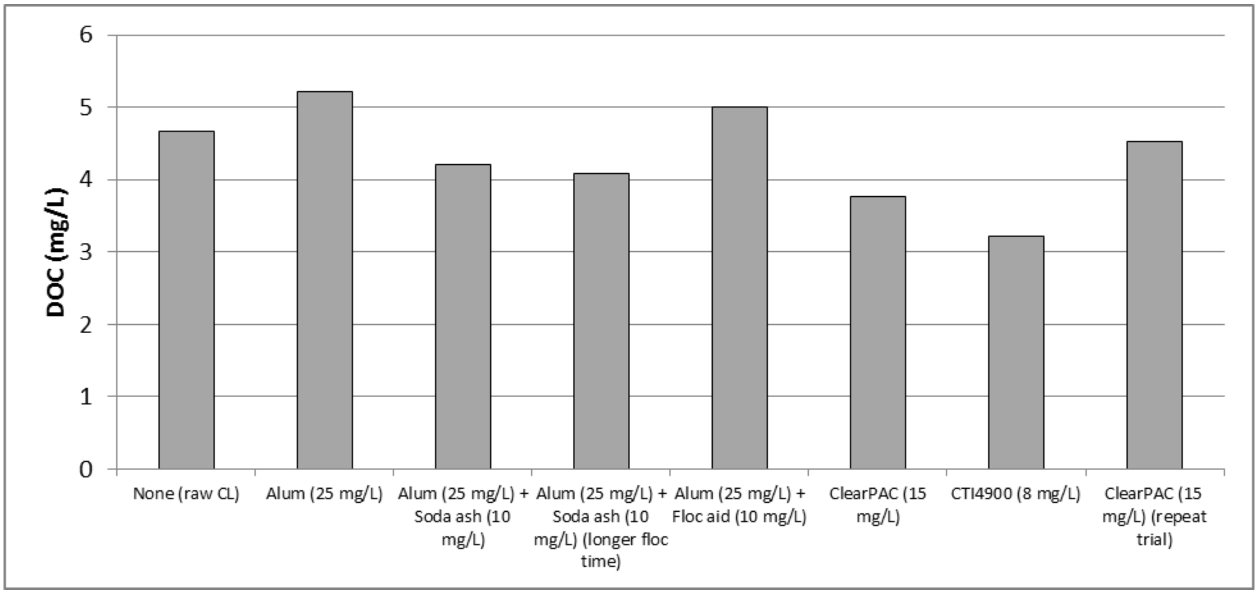


Figure 4-4: Dissolved organic carbon results for selected DAF jar tests

According to the DOC data, coagulation with CTI4900 provided the best removal of organics (31% reduction), and ClearPAC also performed well (19% reduction). Most other conditions resulted in a small decrease in organics (<12% reduction). The addition of floc aid resulted in an increase in organics (+8%): this could be due to the organic polymer in the floc aid contributing to the overall organic level.

The increase in organics noted for alum and the variability between the ClearPAC repeat trials are unusual observations. They may be due to experimental error, or variation in analytical accuracy. Duplicate analyses of raw Stocking Lake water indicated that DOC detection may range ± 0.3 mg/L.

5 RESULTS: SETTLING TESTS

Settling tests were conducted on December 11th, using Chicken Ladder water collected on December 10th. All data sheets from the bench scale settling tests, as well as detailed water quality results from an external laboratory, are appended to this memo.

5.1 Coagulant Optimization

The DAF tests demonstrated that alum did not perform as well as ClearPAC or CTI4900 in terms of key treated water quality parameters (turbidity, UVT and colour). A similar observation was noted during the sedimentation bench-scale testing when alum, ClearPAC and CTI4900 were compared over a narrow range of doses (Tests S1-2).

ClearPAC produced lower turbidity, improved UVT water than alum at lower coagulant doses (on a dry basis). An optimized ClearPAC dose of 20 mg/L produced water with dissolved UVT of 92%, compared to 82% in water treated with the optimized alum dose (25 mg/L). ClearPAC also performed well at a dose of 15 mg/L.

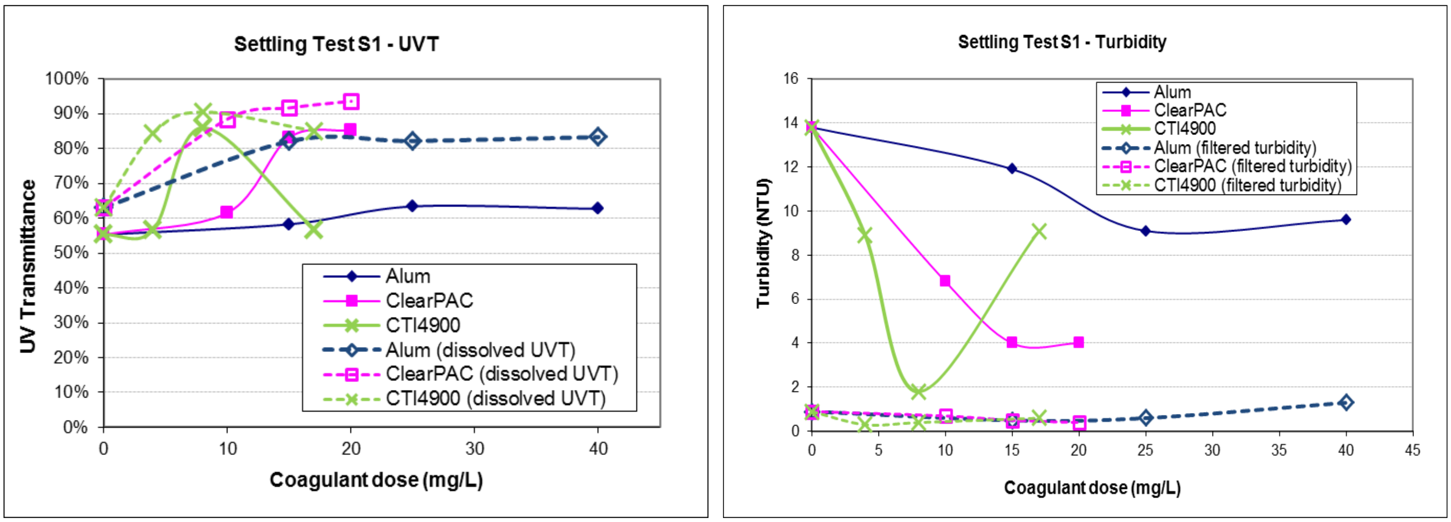


Figure 5-1: Turbidity and UVT measurements for sedimentation tests (alum, ClearPAC and CTI4900)

CTI4900 had a more narrow range of optimized performance: at 8 mg/L, turbidity (1.8 NTU) and UVT (90.5%) were improved compared to the optimized alum and ClearPAC conditions. However, at an increased or decreased CTI4900 dose, the effectiveness of CTI4900 decreased rapidly. Given that CTI4900 is very dose sensitive with respect to the treated water quality for Chicken Ladder water, ClearPAC is the more optimal choice for settling treatment.

Comparing the results for similar coagulants and doses between the two different clarification methods (sedimentation and DAF) indicated that sedimentation produced water with higher UVT. In contrast, DAF appeared to be more effective for colour removal. Turbidity reduction was similar.

5.2 Effect of Alkalinity Addition and Flocculant Aid

Settling Test S3 involved adding soda ash and flocculant aid to check whether they could improve alum treatment performance. The settling test yielded similar results as the DAF testing (Test D3). The lowest dose of soda ash tested (10 mg/L) produced water with improved UVT and clarified water turbidity compared to alum alone, whereas higher doses (20 mg/L and 40 mg/L) yielded poorer floc formation.

In contrast to the DAF observations, the addition of cationic polymer as a flocculant aid (CL2410, a cationic polymer) at two doses (5 and 10 mg/L) improved the dissolved UVT and filtered turbidity. At the lower dose (5 mg/L), clarified turbidity was reduced compared to alum alone (3.7 NTU from 9.9 NTU). This indicates that the addition of low doses of flocculant aid improved alum treatment performance when settling was used as a clarification process.

5.3 Effect of Adsorbent

PAC (at two different doses) was added with the optimized alum dose in Test S2. PAC improved turbidity reduction (from 9.5 NTU to 4.9 NTU), increased UVT (from 81% to 90%) and resulted in less-coloured water (from 43 TCU to 16 TCU) at the higher of two doses tested (approximately 17 mg/L) when compared to alum alone. The lower dose of PAC (approximately 8 mg/L) had little effect on clarified turbidity and UVT.

5.4 Dissolved organic carbon (DOC) results

DOC samples were collected from the best performing jars (in terms of colour, turbidity and UVT) for a number of chemical pre-treatment conditions (Figure 5-2).

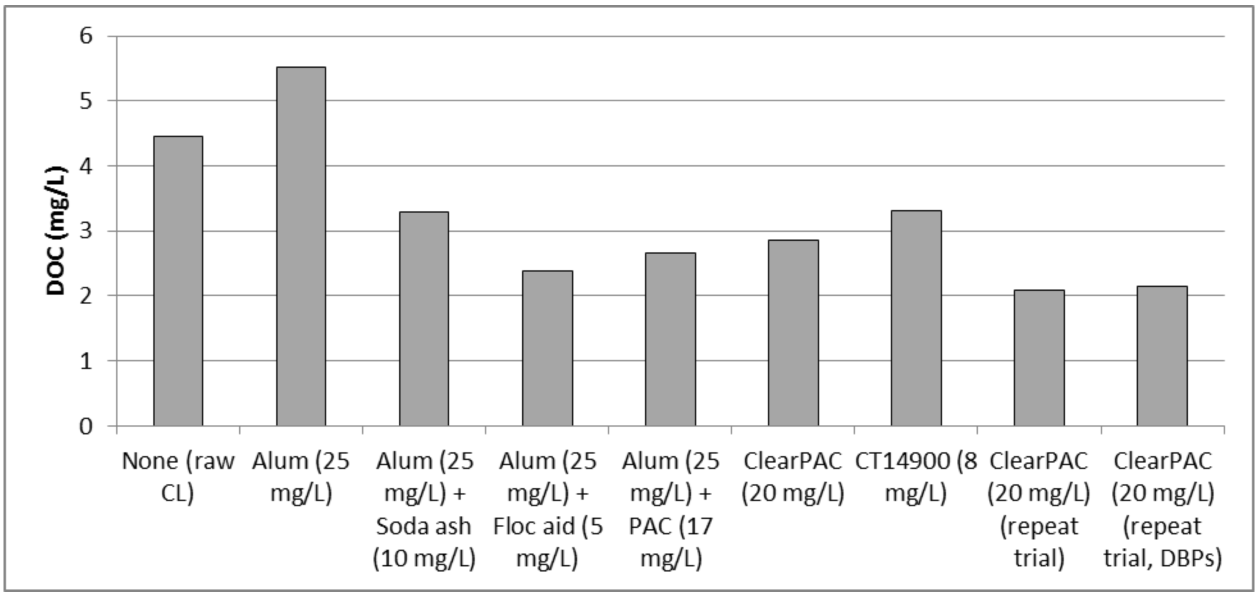


Figure 5-2: Dissolved organic carbon results for selected sedimentation jar tests

According to the DOC data, coagulation with ClearPAC provided the best removal of organics (36-52% reduction). Alum with flocculant aid (5 mg/L) and alum with PAC (17 mg/L) also performed well (46% and 41% reduction of organics, respectively. DOC removals in the settling tests were consistently improved over the DAF tests.

As with the DAF experiments, some inconsistent DOC results were noted, including an increase in DOC for the alum jar test and variability in the ClearPAC trials.

6 RESULTS: STOCKING LAKE AND HOLLAND LAKE TESTS

For the DAF and sedimentation tests, two of the pre-treatment regimes that were most successful were tested again using water from Stocking Lake and Holland Creek. The specific optimized tests are shown in Table 6-1.

Table 6-1: Optimized Pre-Treatment Methods

Clarification Method	Optimized Pre-treatment #1		Optimized Pre-treatment #2	
	Chemical	Dose (mg/L)	Chemical	Dose (mg/L)
DAF	ClearPAC	15	CTI4900	8
Sedimentation	ClearPAC	20	CTI4900	8

Turbidity, filtered turbidity, dissolved UVT and true colour results are shown in Figure 6-1. Generally, the water quality was very similar between DAF and sedimentation-treated waters. The coagulants were less successful at reducing the clarified turbidity in Stocking Lake and Holland Creek, likely due to these sources having lower turbidity initially than the raw Chicken Ladder water. In some cases, turbidity increased: likely, the coagulants were likely overdosed for these waters, which have considerably lower initial turbidity values (1.6 NTU and 1.8 NTU for Stocking and Holland Lakes, respectively) than Chicken Ladder (13.8 NTU). Additionally, the post-filter turbidity values (simulated by filtered turbidity) did not vary significantly between raw and treated water samples; this indicates that the turbidity in these waters was largely suspended and resistant to removal via coagulation.

Dissolved UVT and true colour were improved by pre-treatment under both clarification processes. While sedimentation effectively reduced true colour in Chicken Ladder water, DAF tended to reduce true colour to significantly lower levels than sedimentation in Stocking Lake and Holland Lake waters. Some particles were noted at the bottom of the jars during DAF testing with all water types.

DOC values for Stocking Lake jar tests are shown in Figure 6-2. 11% DOC reduction was noted with DAF treatment, while 18-22% DOC reduction was observed in sedimentation. While DOC showed a smaller percentage reduction over treatment in Stocking Lake water compared to Chicken Ladder, the final DOC values were comparable between water types: approximately 2.8 mg/L using DAF and 2.2 mg/L using sedimentation.

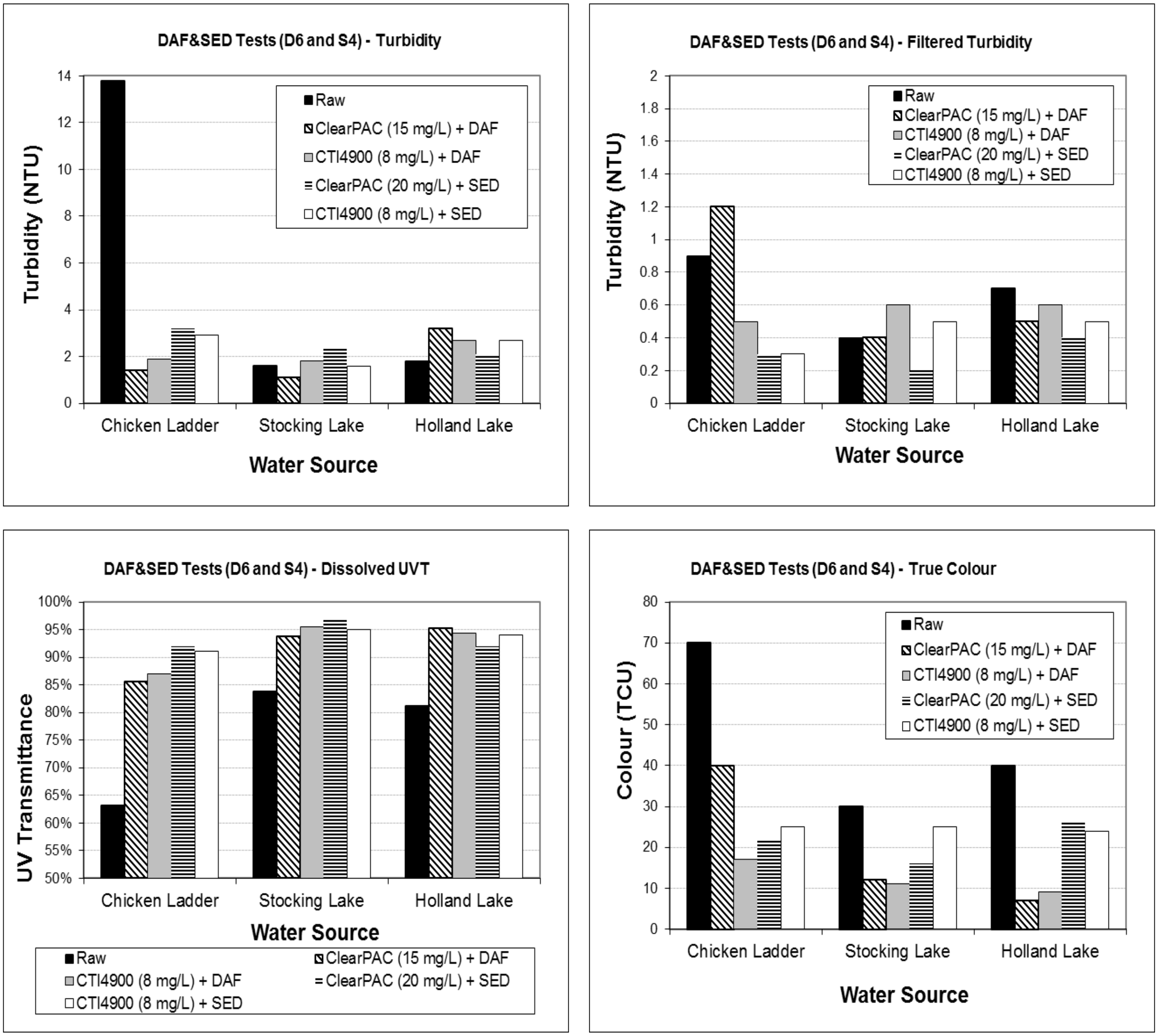


Figure 6.1: Turbidity (clarified and filtered), dissolved UVT and true colour measurements for jar tests with alternate water sources.

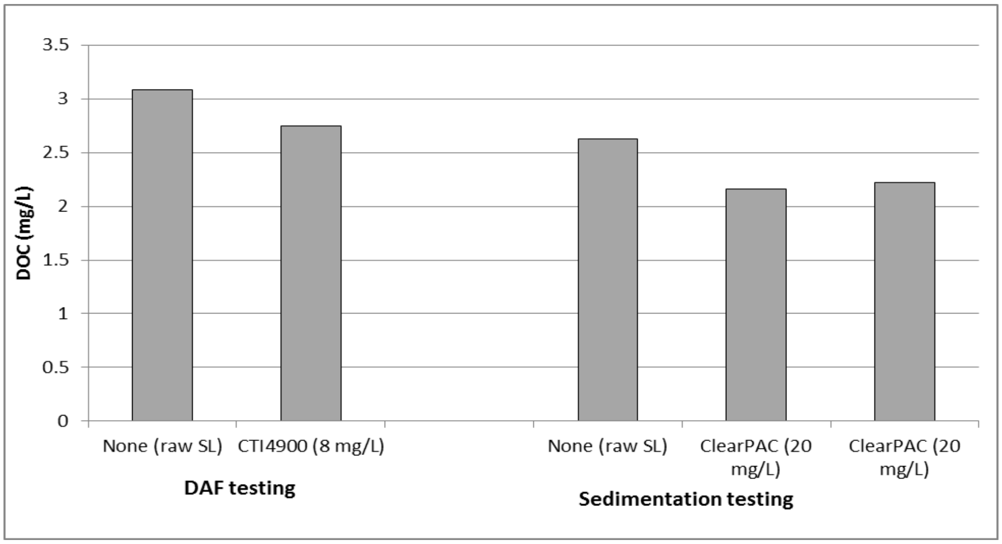
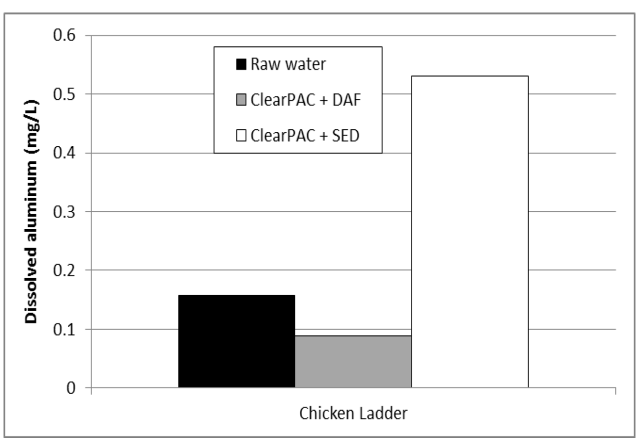


Figure 6.2: Dissolved organic carbon for Stocking Lake water jar tests

One other consideration is the resulting aluminum concentration in the water after clarification (Figure 6.3). High concentrations of dissolved aluminum can result in fouling of membranes. The dissolved aluminum concentration increased from 0.15 µg/L to 0.53 µg/L for sedimentation with Chicken Ladder water. DAF treatment reduced the dissolved aluminum component to <0.1 µg/L. Direct comparison of results is difficult due to the use of different coagulation chemicals and doses. While it is difficult to accurately draw conclusions on aluminum concentrations based upon the bench-scale tests, aluminum concentrations should be monitored during piloting. It should be noted that residual aluminum is the lowest at the optimum coagulant dose. If higher or lower doses than optimum coagulant dose are applied, increased residual aluminum levels are typically expected.



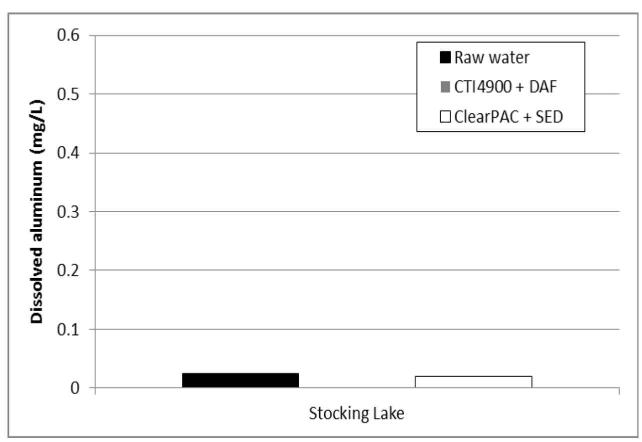


Figure 6.3: Dissolved aluminum concentrations for Chicken Ladder and Stocking Lake waters

7 PROCESS SELECTION

In the bench-scale tests using Chicken Ladder water, sedimentation tended to produce water with lower DOC and higher UVT values compared to DAF. Generally, clarified and filtered turbidity values were comparable between the two clarification methods. Colour was better removed using DAF, both for Chicken Ladder water and the alternative water sources. Additionally, lower residual aluminum concentrations were noted when using DAF when compared to sedimentation. However, some sediment was noted at the bottom of the jars for most chemicals and source waters when DAF was used, which indicates that the flocs formed may not be ideal for removal via DAF.

Overall, sedimentation tended to produce the best water quality in terms of organics concentrations, and therefore was selected for DBP formation potential testing at the bench-scale. ClearPAC at a dose of 20 mg/L was used for these tests as it was considered the optimized coagulant and dose, due to its performance for turbidity, DOC and colour reduction, and increasing UVT to 94%.

8 DBP FORMATION POTENTIAL

Jar tests were repeated using Chicken Ladder and Stocking Lake water to determine the effect of coagulation (20 mg/L ClearPAC) with sedimentation on the disinfection by-product (DBP) formation potential of the water. Water was chlorinated and allowed to react for a set amount of time (1 hour at 10 mg/L initial dose, and 7 days with a dose appropriate to attain a final chlorine residual of 3-5 mg/L). After this time period, the reaction was quenched and samples were collected for the analysis of two major types of DBPs: trihalomethanes (THMs) and haloacetic acids (HAAs). Results are shown in Figures 7.1-2. As an insufficient amount of water was produced in the jar tests, the 7-day HAA formation potential could not be analyzed. HAA formation potential can be confirmed during pilot testing.

For both Chicken Ladder and Stocking Lake waters, chlorinated post-sedimentation waters produced less THMs than chlorinated raw waters. A larger THMFP reduction was noted after 7 days of chlorination than 1 hour: a THMFP reduction of 68% was observed for both Chicken Ladder and Stocking Lake waters. For the shorter chlorination period (1 hour), sedimentation resulted in a larger percent reduction of THMFP in Chicken Ladder water (45%) compared to Stocking Lake water (30%). This indicates that the sedimentation process was able to significantly remove organics responsible for DBP formation from the water. However, the finished THMFP levels for Chicken Ladder water appear to be higher than the GCDWQ limit of 100 µg/L. This suggests an additional organics removal process would be necessary for Chicken Ladder water treatment. Further pre-treatment optimization by PAC during a future pilot study could confirm if THMFP levels could be maintained below the GCDWQ limits.

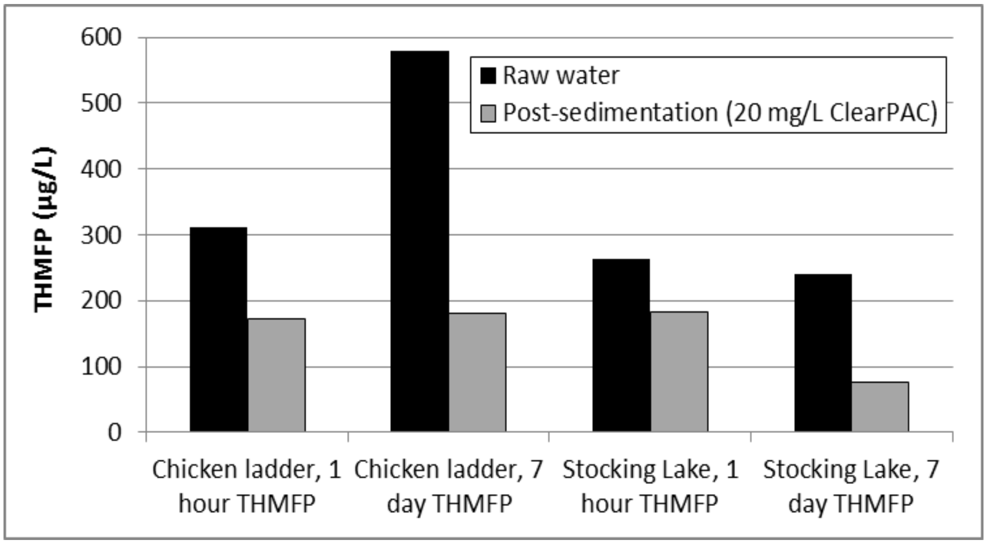


Figure 7.1: THM formation potential for Chicken Ladder and Stocking Lake waters after 1 hour and 7 days of chlorination

HAA formation potential (after 1 hour of chlorination) was reduced by 76% in Chicken Ladder water and 41% in Stocking Lake water after sedimentation; however, the concentrations of HAAs produced in each water type were similar (46 µg/L in Chicken Ladder and 56 µg/L in Stocking Lake).

