USE OF ONLINE MONITORING INSTRUMENTATION FOR COAGULATION OPTIMIZATION

by

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Abstract

Maintenance of optimal water treatment plant (WTP) performance in the presence of rapidly changing raw water quality (e.g. rainfall events and snowmelts) has been shown to be challenging for coagulation/flocculation based plants. During these times, rapid increases in raw water turbidity and colour can be noticed. The purpose of this study was to assess the viability of using online monitoring instruments to provide coagulation process control in response to these changes.

Three WTPs from around the Atlantic Provinces were involved in the study. Each WTP was sourced from surface waters that are low in alkalinity and highly variable in terms of natural organic matter (NOM) and turbidity. Furthermore, the NOM in these source waters was primarily in dissolved form. Plant audits, bench-scale experimentation and full-scale set up of online instrumentation, including a streaming current monitor (SCM) and UV_{254} monitor, were completed to evaluate current operating and coagulation process control approaches as well as to assess the capabilities of each of the monitors under variable source water quality operating periods.

Bench-scale experimentation using a jar tester was completed to evaluate the turbidity and NOM removal capabilities of three coagulants at varying pH. At the pH of minimum solubility, optimal dose for each coagulant was based on the point of diminishing returns for turbidity, dissolved organic carbon (DOC) and UV_{254}. Zeta potential ranged from -15 to 5 mV for each optimally dosed coagulant which showed that when pH was held constant, charge analysis could be used to determine coagulant dose.

Results from the full-scale online instrumentation set up highlighted the necessity of a stable coagulation pH as well as maintenance of the equipment. When a stable pH was not achieved, streaming current results could not be used. Furthermore, when the process lines into the monitors were not regularly drained to remove build up, samples unrepresentative of the source water quality were sent to the monitor for analysis, giving inaccurate readouts. With proper maintenance and a stable pH, SCM and UV_{254} monitors detected changes in raw water quality. The UV_{254} monitor detected increases in raw water UV_{254} that were independent of turbidity. Raw water UV_{254} also rapidly increased with turbidity during a rain event. However, turbidity returned to its pre-event level faster than UV_{254}. Streaming current was able to detect chemical inadequacies during a rain event. At the beginning of a rain event, streaming current was shown to drop below set-point, indicating insufficient coagulant addition.

The main finding from the study showed that both SCM and UV_{254} could detect changes in source water quality under variable conditions. Streaming current, however, was shown to be highly affected by changes in pH. Jar tests must also be frequently run to determine the set-point, as it may shift with changing source water quality due to seasonal changes. When maintained, the UV_{254} monitor can give an instantaneous measurement of organic concentrations in the source water. Preliminary regression analysis demonstrated promise for basing coagulant dose on raw water UV_{254}.

List of Abbreviations and Symbols Used

Alum	Aluminum Sulfate
BBWTP	Brierly Brook Water Treatment Plant
CI	Confidence Interval
CO2	Carbon Dioxide
DAF	Dissolved Air Flotation
DBP	Disinfection By-Product
DBPFP	Disinfection By-Product Formation Potential
DOC	Dissolved Organic Carbon
E. coli	*Escherichia coli*
FWTP	Falmouth Water Treatment Plant
GPM	Gallons per Minute
HAA	Haloacetic Acid
HAAFP	Haloacetic Acid Formation Potential
HB	High Basicity
$KMnO_4$	Potassium Permanganate
L	Litre
mA	Milliamps
MAC	Maximum Acceptable Concentration
MB	Medium Basicity
mg/L	Milligrams per Litre
MGD	Million Gallons Per Day
mL/min	Millilitres per Minute

MLD	Million Litres per Day
mV	Millivolt
MW	Molecular Weight
Na_2CO_3	Soda Ash (Sodium Carbonate)
NaOH	Caustic (Sodium Hydroxide)
nm	Nanometre
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Unit
OG	Operations Guidance
PACl	Polyaluminum Chloride
rpm	Rotations per Minute
SCADA	System Control and Data Acquisition
SCM	Streaming Current Monitor
SUVA	Specific UV Absorbance
SWTP	Stellarton Water Treatment Plant
TCU	True Colour Units
THM	Trihalomethane
THMFP	Trihalomethane Formation Potential
TOC	Total Organic Carbon
UF	Ultrafiltration
UFC	Uniform Formation Conditions
µg/L	Micrograms per Litre
µm	Micron

UV   Ultraviolet

WTP   Water Treatment Plant

Acknowledgments

Chapter 1: Introduction

1.1 Project Rationale

Maintenance of optimal plant performance in the presence of rapidly changing raw water quality (e.g. spikes in turbidity and colour) has been shown to be challenging in the operation of coagulation/flocculation-based water treatment plants (WTPs). Spring melts or heavy rainfall events can lead to spikes in raw water natural organic matter (NOM) concentrations and can lead to decreased filter run times, poor finished water quality and an increase in plant chemical usage and staffing requirements in order to maintain effective coagulation conditions (Dentel & Kingery, 1989; Volk, 2002; Rouse, 2006). This can be a problem for WTPs where raw water conditions change rapidly and limited staffing is available.

A common method for the determination of the required chemical coagulation conditions in WTPs requires the use of a bench-scale jar test apparatus. However, this method is time consuming and under changing raw water conditions, establishing and maintaining proper coagulant dose has been shown to be difficult (Joo *et al*., 1999; Nam *et al*., 2013; Yavich & Van De Wege, 2013). Inability to maintain proper coagulation conditions during these times often leads to plant upsets (Volk, 2002; Rouse, 2006). The purpose of this study was to assess the viability of using online instruments, specifically streaming current monitors (SCM) and UV_{254} monitors, to provide process control capability for coagulation processes in response to rapid changes in source water turbidity and colour.

1.2 Research Objectives

Three WTPs around Nova Scotia were involved in this study. To evaluate the potential of implementing online UV_{254} and/or SCM instrumentation at full-scale for process control of coagulation processes, the project was divided into two primary objectives as outlined below.

1   Conduct an audit at each WTP to determine current operating and coagulation process control treatment approaches and examine coagulation processes under normal source water quality conditions as required;

2   Investigate data collection capabilities of both UV_{254} and SCM online instrumentation through full-scale equipment installation for data mining during variable source water quality operating periods and examine the potential to integrate online instrumentation at full-scale.

1.3 Format of Thesis

Chapter 2 contains a detailed literature review outlining background information on source water parameters and drinking water treatment. Specifically, NOM, mechanisms of coagulation, and previous research that has investigated the use of online UV_{254} and SCM instruments were reviewed and presented. Chapter 3 describes the materials and methods used to complete this study as well as descriptions of each of the WTPs that participated in this study. Chapter 4 presents plant audit and bench-scale coagulation test results for the Stellarton WTP study. Chapter 5 presents plant audit and preliminary online instrumentation results from the second phase of this study outlining the performance capabilities of the online SCM and UV_{254} monitors at the Falmouth WTP. Chapter 6 presents online instrumentation results from the BBWTP and an analysis of the viability of

implementation of the UV_{254} and SCM instrumentation at full-scale. Chapter 7 presents the conclusions from the research project and presents recommendations for future research.

1.4 Originality of Work

Several studies have evaluated the use of SCMs in WTPs for process optimization (Dentel & Kingery, 1989; Bishop, 1992; Adgar *et al*., 2013; Nam *et al*., 2013; Yavich & Van De Wege, 2013; Sibiya, 2014). However, many of the studies based performance capabilities of the monitor on turbidity removal (Dentel *&* Kingery, 1989; Nam *et al*., 2013; Sibiya, 2014). Although most studies reported successful use of the monitor based on turbidity removal, increasing interest and more stringent regulations with respect to the removal of organics from a water supply leads the question on how SCMs can be used to track and optimize NOM removal.

Briley and Knappe (2002) used a SCM to optimize the removal of algae from the source water for Raleigh, North Carolina. However, this study was completed at bench-scale. To minimize fouling on ultrafiltration (UF) membranes, Xia *et al*. (2007) proposed the use of coagulation as pre-treatment prior to filtration and, to reduce operator demands, automatic coagulation was controlled using a SCM. Although the removal of organics using a SCM was considered for both studies, neither study aimed to optimize coagulation conditions. Baxter *et al*. (1999) and Maier *et al*. (2003) used DOC monitors to determine optimal coagulant dose, however the research was completed at bench-scale and was best suited to normal operating conditions.

Though there has been some research on the use of streaming current for optimization of treatment, no study has investigated its use in conjunction with online organic monitoring for determination of optimal coagulation conditions. The work outlined in this thesis considers the use of both monitors to provide process control capabilities. The research shows how both monitors can be used for process control under both normal and challenge water conditions. Furthermore, unlike previous work, this study was completed at full-scale with continuous sampling at one minute intervals for a duration of several months per WTP.

Chapter 2: Literature Review

A review of literature outlining background information on source water quality parameters including NOM and the regulations and processes for the removal of such were investigated. Studies that focused on the optimization of coagulation methods were then reviewed. Specifically, literature that investigated the use of charge analysis, including zeta potential and streaming current, as well as organic monitoring to improve coagulation methods were reviewed.

2.1 Source Water Quality Parameters of Interest

Drinking water is supplied from a variety of sources including surface and groundwater supplies. In all natural water supplies there exists turbidity, pathogens and NOM, in varying quantities. There is a need to remove these water quality parameters for both aesthetic and health reasons. The presence of such may impart colour and taste or odour to the water making it aesthetically unpleasing to drink (AWWA, 2011; Jiao *et al.*, 2014). Others may not exhibit these qualities but may pose serious health risks. The primary goal for municipal water treatment is to eliminate waterborne diseases that are spread by pathogens (Health Canada, 2012). These pathogens may be in the form of bacteria, viruses or protozoans (Singley *et al.*, 1971). However, ability to detect such pathogens within a water supply is difficult. *E. coli* is therefore used an indicator organism; if detected, it may indicate that other pathogens may also be present. For this reason, the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) require that there is no detectable *E. coli* in treated drinking water supplies (Health Canada, 2012).

Turbidity is the measure of the clarity of the water. The measurement of turbidity in a water supply gives an indication of the relative clarity of the water by the amount of light scattered by the particles within the sample (AWWA, 2011). These particles can be derived from organic or inorganic sources. Organic particles can be classified as NOM. However, not all NOM is in the form of suspended particles (Freese *et al.*, 2001). In some cases, the majority of NOM found within a water supply may be in the dissolved phase, as is commonly seen in Atlantic Canada surface waters. Inorganic particles are generally mineral in nature (i.e. clay) but may also include metals such as arsenic, iron, manganese, etc., which may occur naturally or may be due to runoff from contaminated sites (e.g. industry or mining) (AWWA, 2011).

Elevated turbidity can decrease the quality of source waters as most organic contaminants can adsorb onto the suspended particles (Pernitsky & Edzwald, 2006; Nam *et al.*, 2013). To meet pathogen removal goals, the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) have outlined that for conventional and direct filtration systems, filter effluent turbidity must be less than 0.3 NTU 95 % of the time and never exceed 1.0 NTU. Furthermore, slow sand filtration systems must be less than 1.0 NTU 95 % of the time and never to exceed 3.0 NTU. Finally, plants using membrane filtration must achieve turbidity levels less than 0.1 NTU 99 % of the time (Health Canada, 2012). Inability to reduce or remove turbidity from a water source can affect the effectiveness of disinfection (Pernitsky & Edzwald, 2006). Particles remaining in the treated water have the ability to shield microbes from disinfectants (AWWA, 2011). The disinfectants may also react with the particles to further reduce the disinfectant concentrations.

2.1.1   Natural Organic Matter

Natural organic matte (NOM) refers to the broad range of complex organic material that enters water systems via decaying vegetation, organic soils and biological activity. It is found in all water supplies in varying concentrations (Babcock & Singer, 1979; Volk *et al*., 2002; Pernitsky & Edzwald, 2006). NOM can be classified into two fractions – hydrophobic or hydrophilic.

Both the physical and chemical properties of NOM within a source water can impact the effectiveness of coagulation. Research has shown that highly aromatic and high molecular weight (MW) compounds are easier to remove via coagulation (Croue *et al*., 2000; Pernitsky & Edzwald, 2006). Two primary components of NOM are humic substances and fulvic acids, which are hydrophobic fractions and can make up about 80 % by weight of NOM (Babcock & Singer, 1979). Humic substances have a higher MW than fulvic acids which make them easier to remove from water supplies via coagulation methods. Failure to remove these moderate to high MW hydrophobic substances during coagulation can result in the formation of disinfection by-products (DBPs) during the disinfection stage of water treatment (Croue *et al*., 2000; Liang & Singer, 2003). Studies have shown that these chlorinated substances have been linked to increased cancer rates in some populations (USEPA, 2013).

2.1.1.1 Disinfection By-Products

The reaction of NOM with chlorine based disinfectants forms DBPs that have been linked to health issues such as cancer (USEPA, 2013; Nikolaou *et al*., 1999; Volk *et al*., 2002). Because they are formed at the end of a treatment system, WTPs are not capable of

removing these by-products prior to being sent to the distribution system. Optimizing treatment such that DBP formation is reduced is becoming more important. Currently, the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) regulate two groups of DBPs, trihalomethanes (THMs) and haloacetic acids (HAAs), and allow a maximum acceptable concentration (MAC) of 100 and 80 μg/L, respectively (Health Canada, 2012). During normal operating conditions, plants may be able to meet these guidelines.