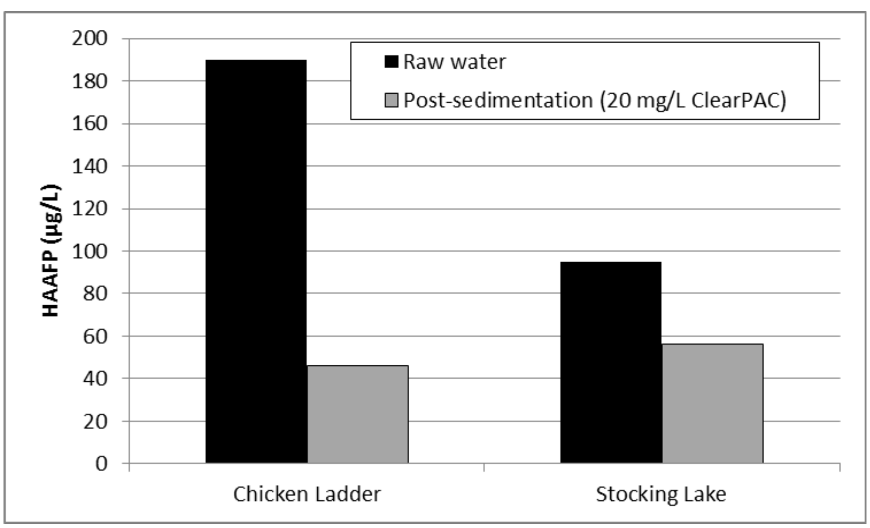


Figure 7.2: HAA formation potential for Chicken Ladder and Stocking Lake waters after 1 hour of chlorination

9 PRE-TREATMENT IMPLICATIONS

While the water quality of the clarified water was similar for both DAF and sedimentation jar tests, floc was consistently noted at the bottom of jars during the DAF jar tests. This indicates that the flocs produced by the source waters may not be best suited for DAF: any floc that does not float will remain in the treated water and sent to the filters, possibly leading to loss of head (in media filters) or fouling (in membranes). Due to this, sedimentation is recommended as the clarification process to be tested at the pilot scale.

One other consideration is the resulting aluminum concentration in the water after clarification. Sedimentation at the bench-scale resulted in higher dissolved aluminum concentrations than DAF; this may be an operational concern for sedimentation if used as a pre-treatment to membranes, as fouling may occur. As a result, coagulation conditions should be selected to minimize the final dissolved aluminum while still achieving pre-treatment goals, and fouling should be monitored during pilot testing.

A few chemical combinations performed well during sedimentation. ClearPAC (20 mg/L) is recommended as the top choice, while CTI4900 (8 mg/L), flocculant aid with alum (25 mg/L alum with 5 mg/L flocculant aid) and PAC with alum (25 mg/L alum with approximately 17 mg/L PAC) also produced high quality water. Pilot testing should be conducted on a number of these chemical combinations, time and budget permitting.

10 SUMMARY

Key observations are:

- Sedimentation and DAF were able to improve the quality of water from Chicken Ladder and Stocking Lake.
- Overall, sedimentation appeared to perform better than DAF as a pre-treatment clarification process. Even though slightly better turbidity was seen in DAF tests compared to sedimentation tests, the flocs tended to settle during DAF tests, and sedimentation was more effective for DOC reduction.
- The optimum alum pre-treatment dose using both clarification processes was 25 mg/L in Chicken Ladder water: during sedimentation, dissolved UVT was improved from 55% to 82%. Adding a lower dose of soda ash (10 mg/L) improved UVT (93% dissolved) and turbidity.
- ClearPAC (at 15 to 20 mg/L) and CTI4900 (at 8 mg/L) produced better water quality in terms of UVT and turbidity than the optimized alum dose.
- For DAF, a flocculation time of 13 minutes appeared to be adequate; increasing it to 30 minutes did not significantly improve water quality.
- A DAF recycle rate of 10-14% appeared to be adequate; increasing the recycle rate to 19-23% did not significantly improve water quality.
- Addition of PAC (approximately 17 mg/L) to optimized alum dose resulted in higher UVT, decreased turbidity and colour during sedimentation.

- Flocculant aid improved water quality when used in conjunction with sedimentation, but caused increased turbidity during DAF.
- Coagulation with 20 mg/L ClearPAC, flocculation and sedimentation reduced THMFP and HAAFP in both Chicken Ladder and Stocking Lake waters.

11 RECOMMENDATION/PILOT TEST IMPLICATIONS

- Select sedimentation as the clarification process to test at the pilot scale.
- Select the following chemicals for pre-treatment:
  - ClearPAC
  - CTI4900
  - Alum + floc aid or alum + PAC (time permitting)
- Provide appropriate chemical feed systems to attain the following dose ranges:
  - ClearPAC: 5 – 30 mg/L
  - CTI4900: 1 – 10 mg/L
  - Alum; 5 – 30 mg/L
  - Floc aid: 1 – 10 mg/L
  - PAC: 5 - 30 mg/L

A separate memo will be issued which describes the recommendations for the pilot study in detail.

Prepared by:

Sabrina Diemert, M.A.Sc., E.I.T.
Process Engineer

Reviewed by:

Sutha Suthaker, Ph.D., P.Eng.
National Practice Leader – Water Treatment

Reviewed by:

PROFESSIONAL ENGINEER
PROVINCE OF BRITISH COLUMBIA
K. D. KOHUT
33868

Jan 27/15

Keith Kohut, M.A.Sc., P.Eng.
Project Manager

Arbutus WTP - Treatability Assessment

DAF TEST RESULTS **TEST NO:** **D1** **DATE:** **10-Dec-14** TESTED BY: Keith/Sabrina

Time chemical addition started: PURPOSE: Optimize Alum Dose

JAR ID		1	2	3	4	5	6
Source		CL	CL	CL	CL	CL	CL
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	Alum	Alum	Alum	Alum	Alum	Alum
	required dose, mg/L	2	8	15	25	40	60
	ml stock added	0.4	1.6	3	5	8	12
Chemical 2	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	N/A	N/A	A	N/A	C	D
	Size mm	-	-	<1	-	1	2
saturator pressure, psi (before/after)		80/75	80/75	80/75	80/75	80/75	80/75
Recycle ratio for DAF		14.0%	11.0%	12.0%	12.0%	12.0%	14.0%
Float thickness, mm		<1	1	<1	1	2	2
Clarified water	pH	6.8	6.8	6.7	6.6	6.6	6.7
	Turbidity, NTU	8.1	8	10.6	10.3	7.8	8.1
	Apparent Colour	143	148	159	153	131	127
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	53%	53%	54%	55%	60%	59%
	Alk-total, as $CaCO_3$	20	20	20	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	81	58	39	40	41	37
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	58%	66%	81%	80%	79%	78%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity, NTU	0.4	0.7	0.7	1	1.1	1.3
Raw water	turbidity, NTU =	10.9	Filtetered water turbidity =	0.7	TOC, mg/L =	
Temp, C	Apparent Color =	160	True color (0.45 um filtered) =	83	DOC, mg/L=	
	Alk-total, as $CaCO_3$	20	Total aluminum =		pH =	6.9
	Alk-HCO_3, as $CaCO_3$		Diss. Aluminum =		UVA, cm-1 =	50.9
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$		Diss, UVA, cm-1 =	55.4
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$		Conductivity umhos =	
Comments: (5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 7 min flotation time before sampling)			Sediment at bottom of tank	Sediment at bottom of tank	Sediment at bottom of tank Sampled for DOC	Sediment at bottom of tank	Sediment at bottom of tank

Associated Engineering GLOBAL PERSPECTIVE. LOCAL FOCUS.

Arbutus WTP - Treatability Assessment

DAF TEST RESULTS **TEST NO:** **D2** **DATE:** **10-Dec-14** TESTED BY: **Keith/Sabrina**

Time chemical addition started: PURPOSE: Compare Cleapac & CTI4900 addition with alum coagulation

JAR ID		**1**	**2**	**3**	**4**	**5**	**6**
Source		**CL**	**CL**	**CL**	**CL**	**CL**	**CL**
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	Alum	ClearPac	ClearPac	ClearPac	CTI4900	CTI4900
	required dose, mg/L	25	5	10	15	8	17
	ml stock added	5	1	2	3	1.6	3.4
Chemical 2	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	D	A	A	F	B	A
	Size mm	2	<1	<1	4	1	<1
saturator pressure, psi		70/68	70/68	70/68	70/68	70/68	70/68
Recycle ratio for DAF		14.0%	12.0%	12.0%	11.0%	12.0%	12.0%
Float thickness, mm		1	0	0	2	2	0
Clarified water Discard colour readings, tainted sample cell (from aluminum testing) has been used.	pH	6.6	6.8	6.8	6.8	6.9	6.8
	Turbidity, NTU	9.1	9.2	9.1	1.6	3.6	10.4
	Apparent Colour	142	156	147	48	54	154
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	59%	55%	55%	80%	79%	54%
	Alk-total, as $CaCO_3$	30	20	20	20	40	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent) Discard colour readings, tainted sample cell (from aluminum testing) has been used.	True Colour	21	56	28	18	16	21
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	85%	67%	78%	89%	90%	89%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	0.9	0.5	0.6	0.6	0.3	1
Raw water	turbidity, NTU =	10.9	Filtetered water turbidity =		0.7	TOC, mg/L =	
Temp, C	Apparent Color =	160	True color (0.45 um filtered) =		83	DOC, mg/L=	
10	Alk-total, as $CaCO_3$	20				pH =	6.9
	Alk-HCO_3, as $CaCO_3$					UVA, cm-1 =	50.9
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$			Diss, UVA, cm-1 =	55.4
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$			Conductivity umhos =	
Comments: (5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 7 min flotation time before sampling)		Some sediment on bottom of jar	Some sediment on bottom of jar	Some sediment on bottom of jar	Sampled for DOC	Small amount of sediment Sampled for DOC	Sediment on bottom of jar

Arbutus WTP - Treatability Assessment

DAF TEST RESULTS | **TEST NO:** **D3** | **DATE:** **10-Dec-14** | TESTED BY: **Keith/Sabrina**

Time chemical addition started: 15:20 | PURPOSE: Effect of Alkalinity addition, flocculant aid

JAR ID		1	2	3	4	5	6
Source		**CL**	**CL**	**CL**	**CL**	**CL**	**CL**
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	Soda ash		Soda Ash	Soda Ash	Floc Aid	Floc Aid
	required dose, mg/L	10		10	20	5	10
	ml stock added	1		1	2	1	2
Chemical 2	type	Alum	Alum	Alum	Alum	Alum	Alum
	lag time (min) added	0	0	0	0	0	0
	required dose, mg/L	25	25	25	25	25	25
	mL stock added	5	5	5	5	5	5
Chemical 3	type	Floc aid					
	lag time (min) added	0					
	required dose, mg/L	5					
	mL stock added	1					
Floc formation (just before 0 rpm)	Type (A,B…)	D	D	B	A	A	B
	Size mm	2	2	1	<1	<1	1
saturator pressure, psi		80/76	80/76	80/76	80/76	80/76	80/76
Recycle ratio for DAF		11.0%	14.0%	14.0%	13.0%	11.0%	14.0%
Float thickness, mm		2.5	2	2	1 (foam)	1 (foam)	<1
Clarified water	pH	6.7	6.6	6.6	6.6	6.6	6.6
	Turbidity, NTU	7.8	6.7	5.8	11.2	9.6	7.6
	Apparent Colour	121	121	81	156	169	167
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	60%	61%	72%	53%	56%	54%
	Alk-total, as $CaCO_3$	20	20	20	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	36	33	23	82	69	40
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	92%	83%	88%	62%	70%	80%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	0.3	0.5	0.4	1.7	1	1

Raw water	turbidity, NTU =		Filtetered water turbidity =		TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =		DOC, mg/L=	
10	Alk-total, as $CaCO_3$				pH =	
	Alk-HCO_3, as $CaCO_3$				UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$		Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$		Conductivity umhos =	

Comments:	1	2	3	4	5	6
(5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 7 min flotation time before sampling)	Less coloured water Some sediment at jar bottom	Less coloured water Some sediment at jar bottom	Less coloured water Some sediment at jar bottom Sampled for DOC	More coloured water Lots of sediment	More coloured water Lots of sediment	More coloured water Lots of sediment Sampled for DOC

Arbutus WTP - Treatability Assessment

DAF TEST RESULTS	**TEST NO:**	**D4**	**DATE:**	**10-Dec-14**	TESTED BY:	**Keith/Sabrina**
Time chemical addition started:	15:30	PURPOSE:	Effect of flocculation time & PAC			

JAR ID		**1**	**2**	**3**	**4**	**5**	**6**
Source		**CL**	**CL**	**CL**	**CL**	**CL**	**CL**
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type		Soda Ash	Soda Ash	ClearPac	PAC	PAC
	required dose, mg/L		10	40	15	8	17
	ml stock added		1	4	3		
Chemical 2	type	Alum	Alum	Alum		Alum	Alum
	lag time (min) added	0	0	0		0	0
	required dose, mg/L	25	25	25		25	25
	mL stock added	5	5	5		5	5
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	E	B	A	E	A	A
	Size mm	3	1	<1	3	0	0
saturator pressure, psi		80	80	80	80	80	80
Recycle ratio for DAF		11.0%	10.0%	13.0%	13.0%	8	11
Float thickness, mm		2	2	0	2	2	4
Clarified water	pH	6.7	6.8	7.3	6.7	6.7	6.7
	Turbidity, NTU	4.9	6.1	6.9	1.7	4.8	7.7
	Apparent Colour	86	72	140	35	64	68
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	64%	70%	53%	78%	71%	79%
	Alk-total, as $CaCO_3$	20	20	60	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	57	30	75	35	37	41
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	81%	87%	65%	88%	85%	87%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	1.1	0.2	0.6	0.2	0.5	0.8

Raw water	turbidity, NTU =		Filtetered water turbidity =		TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =		DOC, mg/L=	
10	Alk-total, as $CaCO_3$				pH =	
	Alk-HCO_3, as $CaCO_3$				UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$		Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$		Conductivity umhos =	

	1	2	3	4	5	6
Comments: (10 min @ 60 rpm, 10 min@ 36 rpm, 10 min@ 20rpm saturation/observations at end, 10 min flotation or 7 min flotation time (Jar 5 & 6) time before sampling)		Sampled for DOC		Colour significantly lower	Colour significantly lower Some PAC settled Sampled for DOC	Colour significantly lower Some PAC settled, some still floating below surface at 7 min flotation

Associated Engineering GLOBAL PERSPECTIVE. LOCAL FOCUS.

Arbutus WTP - Treatability Assessment

DAF TEST RESULTS | **TEST NO:** **D5** | **DATE:** **10-Dec-14** | TESTED BY: **Keith/Sabrina**

Time chemical addition started: 10:00 | PURPOSE: Effect of PAC, Polymer (at higher recycle rate)

JAR ID		1	2	3	4	5	6
Source		CL	CL	CL	CL	CL	CL
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type			Soda Ash		PAC	
	required dose, mg/L			10		8	
	ml stock added			1			
Chemical 2	type	ClearPac	Alum	Alum	CTI4900	Alum	Alum
	lag time (min) added	0	0	0	0	0	0
	required dose, mg/L	15	25	25	8	25	25
	mL stock added	3	5	5	1.6	5	5
Chemical 3	type						Floc. Aid
	lag time (min) added						0
	required dose, mg/L						10
	mL stock added						2
Floc formation (just before 0 rpm)	Type (A,B…)	F	D	B	A	-	A
	Size mm	3	2	1	<1	-	<1
saturator pressure, psi		80/68	80/68	80/68	80/68	80/68	80/68
Recycle ratio for DAF		22.0%	20.0%	20.0%	20.0%	19.0%	23.0%
Float thickness, mm		2	1	0	0.5	2	1
Clarified water	pH	6.7	6.6	6.9	-	-	-
	Turbidity, NTU	3.5	7.4	11	8.1	10.4	7.1
	Apparent Colour	50	114	137	116	126	136
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	78%	63%	61%	66%	67%	56%
	Alk-total, as $CaCO_3$	20	20	20	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	33	30	20	26	15	76
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	87%	88%	92%	91%	88%	64%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	0.2	0.4	0.4	0.7	0.4	1.1

Raw water	turbidity, NTU =		Filtetered water turbidity =		TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =		DOC, mg/L=	
10	Alk-total, as $CaCO_3$				pH =	
	Alk-HCO_3, as $CaCO_3$				UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$		Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$		Conductivity umhos =	

Comments:	1	2	3	4	5	6
(5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 7 min flotation time before sampling)					Some PAC settled on bottom of tank	

Arbutus WTP - Treatability Assessment

DAF TEST RESULTS **TEST NO:** **D6** **DATE:** **10-Dec-14** TESTED BY: **Keith/Sabrina**

Time chemical addition started: 15:00 PURPOSE: Compare water from different sources

JAR ID		**1**	**2**	**3**	**4**	**5**	**6**
Source		**CL**	**CL**	**SL**	**SL**	**HL**	**HL**
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	ClearPAC	CTI4900	ClearPAC	CTI4900	ClearPAC	CTI4900
	required dose, mg/L	15	8	15	8	15	8
	ml stock added	3	1.6	3	1.6	3	1.6
Chemical 2	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	F	A	D	B	None	None
	Size mm	3	<1	2	1	<1	<1
saturator pressure, psi		75/62	75/62	75/62	75/62	75/62	75/62
Recycle ratio for DAF		14.0%	13.0%	12.0%	14.0%	10.0%	11.0%
Float thickness, mm		3	2	1	1	1	1
Clarified water	pH					6.6	6.9
	Turbidity, NTU	1.4	1.9	1.1	1.8	3.2	2.7
	Apparent Colour	64	55	37	61	85	70
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	81%	81%	92%	87%	78%	79%
	Alk-total, as $CaCO_3$	20	20	20	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	40	17	12	11	7	9
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	86%	87%	94%	96%	95%	94%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	1.2	0.5	0.4	0.6	0.5	0.6
Raw water	turbidity, NTU =		Filtetered water turbidity =			TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =			DOC, mg/L=	
10	Alk-total, as $CaCO_3$					pH =	
	Alk-HCO_3, as $CaCO_3$					UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$			Calcium, as $CaCO_3$		Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$			Hardness, as $CaCO_3$		Conductivity umhos =	
Comments:		Looked clearer than jar #2. Sampled for DOC			Sampled for DOC		

Arbutus WTP - Treatability Assessment

SED TEST RESULTS **TEST NO:** **S1** **DATE:** **11-Dec-14** TESTED BY: Sabrina

Time chemical addition started: PURPOSE: Optimize Alum and ClearPAC Doses

JAR ID		1	2	3	4	5	6
Source		CL	CL	CL	CL	CL	CL
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	Alum	Alum	Alum	ClearPAC	ClearPAC	ClearPAC
	required dose, mg/L	15	25	40	10	15	20
	ml stock added	3	5	8	2	3	4
Chemical 2	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	A	B	B	D	F	F
	Size mm	<1	1	1	2	3	3
saturator pressure, psi (before/after)							
Recycle ratio for DAF							
Floc thickness, mm		1	1	1	1	5	5
Clarified water	pH	6.6	-	-	6.6	-	-
	Turbidity, NTU	11.9	9.1	9.6	6.8	4	4
	Apparent Colour	169	129	146	123	57	51
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	58%	63%	63%	62%	83%	85%
	Alk-total, as $CaCO_3$	20	20	20	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	32	34	30	25	21	21
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	82%	82%	83%	89%	92%	94%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity, NTU	0.5	0.6	1.3	0.7	0.5	0.4

Raw water	turbidity, NTU =	13.8	Filtetered water turbidity =	0.9	TOC, mg/L =	
Temp, C	Apparent Color =	184	True color (0.45 um filtered) =	83	DOC, mg/L=	
	Alk-total, as $CaCO_3$	20	Total aluminum =		pH =	6.9
	Alk-HCO_3, as $CaCO_3$		Diss. Aluminum =		UVA, cm-1 =	55.30%
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$		Diss, UVA, cm-1 =	63.10%
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$		Conductivity umhos =	

	1	2	3	4	5	6
Comments: (5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 20 min settling time before sampling)	Sediment on jar bottoms during final flocculation stage	Sediment on jar bottoms during final flocculation stage Sampled for DOC	Sediment on jar bottoms during final flocculation stage	Sediment on jar bottoms during final flocculation stage	Sediment on jar bottoms during final flocculation stage Fluffy, slow-settling floc	Sediment on jar bottoms during final flocculation stage Fluffy, slow-settling floc Sampled for DOC

Associated Engineering GLOBAL PERSPECTIVE. LOCAL FOCUS.

Arbutus WTP - Treatability Assessment

SED TEST RESULTS **TEST NO:** **S2** **DATE:** **11-Dec-14** TESTED BY: **Sabrina**

Time chemical addition started: PURPOSE: Compare alum, CTI4900, PAC + alum

JAR ID		1	2	3	4	5	6
Source		CL	CL	CL	CL	CL	CL
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	Alum	Alum	Alum	CTI4900	CTI4900	CTI4900
	required dose, mg/L	25	25	25	4	8	17
	ml stock added	5	5	5	0.8	1.6	3.4
Chemical 2	type		PAC	PAC			
	lag time (min) added		8	17			
	required dose, mg/L						
	mL stock added						
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	A	B	D	A	A	A
	Size mm	<1	1	2	<1	<1	<1
saturator pressure, psi							
Recycle ratio for DAF							
Floc thickness, mm		<1	1	2	<1	<1	<1
Clarified water Discard colour readings, tainted sample cell (from aluminum testing) has been used.	pH	6.6	6.6	6.7	6.7	6.7	6.7
	Turbidity, NTU	9.5	9.1	4.9	8.9	1.8	9.1
	Apparent Colour	146	124	66	142	30	154
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	62%	68%	82%	57%	86%	57%
	Alk-total, as $CaCO_3$	20	20	20	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent) Discard colour readings, tainted sample cell (from aluminum testing) has been used.	True Colour	43	32	16	23	14	29
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	81%	85%	90%	84%	91%	85%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	1.9	0.5	0.4	0.3	0.4	0.6
Raw water	turbidity, NTU =		Filtetered water turbidity =			TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =			DOC, mg/L=	
	Alk-total, as $CaCO_3$					pH =	
	Alk-HCO_3, as $CaCO_3$					UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$			Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$			Conductivity umhos =	
Comments: (5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 20 min settling time before sampling)			Most PAC settled during 20 rpm floc stage Noticeably less colour	Most PAC settled during 20 rpm floc stage Noticeably less colour Sampled for DOC		More floc than other ACH doses, very fluffy Sampled for DOC	

Arbutus WTP - Treatability Assessment

SED TEST RESULTS **TEST NO:** **S3** **DATE:** **11-Dec-14** TESTED BY: **Sabrina**

Time chemical addition started: PURPOSE: Effect of Alkalinity addition, flocculant aid

JAR ID		**1**	**2**	**3**	**4**	**5**	**6**
Source		**CL**	**CL**	**CL**	**CL**	**CL**	**CL**
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type		Floc aid	Floc aid	Soda ash	Soda ash	Soda ash
	required dose, mg/L		5	10	10	20	40
	ml stock added		1	2	1	2	4
Chemical 2	type	Alum	Alum	Alum	Alum	Alum	Alum
	lag time (min) added	0	0	0	0	0	0
	required dose, mg/L	25	25	25	25	25	25
	mL stock added	5	5	5	5	5	5
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	B	B	B	A	A	A
	Size mm	1	1	1	<1	<1	<1
saturator pressure, psi							
Recycle ratio for DAF							
Floc thickness, mm		1	2	1	2	1	1
Clarified water	pH	6.6	6.6	6.9	6.7	6.9	7.4
	Turbidity, NTU	9.9	3.7	9.3	4.9	9.4	8.2
	Apparent Colour	150	52	155	70	160	158
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	62%	85%	57%	82%	57%	59%
	Alk-total, as $CaCO_3$	20	20	20	20	20	40
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	34	19	32	24	33	75
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	82%	92%	87%	93%	90%	64%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	1	0.5	0.6	0.3	0.4	0.7
Raw water	turbidity, NTU =		Filtetered water turbidity =			TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =			DOC, mg/L=	
	Alk-total, as $CaCO_3$					pH =	
	Alk-HCO_3, as $CaCO_3$					UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$			Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$			Conductivity umhos =	
Comments: (5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 20 min settling time before sampling)			Suspended floc remained after 20 min settling time Sampled for DOC		Suspended floc remained after 20 min settling time Sampled for DOC		

Arbutus WTP - Treatability Assessment

SED TEST RESULTS **TEST NO:** **S4** **DATE:** **11-Dec-14** TESTED BY: **Sabrina**

Time chemical addition started: PURPOSE: Compare water from different sources

JAR ID		**1**	**2**	**3**	**4**	**5**	**6**
Source		**CL**	**CL**	**SL**	**SL**	**HL**	**HL**
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	Clearpac	CTI4900	Clearpac	CTI4900	Clearpac	CTI4900
	required dose, mg/L	20	8	20	8	20	8
	ml stock added	4	1.6	4	1.6	4	1.6
Chemical 2	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	F	A	B	D	none	none
	Size mm	3	<1	1	2	-	-
saturator pressure, psi							
Recycle ratio for DAF							
Floc thickness, mm		4	3	1	1	-	-
Clarified water	pH	6.6	6.9	6.9	7.1	6.6	6.8
	Turbidity, NTU	3.2	2.9	2.3	1.6	2.1	2.7
	Apparent Colour	46	48	38	42	64	72
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	86%	84%	84%	87%	78%	79%
	Alk-total, as $CaCO_3$	20	20	20	20	20	20
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	22	25	16	25	26	24
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	92%	91%	97%	95%	92%	94%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity	0.3	0.3	0.2	0.5	0.4	0.5
Raw water	turbidity, NTU =		Filtetered water turbidity =			TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =			DOC, mg/L=	
	Alk-total, as $CaCO_3$					pH =	
	Alk-HCO_3, as $CaCO_3$					UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$			Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$			Conductivity umhos =	
Comments: (5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 20 min settling time before sampling)		Some floc still suspended after settling time Sampled for DOC	Some floc still suspended after settling time	Some floc still suspended after settling time Sampled for DOC	Some floc still suspended after settling time		

Associated Engineering GLOBAL PERSPECTIVE. LOCAL FOCUS.