2.1.1.2 Quantification of NOM

Total and dissolved organic carbon (TOC and DOC), colour, or UV_{254}, are all examples of parameters that can provide an indication of the total NOM concentration within a water sample (Jiao *et al*., 2014; Volk *et al*., 2002). In a laboratory setting, NOM is quantified by employing TOC as a surrogate parameter. Using a TOC analyzer, NOM is oxidized completely to carbon dioxide (CO_2). The CO_2 is then measured in the gas phase and the amount of TOC, which includes suspended particulate, colloidal and dissolved organic carbon, is reported in mg/L. The total NOM concentration is generally reported to be two times the TOC concentration reported from analysis (Crittenden *et al*., 2005). DOC follows the same procedure but the sample is first filtered through a primed 0.45 μm filter and only reports the dissolved fraction of the organic carbon.

Colour of water can be caused by natural minerals, such as iron and manganese, or by NOM (AWWA, 2012). The colour of water is measured in True Colour Units (TCUs) and measured on a spectrophotometer at a wavelength of 465 nm. The true colour of water is measured after the sample is filtered through a 0.45 μm filter to remove any suspended materials. Currently, the *Guidelines for Canadian Drinking Water Quality* (Health Canada,

2012) only require that treated water meet the aesthetic objective of 15 TCU. Colour within a water sample usually indicates that there are undesirable substances, such as organics, within the water.

Organic substances absorb UV light between 100 and 400 nm wavelengths. Measured on a spectrophotometer at a wavelength of 254 nm, UV_{254} gives a representative value of the aromatic compounds and conjugated double bonds in the water sample (Jiao et al., 2014). Several studies have shown that the hydrophobic, aromatic NOM fractions (e.g. humic substances) are the principle DBP precursors (Croue et al., 2000; Briley & Knappe, 2002; Liang & Singer, 2003). Reduction in UV_{254} during treatment relates to reduction in possible DBP formation as it is an indication that moderate to high MW compounds have been broken down into simpler organic compounds (Lamsal et al., 2010; Jiao et al., 2014). It is also important to note that the relationship between TOC and UV_{254} is unique for each water source as the characteristics for NOM change with location. Volk et al. (2002) showed that fluctuations in DOC closely followed variations in UV_{254} during normal source water quality conditions; however, as source water quality decreased, UV_{254} would increase at a higher magnitude than DOC. Rouse (2006) showed good correlation between DOC and grab UV_{254} samples at the Brick Township WTP in New Jersey, even with variations in source water quality.

2.2 Decreased Source Water Quality

Maintenance of plant performance in the presence of rapidly changing raw water quality has been shown to be challenging (Volk et al., 2002; Adgar et al., 2005). Rapid changes to source waters can be caused by heavy rainfall events, snowmelt conditions or by a highly variable water supply, such as rivers. During these events, increases in either

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turbidity, NOM or both can be noticed. Often times, these increases occur quickly and operators are unable to respond to the changes and struggle to maintain optimal coagulation conditions. Plants that are unable to maintain effective coagulation conditions during these times often see decreased filter run times and poor finished water quality resulting in a reduced amount of NOM removed during treatment (Volk *et al*., 2002; Adgar *et al*., 2005; Sibiya, 2014). Inability to maintain optimal performance during these times could lead to higher DBPs in the treated water. An increase in plant chemical usage and staffing requirements is also usually required (Dentel & Kingery, 1989; Bishop, 1992; Volk, 2002; Rouse, 2006).

2.3 Coagulation

The existence of NOM in source water supplies is challenging for utility operators for many reasons including its role for transporting organic and inorganic pollutants, ability to lead to membrane fouling, serve as a food source in the distribution system and for being the primary precursor for DBP formation (Stevens *et al*., 1976; Babcock & Singer, 1979; White *et al*., 1997; Xia *et al*., 2007; Cheng *et al*., 2010;). Coagulation is a chemical pre-treatment process adopted by drinking WTPs to agglomerate fine particles and NOM prior to clarification. There are four mechanisms by which coagulation of such materials are removed from solution: complexation, enmeshment, adsorption and charge neutralization/destabilization (Pernitsky & Edzwald, 2006). The type and quantity of particulates and NOM within the water source dictates which removal process is dominant. Pernitsky and Edzwald (2006) outline that the removal of particulates are primarily achieved via charge neutralization of the negatively charged particles by adsorption of the positively charged coagulant or by enmeshment of colloids in precipitated metal hydroxide

solids (sweep floc). Alternatively, when considering the removal of NOM, the primary mechanisms are considered to be complexation of NOM with dissolved metal species which leads to precipitation, complexation of NOM with the dissolved metal species which leads to adsorption and finally, direct adsorption of NOM onto precipitated metal hydroxide solids.

The effectiveness of coagulation and its ability to remove particles and NOM from a water source depend on various factors, such as coagulation type and dose, pH, and particle properties. Optimal conditions for turbidity removal are not always the same for removal of NOM. The negative charge NOM exhibits is generally greater than that of particulate matter. Thus, it is associated with higher coagulant demands for effective removal (Pernitsky & Edzwald, 2006). It has been found that coagulant demand is governed by the concentration of NOM for low turbidity waters.

The properties of the organic compounds in the water also play a role on how efficiently NOM can be removed via coagulation. The more hydrophobic the NOM, the more likely coagulation processes can aid in reduction or removal. The specific UV absorbance (SUVA) of the water source gives an indication on the effectiveness coagulation will have on the removal of NOM. Ideally, SUVA values > 4 result in good DOC removals (Edzwald & Tobiason, 1999). Furthermore, Jiao *et al*. (2014) showed a significant relationship between UV_{254} and high MW fractions of NOM ($R^2 = 0.93$). This indicated that the treatment process is selective for the substances which have a UV response at 254 nm. Following coagulation, most high MW substances were removed.

2.4 Optimization Studies

A common method for the determination of the required chemical coagulation conditions in WTPs requires use of a bench-scale jar test apparatus, as shown in Figure 2.1.

Figure 2.1: Phipps and Bird 1-L jar test apparatus

Generally, a bench-scale jar test apparatus consists of four or six 1 to 2 L jars. Raw water samples in each jar are dosed with differing amounts of coagulant. The test is run to mimic full-scale treatment and can be programmed to stir at varying speeds for varying amounts of time to mimic rapid mixing, flocculation and sedimentation processes (AWWA, 2011). The optimal dosage is determined based on turbidity reduction and NOM removal and usually selected based on the point of diminishing returns.

Although effective for day to day process control, running a jar test is time consuming and under rapidly changing raw water conditions, such as during increased rainfall or snowmelt, establishing and maintaining a proper coagulant dose using a jar test has been shown to be difficult (Joo *et al.*, 1999; Yavich & Van De Wege, 2013). Inability

to maintain proper coagulation conditions during these times often leads to loss of process control or a plant upset. In addition, the optimal dose determined using the jar tester may also differ from the optimal dose required at full scale due to variations in the hydrodynamics of the bench- versus full-scale systems (Neuman, 1981; Baxter *et al.*, 1999; AWWA, 2011). For example, a standard jar tester may be used to determine optimal coagulant dose for a plant that uses an upflow clarification system. Although the jar tester mimics sedimentation, an upflow clarifier is a more advanced physical treatment that cannot be duplicated at bench-scale.

2.4.1 Charge Analysis

An alternative method to standard jar tests to determine coagulant dose is to employ charge analysis. Two methods used to monitor the surface charge of colloidal particles include measuring zeta potential and streaming current. Streaming current differs from zeta potential operationally, in the sense it can be monitored continuously and online in real time. In contrast, zeta potential is measured at bench-scale by collection of grab samples from the treatment train post rapid mix (Dentel & Kingery, 1981; Dental & Abu-Orf, 1995).

2.4.1.1 Double Layer Theorem

The double layer theorem, as shown in Figure 2.2, is used to explain the difference between streaming current and zeta potential.
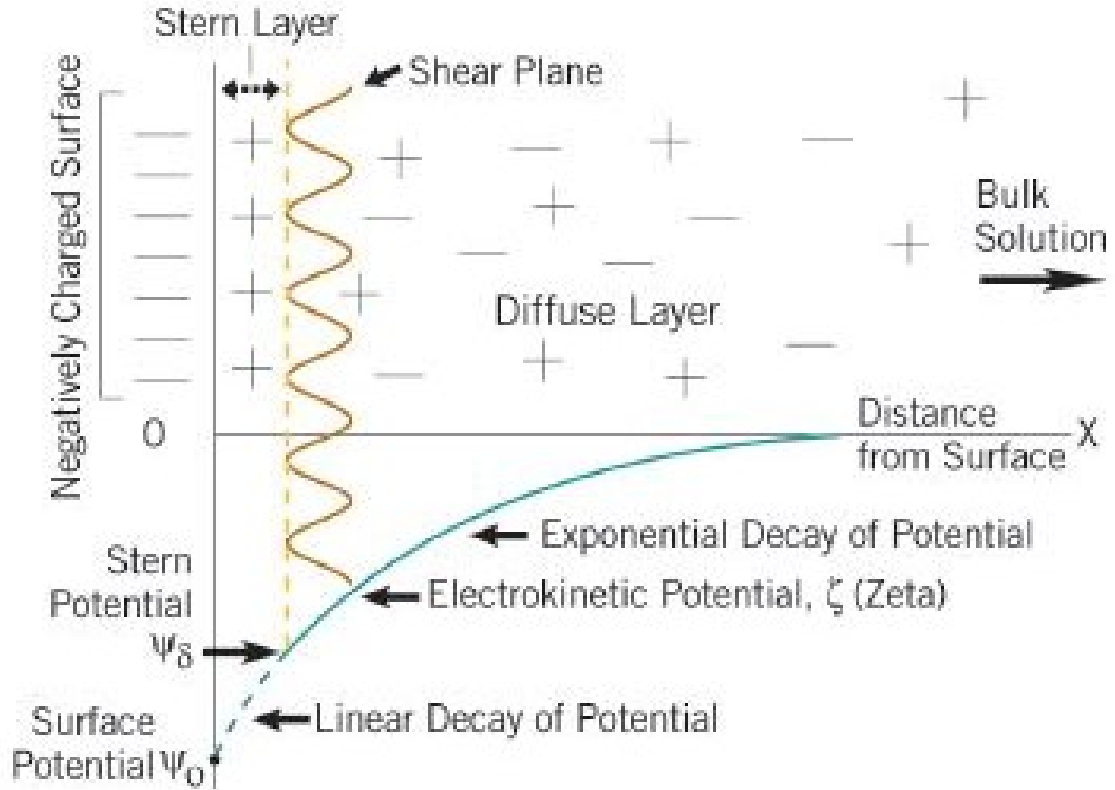
Figure 2.2: Double layer theorem (Particle Sciences, 2012)

The theorem explains that a colloid in suspension has two layers: an inner stern layer and an outer diffuse layer (Singley *et al.*, 1979). The stern layer is composed of a tightly bound layer of positive counter ions. The diffuse layer, which is loosely bound, is attracted to the colloids negatively charge surface, but repelled by the positively charged ions in the stern layer. As the negatively charged colloid travels, some of the positive ions within the diffuse layer will move with the particle and others will not. The boundary between these particles is called the slipping plane (Singley *et al.*, 1979; Chemtrac, 2006).