Arbutus WTP - Treatability Assessment

SED TEST RESULTS **TEST NO:** **T1** **DATE:** **11-Dec-14** TESTED BY: Sabrina

Time chemical addition started: PURPOSE: Evaluate DBP formation

JAR ID		1	2	3	4	5	6
Source		CL	CL	CL	SL	SL	SL
Jar Volume, L		1	1	1	1	1	1
Chemical 1	type	ClearPAC	ClearPAC	ClearPAC	ClearPAC	ClearPAC	ClearPAC
	required dose, mg/L	20	20	20	20	20	20
	ml stock added	4	4	4	4	4	4
Chemical 2	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Chemical 3	type						
	lag time (min) added						
	required dose, mg/L						
	mL stock added						
Floc formation (just before 0 rpm)	Type (A,B…)	F	F	F	B	B	B
	Size mm	3	3	3	1	1	1
saturator pressure, psi (before/after)							
Recycle ratio for DAF							
Float thickness, mm							
Clarified water	pH	6.6	-	-	6.9	-	-
	Turbidity, NTU	3.3	3.1	3.3	1.9	2	2
	Apparent Colour	47	46	49	36	40	36
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	85%	86%	86%	84%	84%	84%
	Alk-total, as $CaCO_3$						
	Alk-HCO_3, as $CaCO_3$						
	Alk-CO_3, as $CaCO_3$						
	Alk-OH, as $CaCO_3$						
Filtered through a 0.45 um filter paper (dissolved constituent)	True Colour	25	19	22	16	22	15
	UVA @ 254 nm, cm-1 =						
	UVT calculated, % =	92%	92%	92%	96%	97%	97%
	Aluminium, mg/L =						
	Calcium, as $CaCO_3$						
	Hardness, as $CaCO_3$						
	DOC, mg/L						
	Turbidity, NTU	0.3	0.3	0.2	0.3	0.3	0.3

Raw water	turbidity, NTU =		Filtetered water turbidity =		TOC, mg/L =	
Temp, C	Apparent Color =		True color (0.45 um filtered) =		DOC, mg/L=	
11	Alk-total, as $CaCO_3$		Total aluminum =		pH =	
	Alk-HCO_3, as $CaCO_3$		Diss. Aluminum =		UVA, cm-1 =	
	Alk-CO_3, as $CaCO_3$		Calcium, as $CaCO_3$		Diss, UVA, cm-1 =	
	Alk-OH, as $CaCO_3$		Hardness, as $CaCO_3$		Conductivity umhos =	

Comments:
(5 min @ 60 rpm, 5 min@ 36 rpm, 3 min@ 20rpm for saturation/observations, 20 min settling time before sampling)

Appendix B – GE Pilot Report

Town of Ladysmith- Ladysmith BC

ZeeWeed®1000 Final Report

Submitted to:

Associated Engineering

Suite 300 - 4940 Canada Way,
Burnaby, BC V5G

Attention: Sabrina Diemert

Submitted by:

GE Water & Process Technologies Canada
3239 Dundas Street West
Oakville, Ontario L6M 4B2

August 2015

ACKNOWLEDGEMENTS

GE Water & Process Technologies would like to thank Associated Engineering for their dedication over the course of the pilot study. GE Water & Process Technologies would also like to thank The Town of Ladysmith Water Treatment Plant Operators for their efforts during the pilot study. Thank you to all involved.

EXECUTIVE SUMMARY

GE Water & Process Technologies, in conjunction with Associated Engineering, conducted a pilot study from March 19th to July 2nd, 2015 using a ZeeWeed® 1000 ultrafiltration (UF) membrane system. The study was conducted at the Town of Ladysmith Water Treatment Plant, located on Vancouver Island, treating Stocking Lake and Chicken Ladder water. The study was conducted to demonstrate the full-scale process and the effectiveness of the system to meet the water quality objectives with pre-treatment using DAF, or coagulation and flocculation.

This document has been written to provide a summary of the operational and analytical results obtained throughout the pilot study. The following sections highlight the conclusions that can be drawn from the Town of Ladysmith pilot study.

Membrane Performance

- The membrane system was operated at the consistent operating conditions shown in Table 13.

Table 13: UF Pilot Membrane Process Operating Conditions

UF Pilot Study Settings	
System Recovery	95%
Flux (Lmh)	51.2
Cycle Time (minutes)*	39
Permeate Flow (L/s)	0.6
Maintenance cleaning protocol	6 times per week using Sodium Hypochlorite @ 250 mg/L 1 time per week using Citric Acid @ 500 mg/L

*pilot cycle time representative of full-scale recovery

- The pilot operated downstream of several variations of pre-treatment for both the Chicken Ladder and Stocking Lake source waters. Raw water from both sources was tested with coagulation and flocculation at many coagulant dosages, as well as with DAF pre-treatment system at many coagulant dosages.
- With the frequency of variations on the pre-treatment conditions, membrane fouling rates and corresponding anticipated cleaning intervals were not calculated for the

various phases of testing. However, the following conclusions may still be drawn in terms of relative performance through the various combinations of raw water and pre-treatment:

- Phase 3 and 4 test runs at 10 mg/L of ClearPAC polyaluminum chloride (PACl) coagulant (1.53 mg/L Al^{3+}) demonstrated low fouling rates on both Chicken Ladder and Stocking Lake DAF Pre-Treated feed water.
- The best overall membrane performance was observed during Phase 5 while operating on the Chicken Ladder source water with coagulation and flocculation pre-treatment with ClearPac coagulant. Unfortunately, as the coagulant dosing was not confirmed, it is unclear what coagulant dose was actually delivered during this phase.
- When the DAF unit was operated with alum during Phase 4 on Chicken Ladder water (unknown alum dose), the membrane system performed well while operating at a temperature of approximately 12 °C.
- For Phase 6 operating on raw water pre-treated by coagulation and flocculation using the CTI4900 aluminum-chlorohydrate coagulant (ACH), good membrane performance was observed at the dosages of 0.2 mg/L as Al^{3+} and 0.6 mg/L as Al^{3+} for the Chicken Ladder and Stocking Lake water sources, respectively.

Water Quality

- While the calcite contactor seemed to negatively impact membrane system performance and was difficult to control, membrane performance stabilized during Phase 5 when the calcite contactor was replaced with a soda ash dosing system. The soda ash dosing enabled the measured alkalinity in the flocculation tank and permeate to meet the target alkalinity of > 30 mg/L as $CaCO_3$. This indicated that the soda ash dosing was an effective means of introducing alkalinity, compatible with the membrane process.

- Throughout the study, the UF permeate turbidity remained less than 0.1 NTU 100% of the time, despite feed turbidity ranging from 0.8 to 4.8 NTU. UF permeate turbidity therefore met the objective of turbidity less than 0.1 NTU 95% of the time and less than 0.3 NTU 100% of the time.
- Permeate Total Organic Carbon (TOC) was consistently below 3 mg/L throughout the pilot study. The best TOC removal was observed during Phases 3 and 4 with DAF pre-treatment using 1.53 mg/L as Al^{3+} of coagulant or more, reducing the permeate TOC to an average of 1.1 to 1.2 mg/L.
- With flocculation pre-treatment, the best TOC removal results were obtained with 0.5 to 0.6 mg/L Al^{3+}, reducing the permeate TOC to approximately 1.8 mg/L on average.
- In order to meet water quality objectives for THMFP and HAAFP, a coagulant dose of greater than 0.6 mg/L as Al^{3+} was needed. The objectives were met at dosages of 1.53 mg/L as Al^{3+}. Reducing the permeate TOC to less than 1.8 mg/L appears to be required, with a target of closer to 1.1 to 1.2 mg/L being required.
- All samples analyzed for aluminum showed aluminum levels below 0.1 mg/L. The objective for aluminum was therefore met.
- Apparent Colour and True Colour were sampled from the permeate during the pilot tests. Results meeting the objectives were fairly easy to achieve, indicating that by dosing the coagulant to target a TOC will easily lead to the color objective being achieved.

Membrane Cleaning

- As the fouling was mainly related to coagulant dosing, or to hardness overdosing when the calcite contactor was in use, acid recovery cleans likely had the most impact on permeability recovery. In general, the non-heated, standard recovery cleans that were done to restore membrane permeability between test runs were effective in restoring permeability, and the standard maintenance cleaning procedures were effective in maintaining membrane permeability during normal operation.

Based on the results of the pilot study, a full scale UF membrane system could be designed using either DAF or coagulation-flocculation pre-treatment, though the DAF would not really be required to remove any turbidity. With either form of pre-treatment, either PACl or ACH could be used effectively. Alum may be effective, though temperature limitations may apply to this coagulant that is not pre-hydrolyzed. Powdered activated carbon (PAC) should be avoided. Even though the TOC is relatively low in the raw water, the coagulant dosage needs to be optimized to meet the targets for THM and HAA.

TABLE OF CONTENTS

1. Introduction

The Town of Ladysmith chose to test GE's ultrafiltration (UF) membrane technology on feed water from two sources: Stocking Lake and Chicken Ladder. The pilot study was conducted at the Town of Ladysmith site, using DAF clarified or coagulated and flocculated water that generally represented the feed water of the proposed future water treatment plant. The study was conducted to demonstrate the full-scale process and the effectiveness of the system to meet the water quality objectives.

In February 2015, Associated Engineering (AE) extended an invitation to GE Water & Process Technologies (GE) to conduct pilot testing for the Town of Ladysmith with a ZeeWeed® 1000 Ultrafiltration Membrane Treatment System for a two month period. In response, GE Water & Process Technologies supplied AE and The Town of Ladysmith with a standard ZeeWeed® 1000 Ultrafiltration pilot. The study began in March 2015.

This document has been written to provide a summary of all operational, analytical, and cleaning results obtained throughout the Town of Ladysmith pilot study. The pilot objectives are stated in Section 2. Basic operating principles are presented in Section 3. Section 4 outlines the operational terminology that is used to characterize the membrane performance. Detailed discussions of membrane performance, water quality, and cleaning results are presented in Sections 5 through 7.

2. Pilot Objectives

The Town of Ladysmith pilot study objectives were as follows:

- Demonstrate the ability of a suitable up-front technology to provide alkalinity into the raw water stream.
- Compare the performance of three coagulants (Alum, ClearTech's ACH CTI4900, and ClearTech's PACl ClearPac) and determine the optimal dosing rate for each to achieve the target water quality.
- Evaluate membrane performance and water quality over the range of coagulant types and dosing rates on raw water from Chicken Ladder and from Stocking Lake.
- Evaluate membrane performance and water quality treating raw water from Chicken Ladder and from Stocking Lake with DAF pre-treatment.
- Demonstrate that the UF system will produce treated water that will meet the treated water turbidity guarantee that would be provided for the UF system of ≤ 0.1 NTU 95% of the time and < 0.3 NTU 100% of the time.
- Evaluate the ability of the UF system with pre-treatment to meet the treated water objectives outlined in Table 2 below.

Table 1: Treated Water Objectives

Parameter	Target Values
Total Organic Carbon (TOC)	As low as possible
Total aluminum	≤ 0.1 mg/L
Color	≤ 15 TCU
Trihalomethane formation potential (THMFP)	≤ 100 ug/L
Haloacetic acid formation potential (HAAFP)	≤ 80 ug/L

3. Membrane, Process, and Pilot Descriptions

3.1. ZeeWeed® 1000 Water Treatment Process

ZeeWeed® based drinking water treatment is a low energy immersed ultrafiltration membrane process that consists of outside-in, hollow-fiber modules immersed directly in the feed-water (Figure 1). The small pore size of the ultrafiltration membranes ensures that no particulate matter, including *Cryptosporidium* oocysts, *Giardia* cysts, suspended solids or other suspended contaminants of concern, will pass into the treated water stream.

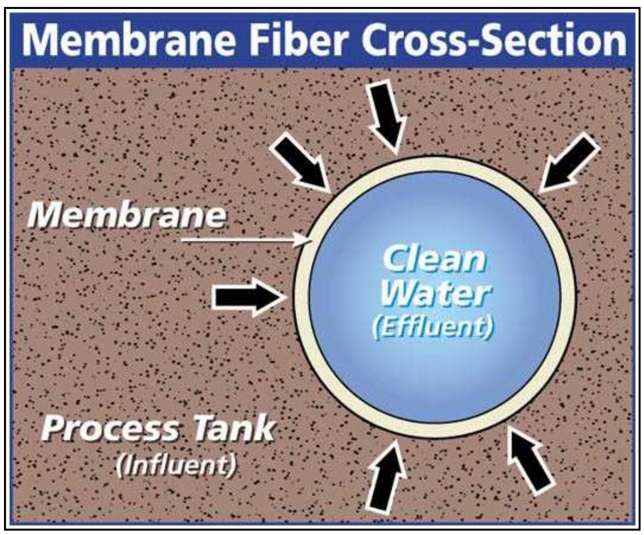


Figure 1: Membrane Fiber Cross-Section

The ZeeWeed® 1000 system is operated as a simple semi-batch process where filtration and backwash alternate in sequence. During the filtration cycle, permeate is withdrawn through the membranes by applying vacuum to the permeate piping. The water removed by permeation is replaced with feed water to maintain a constant level in the tank. No aeration is used while in filtration mode. At the end of each filtration cycle (typically 20 – 60 minutes), a backwash is performed. During the backwash, the membranes are simultaneously aerated and backpulsed to dislodge solids. Solids are loosened from the surface of the membranes and suspended in the process tank due to the aeration. Once the backpulse is complete, the process tank is completely drained, which rids the tank of any accumulated solids. The process tank is then refilled with feed water and production resumes.

3.2 ZeeWeed® 1000 Membrane

Figure 2 illustrates an individual ZeeWeed® 1000 membrane element, which is the building block and smallest replaceable unit within a ZeeWeed® 1000 filtration system. One ZeeWeed® 1000 membrane element consists of thousands of horizontally oriented hollow fibers mounted between two vertical plastic headers. Shrouds enclose the fibers, leaving only the bottom and top open to create a vertical flow upwards through the fiber bundles. The membrane element characteristics are summarized in Table 3.

Figure 2: ZeeWeed® 1000 Module

Table 2: ZeeWeed® 1000 Membrane Module Characteristics

Size of module used in study (LxHxW)	691 mm X 685 mm x 107 mm (27.2" x 27.0" x 4.2")
Configuration	Outside-in hollow fiber
Nominal membrane area	41.8 m^2 (450 ft^2)
Nominal membrane pore size	0.02 µm
Membrane material / construction	Proprietary polymer
Membrane surface properties	Non-ionic and Hydrophilic
Typical operating transmembrane pressure	-90 to 90 kPa (-13 to 13 psi)
Maximum operating temperature	40 °C (104 °F)
Operating pH range	5.0 - 9.5

A ZeeWeed® 1000 train is a production unit containing a number of elements immersed in an open tank. Figure 3 shows a train containing up to 12 elements. Feed enters each train from a feed pipe. Permeate is collected through a common header. Backwash water is removed through a backwash drain pipe

Figure 3: ZeeWeed® 1000 Train

3.3 ZeeWeed® 1000 Pilot

GE Water & Process Technologies supplied a pilot-scale ZeeWeed® 1000 system for the evaluation study at The Town of Ladysmith, including one (1) ZeeWeed® 1000 membrane module manufactured by GE Water & Process Technologies. A photograph of the typical equipment used in a pilot set-up is shown in Figure 4. The pilot skid includes a 500 µm automatic strainer upstream of the UF membrane tank.

Figure 4: Typical ZeeWeed® 1000 Ultrafiltration Pilot System

4 OPERATIONAL TERMINOLOGY

Flux, transmembrane pressure, permeability, recovery, backwash properties (frequency, duration, flux, pressure, permeability, and airflow) and chemical clean properties (frequency, chemical type, and chemical dose) are operating parameters used to evaluate the performance of the ZeeWeed® 1000 membrane. These terms are described in the following paragraphs, along with remarks about the values employed or achieved during piloting. Detailed discussions of pilot results follow in Sections 5 to 7.

4.1 Flux

Flux is a measure of the rate at which the product (or permeate) passes through the membrane per unit of outside surface area of membrane. It is reported in units of liters/metre^2/hour (Lmh). The net flux is a calculation that takes into account the frequency and duration of backwashing, accounting for the lost production time as well as the actual volume of permeate lost during the backwash. In addition, losses associated with maintenance cleans and recovery cleans are taken into account. The instantaneous flux does not account for the backpulse volume that is used during backwashing or the volume of permeate used during the maintenance cleans, and is therefore a higher value.

All fluxes presented in this report are instantaneous. In typical systems the instantaneous flux is a factor of approximately 1.15 times the net flux. Net flux is determined in the final design based on specific design points (such as backpulse frequency, tank volumes etc).

Figures A1, A5, A10, A13, A16, and A19 illustrate the instantaneous fluxes for each of the phases of the study. The pilot was operated at a consistent instantaneous design flux of 51.2 Lmh.

4.2 Transmembrane Pressure

Transmembrane pressure (TMP) refers to the vacuum required to pull clean water through the ultrafiltration membrane. The ZeeWeed® 1000 system is designed to maintain a constant flux. Therefore, as the membrane becomes fouled, the transmembrane pressure increases. A cleaning is typically required once the transmembrane pressure reaches approximately 90 kPa.

TMP is a parameter that is typically corrected to account for temperature variations. Adjusting the TMP for temperature allows the influence of fouling to be isolated from those variations caused by temperature. The formula used to calculate TMP at x°C is shown below:

$$TMP\,@\,x^{\circ}C = TMP\,@\,T * \frac{Viscosity_x}{Viscosity_T}$$

TMP profiles for the various phases of the study are shown in Figures A3, A7, A10, A13, A16, and A19. The temperature ranged between 5°C and 9°C over the course of the study.

A detailed discussion of TMP data is presented in Section 5.

4.3 Permeability

Permeability is a calculated parameter of flux normalized against transmembrane pressure for ultrafiltration membranes. It is reported in units of Lmh/bar. Permeability is another parameter that is typically corrected to account for temperature variations. Adjusting the permeability for temperature allows the influence of fouling to be isolated from those variations caused by temperature. The formula used to calculate permeability at x°C is shown below:

$$Permeability@x°C = Permeability@T * \frac{Viscosity_T}{Viscosity_x}$$

Temperature corrected (to 20 °C) membrane permeability for each of the phases of the study is shown in Figures A2, A6, A9, A12, A15, and A18. The temperature corrected permeability varied from 277 Lmh/bar to 34 Lmh/bar and averaged 153 Lmh/bar over the course of the study.

4.4 Recovery

The recovery is the percent of the raw water passing through the membrane as permeate.

For the ultrafiltration membrane, recovery is primarily controlled by flux and length of the filtration cycle since the membrane operates in a batch process. The only waste created through the ZeeWeed® 1000 process is that which is rejected and disposed of either during the backwash procedure or during cleaning. The backwash frequency is varied in order to achieve the desired recovery set point.

In the case of this pilot study, the membrane system was operated at a constant recovery of 95%, with a cycle time of 39 minutes.

4.5 Backwash Properties

The backwash is used as a method of cleaning in the ZeeWeed® 1000 process. Typically, every 20-60 minutes, flow is reversed through the membrane (backpulsed) for 15 seconds, pushing clean water from the inside of the membrane lumen to the outside. The water used for the backpulse is permeate that has been collected in the backpulse tank. Following the membrane backpulse, the contents of the membrane tank are completely drained to rid the tank of any accumulated solids.

Backpulse flux refers to the rate at which the backpulse water (permeate from the backpulse tank) passes through the membrane per unit of surface area of membrane. The backpulse flux is typically set to equal the permeate flux.
Backpulse pressure is the transmembrane pressure required to push clean water from the inside to outside of the membrane during a backpulse. Backpulse permeability is a calculated parameter that represents the permeability of the membrane observed when the flow through the membrane is reversed.

Air is applied only during the backwash and clean procedures for the ZeeWeed® 1000 process. The air is supplied to the bottom of the membrane module. As it travels through the membrane stack to the surface of the process tank, it scours the outside of the membrane fibers and removes any larger particles that have adhered to the surface of the fibers. In addition, the airflow creates an airlift effect within the membrane tank to hold in suspension any solids from the membrane surface so that they are easily flushed out of the membrane tank during the drain at the end of the backwash and cleaning procedures. The air remains on during the tank drain portion of the backwash.

During this pilot study, the backpulse flux was maintained as equal to the permeate flux except during Phase 1 where the backpulse flux was approximately 30 Lmh. The backwash frequency was set at 39 minutes when operating at 51.2 Lmh in order to achieve 95% recovery, and the aeration rate was set to 5.1 dm^3/h (3 dcfm). The flux, TMP, and temperature corrected (to 20 °C) permeability for the backpulse are included on the figures illustrating these parameters during production.

4.6 Chemical Cleans

Maintenance clean is another operational strategy used to control ultrafiltration membrane fouling. Maintenance cleans can be performed at frequencies typically ranging from once per day to once per week, but the frequency can be increased or decreased as needed.

Standard maintenance cleans involve chemical addition. During these cleans the process tank is drained and then filled with permeate. Chemicals such as sodium hypochlorite or citric acid are added to achieve a desired concentration in the process tank. Once the tank is full, the membranes are soaked in the chemical solution for 15 minutes and then the solution is drained from the tank. Standard sodium hypochlorite doses range from 50 to 250 mg/L. Citric acid is typically used at 0.5 to 2 g/L. Before resuming production, chemical residuals are flushed from the process tank.

During this pilot study, a consistent maintenance cleaning protocol was maintained, with six (6) cleans per week performed using 250 mg/L of sodium hypochlorite, and one (1) clean per week performed using 500 mg/L of citric acid. Maintenance cleans were not heated.

Recovery cleans are performed less frequently and at higher concentrations compared to maintenance cleans. In addition, the soak time is extended typically to at least five hours, and the cleaning solution may be heated to approximately 35 °C. Standard recovery clean doses for the ultrafiltration system are 500 mg/L of sodium hypochlorite and 2,000 mg/L of citric acid with mineral acid addition to target a pH of 2.1. During this study, recovery cleans were performed as required based on the TMP and permeability of the membranes. Details of the recovery cleans performed are presented in Section 7.

4.7 Pre-treatment

During the phases of the pilot study performed on coagulated and flocculated feed water, the pilot feed water for the Town of Ladysmith site was pre-treated using alkalinity and pH adjustment for coagulation optimization, followed by coagulant addition up stream of the pilot flocculation tank. The pre-treatment targets for the flocculation tank (post coagulant dosing) are shown in Table 4.

Table 3: Pre-treatment Water Objectives

Parameter	Target Values
Alkalinity	~30 mg/L as $CaCO_3$
pH	6.5-7.2

Initially, GE provided a calcite contactor to raise the alkalinity to 30 mg/L as $CaCO_3$. Due to the difficulty in controlling the alkalinity in this manner, the calcite contactor was replaced with a 5% soda ash solution dosing system partway through the pilot study. The pH adjustment throughout the study was performed using sulfuric acid. The pilot coagulation and flocculation pre-treatment arrangement is shown in the process flow diagram in Appendix C.

During the phases of the pilot study performed on DAF effluent, the pilot feed water was pre-treated by coagulant addition and a pilot DAF unit supplied by Corix. The alkalinity and pH were not adjusted.

The pre-treated feed water to the UF membrane tank was screened to 0.5 mm.

5 DISCUSSION - MEMBRANE PERFORMANCE

During the Town of Ladysmith pilot study, the UF pilot was operated at consistent membrane process operational parameters. The operating conditions are summarized in the tables below.

Table 4: UF Pilot Membrane Process Operating Conditions

UF Pilot Study Settings	
System Recovery	95%
Flux (Lmh)	51.2
Cycle Time (minutes)*	39
Permeate Flow (L/s)	0.6
Maintenance cleaning protocol	6 times per week using Sodium Hypochlorite @ 250 mg/L 1 time per week using Citric Acid @ 500 mg/L

*pilot cycle time representative of full-scale recovery

As the main objective of the study was to evaluate the impacts of the pre-treatment process on the treated water quality from the two raw water sources, the pre-treatment conditions were varied over the course of the pilot study, as outlined in the summary below.

Table 5: UF Pilot Pre-Treatment Operating Conditions

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6A	Phase 6B
Date range	March 19 – April 1	April 14 – April 21	April 21 – May 6	May 7 – May 14	May 20 – June 16	June 19 – June 20	June 23 – July 2
Raw water source	Chicken Ladder	Chicken Ladder	Chicken Ladder	Stocking Lake	Chicken Ladder	Chicken Ladder	Stocking Lake
Pre-treatment type	Coag/Floc	None	DAF	DAF	Coag/Floc	Coag/Floc	Coag/Floc
Alkalinity control	Calcite	Calcite	N/A	N/A	Soda ash	Soda ash	Soda ash
Coag. type	ClearPac (PACl)	None	ClearPac (PACl) Alum + PAC	ClearPac (PACl) Alum ClearPac (PACl)	ClearPac (PACl)	CTI4900 (ACH)	CTI4900 (ACH)
Coag. dose (mg/L as Al^{3+})	1.53 0.50	N/A	1.53 0.66 + 8 mg/L PAC	1.53 Unknown 2.3	0.1 0.5 0.76	0.2	0.6

While the original workplan included testing alum in the coagulation and flocculation pre-treatment options, the alum was only tested in the DAF pre-treatment due to time limitations.

For reference, the properties of the ClearTech coagulants tested are summarized as follows:

- ClearPac polyaluminum chloride (PACl): 34% active product, 9.9% Al_2O_3 = 5.2% as Al^{3+}, 54% basicity
- CTI4900 aluminum chlorohydrate (ACH): 25-50% active product (assume 37.5%), 12.2-12.7% Al^{3+}, 82.5-84.3% basicity

5.1. Phase 1: Chicken Ladder water with calcite and ClearPac

The UF pilot was placed into operation on March 19th, 2015 treating Chicken Ladder Water with pre-treatment consisting of a calcite contactor for alkalinity addition, sulfuric acid dosing for pH control to 7.2 in the flocculation tank, and coagulation/flocculation using ClearPAC (PACl) coagulant. The coagulant was dosed to the feed water at 1.53 mg/L as Al^{3+} (10 mg/L as product).

The membrane reached critical TMP (>80 kPa) within a few days. A couple of recovery cleans using citric acid and mineral acid were able to recover membrane permeability, and the pilot was restarted with a lower coagulant dose of 0.5 mg/L as Al^{3+} (3.2 mg/L as product) on March 31st. As the critical TMP was reached in less than a day, the pilot operation was shut down on April 1st. The Chicken Ladder + ClearPAC testing was put on hold until the issues with the calcite contactor could be addressed.

As pilot operation was unstable during this phase, the operating data and analytical data have not been included in this report.

5.2. Phase 2: Chicken Ladder water with calcite and no coagulant

The pilot unit was restarted on April 14th after several acid recovery cleanings were performed to remove the coagulant and hardness scale caused by the calcite contactor that had accumulated on the membrane, and restore permeability to the membrane. The pilot unit was restarted on Chicken Ladder water, with pre-treatment consisting of the calcite contactor only. Coagulant dosing was eliminated to determine whether the membrane fouling was caused by the calcite contactor, or the coagulant. The TMP continued to increase at an unsustainable rate, indicating that the calcite contactor was likely the issue.

On April 16th, the calcite contactor was bypassed, and the pilot was operated on raw water without any pre-treatment to evaluate the membrane performance at these conditions. As the fouling rate remained high and the membrane had reached terminal TMP multiple times, it was unclear whether the fouling rate was high due to the feed water quality, or due to the permeability not having been properly recovered from the recovery cleans performed. GE therefore decided to replace the membrane with a new one, and the pilot was shut down on April 21st to prepare for the next testing phase to run the pilot on DAF pretreated water with the new membrane module installed.

The operating data for this test run on Chicken Ladder water are shown in Figures A1 to A4.

Samples that were collected and analyzed during this phase of the testing showed that while the permeate met the turbidity objective, the permeate did not meet the water quality objective for color without pretreatment. The following table summarizes the laboratory data for the Chicken Ladder Water with calcite and no coagulant test run.

Table 6: Phase 2: Chicken Ladder water with calcite and no coagulant Permeate Data

Pre-treatment	Coagulation + Flocculation
Chemical(s)	Calcite Contactor
Turbidity (NTU)	<0.003
UVT (%)	76.1 - 82.2 (79.0)
Apparent Colour (TCU)	10 - 20 (15)
True Colour (TCU)	19 - 31 (24)
pH	2.7 - 7.4 (6.5)
Alkalinity (mg/L as CaCO3)	5.9 - 26.1 (18.7)
TOC (mg/L)	2.7 - 2.8 (2.8)
THMFP (µg/L)	-
HAAFP (µg/L)	-

*Averaged data shown in parenthesis.

5.3. Phase 3: Chicken Ladder water with DAF using ClearPac

The UF pilot membrane was replaced on April 21st and the system started again on DAF Pretreated Chicken Ladder Water with ClearPac coagulant being dosed at 10 mg/L as product (1.53 mg/L as Al^{3+}). The membrane performance was stable at these conditions, and minimal fouling was observed

On April 29th, the ClearPac coagulant was replaced with 8 mg/L PAC (Powdered Activated Carbon) + 15 mg/L Alum 0.66 mg/L as Al^{3+}). This caused the membrane fouling rate to increase dramatically, and the pilot system reached critical TMP on May 7th. These operating conditions were therefore unsustainable.

Flux, TMP, permeability, and permeate TOC data for this phase are provided in Figures A5 to A8.

Analytical data for the DAF Pretreated Chicken Ladder showed that the permeate quality met all of the treated water objectives outlined in Table 1. TOC results were the lowest observed during the pilot study. The following table summarizes the laboratory data for the DAF Pretreated Chicken Ladder Water.

Table 7: DAF Pre-treated Chicken Ladder Permeate Data

Pre-treatment	DAF	DAF	
Chemical(s)	10 mg/L PACl (1.53 mg/L Al_3^+)	15 mg/L alum	8 mg/L PAC
Turbidity (NTU)	< 0.004	< 0.004	
UVT (%)	95.2 - 97.1 (96.1)	82.0 - 97.5 (94.3)	
Apparent Colour (TCU)	5	5	
True Colour (TCU)	5	5 - 21 (9)	
pH	6.6 - 6.9 (6.8)	5.3 - 7.0 (5.9)	
Alkalinity (mg/L as CaCO3)	3.2 - 4.5 (4.0)	1.0 - 6.4 (3.0)	
Aluminum (mg/L)	-	-	
TOC (mg/L)	1.0 - 2.4 (1.2)	0.9 - 1.8 (1.1)	
DOC (mg/L)	-	-	
THMFP (µg/L)	66	-	
HAAFP (µg/L)	24	-	

*Averaged data shown in parenthesis.

5.4. Phase 4: Stocking Lake water with DAF using ClearPac

On May 7th the pilot was shut down for a membrane cleaning to restore permeability after the fouling from the PAC + Alum run. Between May 7th and May 13th, the DAF pre-treatment system was connected to Stocking Lake Water. Initially, the coagulant in use was ClearPac at 10 mg/L as product (1.53 mg/L as Al^{3+}). The membrane system performed well at these operating conditions.

On May 9th, the operators accidently switched the coagulant to alum. The system performed well even though the wrong coagulant was used. In comparison to the operation in Phase 3 with alum + PAC being used in the DAF, the membrane system performed much better which might indicate that the issue in Phase 3 related mainly to the presence of PAC and that operation with alum would be acceptable at this operating temperature of approximately 12 °C.

The error in coagulant was noticed on May 11th, and the DAF was switched back to ClearPAC at a dosing rate of 15 mg/L (2.3 mg/L as Al^{3+}). The membrane fouled soon after the switch back to ClearPAC, likely due to an upset with the DAF pre-treatment system.

The pilot performance data is shown in Figures A9 to A11.

Analytical data for the Stocking Lake Water with DAF using ClearPac (and alum) phase showed that the permeate water quality met all objectives outlined in Table 1. The data from this phase showed the best TOC removal of the entire pilot study for Stocking Lake with DAF pretreatment using 2.3 mg/L as Al^{3+} of the ClearPac coagulant.

The following table is a summary of the laboratory data collected from the DAF Pre-treated Stocking Lake Water.

Table 8: DAF Pre-treated Stocking Lake Permeate Data

Pre-treatment	DAF	DAF
Chemical(s)	10 mg/L PACl (1.53 mg/L Al^{3+})	15 mg/L PACl (2.3 mg/L as Al^{3+})
Turbidity (NTU)	< 0.004	< 0.004
UVT (%)	87.3 - 89.0 (88.2)	96.2 - 97.1 (96.7)
Apparent Colour (TCU)	5	5
True Colour (TCU)	10 - 12 (11)	5
pH	7.0 - 7.4 (7.2)	6.5 - 6.7 (6.6)
Alkalinity (mg/L as CaCO3)	9.4 - 13.0 (11.2)	3.8 - 5.3 (4.4)
Aluminum (mg/L)	-	0.01
TOC (mg/L)	2.2 - 2.3 (2.3)	1.0 - 1.3 (1.1)
DOC (mg/L)	-	-
THMFP (µg/L)	-	73
HAAFP (µg/L)	-	21

*Averaged data shown in parenthesis.

5.5. Phase 5: Chicken Ladder water with soda ash and ClearPac

Prior to the start of this phase, the membranes were recovery cleaned. Since the troubleshooting of the calcite contactor operation was requiring a lot of time, and the full-scale plant would most likely not use calcite for alkalinity control, the calcite contactor was replaced with a soda ash dosing system which consisted of a mixing tank and a chemical dosing pump. The pump was set to dose 60 mg/L soda ash, delivered as a 5% solution, to increase the feed alkalinity following coagulant addition to approximately 30 mg/L $CaCO_3$.

When the pilot was initially started on May 15th, the feed water pH was greater than 10. As that is outside the feed water guidelines, the pilot unit was turned off. The pipeline bringing the feed water to the pilot was flushed and the pH returned to normal such that the pilot could restart on May 20th. In order to ensure that the membrane system reacted well to the pre-treatment chemicals, these were introduced gradually. On May 20th, the pilot was started with no pre-treatment chemicals, just on raw water. On May 21st, the soda ash dosing and pH control were introduced. The membrane system performance remained stable with the introduction of the soda ash, and the measured alkalinity in the flocculation tank and permeate met the target alkalinity of > 30 mg/L as $CaCO_3$. This indicated that the soda ash dosing was an effective means of introducing alkalinity, compatible with the membrane process.

On May 22nd, the coagulant was introduced. For this run, Clear PAC (PACl) coagulant was tested at three concentrations. The pilot system performed well on the initial dose of 0.66 mg/L as product (0.1 mg/L Al^{3+}), the subsequent dose of 3.3 mg/L as product (0.5 mg/L Al^{3+}) which started on May 25th, and the third dosage of 5 mg/L as product (0.76 mg/L Al^{3+}) which was started on May 28th. Operation was successful at each dose, but due to the short test duration, long term performance could not be evaluated. On May 29th the chemical dosing pump lost prime and the operators were unable to restart the pumps.

The pilot performance data for this portion of the phase is shown in Figures A12 to A14.

Since the operators were not certain when the coagulant pumps failed, and whether the pilot had actually operated at the expected coagulant dosing rates, the decision was made to repeat the run at the 5 mg/L as product (0.76 mg/L Al^{3+}) dosage starting on June 4th. As the membrane system seemed to be fouling, the coagulant dose was decreased to 3.3 mg/L as product (0.5 mg/L as Al^{3+}) on June 8th. While the membrane system performed well at these conditions, around June 9th, the pH in the flocculation tank became unstable and the operators noted problems with dosing the soda ash for alkalinity control which affects the pH.

The pH setpoint for the acid dosing on the feed was decreased from 7 to 6.5 in an attempt to increase the TOC removal on June 11th. No conclusions can be drawn from this change since the pH was unstable after the operators changed the setpoint from 7.0 to 6.5.

Unfortunately, the operators continued to note issues with the soda ash dosing, tried to troubleshoot the pH pump, and again noticed that the coagulation pump was air locked. The membrane system TMP increased rapidly after the issues with the soda ash, until the pilot shutdown on June 16th due to critical TMP, likely caused by insufficient alkalinity.

GE decided to have a field service technician onsite to monitor the pilot so that the project could be finished without further dosing pump failures.

The pilot performance data for this portion of the phase is shown in Figures A15 to A17.

Samples collected during the Chicken Ladder water with soda ash and ClearPac run showed that the permeated water quality met the treated water quality objectives. THMFP and HAAFP samples were not collected during this run. The following table is a summary of the laboratory data collected from this test run.

Table 9: Chicken Ladder PACl Test Run Permeate Data

Pre-treatment	Coagulation + flocculation	Coagulation + flocculation	Coagulation + flocculation
Chemical(s)	0.66 mg/L PACl (0.1 mg/L Al_3^+) 60 mg/L soda ash	3.3 mg/L PACl (0.5 mg/L Al_3^+) 60 mg/L soda ash	5 mg/L PACl (0.76 mg/L Al_3^+) 60 mg/L soda ash
Turbidity (NTU)	<0.004	< 0.003	< 0.003
UVT (%)	86.6	86.5 - 91.5 (89.2)	85.6 - 92.5 (88.3)
Apparent Colour (TCU)	5	5	5 - 10 (7)
True Colour (TCU)	15	8 - 16 (11)	7 - 19 (14)
pH	7.2	4.6 - 7.6 (6.7)	6.9 - 7.7 (7.4)
Alkalinity (mg/L as CaCO3)	15.5	5.7 - 34.3 (12.6)	8.8 - 37.3 (25.5)
Aluminum (mg/L)	-	0.06	-
TOC (mg/L)	2.1	1.6 - 2.2 (1.8)	2.0 - 2.1 (2.1)
DOC (mg/L)	-	-	-
THMFP (µg/L)	-	-	-
HAAFP (µg/L)	-	-	-

*Averaged data shown in parenthesis.

5.6. Phase 6A: Chicken Ladder water with soda ash and ACH

On June 19th the pilot was tested on Chicken Ladder Water using ACH as the coagulant. The ACH was dosed at 1.3 mg/L as product (0.2 mg/L as Al^{3+}) and the system performed with a low fouling rate well until it shut down on June 20th due to an air compressor failure.

The pilot performance data for this phase is shown in Figures A18 to A20.

5.7. Phase 6B: Stocking Lake water with soda ash and ACH

On June 23rd the pilot was tested using Stocking Lake water and 4 mg/L ACH as product (0.6 mg/L as Al^{3+}) and the system ran without incident and with a low fouling rate to July 2nd.

The pilot performance data for this phase is shown in Figures A18 to A20.

The laboratory data for the Chicken Ladder and Stocking Lake water with soda ash and ACH run shows that the permeate water quality met the targets for all parameters with the exception of THMFP and HAAFP. The water quality data indicates that these coagulant dosages were too low to sufficiently remove organics. The following table is a summary of the laboratory data collected from the Chicken Ladder & Stocking Lake Water ACH test.

Table 10: Chicken Ladder and Stocking Lake ACH Test Run Permeate Data

Feed Water Source	Chicken Ladder		Stocking Lake	
Pre-treatment	Coagulation + flocculation		Coagulation + flocculation	
Chemical(s)	1.3 mg/L ACH (0.2 mg/L Al_3^{+})	60 mg/L soda ash	4 mg/L ACH (0.6mg/L Al_3^{+})	60 mg/L soda ash
Turbidity (NTU)	< 0.003		< 0.003	
UVT (%)	-		89.8 - 92.0 (91.1)	
Apparent Colour (TCU)	-		5	
True Colour (TCU)	-		7 - 9 (7)	
pH	-		7.6 - 7.9 (7.8)	
Alkalinity (mg/L as CaCO3)	-		38.6 - 43.7 (40.6)	
TOC (mg/L)	2.3		1.8 - 1.9 (1.8)	
DOC (mg/L)	-		-	
THMFP (µg/L)	-		200	
HAAFP (µg/L)	-		164	

*Averaged data shown in parenthesis.

6 DISCUSSION - WATER QUALITY

Analytical sampling of the feed, and UF permeate was conducted by Associated Engineering and the city operators. The samples were sent for analysis to Maxxam Analytics in Vancouver, British Columbia. The results of the analytical sampling are summarized in Tables B1, B2 and B3 in Appendix B.

6.1 Turbidity

Turbidity is a measure of the clarity of water and is commonly expressed in nephelometric turbidity units (NTU). Suspended solids and colloidal matter (e.g. clay, silt and microscopic organisms) cause turbidity. In this pilot study, the ZeeWeed 1000® feed water was continuously monitored on-line with a HACH 1720D turbidimeter measuring either raw water turbidity prior to coagulant addition and flocculation, or DAF effluent turbidity, depending on the pre-treatment in use. The ZeeWeed 1000® permeate was continuously monitored on-line with a HACH Filtertrak 660 laser turbidimeter.

Figure B1 plots the results of the UF feed and permeate turbidity for the study. This data is from the on-line instruments on the ZeeWeed 1000® pilot skid. The UF feed turbidity averaged 0.47 NTU with a maximum of 0.68 NTU for the Raw Stocking Lake water, and averaged 0.36 NTU with a maximum of 0.65 NTU for the Raw Chicken Ladder Water. DAF Pre-Treated water averaged 0.26 NTU. While this does represent as much as 45% reduction in turbidity across the DAF, the turbidity is so low in the raw water that turbidity removal by the DAF is insignificant in impact to the UF performance.

The UF permeate turbidity averaged 1.1 mNTU. The permeate turbidity remained below 0.1 NTU 100% of the time, regardless of the incoming turbidity. UF permeate turbidity therefore met the objective of turbidity less than 0.1 NTU 95% of the time and less than 0.3 NTU 100% of the time.

6.2 Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Color, and Trihalomethanes (THMs)

Permeate Total Organic Carbon (TOC) was measured inline using a GE Sievers M5310C TOC Analyzer. The inline permeate TOC results are shown in Figure B2. The external lab results for raw water TOC, raw water DOC, and permeate color are presented in Tables B1, B2 and B3 in Appendix B.

Based on historical data, the raw Chicken Ladder water averaged about 2.71 mg/L TOC and 2.46 mg/L DOC for samples collected in 2014. A sample of raw Chicken Ladder water collected during the pilot study was consistent and showed a TOC of 3.03 mg/L and a DOC of 2.44 mg/L, indicating that 80% of the organics are dissolved. The true color was measured in the range of 19 to 42 TCU, with an average of 27 TCU.

In terms of TOC removal, the best results for the Chicken Ladder water were obtained with DAF Pre-Treated water using 15 mg/L alum (0.66 mg/L as Al^{3+}) + 8 mg/L powdered activated carbon (PAC), with TOC being reduced to 0.9 to 1.8 mg/L (average of 1.1 mg/L) in the UF permeate. However, the permeate TOC results were not significantly better than those obtained with DAF Pre-Treated water + 10 mg/L PACl (1.53 mg/L Al^{3+}), and the operation with the alum + PAC led to higher permeate color and poor membrane performance as discussed in Section 5.

With the DAF pre-treatment with 10 mg/L ClearPac (1.53 mg/L as Al^{3+}), TOC was reduced to 1.0 to 2.4 mg/L (average of 1.2 mg/L) in the permeate on average. This corresponds to an average removal of 60%. The color was reduced to 5 TCU consistently, corresponding to an average removal of 81%. With this level of pre-treatment, the THM formation potential was reduced to 66 ug/L, which is below the regulatory level of 100 ug/L and the HAA formation potential was reduced to 24 ug/L, which is below the regulatory level of 80 ug/L.

With flocculation pre-treatment, the best results were obtained with 3.3 mg/L ClearPac (0.5 mg/L Al^{3+}), with 1.6 to 2.2 mg/L (average of 1.8 mg/L) TOC in the permeate. This corresponds to an average removal of 40%. The color was reduced to 8 to 16 TCU (average 11 TCU), corresponding to an average removal of 59%.

With no pre-treatment (Phase 2), the permeate TOC was 2.7 to 2.8 mg/L (average 2.8 mg/L), corresponding to a removal of less than 10%. This corresponds to the UF removing the particulate portion of the TOC (i.e. the difference between the TOC and the DOC), allowing for some difference between the laboratory readings for DOC, and the online permeate TOC analyzer readings. The color was 19 to 31 TCU (average 24 TCU), which represents negligible removal.

Based on historical data, the raw Stocking Lake water averaged 2.63 mg/L TOC and 2.3 mg/L DOC for samples collected in 2014. A sample of raw Stocking Lake water collected during the pilot study was consistent and showed a TOC of 2.51 mg/L and a DOC of 2.06 mg/L, indicating that 82% of the organics are dissolved. These organics levels are slightly lower than those from the Chicken Ladder water source. The true color was in the range of 5 to 15 TCU, with an average of 8 TCU, which is also lower than for the Chicken Ladder water source.

In terms of TOC removal, the best results for the Stocking Lake water were obtained with DAF Pre-Treated water + 15 mg/L PACl (2.32 mg/L Al^{3+}) with TOC being removed to 1.0 to 1.3 mg/L (average of 1.1 mg/L) TOC in the permeate. This corresponds to an average removal of 56%. The color was reduced to 5 TCU consistently, corresponding to an average removal of 37%. With this level of pre-treatment, the THM formation potential was reduced to 73 ug/L, which is below the regulatory level of 100 ug/L and the HAA formation potential was reduced to 21 ug/L, which is below the regulatory level of 80 ug/L.

With flocculation pre-treatment, the best results were obtained with 4 mg/L ACH (0.6 mg/L Al^{3+}), with 1.8 to 1.9 mg/L (averaging 1.8 mg/L) TOC in the permeate. This corresponds to an average removal of 28%. The color was reduced to 5 TCU consistently, corresponding to an average removal of 37%. The THMFP for this phase was measured at 200 ug/L, while the HAAFP was measured at 164 ug/L. These significantly exceed the targets, which would indicate that the coagulant dose was too low to sufficiently remove the organics that lead to the formation of THM and HAA.

The table below compares the THMFP and HAAFP measurements throughout the study. Based on the results from the Stocking Lake water with 0.6 mg/L as Al^{3+} of coagulant dosing, it would seem that reducing the TOC to 1.8-1.9 mg/L is not sufficient for meeting the THM and HAA limits. Instead, the TOC needs to be reduced to closer to 1.1 to 1.2 mg/L as Al^{3+} on average.

Table 11: THMFP and HAAFP Comparison

	Coagulant dose	Permeate TOC (mg/L)	Permeate THMFP (ug/L)	Permeate HAAFP (ug/L)
Chicken Ladder water with DAF	10 mg/L ClearPac PACl (1.53 mg/L as Al^{3+})	1.0 – 2.4 (1.2)	66	24
Stocking Lake water with DAF	15 mg/L ClearPac PACl (2.3 mg/L as Al^{3+})	1.0 – 1.3 (1.1)	73	21
Stocking Lake water with coagulation/flocculation	4 mg/L CTI4900 ACH (0.6 mg/L as Al^{3+})	1.8 – 1.9 (1.8)	200	164

6.3 Aluminum

Only a few samples were analyzed for aluminum in the UF permeate, and all of these showed aluminum levels below 0.1 mg/L. The objective for aluminum was therefore met.

7 DISCUSSION - CLEANING

A recovery clean is required to restore the permeability of a membrane once the membrane becomes fouled. A fouled membrane condition occurs if the TMP approaches and does not stabilize at values of approximately 90 kPa. The cleaning chemicals that are typically used are sodium hypochlorite for the removal of organic foulants and citric acid for the removal of inorganic contaminants.

The standard procedure for cleaning the ZeeWeed® 1000 membranes consists of soaking them for 4-6 hours in a 500 mg/L sodium hypochlorite solution that has been heated to approximately 35 °C. This procedure is then repeated with a citric acid solution at a concentration of 2,000 mg/L with hydrochloric acid addition to depress the pH to 2.1. Variations upon this practice can include only using one of the cleaning chemicals, omitting heating, and changing chemical concentrations and/or durations.

Recovery cleans were needed during the testing at Ladysmith due to fouling from coagulant overdosing, and due to excess hardness being added by the calcite contactor in the early stages of the pilot study. For the recovery cleans performed at Ladysmith, the membranes were soaked 6 to 12 hours in 2,000 mg/L citric acid solution with 250 mg/L hydrochloric acid addition to further reduce the pH to 2.0 to 2.5. Then, the membrane was rinsed and soaked in a 500 mg/L sodium hypochlorite solution. The cleanings were done without heating and the permeability results showed that the permeability was restored. While results were not compiled to show the difference in permeability recovery between the acid and the sodium hypochlorite cleans, the acid cleans most likely recovered most of the permeability during this pilot study based on the suspected foulants being inorganic in nature (metal coagulant, and hardness).

Table 12: UF Pilot Membrane Recovery Clean Effectiveness

Date	Cleaning Type	Temperature Corrected Permeability at 20°C (Lmh/bar)	
		Before	After
April 21	Acid cleaning only	49.56	200.79
May 7	Acid/Hypo Clean	39.83	146.13
May 13	Acid/Hypo Clean	43.47	115.91
June 16	Acid/Hypo Clean	61.49	141.63

8 CONCLUSIONS

The following sections highlight the conclusions that can be drawn from the Town of Ladysmith pilot study.

Membrane Performance

- The membrane system was operated at the consistent operating conditions shown in Table 13.

Table 13: UF Pilot Membrane Process Operating Conditions

UF Pilot Study Settings	
System Recovery	95%
Flux (Lmh)	51.2
Cycle Time (minutes)*	39
Permeate Flow (L/s)	0.6
Maintenance cleaning protocol	6 times per week using Sodium Hypochlorite @ 250 mg/L 1 time per week using Citric Acid @ 500 mg/L

*pilot cycle time representative of full-scale recovery

- The pilot operated downstream of several variations of pre-treatment for both the Chicken Ladder and Stocking Lake source waters. Raw water from both sources was tested with coagulation and flocculation at many coagulant dosages, as well as with DAF pre-treatment system at many coagulant dosages.
- With the frequency of variations on the pre-treatment conditions, membrane fouling rates and corresponding anticipated cleaning intervals were not calculated for the various phases of testing. However, the following conclusions may still be drawn in terms of relative performance through the various combinations of raw water and pre-treatment:
    - Phase 3 and 4 test runs at 10 mg/L of ClearPAC polyaluminum chloride (PACl) coagulant (1.53 mg/L Al^{3+}) demonstrated low fouling rates on both Chicken Ladder and Stocking Lake DAF Pre-Treated feed water.
    - The best overall membrane performance was observed during Phase 5 while operating on the Chicken Ladder source water with coagulation and

flocculation pre-treatment with ClearPac coagulant. Unfortunately, as the coagulant dosing was not confirmed, it is unclear what coagulant dose was actually delivered during this phase.

- When the DAF unit was operated with alum during Phase 4 on Chicken Ladder water (unknown alum dose), the membrane system performed well while operating at a temperature of approximately 12 °C.
- For Phase 6 operating on raw water pre-treated by coagulation and flocculation using the CTI4900 aluminum-chlorohydrate coagulant (ACH), good membrane performance was observed at the dosages of 0.2 mg/L as Al^{3+} and 0.6 mg/L as Al^{3+} for the Chicken Ladder and Stocking Lake water sources, respectively.

Water Quality

- While the calcite contactor seemed to negatively impact membrane system performance and was difficult to control, membrane performance stabilized during Phase 5 when the calcite contactor was replaced with a soda ash dosing system. The soda ash dosing enabled the measured alkalinity in the flocculation tank and permeate to meet the target alkalinity of > 30 mg/L as $CaCO_3$. This indicated that the soda ash dosing was an effective means of introducing alkalinity, compatible with the membrane process.
- Throughout the study, the UF permeate turbidity remained less than 0.1 NTU 100% of the time, despite feed turbidity ranging from 0.8 to 4.8 NTU. UF permeate turbidity therefore met the objective of turbidity less than 0.1 NTU 95% of the time and less than 0.3 NTU 100% of the time.
- Permeate Total Organic Carbon (TOC) was consistently below 3 mg/L throughout the pilot study. The best TOC removal was observed during Phases 3 and 4 with DAF pre-treatment using 1.53 mg/L as Al^{3+} of coagulant or more, reducing the permeate TOC to an average of 1.1 to 1.2 mg/L.

- With flocculation pre-treatment, the best TOC removal results were obtained with 0.5 to 0.6 mg/L Al^{3+}, reducing the permeate TOC to approximately 1.8 mg/L on average.
- In order to meet water quality objectives for THMFP and HAAFP, a coagulant dose of greater than 0.6 mg/L as Al^{3+} was needed. The objectives were met at dosages of 1.53 mg/L as Al^{3+}. Reducing the permeate TOC to less than 1.8 mg/L appears to be required, with a target of closer to 1.1 to 1.2 mg/L being required.
- All samples analyzed for aluminum showed aluminum levels below 0.1 mg/L. The objective for aluminum was therefore met.
- Apparent Colour and True Colour were sampled from the permeate during the pilot tests. Results meeting the objectives were fairly easy to achieve, indicating that by dosing the coagulant to target a TOC will easily lead to the color objective being achieved.