The electric potential that exists between the colloid surface and this boundary is referred to as zeta potential (Singley *et al.*, 1979). To measure this potential, a sample is placed in a capillary cell with electrodes at either end and a potential is applied, as shown in Figure 2.3. It is the velocity of the particles moving towards the electrode of their

opposite charge that is measured and expressed in a relative unit field strength (Malvern, 2008).
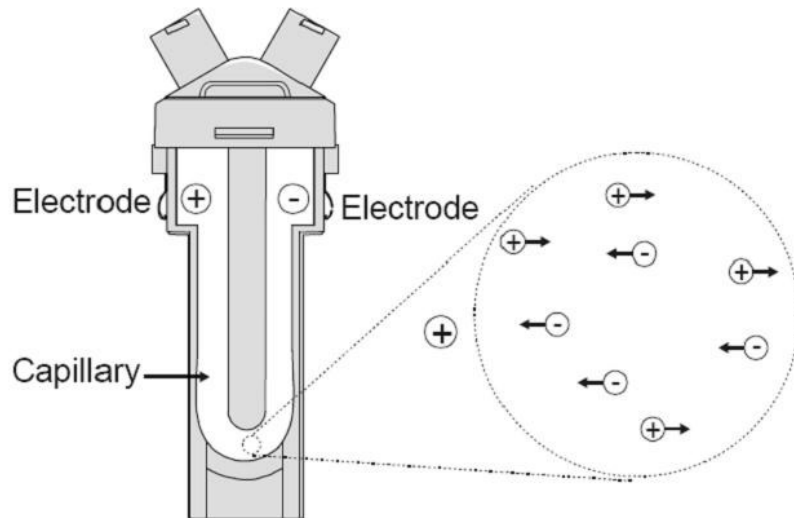
Figure 2.3: Cross-section of a capillary cell used to measure zeta potential (Malvern, 2008)

2.4.1.2 Measurement of Streaming Current

Measurement of streaming current differs from zeta potential in terms of the nature by which an electrical field is applied. When exposed to a shear force, ions within the diffuse layer can become displaced (Chemtrac, 2006; AWWA, 2011). The current generated by the movement or flow of cationic particles past a stationary charged surface is measured. Operationally, streaming current meters consist of a reciprocating piston in a dead-end cylinder, as shown in Figure 2.4 (Dentel & Abu-Orf, 1995).
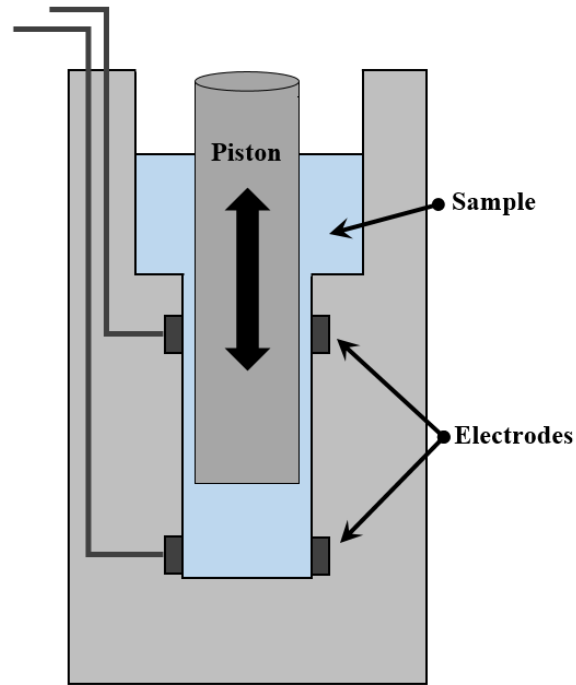
Figure 2.4: Cross section of a streaming current piston and cylinder

The annulus, the space between the piston and cylinder, is fed new sample caused by the pump-like motions of the piston. The charged colloids within the sample become momentarily attached to the piston and cylinder walls (Walker *et al*., 1996; Chemtrac, 2006). Electrodes, located at opposite ends of the annular space, generate a streaming current caused when ions beyond the slipping plane assume the velocity of the fluid moved in and/or out of the annulus. The current is then amplified and then reported in terms of relative units which may give insight as to whether a coagulant is being overdosed or under dosed based on previous calibration (Chemtrac, 2006; AWWA, 2011).

The streaming current set-point is determined by running a jar test to find the optimal coagulant dose. The streaming current found at this dose is then considered the set-point, or the streaming current target. Alternatively, a WTP operating with high

efficiencies under normal source water quality conditions may choose to base their set-point on the full-scale streaming current reading at this time.

2.4.1.3 Use of Charge Analysis for Coagulation Optimization

Prior to the use of streaming current, many operators used zeta potential to determine optimal coagulation conditions (Black & Willems, 1961; Bean *et al.*, 1964; Gupta *et al.*, 1975; Bhattacharjya *et al.*, 1976; Neuman, 1981; Tseng *et al.*, 2000). Optimal coagulation conditions were found when there was a sign reversal of the zeta potential. More specifically, optimal turbidity removal was found when the zeta potential was 0 or slightly positive (Black & Willems, 1961; Bean *et al.*, 1964) whereas optimal colour removal was found at a slightly negative zeta potential between -10 and -5 mV (Black & Willems, 1961; Tseng *et al.*, 2000). Neuman (1981) also outlined several case studies in the United States in which zeta potential was used at full-scale to optimize coagulation which resulted in longer filter runtimes and lower clearwell turbidity.

Streaming current has also been used to determine optimal coagulation conditions. The major benefit of using a SCM over zeta potential is its ability to measure charge online and in realtime (Dentel & Kingery, 1981; Dental & Abu-Orf, 1995). Measurement of zeta potential has been found to be time consuming and few plants have used it to control coagulant dosage (Dentel & Kingery, 1989). However, several studies have evaluated the use of streaming current in WTPs for optimization of treatment (Dentel & Kingery, 1989; Bishop, 1992; Adgar *et al.*, 2013; Nam *et al.*, 2013; Yavich & Van De Wege, 2013; Sibiya, 2014). Dentel and Kingery (1989) conducted an independent assessment of SCMs which included a survey sent to 89 WTPs around the United States to gain a database on experience and assessment of SCM capabilities at each plant as well as on-site studies at

ten WTPs of the application of SCM in water treatment. Survey results showed that of the 35 plants that responded, 88 % were satisfied with the installation and 81 % observed a good to excellent correlation to process performance. The on-site studies showed that using SCMs to control coagulation reduced turbidity in eight of the 10 plants and allowed an average chemical cost savings of 12 %.

The feasibility of using a SCM to control coagulant dose in high turbidity waters was investigated at bench-scale by Nam *et al.* (2013). The efficiency of the monitor in that study was based on the removal of turbidity and it was found that a SCM was able to determine optimal coagulation conditions similar to that found with jar tests but in a shorter time frame. Sibiya (2014) also evaluated the use of a SCM at bench-scale to control coagulant dose under periods of changing raw water turbidity and found it minimized under and overdosing of coagulant.

To overcome fouling of UF membranes, Xia *et al.* (2007) proposed the use of coagulation as a pre-treatment prior to membrane filtration for the removal of NOM. Automatic coagulation was controlled using a SCM. When streaming current values were slightly positive, an increased DOC removal from 8.5 to 47 % was observed when using an alum dose of 14 mg/L.

Yavich and Van De Wege (2013) developed a feed-forward convergence model to predict required chemical feeds based on source water and operating parameters. When the model was tested in conjunction with a SCM, it was found that there were some instances when the model was under-dosing which was detected by drops in streaming current. Further research indicated that the streaming current was detecting increases in NOM. Briley and Knappe (2002) also successfully used a SCM at bench-scale to optimize coagulation for the removal of algae.

2.4.1.4 Maintenance of Constant pH for Effective Use of Streaming Current

Maintaining a constant pH is necessary for effectively using streaming current to determine coagulant dose. The surface charge of particles and the charge carried on the functional groups of NOM are affected by changes in pH. Additionally, the positive charge exhibited by coagulants, specifically aluminium and ferric based coagulants, is less at higher pH (AWWA, 2011). The Langsett WTP in Yorkshire introduced a SCM to control ferric sulphate dosing (Bishop, 1992). Initially, variations in pH were adversely affecting the operation of the SCM. When a modification to the pH system that set a range of 5.6 ± 0.3 was installed, the plant saw excellent treated water quality in terms of colour and a cost savings of over £20,000 per year.

The Broken Scar Treatment Works in Northeast England also introduced a SCM to their pilot plant to investigate practical application to control chemical coagulation processes as the source water is prone to extreme variations (Adgar & Jones, 2005). Like Bishop (1992), variations in pH disturbed the SCM readout. The relationship between pH and streaming current was developed and a modification was made to the feed-forward model to automatically correct the streaming current output based on the pH reading. The model showed promising results at the pilot plant with further use at full-scale to be considered.

2.4.2 Organic Monitoring

Although many studies highlight the importance of removing organics from source water for improved treated water quality (Jiao *et al*., 2014; Cheng *et al*., 2010; Xia *et al*., 2007), there have been few studies that have considered online analysis of organics for optimization of coagulation processes or for monitoring purposes. Some research has been

completed that used advanced online instrumentation to aid the determination of coagulant dose for the removal of undesirable organic matter.

The Brick Township Municipal Utilities Authority WTP in New Jersey sources its plant from a variety of water supplies including the Metedeconk River, both deep and shallow wells, an aquifer and a reservoir with average DOC values in the 4 to 5 mg/L range (Rouse, 2006). Due to the variations in source water quality, maintaining optimal coagulation conditions has been shown to be challenging. To aid in determination of coagulation dose, the plant installed a DOC monitor (AV400, ABB) to measure raw water concentrations. The initial data showed that grab UV_{254} readings, sampled intermittently every 4 hours, followed the same trend as the online DOC readings. The operators now track coagulant dose with the online DOC measurements to eliminate over and underfeeding of chemical (Rouse, 2006).

Volk *et al*. (2002) completed a study which monitored daily organic matter concentrations in source and treated waters using an online TOC analyzer (Model 800, Sievers) to determine the fluctuations of organic matter over time and to assess the overall removal during treatment. The source water was supplied from the White River in Muncie, Indiana which experienced upset conditions during heavy rainfall events. The study found that precipitation events led to increases in raw water DOC by as much as 3.5 fold which led to an increase in treated water organic levels. It was also found that there was a significant difference between winter and summer DOC concentrations with a 66 % increase between the seasons.

2.4.3   Model Development for Coagulation Optimization

During times of rapidly changing raw water quality, such as spring thaws or heavy rainfall events, operators may struggle to maintain optimal coagulation conditions (Joo *et al.*, 2000; Yavich & Van De Wege, 2013). Process control is usually accomplished by the operators based on their own experience or by running a jar test (Wu & Lo, 2008). However, when the source water quality is changing rapidly, jar tests are inefficient and ineffective. The shortcomings of using a jar test to predict optimal coagulant dose, however, can be overcome by using a predictive model.

Many researchers have identified the need and benefit of developing relationships or models for the prediction of optimal coagulant dose (Baxter *et al.*, 1998; Joo *et al.*, 1999; Deveughele & Do-Quang, 2004; Maier *et al.*, 2004; Adgar & Jones, 2005; Rouse, 2006; Wo & Ki, 2008; Yavich and Van De Wege, 2013). Joo *et al.* (2008) describes that most of the models developed to predict optimal dose can be classified into one of two categories: the first category uses a feed-back control approach based on the changes in charge analysis of the rapid mix effluent. The second category develops relationships between known source and finished water quality with past coagulant doses. Examples of these models include a predictive model presented by Rouse (2006) where coagulant dose was tracked with online DOC measurements. A feed-forward convergence model to predict required chemical feeds based on source water and operating parameters has been presented by Yavich and Van de Wege (2013) whereas Adgar and Jones (2005) proposed a feed-forward model which corrects streaming current output with pH .

Chapter 3: Materials and Methods

3.1 Water Treatment Plants

Three conventional filtration WTPs in Nova Scotia were used as field study sites for this study. Online SCM and UV_{254} instruments were set up at each plant for a duration of three to four months. The locations include Stellarton Water Treatment Plant (SWTP) in Stellarton, the Brierly Brook Water Treatment Plant (BBWTP) in Antigonish and the Falmouth Water Treatment Plant (FWTP) in Falmouth.

3.1.1   Stellarton Water Treatment Plant (SWTP)

The SWTP is a 4.5 MLD conventional filtration plant followed by membrane filtration which supplies drinking water to the Town of Stellarton. The source of the water supply for this drinking water plant is the East River. Table 3.1 outlines the source water quality of the East River from samples collected from April to June, 2013.

Table 3.1: Source water quality of the East River in Stellarton

Parameter	Average	Comment
pH	6.4 ± 0.57	Slightly acidic
Turbidity, NTU	6.2 ± 6.4	Variable turbidity
UV_{254}, cm^{-1}	0.159 ± 0.036	
True Colour, TCU	21 ± 6	
TOC, mg/L	3.8 ± 0.8	Moderate to high
DOC, mg/L	3.6 ± 0.8	organic content

The river has variable turbidity with moderate TOC and DOC concentration levels. Variations in source water quality are noticed more in the Spring, Summer and Fall as opposed to the Winter months. A schematic of the SWTP can be seen in Figure 3.1.

Stellarton Water Treatment Plant
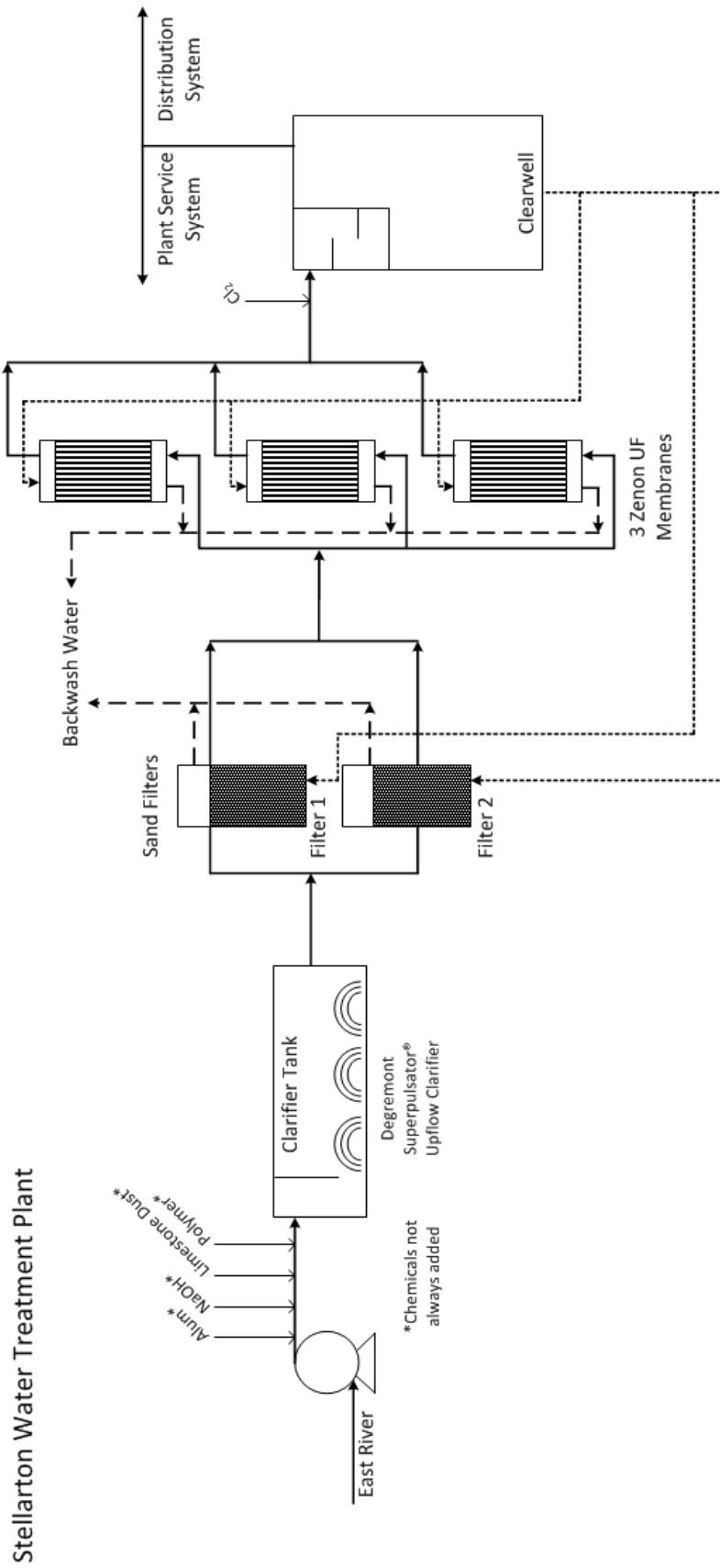
Figure 3.1: Schematic of the Stellarton Water Treatment Plant

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The plant is equipped to dose with alum and pH adjust with caustic (NaOH) at the influent into the plant. Magnafloc® LT 25 polymer and limestone dust by Graymont can also be added to assist with coagulation and to act as a weighting agent.

The SWTP plant uses a Degremont Superpulsator® upflow clarification system. The system works by drawing water from the rapid mix tank into the vacuum chamber. The water enters the clarifier basin via the distribution channel where the coagulated water is evenly distributed along the bottom of the basin using a series of laterals with downward pointing orifices. When the vent valve, located on top of the vacuum chamber, is opened, the water within the chamber drops pushing more water through the distribution channel and into the clarifier basin. When the vent valve is closed, the water within the vacuum chamber rises again. The motion created when opening and closing the vent valve creates a pulse-like motion of water entering the clarifier.

Once in the clarifier basin, the flocculated water is forced upwards through a series of inclined settling plates. The sludge mass is directed downwards on the front side of the plates. An eddy is created which circulates lighter particulate between the plates. This promotes contact of solids within the water with the sludge that is being directed downwards on the plate face.

Sludge concentrators collect sludge with each pulse. As the water levels rises, it creates an upward motion of the sludge bed causing it to spill over into the concentrator. When this chamber becomes full, the sludge removal piping pumps the sludge out.

Following clarification, the water is passed through a sand filter prior to being fed through three parallel UF membranes. The water is chlorinated before leaving the plant.

3.1.2 Brierly Brook Water Treatment Plant (BBWTP)

The BBWTP is a conventional filtration plant that has a 1.8 MGD capacity and supplies drinking water to the Town of Antigonish. The source water is supplied by a reservoir created by the James River. The source water is similar to that of other Atlantic Canada water sources in that it is low in alkalinity, variable in turbidity and has moderate organic levels. Table 3.2 outlines the source water quality for the James River reservoir as sampled from May to August, 2013.

Table 3.2: Source water quality of the James River reservoir in Antigonish

Analyte	Average	Comment
pH	6.4 ± 0.2	
Turbidity, NTU	4.98 ± 5.82	Maximum 70
Colour, TCU	78 ± 33	Maximum 207
UV$_{254}$, cm^{-1}	0.211 ± 0.09	Maximum 0.599
TOC, mg/L	5.1 ± 0.6	Moderate to high
DOC, mg/L	4.9 ± 0.5	organic content

The BBWTP was built in 2006 and is equipped with a dissolved air flotation (DAF) clarification system. A schematic of the plant is shown in Figure 3.2.
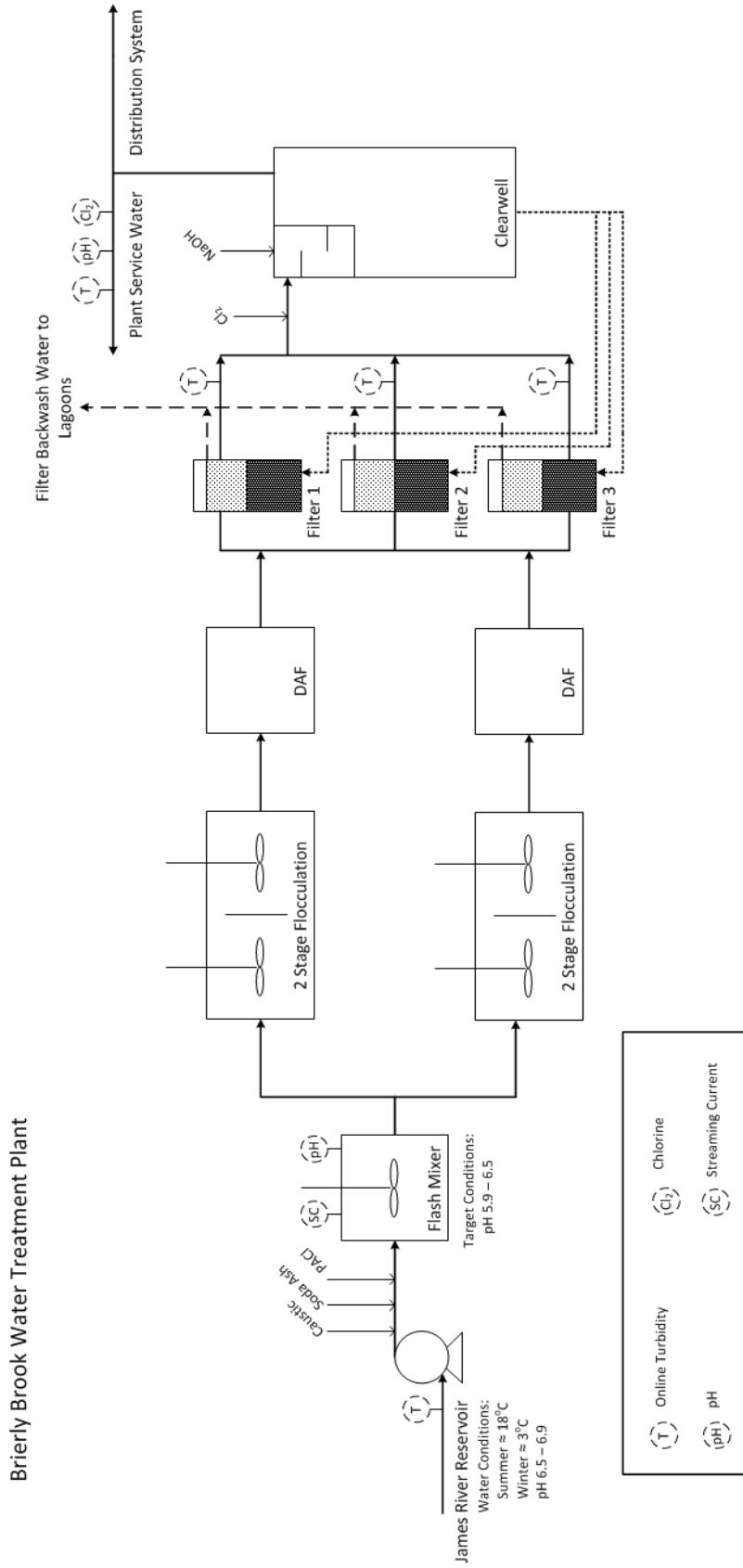
Figure 3.2: Schematic of the Brierly Brook Water Treatment Plant

The BBWTP plant is currently dosing with caustic (NaOH) for pH control and a medium basicity (MB) polyaluminum chloride (PACl) as the coagulant. It also has the ability to dose with soda ash (Na_2CO_3) for pH control and alkalinity addition. After rapid mixing, the plant divides into two parallel treatment trains consisting of two-stage flocculation for 30 minutes prior to clarification with DAF. The water from the two treatment trains is then combined before leading to three dual media anthracite and sand filters which have a detention time of approximately eight minutes. The water is then pH adjusted with caustic and chlorinated prior to leaving the plant.

The plant currently has a SCM installed immediately after the rapid mix tank. The operators are using the monitor to indicate a change in the raw water quality and when to increase or decrease their coagulant dose. When the water quality begins to deteriorate, the SCM begins to read more negative. When the streaming current drops out of the set range (i.e. ± 10 of the set-point), an alarm is set to sound to indicate such a change. Operators then increase coagulant dose such that the streaming current is brought back into the acceptable range. This method, although effective, can be timely (often hours) and requires operators to be on site monitoring and adjusting chemical addition until raw water quality returns to acceptable levels.

3.1.3   Falmouth Water Treatment Plant (FWTP)

The FWTP supplies drinking water to the small Town of Falmouth. The water is supplied from a reservoir which pulls water from the French Mill Brook and its watershed. The plant has a capacity of 1.7 MLD. However, the plant only operates between six and seven hours a day. Table 3.3 outlines the source water quality of the French Mill Brook Reservoir as sampled in July, 2014.

Table 3.3: Source water quality of the French Mill Brook Reservoir in Falmouth

Parameter	Average	Comment
pH	7.3 ± 0.1	
Turbidity, NTU	9.4 ± 6.6	Variable turbidity
UV$_{254}$, cm^{-1}	0.147 ± 0.063	
True Colour, TCU	28 ± 13	
TOC, mg/L	3.4 ± 0.6	Moderate to high organic content
DOC, mg/L	3.2 ± 0.6	

A schematic of the FWTP is shown in Figure 3.3.

Falmouth Water Treatment Plant
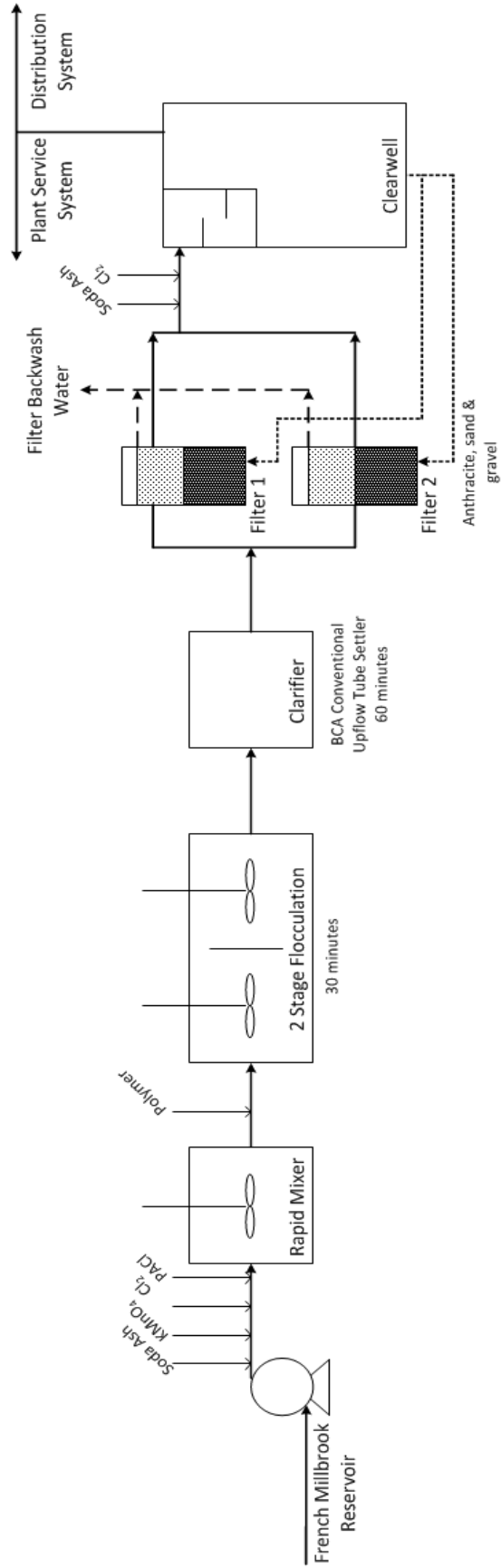
Figure 3.3: Schematic of Falmouth Water Treatment Plant

The FWTP plant uses SternPac®, a medium basicity PACl coagulant, as well as soda ash for pH adjusting and potassium permanganate ($KMnO_4$) for iron and manganese removal. Polymer is added immediately after rapid mixing to aid in floc formation. Following a 30 minute hydraulically mixed flocculation period, water is sent to the settling upflow tube settler clarifier for a one hour detention time. This is shown in Figure 3.4.

Figure 3.4: Rapid mix, flocculation, clarifier and filter tanks at the FWTP

The flow enters the bottom of the settler and flows upwards through the 60º inclined tube modules. Heavier flocs settle whereas lighter particles are retained within the tubes to form larger flocs which later settle. The clarified water is collected at the top of the tank where it is sent to two dual media sand and anthracite filters. Water is then pH adjusted with soda ash and chlorinated prior to leaving the plant.