Membrane Cleaning

- As the fouling was mainly related to coagulant dosing, or to hardness overdosing when the calcite contactor was in use, acid recovery cleans likely had the most impact on permeability recovery. In general, the non-heated, standard recovery cleans that were done to restore membrane permeability between test runs were effective in restoring permeability, and the standard maintenance cleaning procedures were effective in maintaining membrane permeability during normal operation.

Based on the results of the pilot study, a full scale UF membrane system could be designed using either DAF or coagulation-flocculation pre-treatment, though the DAF would not really be required to remove any turbidity. With either form of pre-treatment, either PACl or ACH could be used effectively. Alum may be effective, though temperature limitations may apply to this coagulant that is not pre-hydrolyzed. Powdered activated carbon (PAC) should be avoided. Even though the TOC is relatively low in the raw water, the coagulant dosage needs to be optimized to meet the targets for THM and HAA.

APPENDIX A. MEMBRANE PERFORMANCE RESULTS

List of Figures

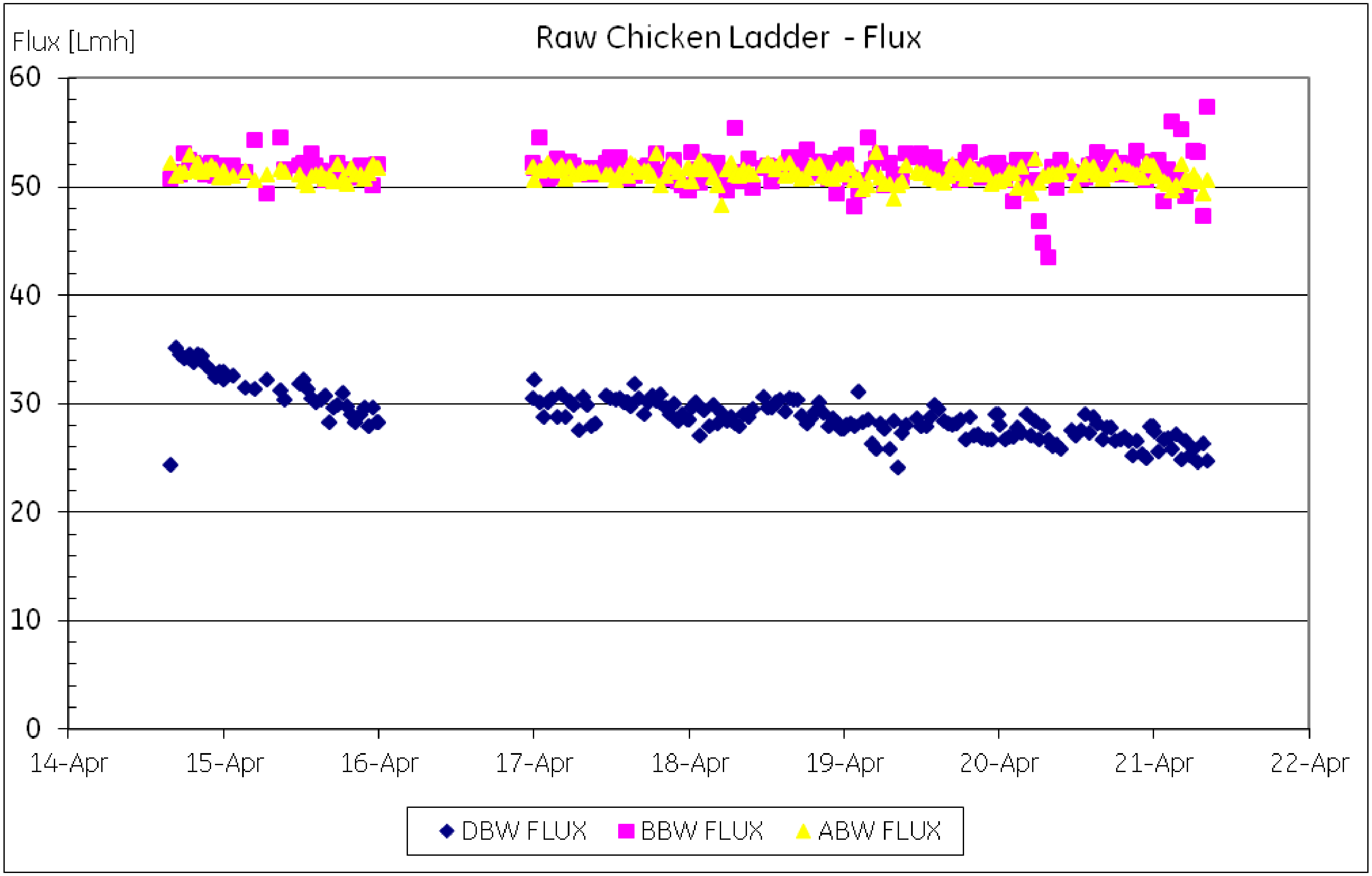


Figure A1: Phase 2 Raw Chicken Ladder Flux

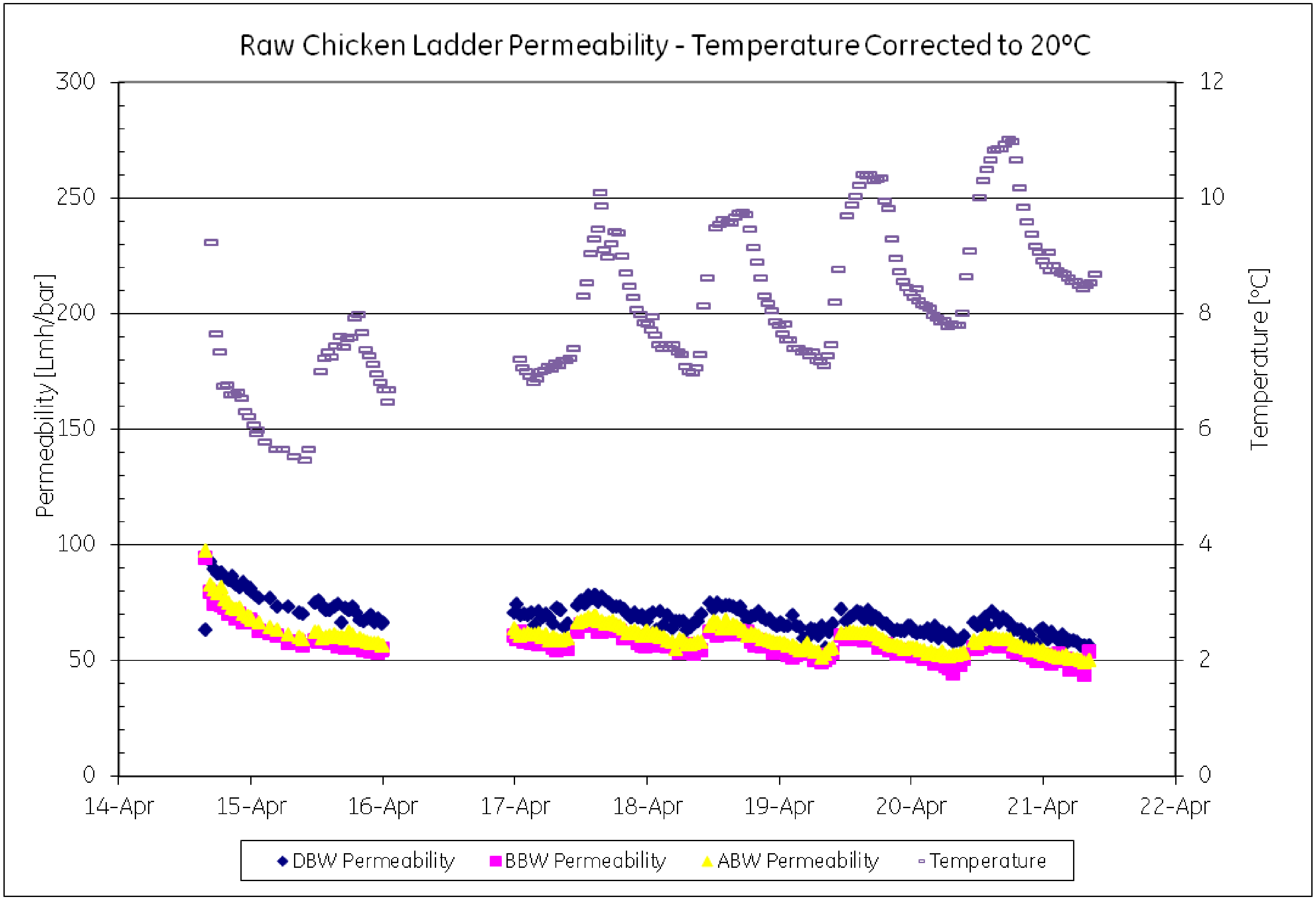


Figure A2: Phase 2 Raw Chicken Ladder Permeability

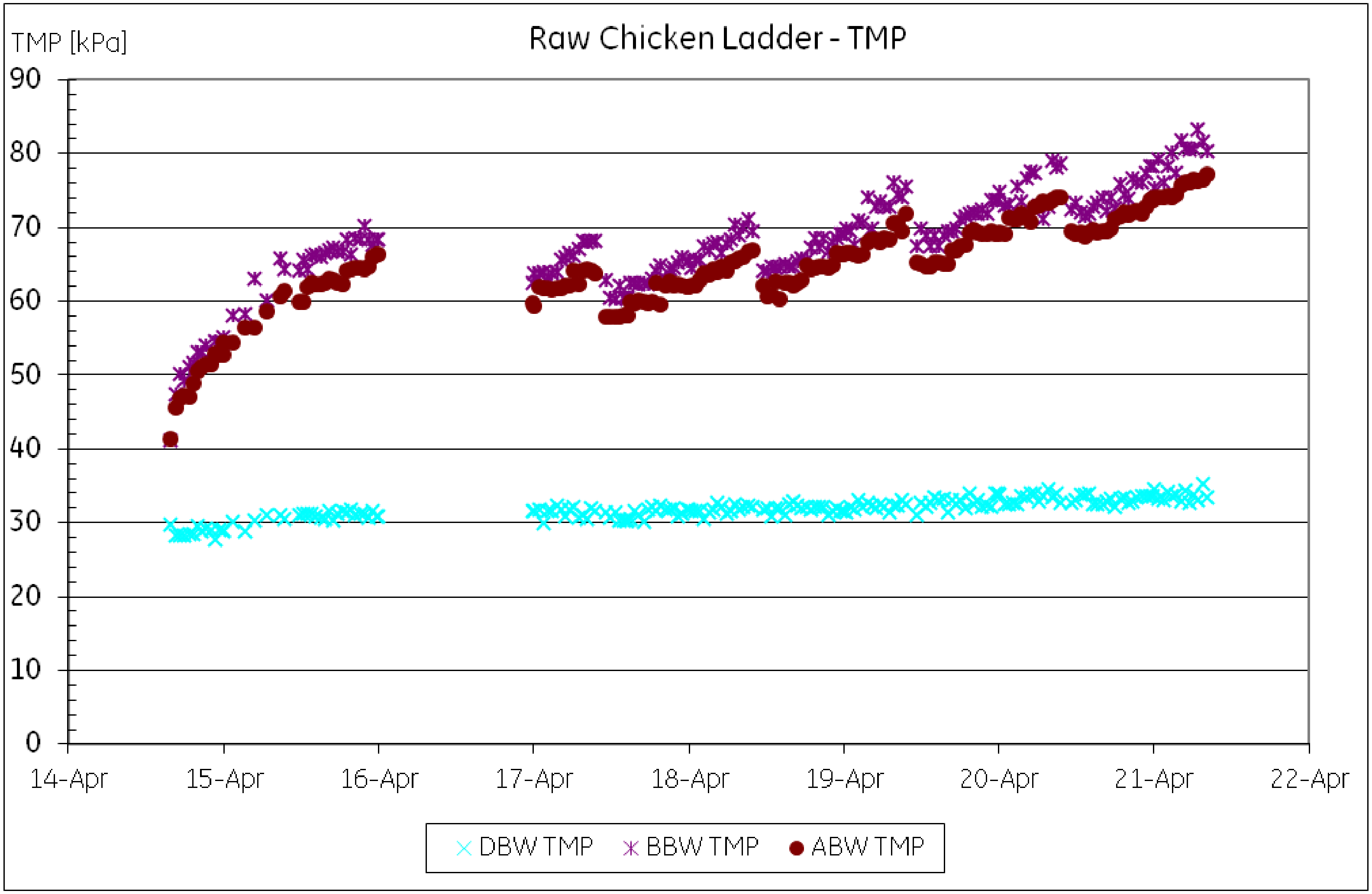


Figure A3: Phase 2 Raw Chicken Ladder TMP

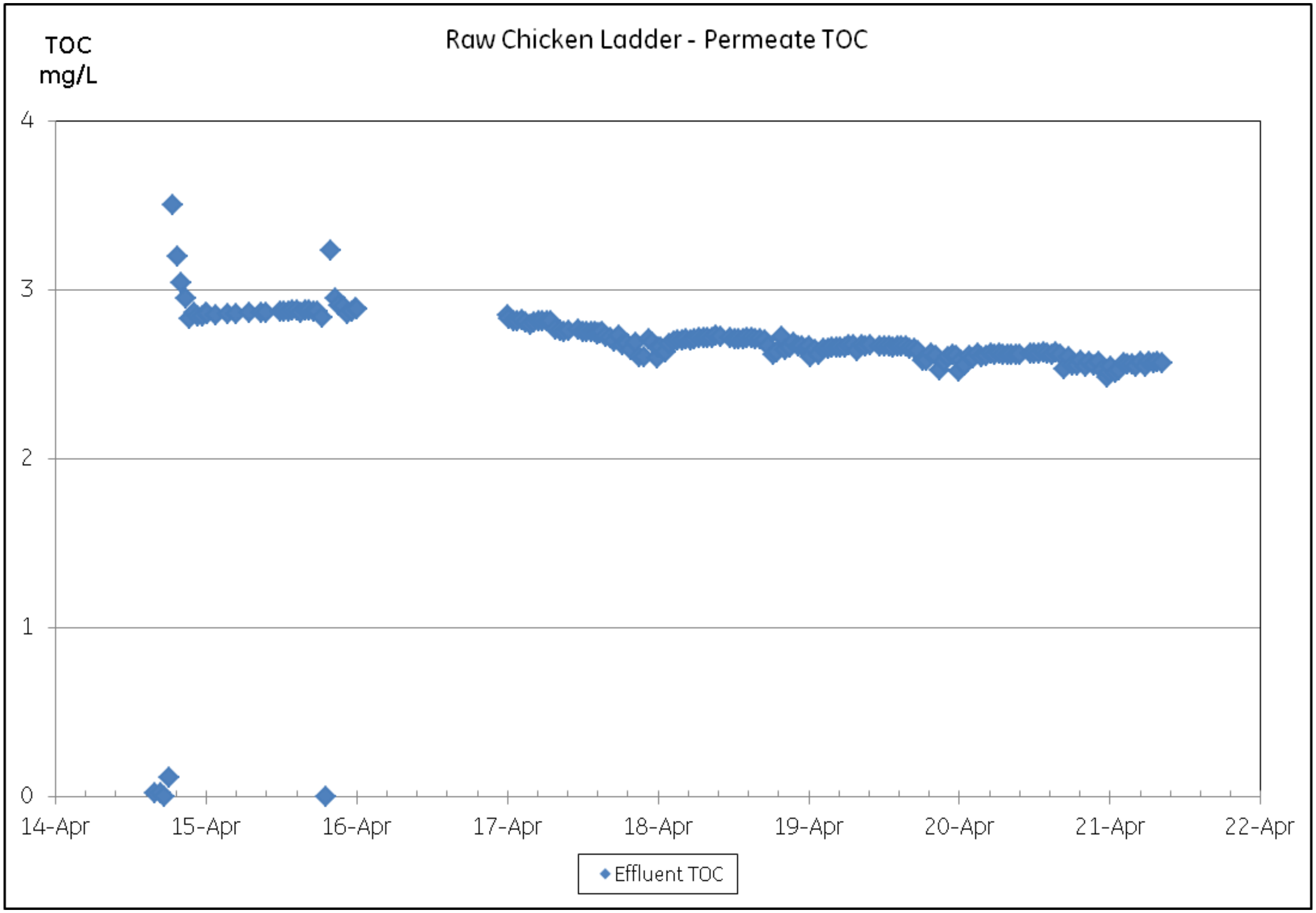


Figure A4: Phase 2 Raw Chicken Ladder Water Permeate TOC

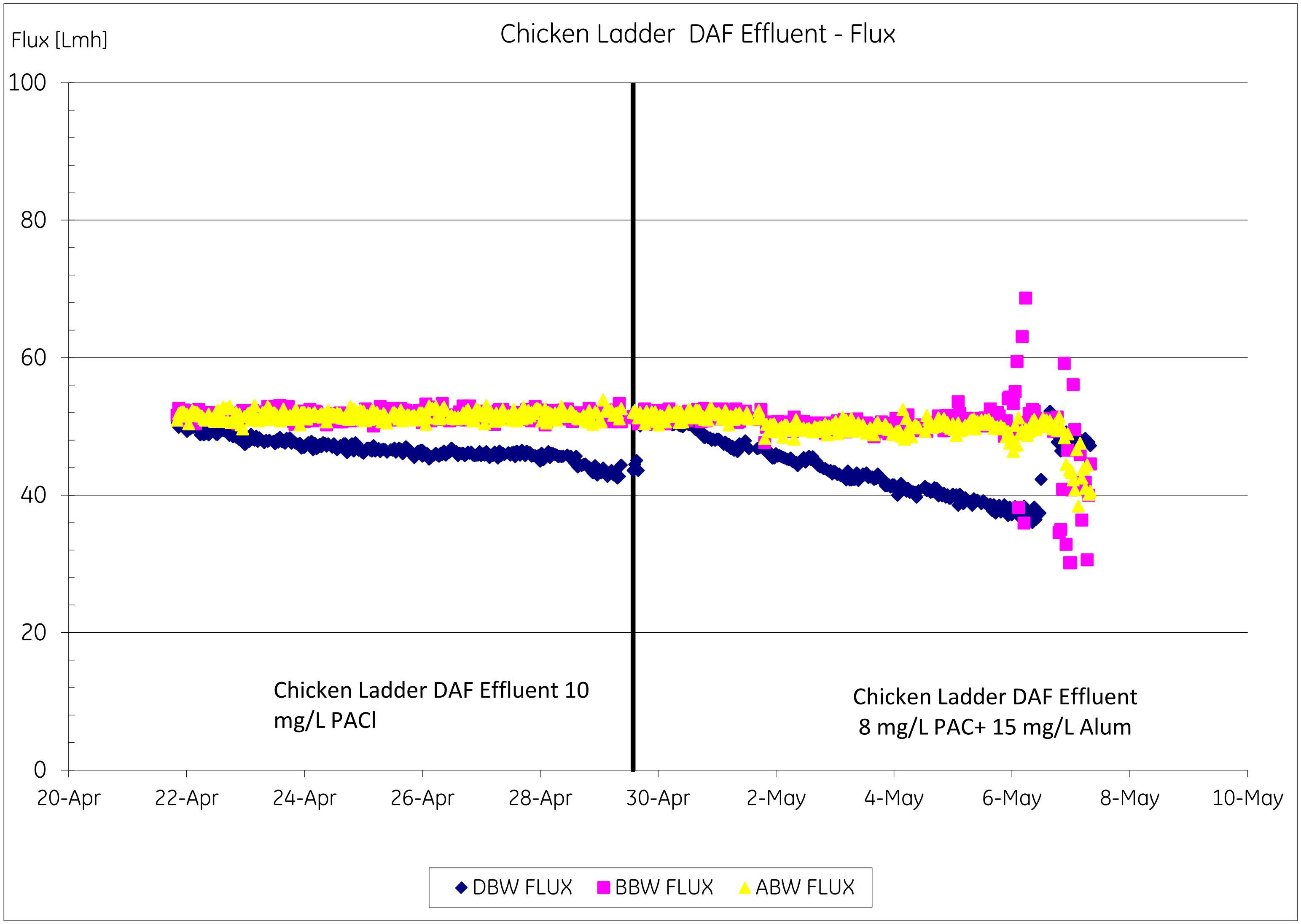


Figure A5: Phase 3 Chicken Ladder DAF Effluent Flux

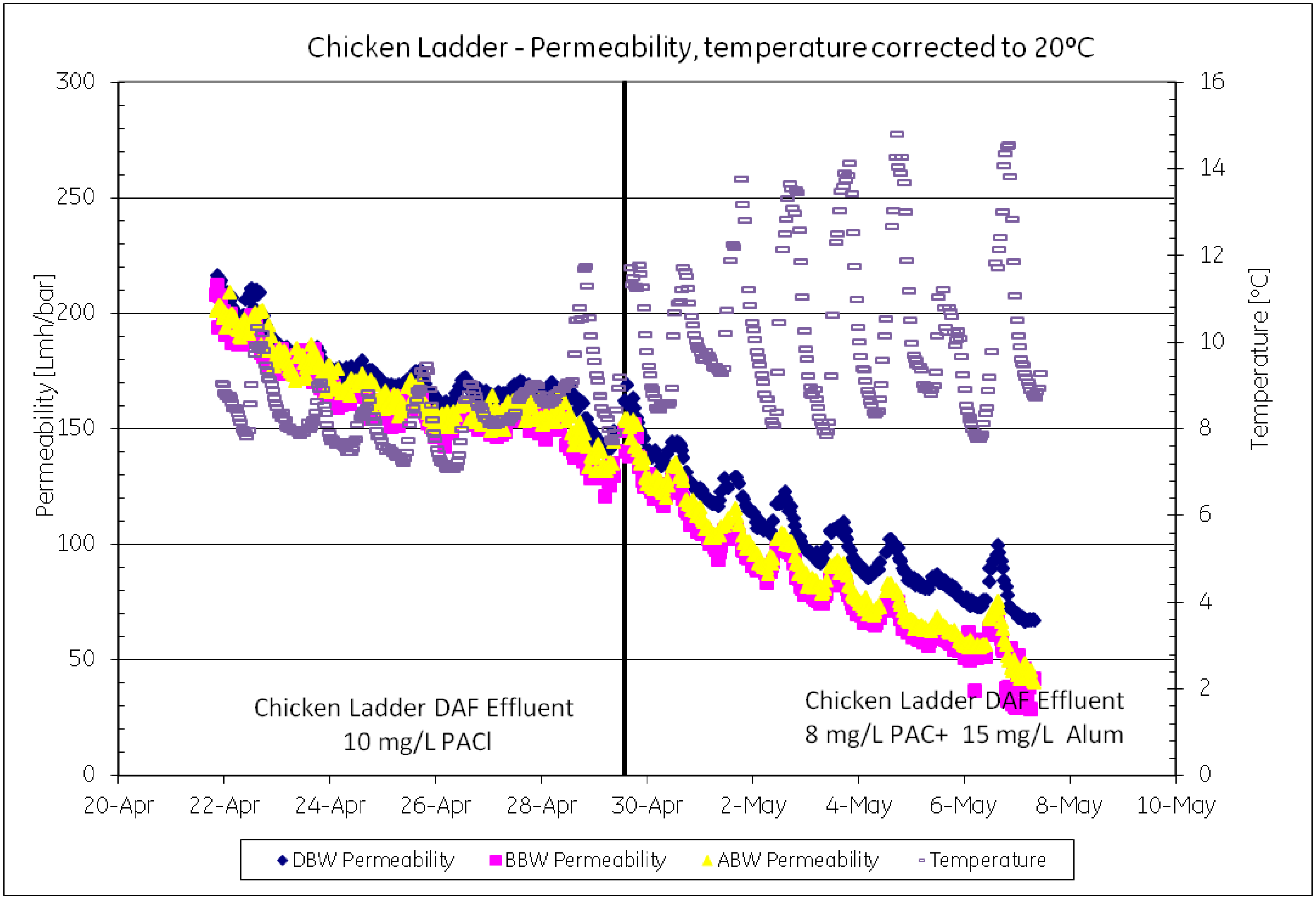


Figure A6: Phase 3 Chicken Ladder DAF Effluent Permeability

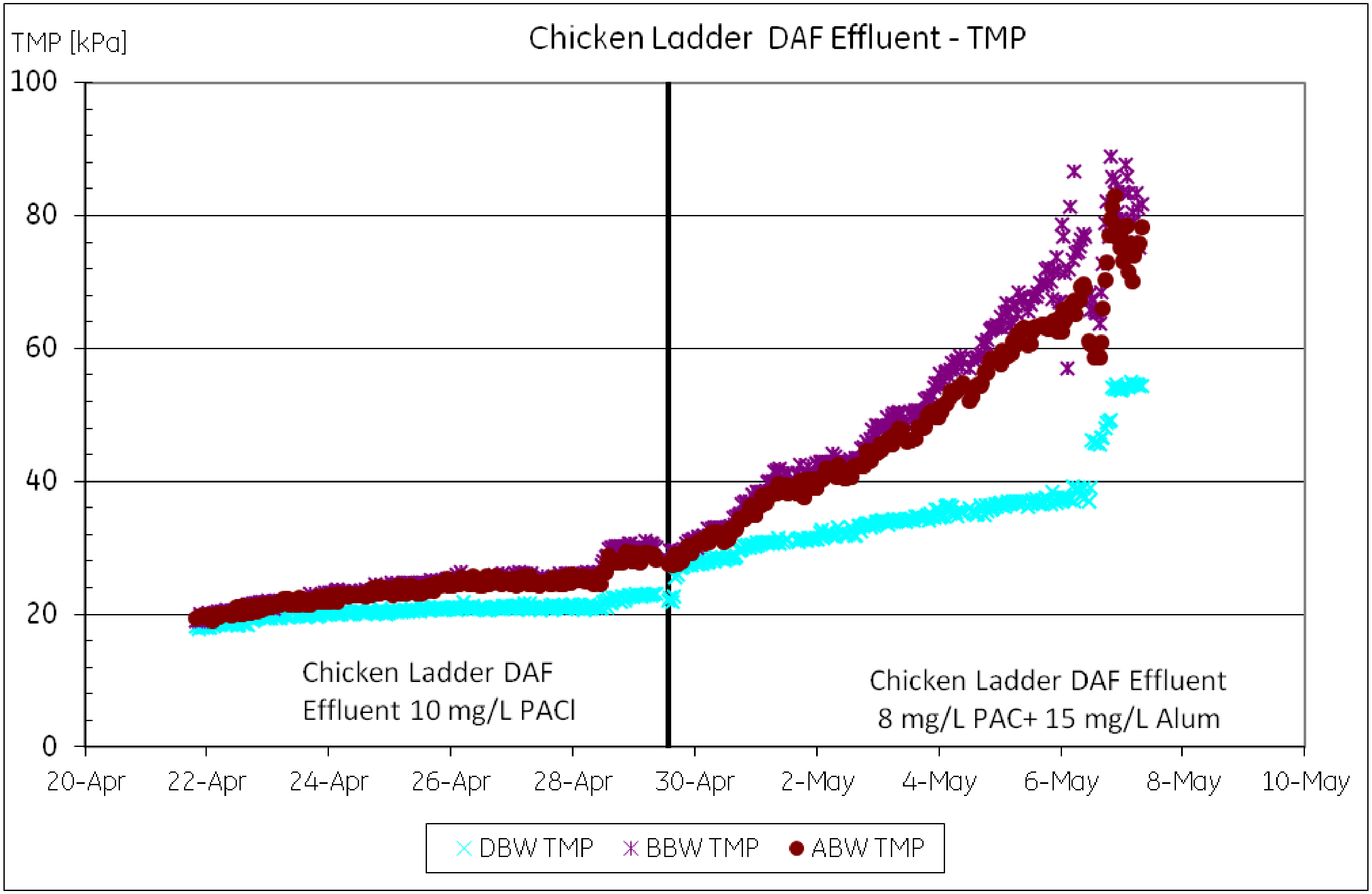


Figure A7: Phase 3 Chicken Ladder DAF Effluent TMP

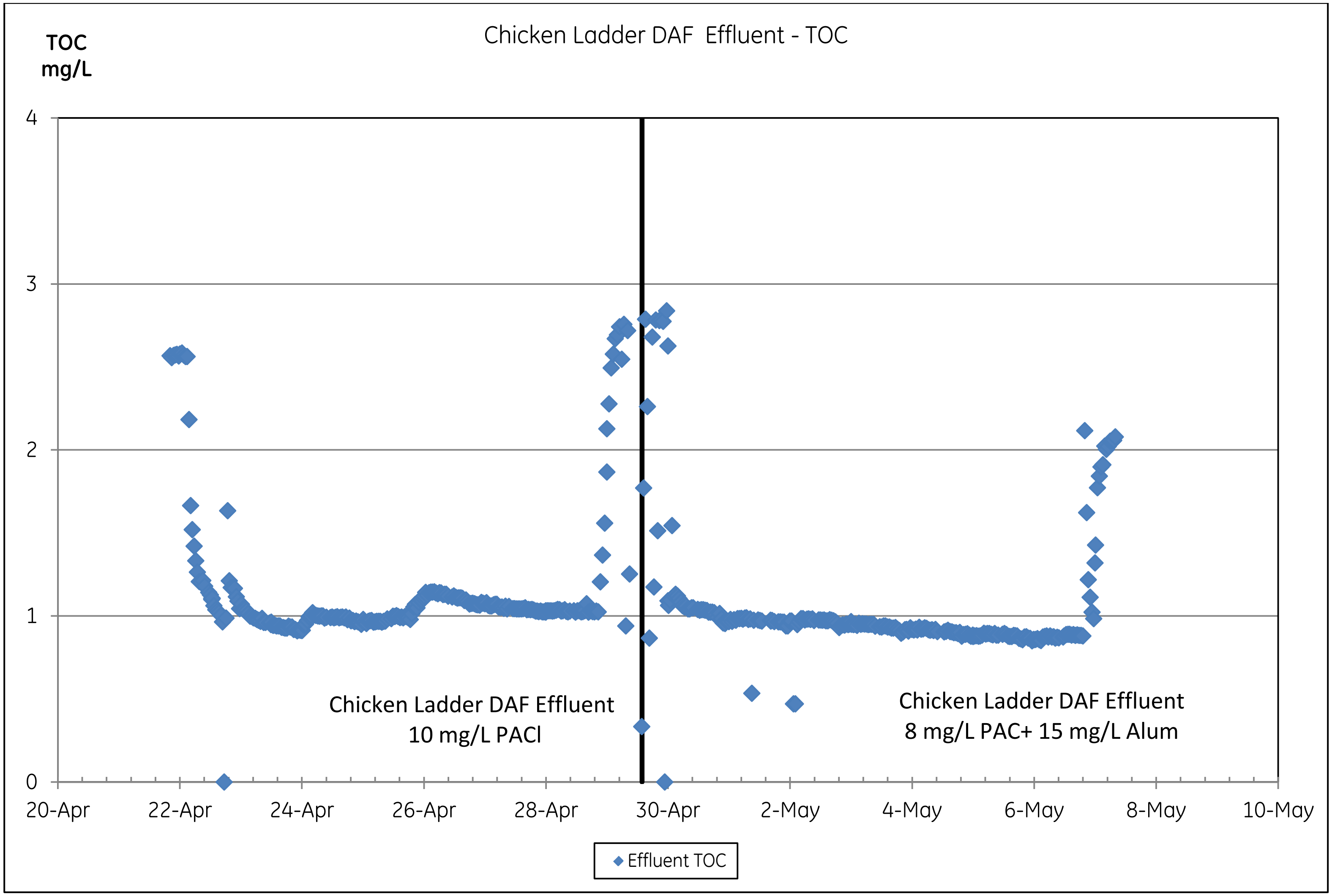


Figure A8: Phase 3 Chicken Ladder DAF Effluent TOC

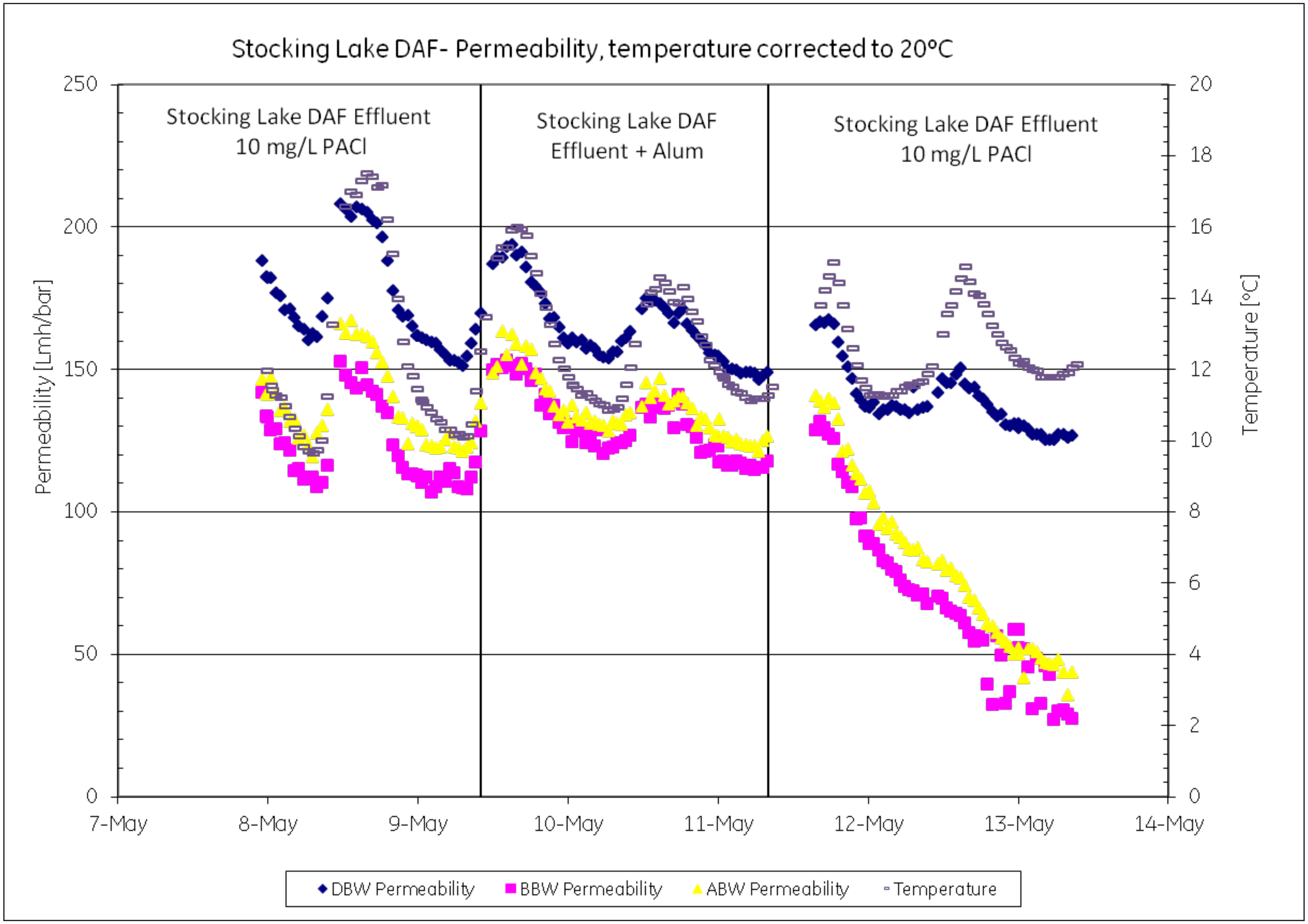


Figure A9: Phase 4 Stocking Lake DAF Effluent Permeability

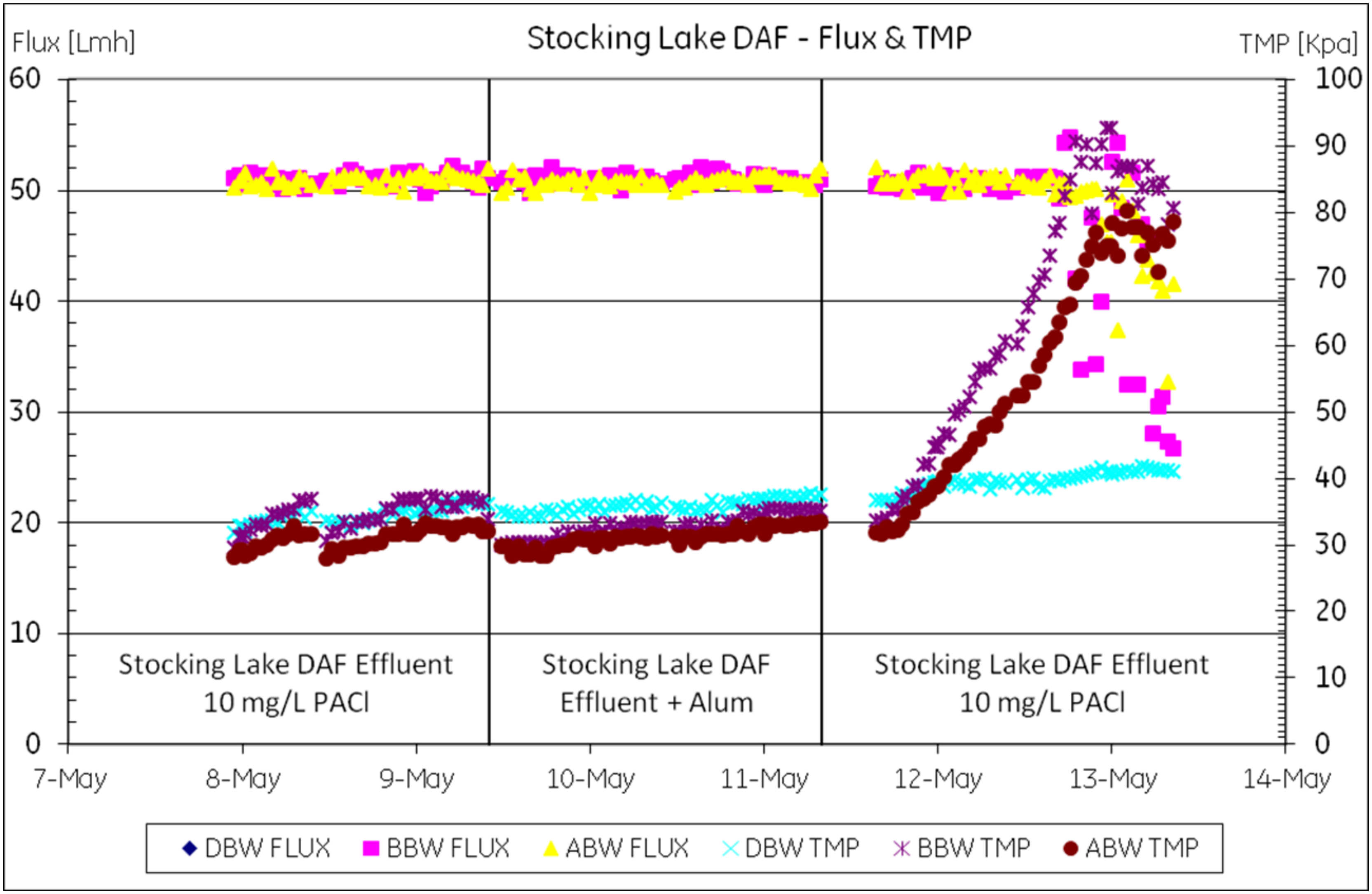


Figure A10: Phase 4 Stocking Lake DAF Effluent Flux & TMP

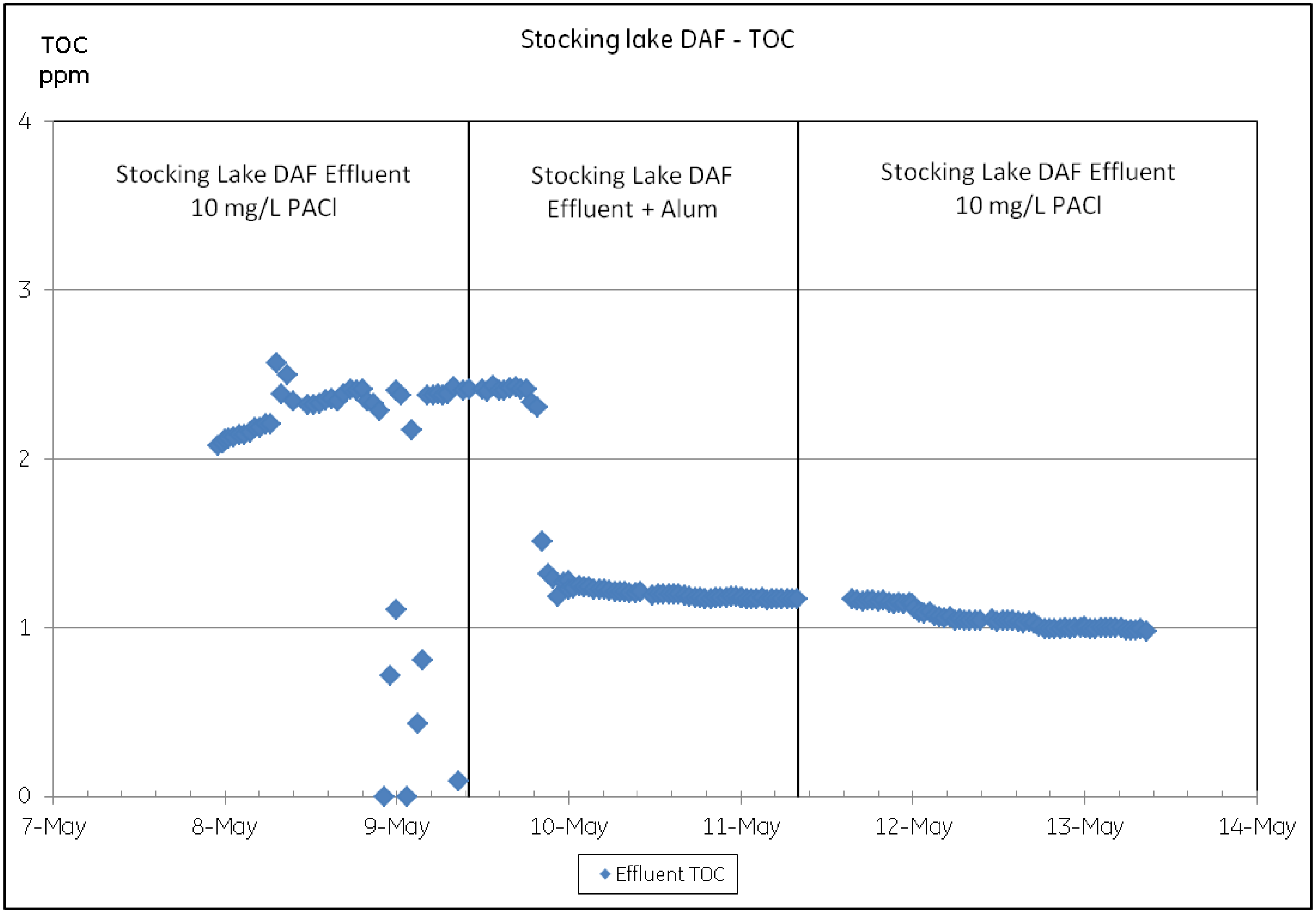


Figure A11: Phase 4 Stocking Lake DAF Effluent TOC

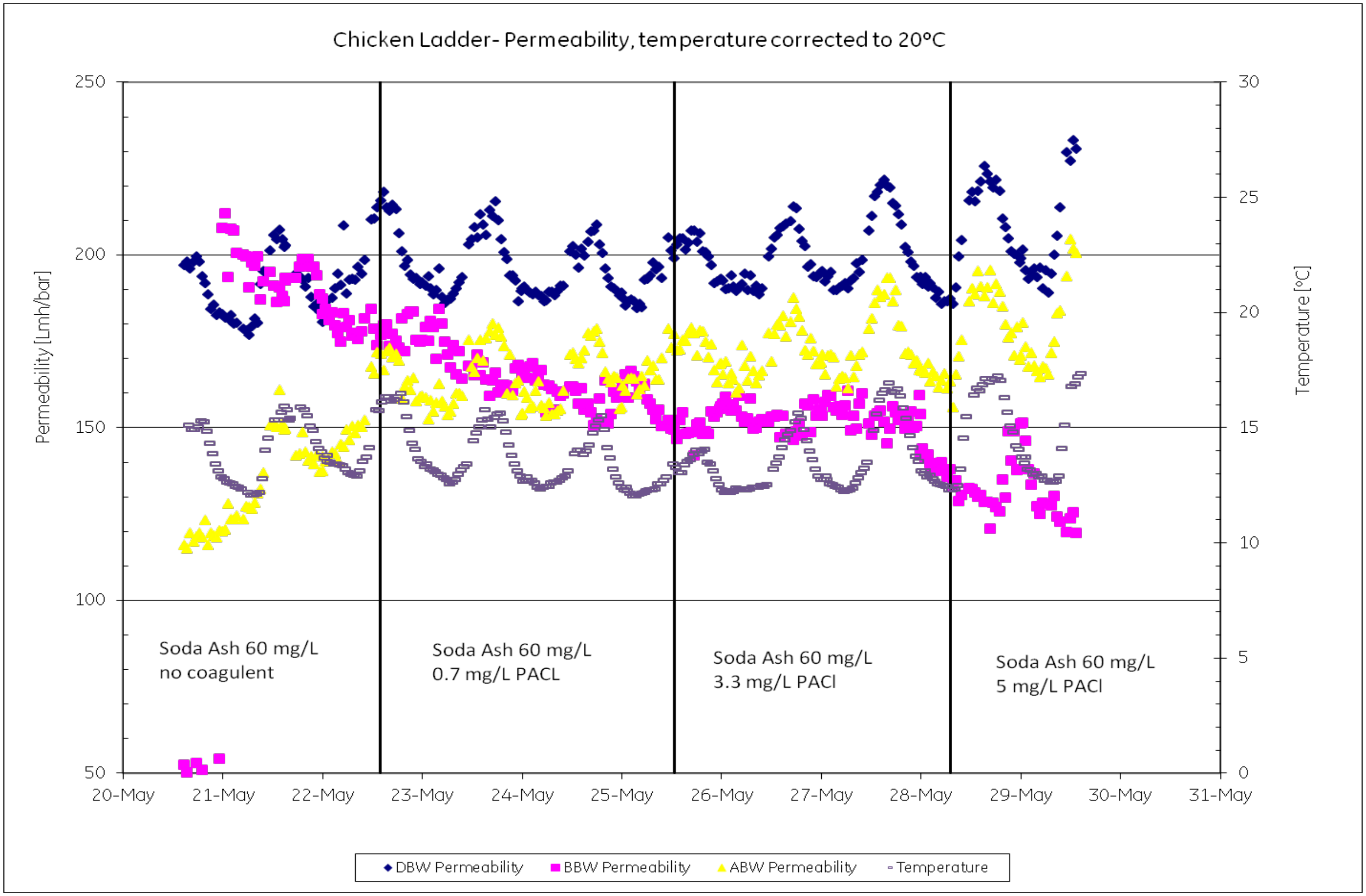


Figure A12: Phase 5 Chicken Ladder Permeability

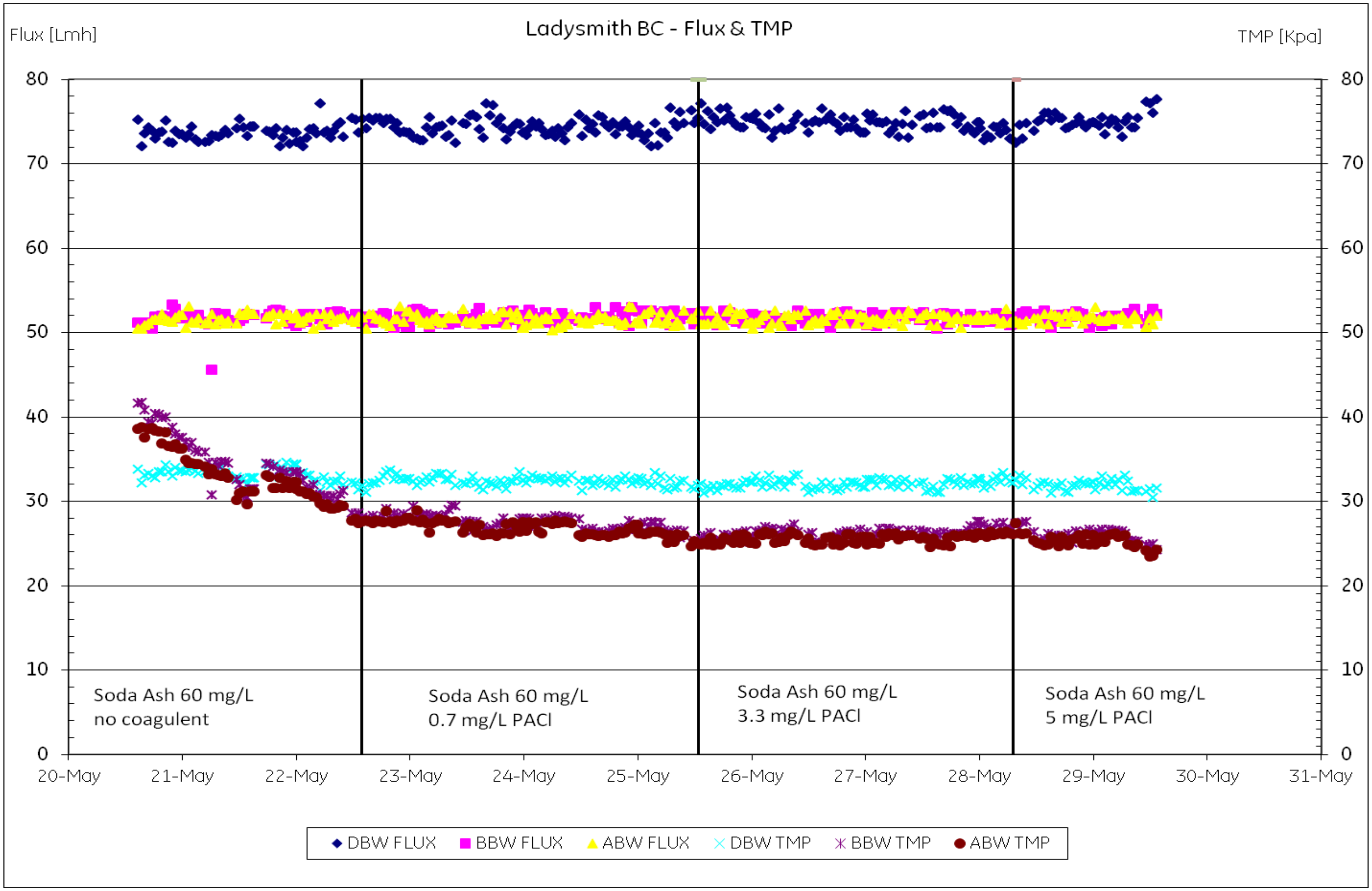


Figure A13: Phase 5 Chicken Ladder Flux & TMP

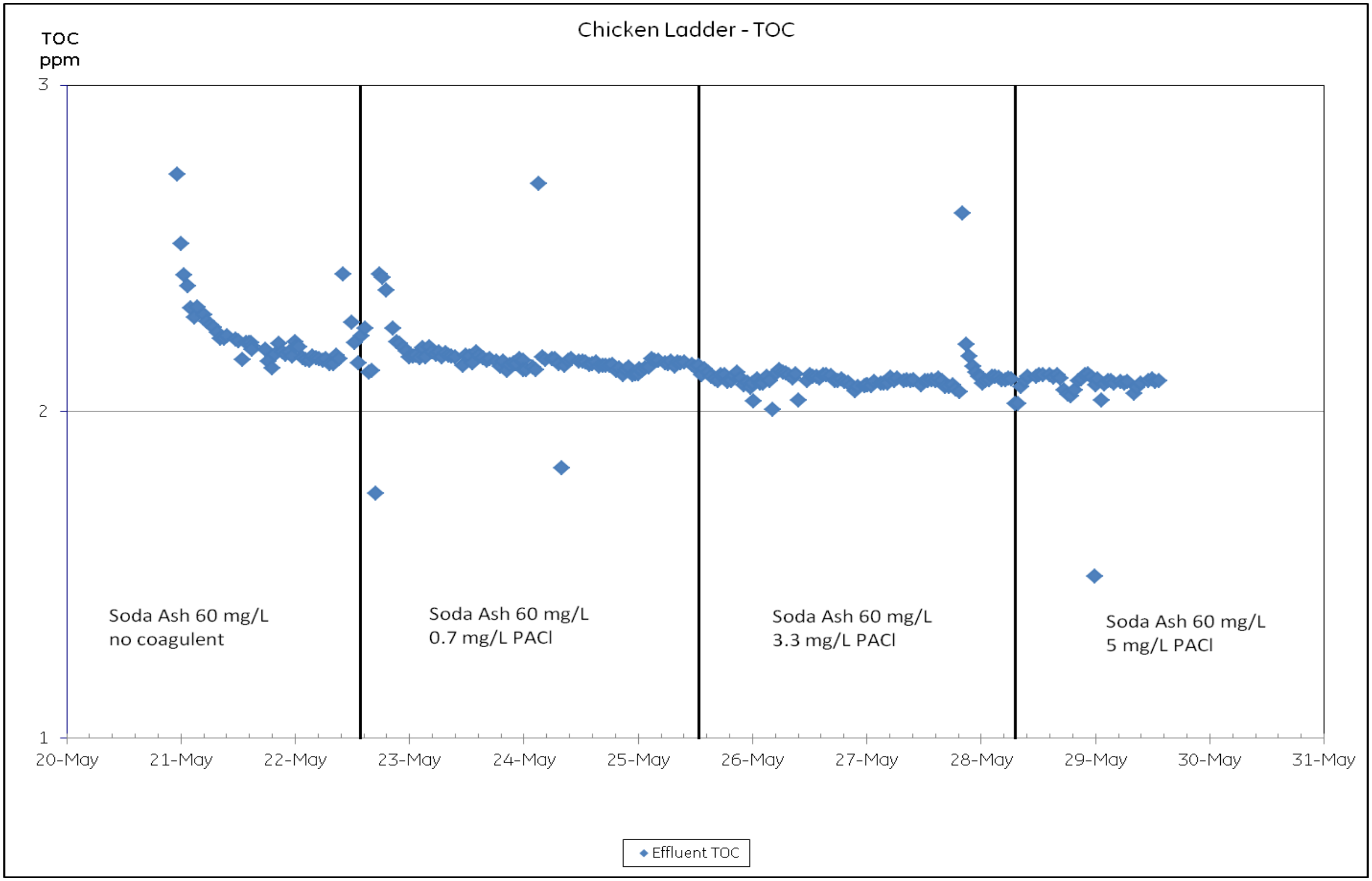


Figure A14: Phase 5 Chicken Ladder TOC

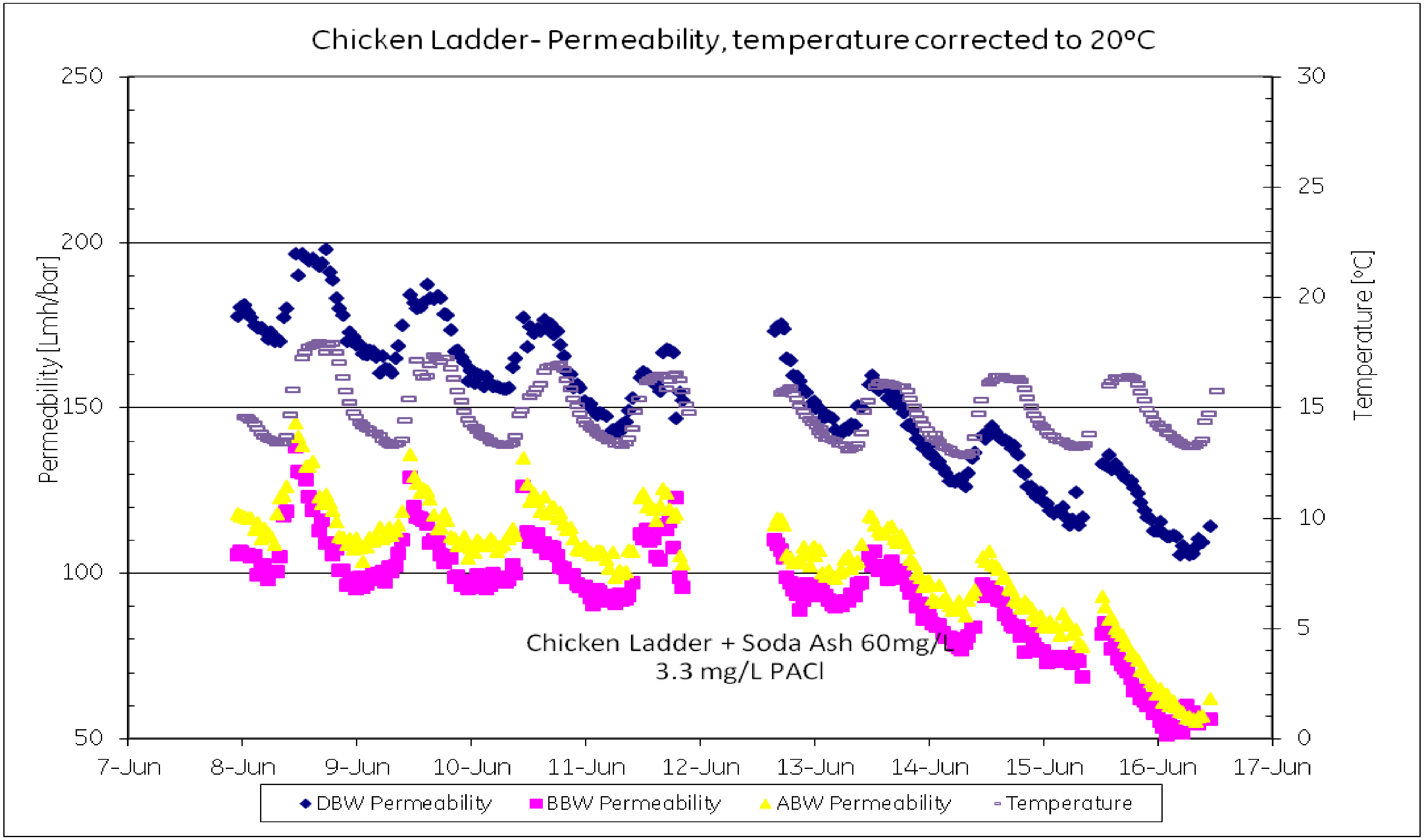


Figure A15: Phase 5 Chicken Ladder 3.3 mg/L PACl Permeability

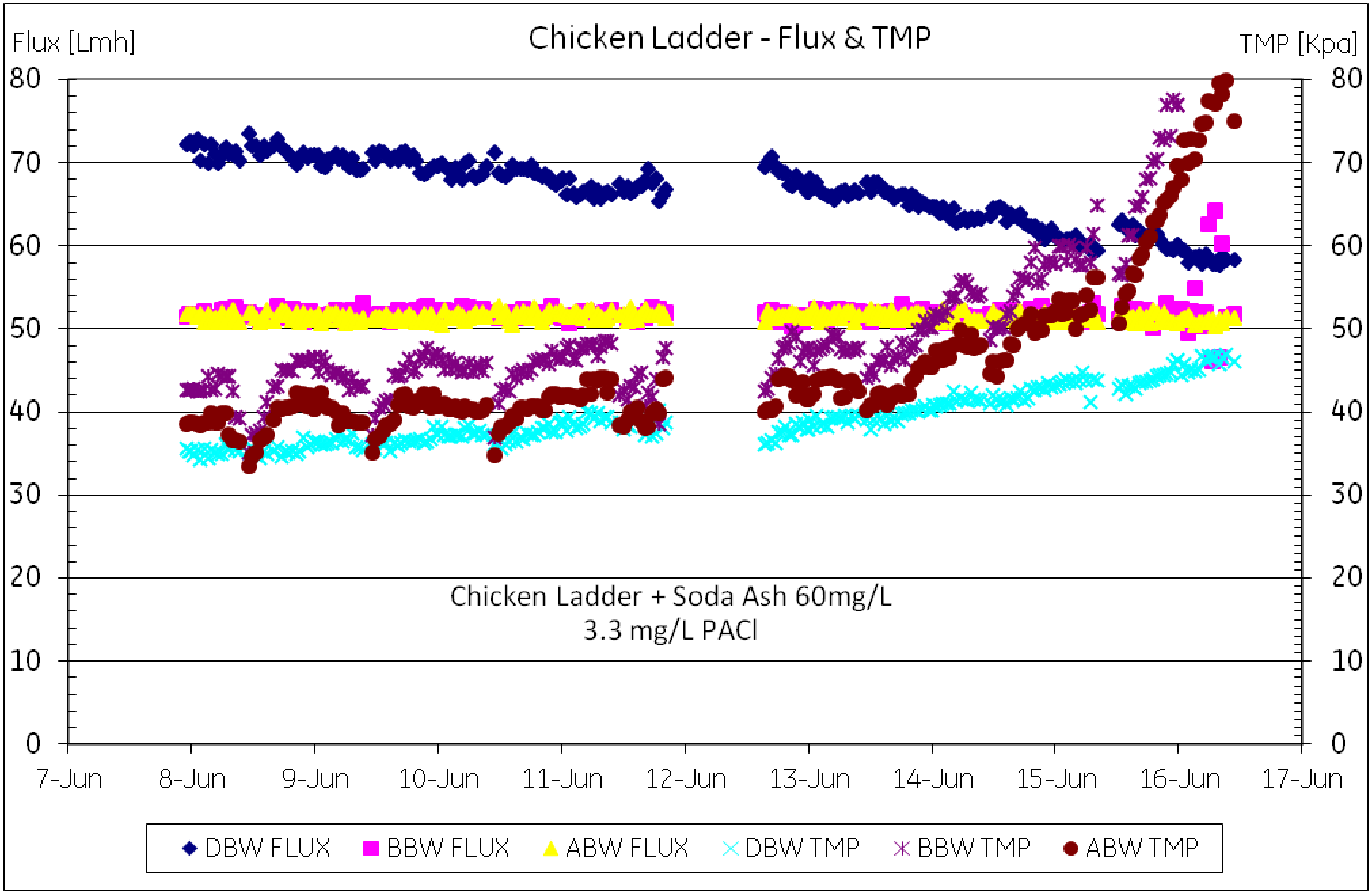


Figure A16: Phase 5 Chicken Ladder 3.3 mg/L PACl Flux & TMP

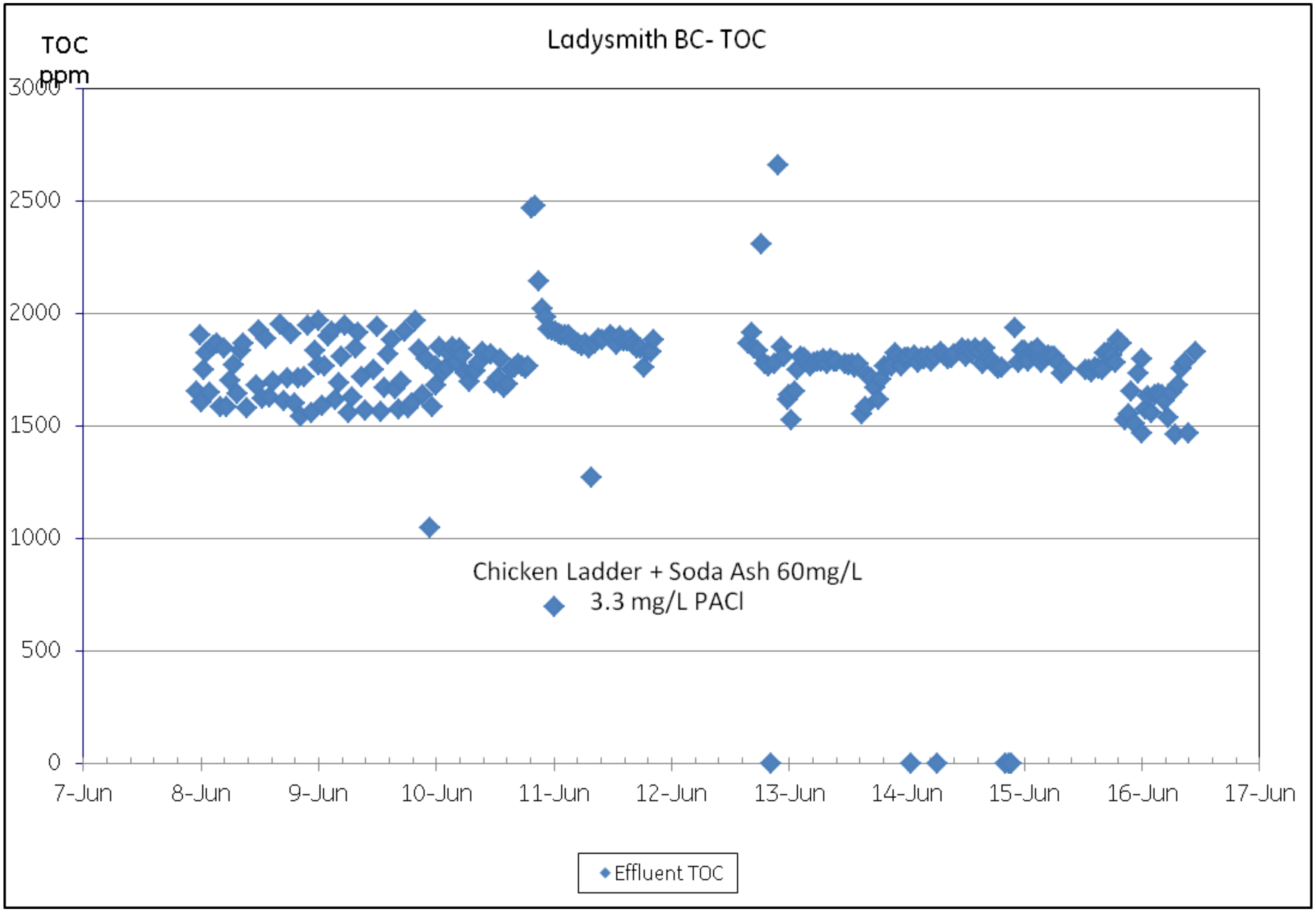


Figure A17: Phase 5 Chicken Ladder 3.3 mg/L PACl Permeate TOC

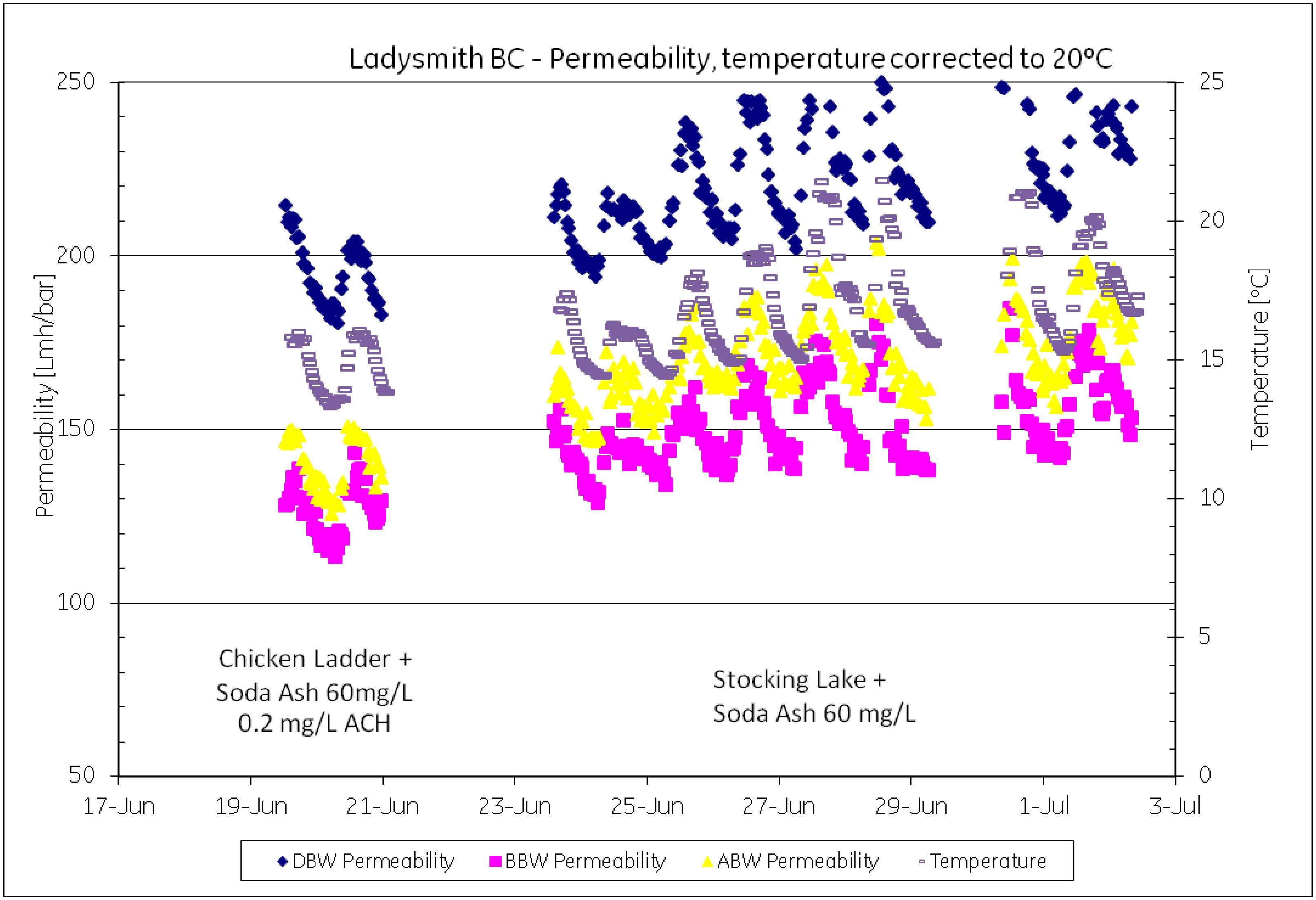


Figure A18: Phase 6 Chicken Ladder & Stocking Lake ACH Test Permeability

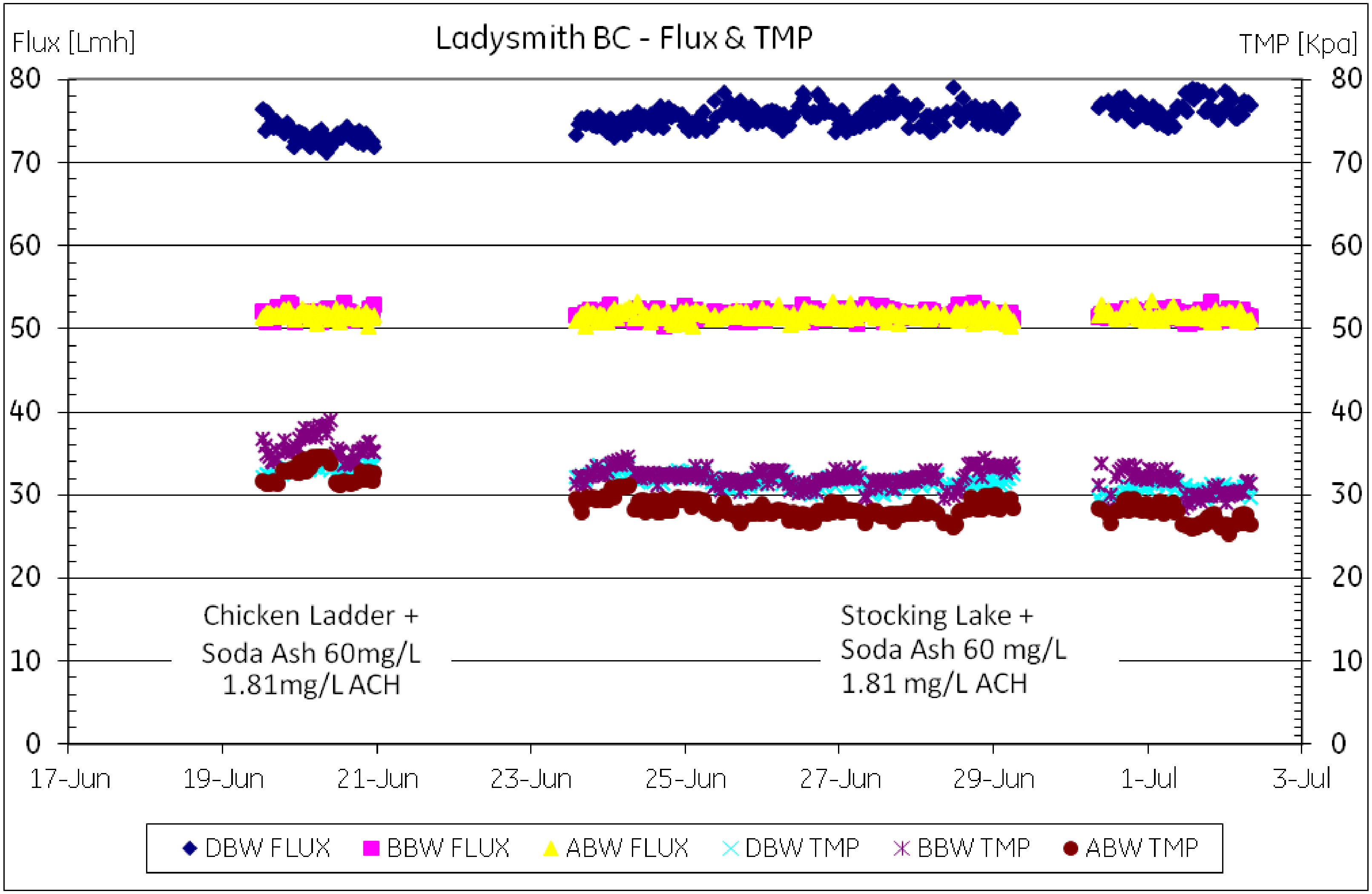


Figure A19: Phase 6 Chicken Ladder & Stocking Lake ACH Test Flux & TMP

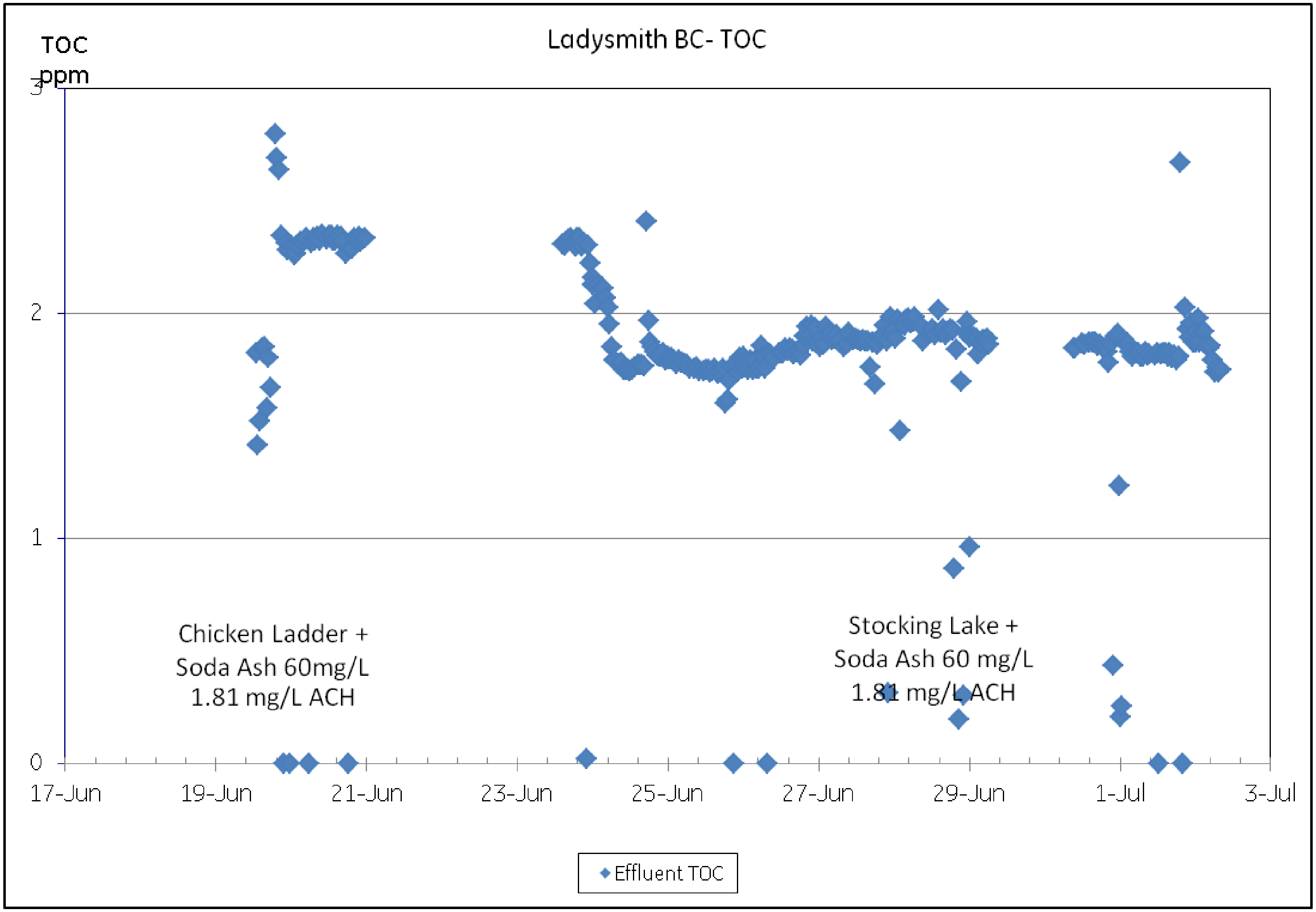


Figure A20: Phase 6 Chicken Ladder & Stocking Lake ACH Test Permeate TOC

APPENDIX B. WATER QUALITY RESULTS

List of Figures and Tables