3.2 Bench-Scale Testing

During the audits of some of the WTPs involved in the study, bench-scale jar testing was necessary to ensure coagulation processes were optimized under normal source water quality conditions. For the audit, source water and treated water samples through the treatment trains were collected for analysis. Each sample was analyzed for pH, turbidity, total organic carbon (TOC), dissolved organic carbon (DOC), UV_{254}, true colour, trihalomethane formation potential (THMFP) and haloacetic acid formation potential (HAAFP) to determine the removal capabilities of the current treatment trains. Depending on the results of the audit, further bench-scale testing using a standard jar test apparatus (Phipps and Bird, Fisher Scientific) was completed to optimize coagulation processes under normal source water quality conditions.

Bench-scale testing to optimize pre-treatment under normal source water quality conditions was completed using a six paddle jar test apparatus (Phipps and Bird, Fisher Scientific) with 2 L jars. Three coagulants supplied by Kemira Water Solutions Canada Ltd. were used for the study: A medium basicity (MB) polyaluminium chloride (PACl) (PAX XL 6), a high basicity (HB) PACl (PAX XL 1900) and alum.

3.3 Online Instrument Data Collection at Full-Scale

Two sets of online UV_{254} and SCM instruments were used to monitor water quality in this study. The first set included a Chemtrac UVM5000 UV_{254} monitor and SCM2500 SCM. The second set included a RealTech M3000 UV_{254} monitor and a HACH AF7000 SCM. Each set of instruments are shown in Figures 3.5a and 3.5b.

Figure 3.5: a) Chemtrac UV$_{254}$ and SCM monitors; b) RealTech UV$_{254}$ and HACH SCM monitors

Each plant had the online UV$_{254}$ and SCM instruments set up for a duration of three to four months. Data were logged using an external 4-channel data logger (Onset) with 4 – 20 mA output and was collected weekly and exported using HOBOware Pro software. In addition to the UV$_{254}$ and streaming current data collected from the online instruments, other data from the supervisory control and data acquisition (SCADA) system from each plant were also gathered. These data included flow, temperature, turbidity measurements from the raw water, filter effluent and clearwell process lines, coagulation and clearwell pH and coagulant dose. Data collected from full-scale waereused to evaluate the performance capabilities of each plant and determine whether installing online instrumentation for coagulation process control was a viable option.

3.3.1 UV$_{254}$ Monitors

The UV$_{254}$ monitors were used to sample water at two locations within each treatment train. The first water sample location was on the raw water and the second on the filter effluent water. The flow rate of the UV$_{254}$ instruments was maintained at

approximately 500 mL/ min, which was within the recommended range of 300 to 1000 mL/ min as set by both manufacturers. The monitors were set to dual mode, switching every 15 minutes from sampling raw water to filter effluent water. The monitors required 10 seconds to record a measurement, however measurements were only logged every minute onto the datalogger.

3.3.2 Streaming Current Monitors

The SCMs were placed after rapid mixing to capture a representative value of the net charge of the particles within the water and coagulant. The flow rate was maintained at 5.0 GPM, which was the recommended flowrate for the monitors as set by the manufacturers. The SCM had a quick response time of one second, however measurements were only logged every minute.

3.4 Analytical Methods

All laboratory analyses were completed in the Clean Water Laboratory at Dalhousie University following procedures outlined in Standard Methods for the Examination of Water and Wastewater (APHA, 2012).

pH was measured using a Fisher Scientific Accumet XL50 meter and Fisher Scientific AccuFlow electrodes. The meter was first calibrated using pH 4, 7 and 10 buffers. Turbidity was measured using a HACH 2100 turbidimeter.

Samples for TOC and DOC were collected in a 40 mL headspace free glass vial and acidified to pH 2 using 85 % phosphoric acid prior to being analyzed on a Shimadzu TOC-V CSH TOC Analyzer which has a detection limit of 0.08 mg/L. DOC samples were first filtered through 0.45 µm filter paper that had been pre-rinsed with 500 mL of deionized

water obtained from a Milli-Q purification system. UV_{254} and true colour were measured on a HACH DR 5000 spectrophotometer. Both of these samples were also filtered through pre-rinsed 0.45 μm filter paper prior to measurement.

To compare DBP formation potential (DBPFP) between each stage of treatment, the uniform formation conditions (UFC) test was employed. The UFC test holds pH (8.0 ± 0.2), temperature (20.0 ± 1.0 ºC), incubation time (24 ± 1 h) and chlorine residual (1.0 ± 0.4 mg/L as free chlorine) under constant conditions to allow for direct comparison of each stage of treatment under similar conditions.

In addition to the parameters measured during the plant audit, total and dissolved aluminum as well as zeta potential were also measured for the bench-scale optimization of pre-treatment experiments. Samples for total and dissolved aluminum were collected and acidified using concentrated nitric acid prior to being analyzed on a Thermo Scientific X-Series ICP-MS which has a detection limit of 0.004 mg/L. Dissolved aluminum was first filtered through 0.2 μm filter paper. Zeta potential was measured using the Malvern Zetasizer.

3.5 Data Analysis

Error bars appearing on graphs represent one standard deviation from the mean from two separate jar test experiments. Paired t-tests (α = 5 %) were performed to determine statistical significance. All statistical analysis was completed using Minitab 17 software (Minitab Inc.). Regression analysis was completed using Microsoft Excel and Minitab 17.

Chapter 4: Bench-Scale Coagulation Optimization Study

4.1 Introduction

Prior to the installation of the instrumentation, the Stellarton WTP (SWTP) was audited to determine current coagulation process operations under normal source water quality conditions. The plant audit conducted involved collection of samples for analysis and operating data to determine turbidity and NOM removal capabilities and efficiencies. Emphasis was placed on determining what coagulation pH targets existed and approaches to maintain a constant pH during coagulation.

4.2 Materials and Methods

4.2.1 Plant Audit Data Collection

Water samples were collected prior to each stage of treatment including raw water, clarifier effluent, sand filter filtrate, membrane permeate and plant effluent. Each sample was analyzed for pH, turbidity, TOC, DOC, UV_{254}, true colour, THMFP and HAAFP. The audit also consisted of a plant tour and an interview with the plant's head operator discussing current plant operations.

4.2.2 Bench-Scale Jar Test Experiments

Bench-scale experiments were completed for SWTP to evaluate turbidity and NOM removal capabilities of three different coagulants at varying pH. Due to the results from the audit phase for the SWTP, it was determined that such experiments were required to improve current coagulation conditions at the plant. Furthermore, the source water for the SWTP was low in alkalinity and highly variable in terms of turbidity and NOM, which is representative of all source waters involved in the study, and results from the bench-scale work could be applied to other WTPs with similar source water. The purpose of the

experiments was to determine the impact of coagulant type, dose and varied pH on coagulation performance. Specifically, two polyaluminum chloride (PACl) coagulants were examined as well as aluminum sulphate (alum), which has been used by the SWTP in the past. A medium basicity (MB) PACl, and a high basicity (HB) PACl, supplied by Kemira Water Solutions Canada, Ltd., were used in the bench-scale study. Medium and high basicity products minimize pH fluctuation during treatment and have been shown to perform well in cold-water applications. Each coagulant was evaluated at 10, 35, and 60 mg/L doses, representing a low, medium and high dose. Additionally, pH was adjusted to the corresponding pH of minimum solubility for each coagulant, as outlined in Table 4.1, using caustic or soda ash.

Table 4.1: pH of minimum solubility at 20°C for the selected coagulants

Coagulant	20 °C
MB PACl (PAX XL6)	6.2
HB PACl (PAX XL1900)	6.7
Alum	6.0

A third trial was run without pH adjustment to simulate how reactions would occur without maintaining optimal pH. All experiments were run in duplicate.

To run the experiment, a sedimentation jar test experiment was employed using a jar test apparatus (Phipps & Bird, Fischer Scientific). A review of published literature showed that there is currently no lab-scale jar test procedure designed to simulate up-flow clarification. However, conducting standard jar test experiments provides fundamental information on floc formation and settling performance under different test conditions. Rapid mix (300 rpm) was run for one minute followed by two-stage flocculation (40 and 20 rpm, respectively) for ten minutes each. Finally, a settling period of one hour was

allowed before collection of sample for analysis. A small sample (~15 mL) was collected following rapid mix to measure zeta potential.

4.2.3 Analytical Methods

All analytical methods used in this chapter for plant audits and bench-scale experiments are outlined in Section 3.4 in Chapter 3: Materials and Methods.

4.3 Stellarton Water Treatment Plant Audit

An audit of the SWTP was conducted on April 25th, 2013. The plant is equipped to dose with alum and pH adjust with caustic (NaOH) at the influent of the plant. However, at the time of the audit, no chemicals were being added for treatment prior to filtration. Initial inabilities to maintain a stable pH of minimum solubility during coagulation allowed dissolved alum to pass through the treatment train and led to an increased amount of membrane fouling, ultimately forcing operators to remove coagulant addition.

For the audit, water samples were collected prior to each stage of treatment at the SWTP including raw water, clarifier effluent and sand filter filtrate. Figure 4.1 shows the turbidity measurements at each stage of treatment in the SWTP.
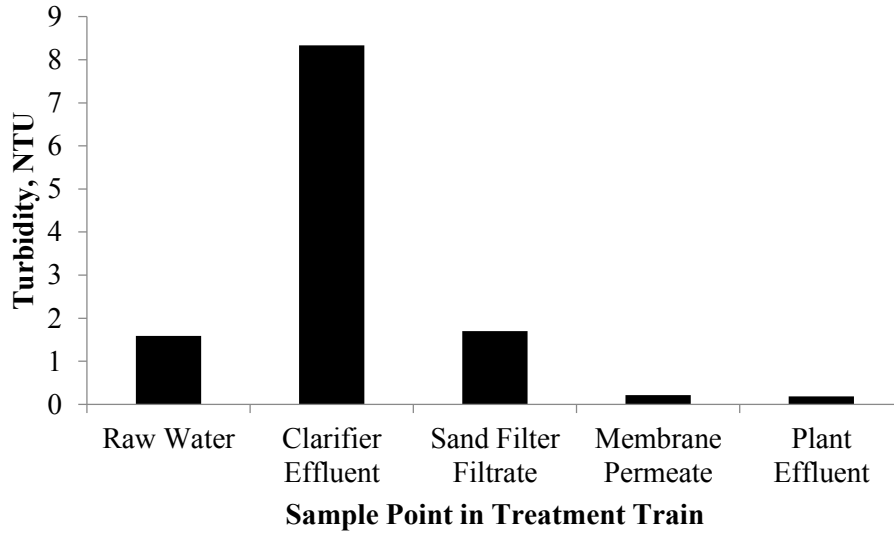
Figure 4.1: Profile of SWTP turbidity (April 25th, 2013)

On the day of the WTP audit, the source water turbidity was low. However, a sharp spike in turbidity was observed in the clarifier effluent. Turbidity was shown to be reduced following both sand and UF filtration. At the time of sampling, there were no coagulation or pH adjustment chemicals in use at the plant, and therefore it is assumed that the clarifier was not operating at optimum performance. The spike in turbidity may also have been caused by the method of sample collection and an inadequate purge time to drain the sample line from sludge build up. Having higher levels of turbidity passing through this stage of treatment can lead to shorter filter run times. Although turbidity was shown to be to be removed via sand and UF filtration, without the aid of chemical addition and clarification, decreased filter run times may be seen.

Raw water TOC and DOC measurements for the water collected during the audit were 3.3 and 3.1 mg/L, respectively. This demonstrates that NOM was primarily in the dissolved form. This is a typical characteristic for surface water in Atlantic Canada. Figure 4.2 shows the removal of TOC and DOC at each stage of treatment of the SWTP.
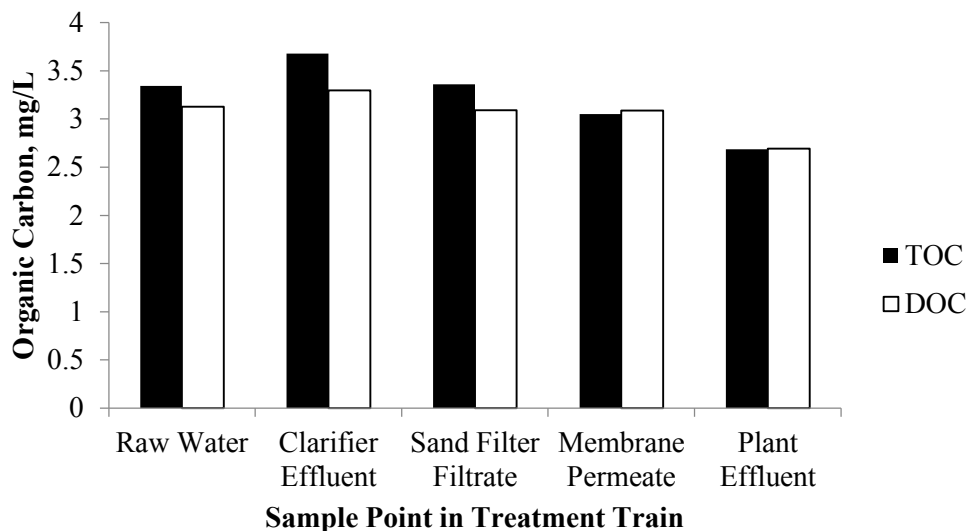
Figure 4.2: Profile of SWTP TOC and DOC concentrations (April 25th, 2013)

From the data collected during the plant audit, it can be seen that limited removal of NOM was achieved during each stage of treatment. Less than 20 % of TOC and DOC were removed during treatment. The small decrease in TOC and DOC observed after chlorination is likely indicative of oxidation reactions occurring with NOM and chorine. Inability to remove organic matter during treatment can lead to formation of DBPs during the disinfection stage of treatment. The *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) recommend a maximum acceptable concentration (MAC) of 100 and 80 μg/L for THMs and HAAs, respectively.