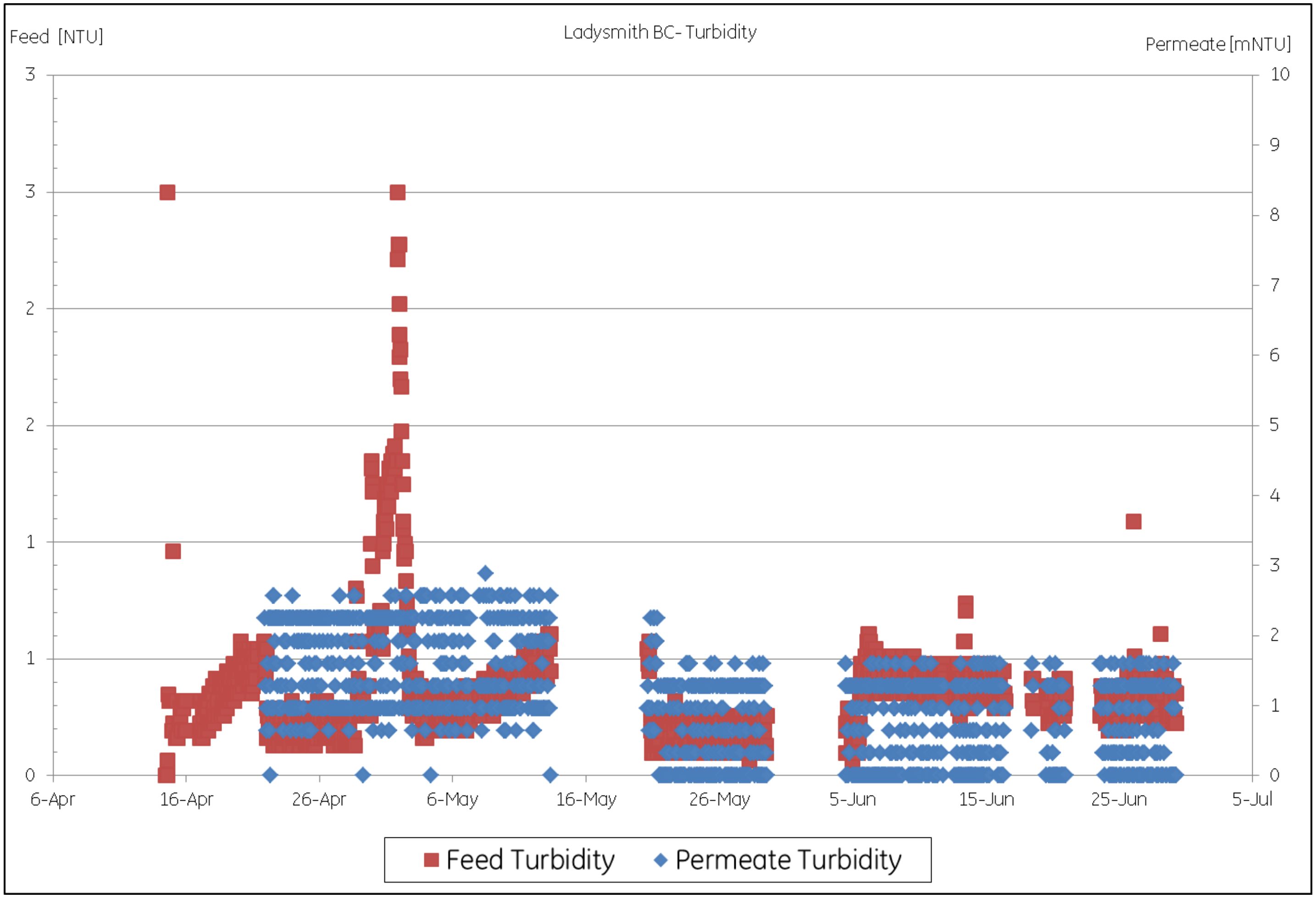


Figure B1: On-line Feed and Permeate Turbidity Data

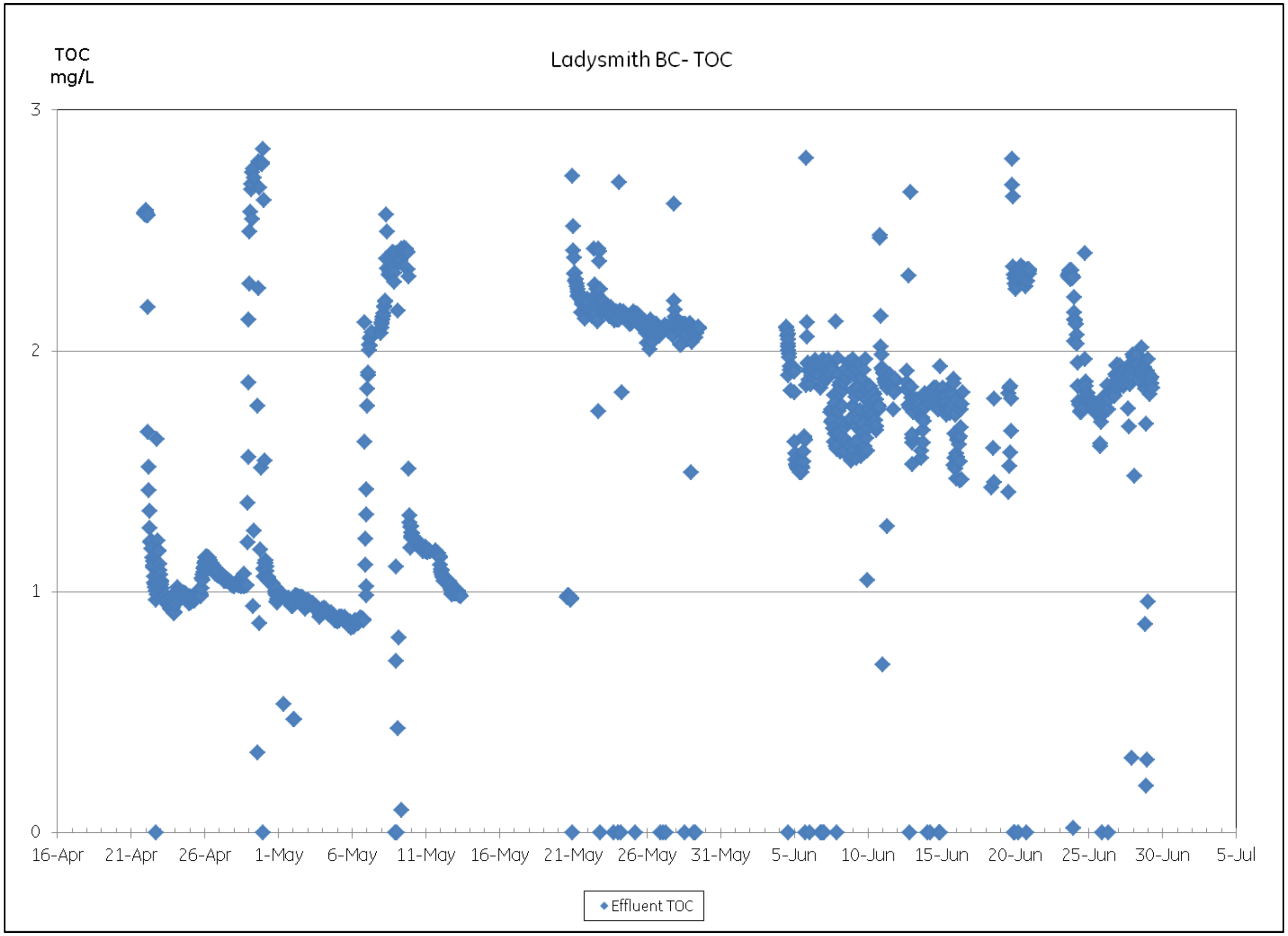


Figure B2: Permeate Total Organic Carbon (TOC) Data

Table B1: Summary of Pilot Results with Chicken Ladder Water

Pre-treatment	Filter	Chemical(s)	mg/L as Al3+	Days	Turbidity (NTU)	UVT (%)	Apparent Colour (TCU)	True Colour (TCU)	pH	Alkalinity (mg/L as $CaCO_3$)	Aluminum (mg/L)	TOC (mg/L)	DOC (mg/L)	THMFP (ug/L)	HAAFP (ug/L)
Raw Chicken Ladder water (no treatment)				57	0.20 - 0.65 (0.36)	68.0 - 83.2 (79.0)	5 - 30 (13)	19 - 42 (27)	6.8 - 7.5 (7.0)	5.3 - 14.2 (7.2)	0.06 - 0.09	3.03	2.44	220	166
DAF	UF membrane	10 mg/L PACl	1.53	7	< 0.004	95.2 - 97.1 (96.1)	5 - 5 (5)	5 - 5 (5)	6.6 - 6.9 (6.8)	3.2 - 4.5 (4.0)	-	1.0 - 2.4 (1.2)	-	66	24
DAF	UF membrane	15 mg/L alum 8 mg/L PAC	0.66	8	< 0.004	82.0 - 97.5 (94.3)	5 - 5 (5)	5 - 21 (9)	5.3 - 7.0 (5.9)	1.0 - 6.4 (3.0)	-	0.9 - 1.8 (1.1)	-	-	-
Coagulation + flocculation	UF membrane	Calcite Contactor	0	13	< 0.003	76.1 - 82.2 (79.0)	10 - 20 (15)	19 - 31 (24)	2.7 - 7.4 (6.5)	5.9 - 26.1 (18.7)	-	2.7 - 2.8 (2.8)	-	-	-
Coagulation + flocculation	UF membrane	0.7 mg/L PACl 60 mg/L soda ash	0.1	3	<0.004	86.6	5	15	7.2	15.5	-	2.1	-	-	-
Coagulation + flocculation	UF membrane	3.3 mg/L PACl 60 mg/L soda ash	0.5	13	< 0.003	86.5 - 91.5 (89.2)	5 - 5 (5)	8 - 16 (11)	4.6 - 7.6 (6.7)	5.7 - 34.3 (12.6)	0.06	1.6 - 2.2 (1.8)	-	-	-
Coagulation + flocculation	UF membrane	5 mg/L PACl 60 mg/L soda ash	0.76	3	< 0.003	85.6 - 92.5 (88.3)	5 - 10 (7)	7 - 19 (14)	6.9 - 7.7 (7.4)	8.8 - 37.3 (25.5)	-	2.0 - 2.1 (2.1)	-	-	-
Coagulation + flocculation	UF membrane	1.3 mg/L ACH 60 mg/L soda ash	0.2	4	< 0.003	-	-	-	-	-	-	2.3	-	-	-

Table B2: Summary of Pilot Results with Stocking Lake Water

Pre-treatment	Filter	Chemical(s)	mg/L as Al3+	Days	Turbidity (NTU)	UVT (%)	Apparent Colour (TCU)	True Colour (TCU)	pH	Alkalinity (mg/L as $CaCO_3$)	Aluminum (mg/L)	TOC (mg/L)	DOC (mg/L)	THMFP (ug/L)	HAAFP (ug/L)
Raw Stocking Lake water (no treatment)				23	0.43 - 0.68 (0.47)	80.8 - 87.0 (84.0)	5 - 15 (8)	14 - 29 (17)	7.0 - 7.5 (7.2)	9.0 - 13.2 (10.9)	0.04	2.51	2.06	270	175
DAF	UF membrane	10 mg/L PACl	1.53	2	< 0.004	87.3 - 89.0 (88.2)	5 - 5 (5)	10 - 12 (11)	7.0 - 7.4 (7.2)	9.4 - 13.0 (11.2)	-	2.2 - 2.3 (2.3)	-	-	-
DAF	UF membrane	15 mg/L PACl	2.32	3	< 0.004	96.2 - 97.1 (96.7)	5 - 5 (5)	5 - 5 (5)	6.5 - 6.7 (6.6)	3.8 - 5.3 (4.4)	0.01	1.0 - 1.3 (1.1)	-	73	21
Coagulation + flocculation	UF membrane	4 mg/L ACH 60 mg/L soda ash	0.6	8	< 0.003	89.8 - 92.0 (91.1)	5 - 5 (5)	7 - 9 (7)	7.6 - 7.9 (7.8)	38.6 - 43.7 (40.6)	-	1.8 - 1.9 (1.8)	-	200	164

Table B3: Summary of Pilot Analytical Data

Start Up														
	Raw Water							Membrane Permeate						
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
9-Mar	81.1	7.51	10	23.2	7.06	-	-	-	-	-	-	-	-	-
10-Mar	81.7	6.95	10	21.1	7.01	-	-	-	-	-	-	-	-	-
11-Mar	81.8	8.78	10	21.5	7.09	-	-	-	-	-	-	-	-	-
12-Mar	76.7	7.14	10	32.2	7.06	-	-	-	-	-	-	-	-	-
13-Mar	73.3	6.2	15	38.1	6.93	-	-	-	-	-	-	-	-	-
16-Mar	68	6.93	30	42.3	7.13	3.21	2.88	-	-	-	-	-	-	-
17-Mar	71.4	5.49	30	37	6.91	-	-	-	-	-	-	-	-	-
18-Mar	75.5	5.47	20	29.7	6.97	-	-	-	-	-	-	-	-	-

Phase 1 Chicken Ladder Water with Calcite and ClearPAC														