UV_{254} has been shown to be an excellent surrogate for TOC and gives a representative value of the fraction of organics that will react with chlorine to form DBPs. Figure 4.3 shows the reduction of UV_{254} at each stage of treatment at the SWTP.
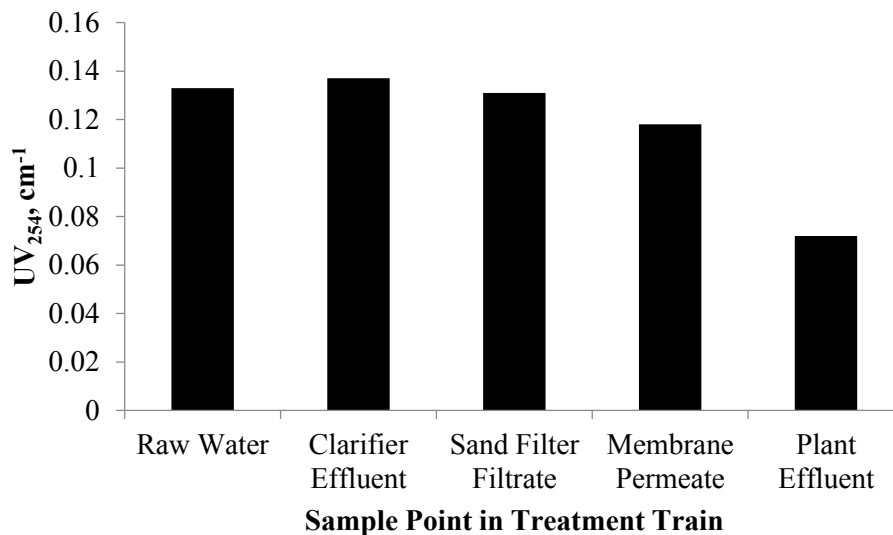
Figure 4.3: Profile of SWTP UV_{254} (April 25th, 2013)

From the data collected, it can be seen that, similar to TOC and DOC, UV_{254} was not reduced during any stage of treatment. A small decrease is shown after chlorination, again indicating oxidation of aromatic organic compounds has occurred. Overall, the results showed that TOC, DOC and UV_{254} were not reduced at full-scale without coagulation addition.

To evaluate DBPFP between each stage of treatment at the SWTP, the UFC testing was employed. Results from the tests are shown in Figure 4.4.
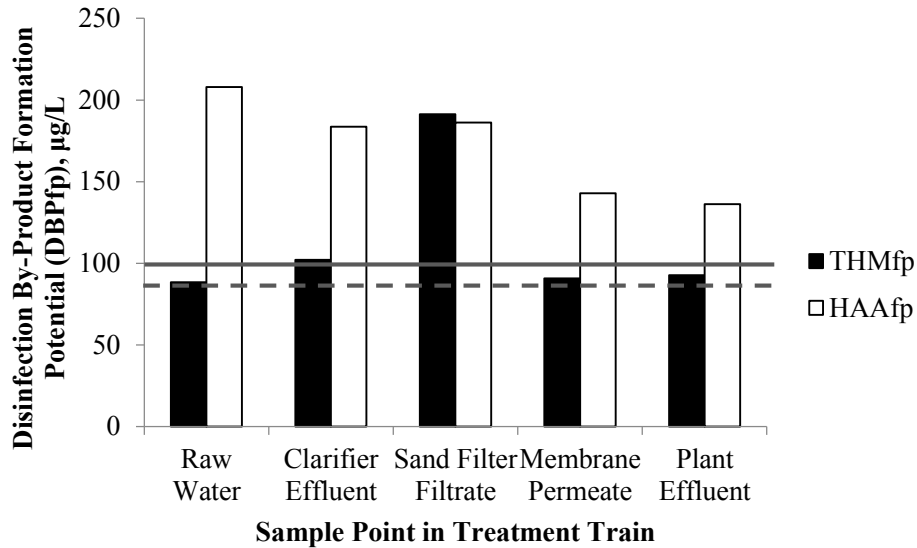
Figure 4.4: Profile of SWTP DBPFP (April 25th, 2013)

Results from UFC testing showed that DBPFP at each stage of treatment was not reduced from raw water concentrations. The solid grey line represents the MAC guideline for THMs (100 µg/L) and the dashed grey line represents the MAC guideline for HAAs (80 µg/L) in treated water. Although the UFC test results for DBPFP cannot be directly compared to the set guidelines, the results show that levels are not being reduced at any stage of treatment at the plant. THMFP and HAAFP concentrations formed under the UFC test can be an overestimate of actual concentrations formed during treatment due to the elevated chlorine dosage and extended contact time. Ultimately, the test is indicative that the fraction of NOM responsible for DBP formation was not being removed with treatment practices at the SWTP at the time of the plant audit.

pH control is essential for achieving optimal coagulation conditions and treatment performance. During the time of analysis, the SWTP was not adding coagulant. Raw water pH was measured to be 6.8 as shown in Figure 4.5.
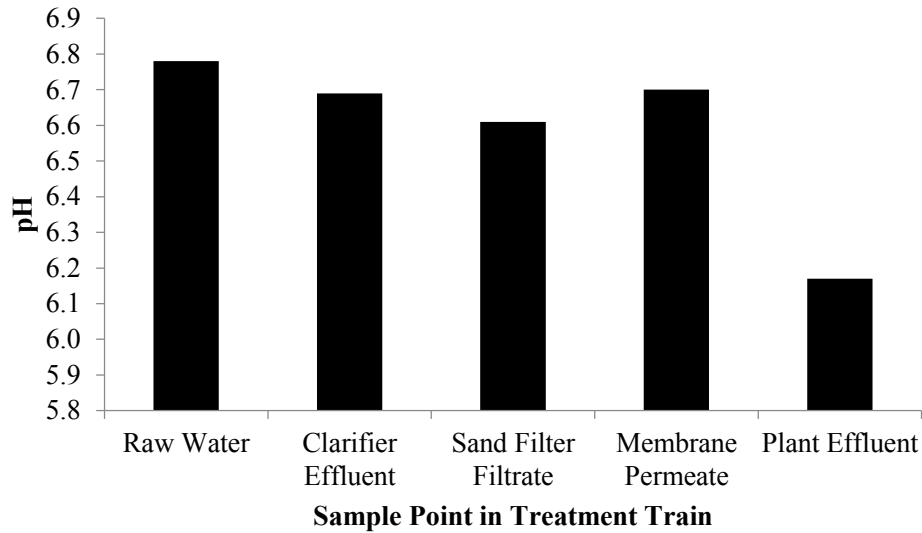
Figure 4.5: Profile of SWTP pH (April 25th, 2013)

If alum were added, achieving a pH of 6.0 at 20 ºC or 6.2 at 5 ºC would result in minimum solubility of the chemical and reduce dissolved aluminum concentrations in the treated water.

4.4 Bench-Scale Treatability Study

Jar test experiments were conducted to evaluate three coagulants (MBPACl, HBPACl and alum) to determine the impact of variable dose on treatment performance with respect to turbidity and NOM removal. Two pH targets were also evaluated during this set of experiments to examine the impact of NOM removal with coagulation run at the pH of minimum solubility and at natural pH. This testing was conducted on samples collected from the SWTP source water on June 8th, 2013. From the three coagulant dosages evaluated in the jar testing, specifically 10, 35 and 60 mg /L, an optimal dose was chosen for each coagulant based on turbidity, DOC and UV$_{254}$ removal as well as zeta potential. The results for each coagulant are outlined below.

4.4.1 Coagulant Dose Experiments

Medium Basicity PACl (MBPACl)

Figure 4.6 outlines turbidity removal at 10, 35 and 60 mg/L of the MBPACl coagulant with pH adjustment to 6.2 using caustic and soda ash as well as a trial with no pH adjustment (i.e., natural pH).
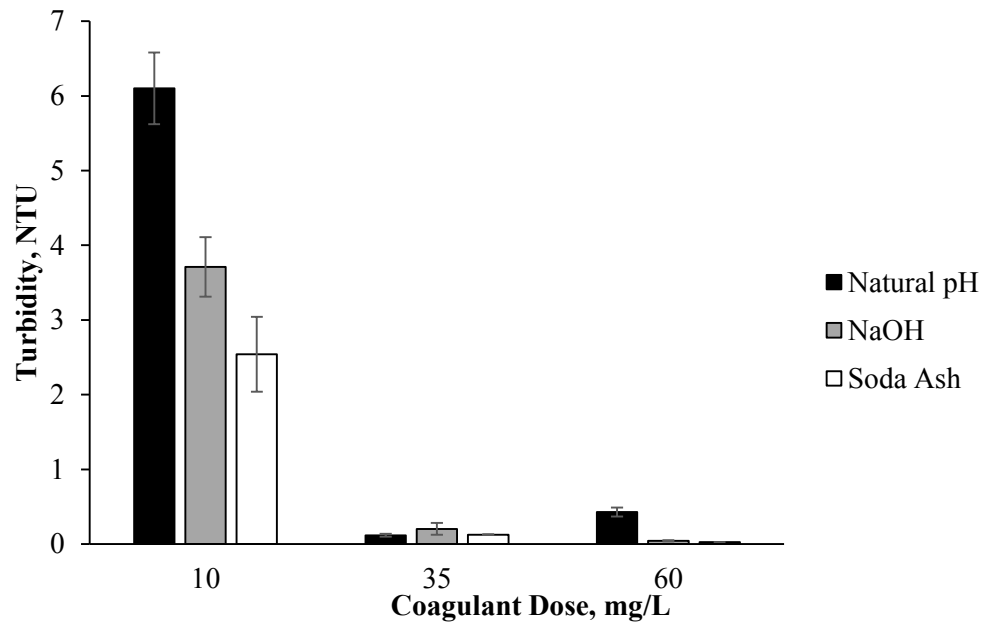
Figure 4.6: Turbidity removal with MBPACl

Turbidity of the raw water was 10.7 NTU. From Figure 4.6, it can be seen that the addition of the MBPACl significantly reduced the turbidity at 35 and 60 mg/L both with and without pH adjusting. DOC removal using the MBPACl is shown in Figure 4.7.
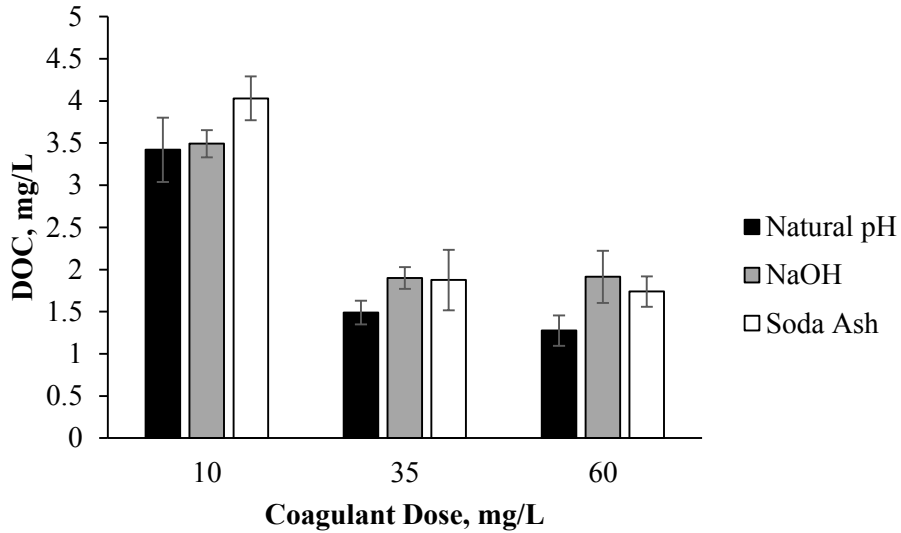
Figure 4.7: DOC removal with MBPACl