Raw Water								Membrane Permeate						
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
19-Mar	77.3	5.74	20	28	6.92	-	-	-	-	-	-	-	-	-
20-Mar	72.2	6.86	15	39.7	6.97	-	-	-	-	-	-	-	-	-
23-Mar	74.3	5.62	20	39.5	6.86	-	-	-	-	-	-	-	-	-
24-Mar	76	5.9	20	29.2	6.89	-	-	76.1	22.1	20	31	6.81	-	-
25-Mar	77.2	5.48	15	27.4	6.84	-	-	79.1	20.3	20	24	6.83	-	-
26-Mar	74	6.62	20	36.5	6.97	-	-	-	-	-	-	-	-	-
27-Mar	76	5.52	15	32.9	6.82	-	-	77.8	23.5	10	27	7.08	-	-
30-Mar	75.2	5.72	20	30.4	6.91	-	-	-	-	-	-	-	-	-
31-Mar	73.1	6.08	20	37	6.92	-	-	-	-	-	-	-	-	-
1-Apr	74.9	5.25	20	32.6	6.92	-	-	76.9	26.1	20	26	7.43	-	-
2-Apr	76.6	6.16	15	31	6.91	-	-	77.1	21.5	10	30	7.26	-	-
8-Apr	79.5	6.13	15	27	6.98	-	-	-	-	-	-	-	-	-
9-Apr	80.2	6.16	10	24.8	6.95	-	-	-	-	-	-	-	-	-
10-Apr	80	9.23	10	24.8	7.18	-	-	-	-	-	-	-	-	-
13-Apr	80.4	6.28	10	22.7	6.93	3.03	2.44	-	-	-	-	-	-	-

Phase 2: Chicken Ladder water with calcite and no coagulant														
	Raw Water							Membrane Permeate						
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
14-Apr	80.2	5.52	15	23.9	6.96	-	-	80.3	<0.5	20	20	2.74	-	-
15-Apr	79.8	5.98	15	23.1	6.92	-	-	82.2	11.3	10	19	7.11	-	-
16-Apr	80.1	6.58	15	25.1	6.9	-	-	82.2	5.91	10	19	6.89	-	-
17-Apr	81.3	5.8	10	25.5	6.95	-	-	-	-	-	-	-	-	-
20-Apr	81.6	7.38	10	20.5	7.09	-	-	83.6	6.56	5	17	7.01	-	-
21-Apr	82.2	7.58	5	19.9	7.14	-	-	83.8	7.11	5	18	7.09	-	-

Phase 3: DAF Pre-treated Chicken Ladder with ClearPAC															
	Raw Water							Membrane Permeate							
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
23-Apr	83.1	6.64	10	19.5	7.16	-	-	96.1	3.23	5	5	6.73	-	-
24-Apr	81.7	7.24	10	19	7.11	-	-	95.9	4.47	5	5	6.89	-	-
27-Apr	80	6.81	10	28.2	6.94	-	-	95.2	4.05	5	5	6.64	-	-
28-Apr	80.1	7.31	5	29.3	7.16	-	-	96.4	4.36	5	5	6.83	-	-
29-Apr	80.5	6.35	10	21.5	7.05	-	-	82	6.42	5	21	6.98	-	-
1-May	81.6	7.19	10	20	7.07	-	-	97.2	<0.5	5	5	5.46	-	-
4-May	82.9	8.7	5	26	7.17	-	-	97.5	0.96	5	7	5.81	-	-
5-May	83.2	7.66	10	18.9	7.04	-	-	97.5	<0.5	5	5	5.34	-	-
6-May	82.7	6.54	5	22.9	6.92	-	-	97.3	1.61	5	5	6.08	-	-

Phase 4: Stocking Lake Eater with DAF using ClearPAC														
	Raw Water							Membrane Permeate						
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
7-May	83.4	9.08	10	17.5	7.03	-	-	89	9.37	5	10	7.02	-	-
8-May	84.2	13.2	15	13.5	7.3	-	-	87.3	13	5	12	7.4	-	-
11-May	83.9	13.1	5	14.1	7.21	-	-	96.2	4.07	5	5	6.48	-	-
12-May	83.7	11.3	5	18	7.2	2.51	2.06	96.7	5.3	5	5	6.73	1.04	0.63
13-May	83.5	10.5	5	16.2	7.2	-	-	97.1	3.77	5	5	6.54	-	-
14-May	83.9	10.5	10	16.5	7.15	-	-	-	-	-	-	-	-	-
15-May	84	12.4	10	16.2	7.4	-	-	-	-	-	-	-	-	-

Phase 5: Chicken Ladder Water with Soda Ash and ClearPAC														
	Raw Water							Membrane Permeate						
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
19-May	84.1	10.9	5	15	7.35	-	-	-	-	-	-	-	-	-
20-May	83.9	9.71	15	15	7.1	-	-	-	-	-	-	-	-	-
21-May	83.9	9.75	5	18.7	7.14	-	-	86.9	10.2	5	15	7.29	-	-
22-May	81.1	10.8	15	19.7	7.02	-	-	86.6	15.5	5	15	7.21	-	-
25-May	83.8	10.6	5	15	7.12	-	-	86.8	6.99	5	13	6.91	-	-
26-May	80.8	9.01	10	28.5	6.98	-	-	87.1	5.75	5	15	6.87	-	-
27-May	85.1	10.4	5	17.8	7.08	-	-	86.5	7.15	5	16	6.74	-	-
28-May	85.5	10.6	10	17.6	7.18	-	-	86.9	37.3	5	15	7.53	-	-
29-May	87	9.25	5	15.5	7.11	-	-	85.6	8.8	10	19	6.92	-	-