The initial DOC concentration of the raw water was 4.2 mg/L. Following a similar trend as turbidity, DOC was also significantly reduced at the higher coagulant doses as shown in Figure 4.7. The data showed that there was not a significant difference between the 35 and the 60 mg/L coagulant doses in terms of DOC removal, indicating that for this test, the point of diminishing returns is at the 35 mg/L dose. UV_{254} removal is shown in Figure 4.8.
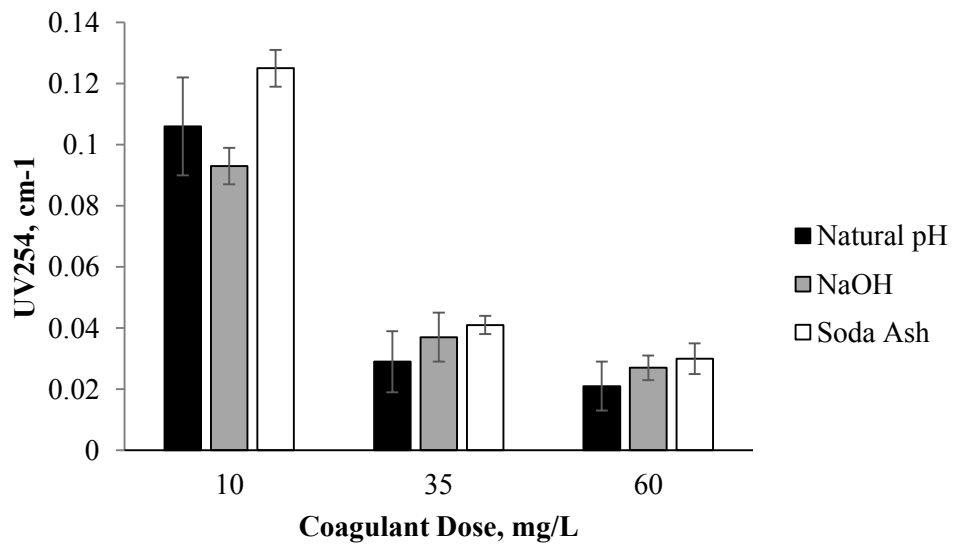
Figure 4.8: UV_{254} removal with MBPACl

The initial raw water UV_{254} was 0.184 cm^{-1}. UV_{254} was also shown to be significantly reduced upon the addition of 35 and 60 mg/L of coagulant, as shown in Figure 4.8. For both the 35 and 60 mg/L tests, the greatest reduction in UV_{254} was shown without pH adjustment. The natural pH for both of these tests was 4.9 and 4.1, respectively. Though a slightly greater UV_{254} removal was observed without pH control of the water during coagulation, these tests showed the highest dissolved aluminum concentrations in the settled water at 300 and 7,500 µg/L. pH adjustment to a target of 6.2 during coagulation with the addition of caustic and soda ash resulted in total dissolved aluminum concentrations in the settled water of 100 µg/L for both 35 and 60 mg/L coagulant dose.

Other studies have shown that optimal coagulation conditions are achieved at a zeta potential between -10 and -5 mV (Black & Willems, 1961; Bean *et al.*; 1964 Tseng *et al.*, 2000). This is, however, dependent upon maintaining a consistent pH. Variations in pH can alter the magnitude of the electrostatic repulsions of the organics within a water sample. As pH increases or decreases, these repulsions can become greater or weaker, thus changing the magnitude and alter the zeta potential. Because shifts in pH can alter the surface chemistry, pH should be held constant when using a jar test to determine optimal dose. For that reason, zeta potential, or any charge analysis (e.g. streaming current), cannot be considered as a defining parameter for identifying optimal performance under natural pH conditions. Figure 4.9 outlines zeta potential for the MBPACl.
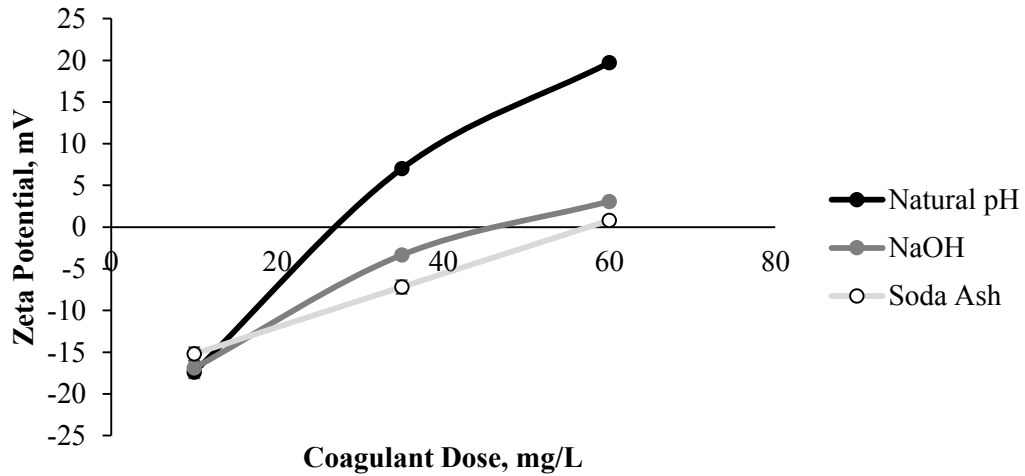
Figure 4.9: Zeta potential for MBPACl

From Figure 4.9, it is evident that the dose that achieved the best removal for the MBPACl is 35 mg/L for both pH adjusted tests (caustic and soda ash). For the source water collected during the plant audit, the optimal dose for the MBPACl product was found to be 35 mg/L. This was based on turbidity, UV_{254}, DOC, zeta potential and aluminum concentrations.

High Basicity PACl (HBPACl)

Figure 4.10 outlines the turbidity removal at 10, 35 and 60 mg/L of the HBPACl coagulant with pH adjustment to 6.7 using caustic and soda ash as well as a trial with no pH adjustment (i.e. natural pH).

Figure 4.10: Turbidity removal with HBPACl

Initial raw water turbidity was 10.7 NTU. Under natural pH conditions, turbidity remains high, especially when compared to both caustic and soda ash trials for the 35 and 60 mg/L trials. Reductions in turbidity are shown at each dose, when pH adjusted with caustic. Soda ash shows a similar trend, aside from a slight increase at the 35 mg/L dose. Reductions of NOM at these dosages will be considered in the form of DOC and UV_{254} reductions. Like turbidity, reductions in DOC at higher doses using the HBPACl were also noticed, as shown in Figure 4.11.
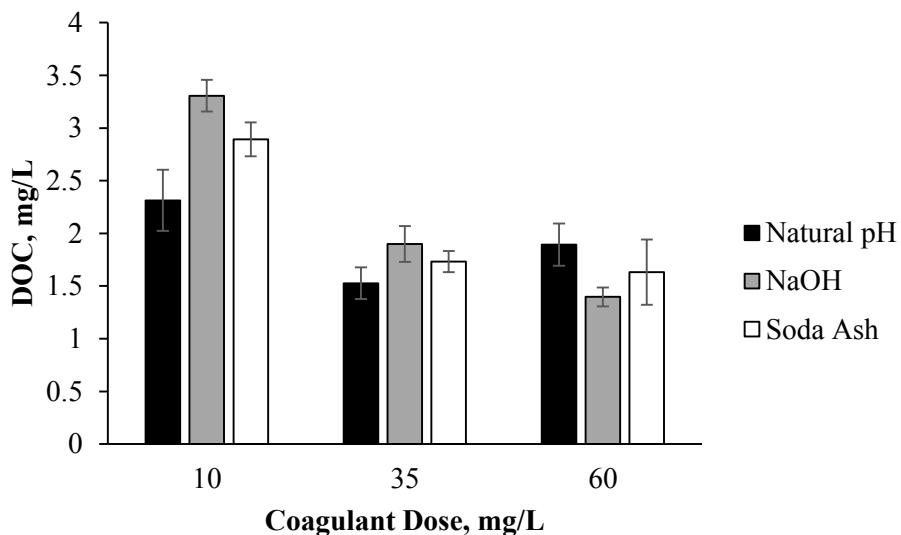
Figure 4.11: DOC removal with HBPACl

The raw water DOC concentration was 4.2 mg/L. Reductions in DOC are shown at each dose when pH adjusted with caustic. Similarly, DOC is also reduced with soda ash. The greatest removal of DOC was found at the 35 and 60 mg/L coagulant doses. A similar trend is shown with UV_{254} in Figure 4.12.
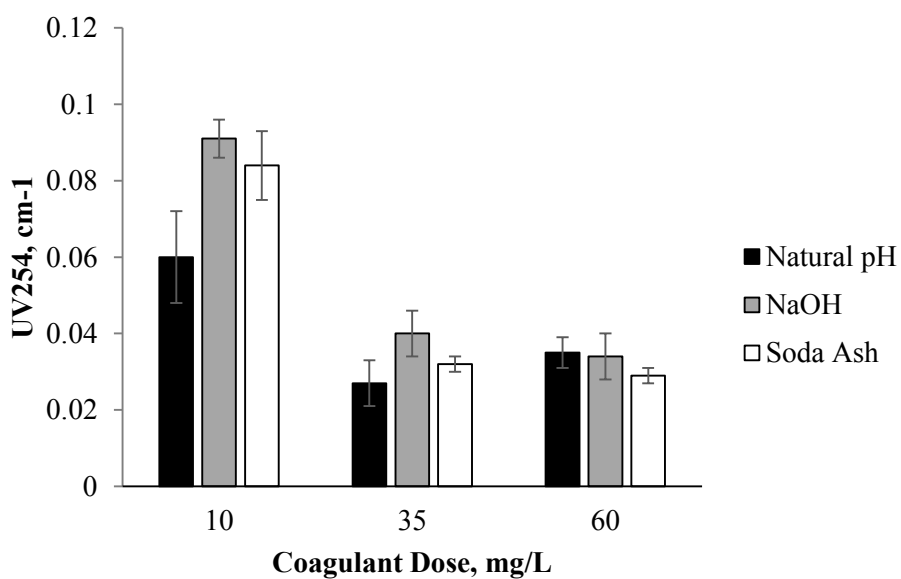
Figure 4.12: UV_{254} removal with HBPACl

Raw water UV_{254} was 0.184 cm^{-1}. Reductions between 75 and 85 % are shown for both the 35 and 60 mg/L dose. Although high reductions at these doses are also found under natural pH conditions, higher aluminum concentrations in the finished water greater than 5000 µg/L are found. Figure 4.13 represents the zeta potential for the HBPACl coagulant.
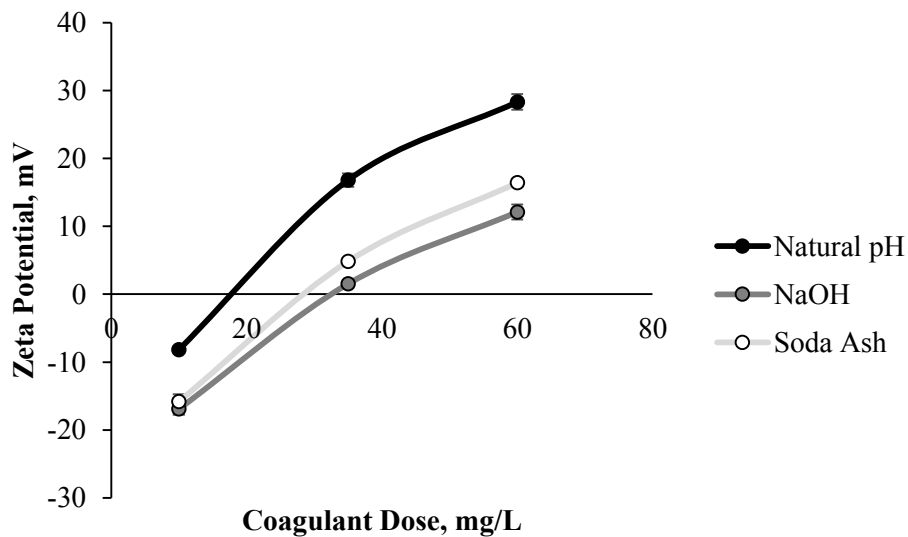
Figure 4.13: Zeta potential for HBPACl

Optimal zeta potential generally falls within the -10 to -5 mV range for turbidity and colour removal. From the graph, it can be seen that for the water collected during the plant audit, the optimal dose for the HBPACl falls at 35 mg/L or slightly below. When considering turbidity, UV_{254}, DOC, zeta potential and aluminum concentrations, the dose that achieved the best removal for the HBPACl product is 35 mg/L or slightly lower. Under natural pH conditions, turbidity was not greatly reduced with this coagulant.