5-Jun	82.5	14.2	10	22.4	7.51	-	-	92.5	30.4	5	7.2	7.73	-	-
8-Jun	81.8	10.6	10	24.1	7.31	-	-	91.5	6.49	5	8.7	7.03	-	-
9-Jun	81.6	9.77	5	26.9	7.16	-	-	89.6	7.49	5	8.1	6.95	-	-
10-Jun	81.2	9.2	10	21.6	7.39	-	-	90.7	6.46	5	7.9	7.02	-	-
11-Jun	81.2	9.68	10	22.6	7.42	-	-	89.9	34.3	5	10	7.62	-	-
15-Jun	82.1	8.73	10	20.5	7.37	-	-	90.3	33.3	5	8.1	4.59	-	-
16-Jun	81.5	9.58	10	22.3	7.25			90.5	5.69	5	9.7	6.98	-	-

Phase 6A : Chicken Ladder Water with Soda Ash and ACH															
	Raw Water							Membrane Permeate							
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
22-Jun	82.8	10.8	10	23.7	7.28	-	-	69.4	29.6	30	37	7.67	-	-

Phase 6B : Stocking Lake Water with Soda Ash and ACH														
	Raw Water							Membrane Permeate						
Date	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC	UVT	Alkalinity	Colour, Apparent	Colour, True	pH	TOC	DOC
24-Jun	83.4	10.3	10	13.7	7.17	-	-	77.2	24.4	10	19	6.48	-	-
25-Jun	85.3	10.4	5	14.2	7.04	-	-	92	39.2	5	6.8	7.65	-	-
26-Jun	85.1	12.8	10	15.1	7.21	-	-	91.4	40.8	5	6.9	7.64	-	-
29-Jun	85	10.5	10	14.5	7.12	-	-	89.8	38.6	5	9.2	7.84	-	-
2-Jul	83.8	12.9	5	14.5	7.47	-	-	91	43.7	5	6.8	7.87	-	-

APPENDIX C. PROCESS FLOW DIAGRAM

List of Figures and Tables

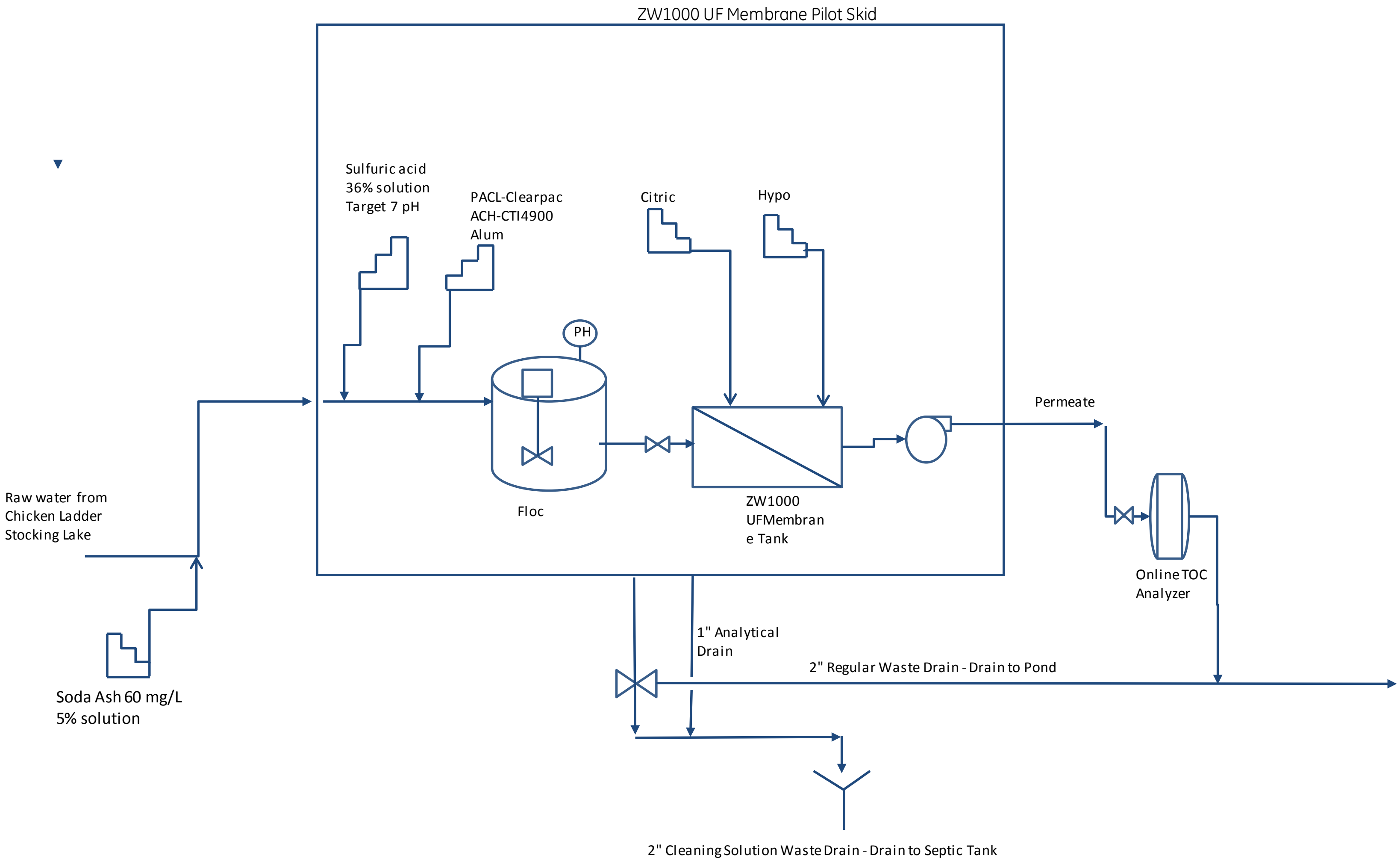


Figure C1: Town of Ladysmith Pilot PFD

Appendix C – Capital Cost Estimates

Township of Ladysmith
Arbutus Water Treatment Plant
Conceptual Design Cost Estimates - Phase 2 Expansion

1-Sep-15

Description	DAF and Media Filtration - 3 tanks and 3 trains, 50% redundancy	Membrane Filtration - 3 trains, 50% redundancy	DAF Addition - 3 tanks, 50% redundancy
Flow (L/s)	125	125	125
Division 1 - General Requirements	$ 50,000	$ 50,000	$ 50,000
Division 2 - Sitework			
2.1 - Site Preparation	$ 175,000	$ 150,000	$ 25,000
2.2 - General Site Grading	$ 175,000	$ 125,000	$ 50,000
2.3 - Excavation for Buildings, Treatment Ponds, and Other Facilities	$ 400,000	$ 350,000	$ 50,000
2.4 - Inlet / Outlet Piping Connections	$ 415,000	$ 415,000	$ -
2.5 - General Site Drainage	$ 110,000	$ 110,000	$ -
2.6 - Construct New Access Roads Around Site	$ 85,000	$ 60,000	$ 25,000
2.7 - Miscellaneous Site Work	$ 235,000	$ 215,000	$ 50,000
Division 3 - Concrete	$ 522,515	$ 213,550	$ 378,365
Division 4 - Masonry	$ 105,360	$ 98,880	$ 27,540
Division 5 - Metals	$ 122,120	$ 104,820	$ 35,660
Division 7 - Thermal Moisture Protection	$ 38,700	$ 35,604	$ 13,158
Division 8 - Doors and Windows	$ 20,000	$ 20,000	$ -
Division 9 - Finishes	$ 87,696	$ 87,696	$ 5,000
Division 10 - Specialties	$ 10,000	$ 10,000	$ -
Division 11 - Equipment	$ 3,930,800	$ 2,669,133	$ 1,386,500
Division 14 - Cranes	$ 50,000	$ 50,000	$ 15,000
Division 15 - Mechanical	$ 682,500	$ 602,000	$ 154,500
Division 16 - Electrical and Controls	$ 366,400	$ 375,500	$ 57,600
Contractor Overhead (15%)	$ 1,137,164	$ 861,328	$ 348,499
Contractor Profit (10%)	$ 758,109	$ 574,218	$ 232,332
Subtotal	$ 9,476,364	$ 7,177,729	$ 2,904,154
Property Purchase	$ -	$ -	$ -
Total Direct Costs	$ 9,476,364	$ 7,177,729	$ 2,904,154
Management and Engineering (20%)	$ 1,895,273	$ 1,435,546	$ 580,831
Construction Contingency Allowance (20%)	$ 1,895,273	$ 1,435,546	$ 580,831
Total	$ 13,266,910	$ 10,048,821	$ 4,065,816