Alum

Figure 4.14 outlines the turbidity removal using alum at 10, 35 and 60 mg/L of alum with pH adjustment to 6.0 using caustic and soda ash as well as a trial with no pH adjustment.
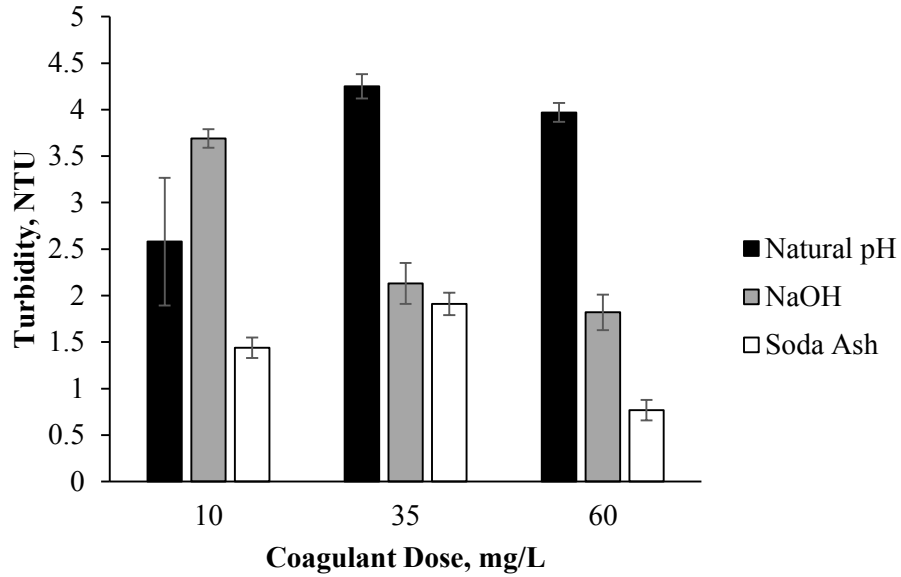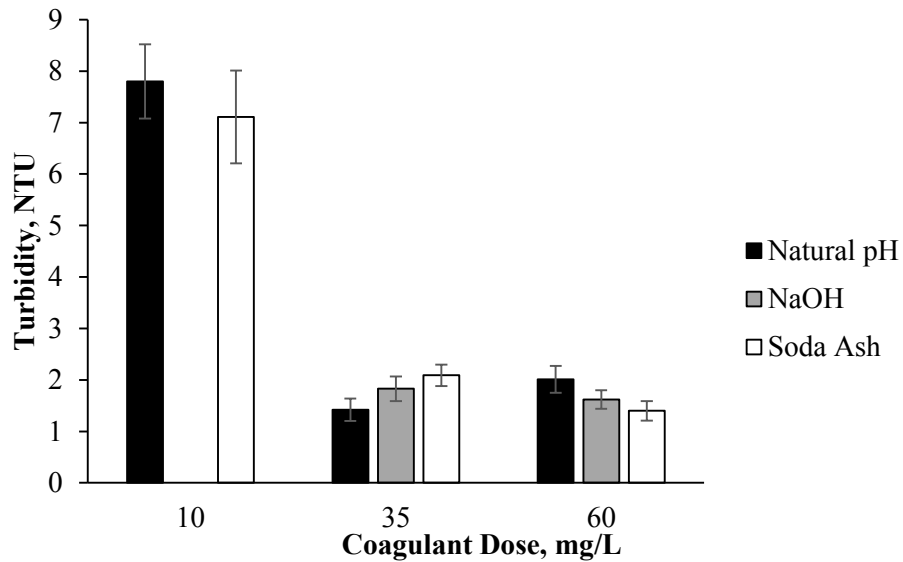

Figure 4.14: Turbidity removal with alum

The raw water turbidity was 10.7 NTU. Similar to the two PACl products, the highest reduction in raw water turbidity using alum is shown at 35 and 60 mg/L doses. At these doses, turbidity reductions between 78 and 85 % were shown for all pH trials. Reductions in DOC and UV_{254} follow a similar trend to turbidity, as shown in Figures 4.15 and 4.16.
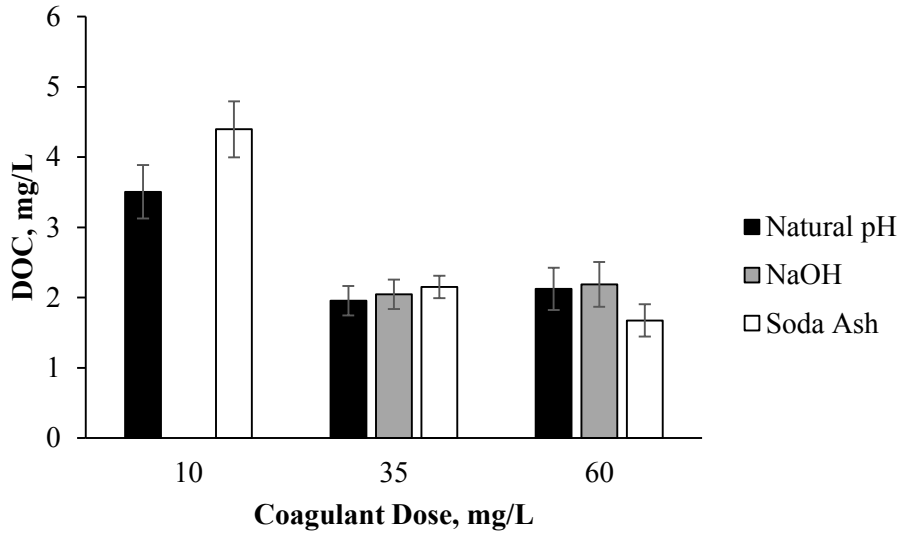
Figure 4.15: DOC removal with alum
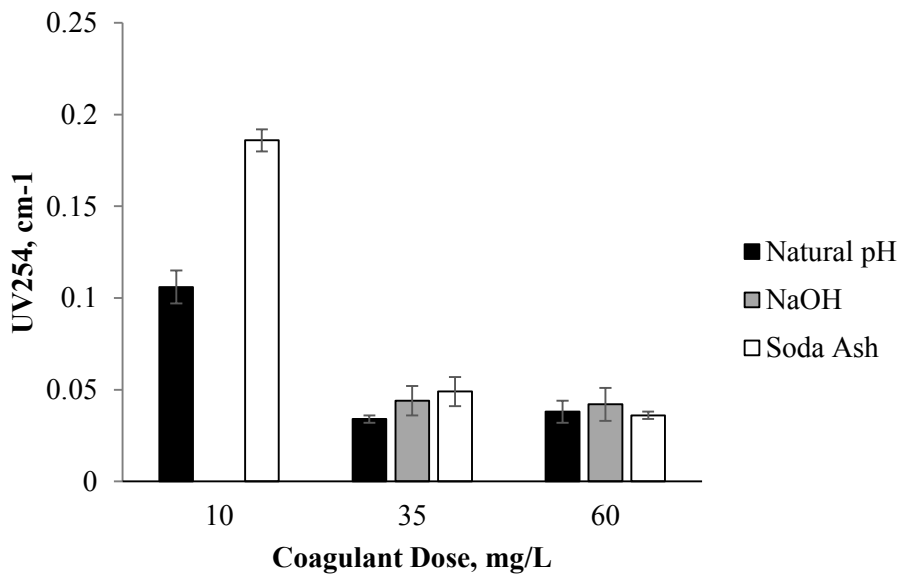
Figure 4.16: UV_{254} removal with alum

Raw water DOC was 4.2 mg/L and UV_{254} was 0.184 cm^{-1}. Both DOC and UV_{254} were reduced at both 35 and 60 mg/L of alum. There was approximately a 50 % reduction in DOC at these doses with high reductions in UV_{254} (79.6 to 86.1 %) also shown at the higher doses for all pH trials. However, the difference in aluminum concentrations in the

treated water between natural pH conditions and pH adjusted trials with either caustic or soda ash was shown to be ten-fold. Zeta potential for these tests is shown in Figure 4.17.
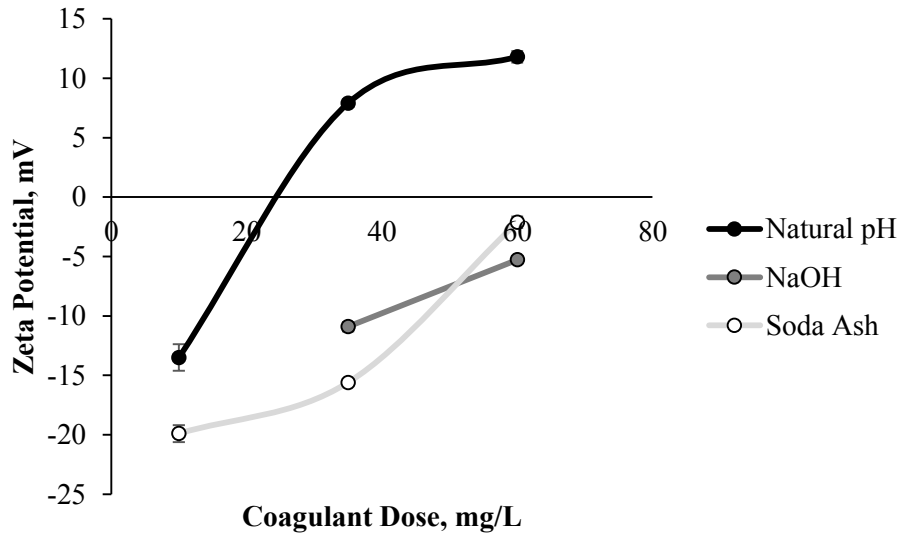
Figure 4.17: Zeta potential for alum

Zeta potential results indicate that similar to the MB and HBPACl coagulants, for the source water collected during the plant audit, the dose of alum that achieved the best removal was found to be 35 mg/L. Overall, based on turbidity, UV_{254}, DOC, zeta potential and aluminum concentrations, the best dose for the jar test using alum, was 35 mg/L.

4.4.2   Comparison of Coagulants at a Constant Dose

For the source water collected during the plant audit, the dose for alum and both the MB and HBPACl that achieved that best removal rates was determined to be 35 mg/L. To compare the three coagulants, turbidity, DOC and UV_{254} reductions found at 35 mg/L for each product were examined. For each coagulant, data from the trials with pH adjustments using caustic and soda ash are shown as well as the trial with no pH adjustment. Figure 4.18 outlines the turbidity removal for each of the coagulants used the three pH conditions.
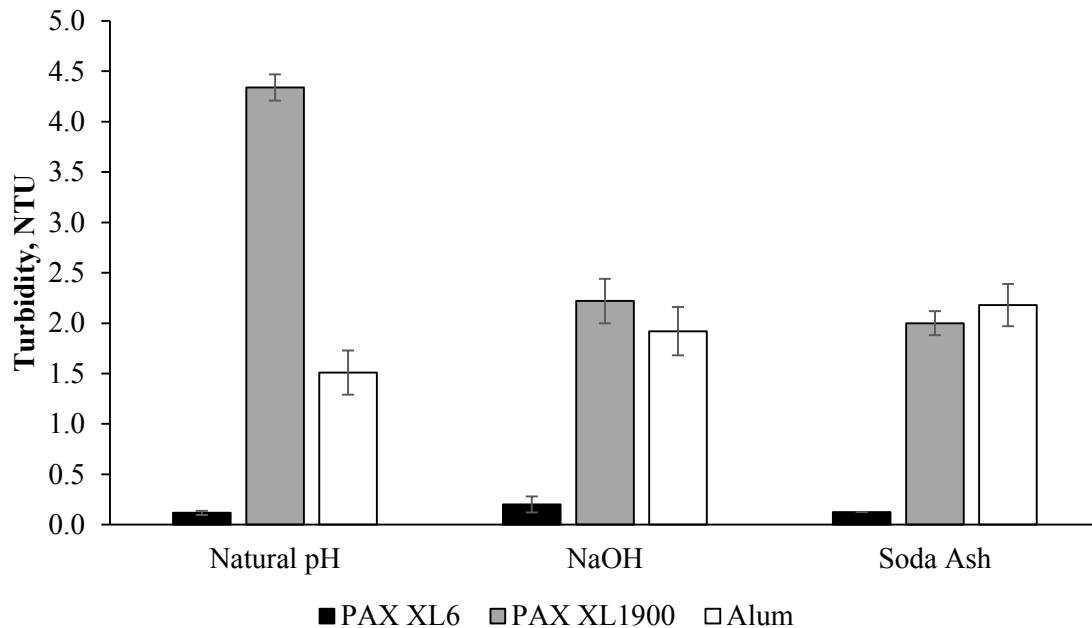
Figure 4.18: Turbidity at 35 mg/L for all three coagulants

From the graph, the MBPACl coagulant showed the greatest turbidity removal capabilities. The initial turbidity of the raw water was 10.7 NTU. Under optimal coagulant dose (approximately 35 mg/L for all three coagulants), the MBPACl coagulant achieved substantially higher removal of turbidity for both caustic and soda ash trials, 98.1 and 98.8 %, respectively, compared to the HBPACl product (79.3 and 81.3 %) and alum (82.1 and 79.6 %). At the 35 mg/L dose, there was however, not as an observable difference in DOC removal between the three coagulants. This is shown in Figure 4.19.
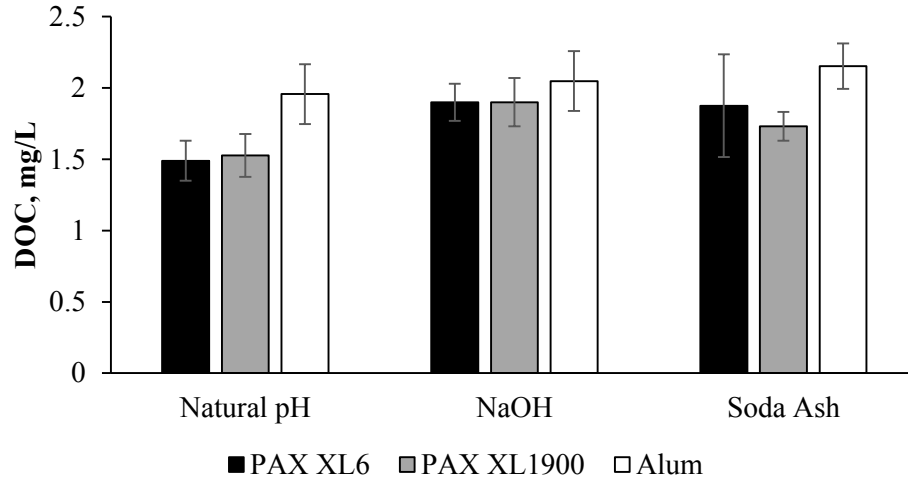
Figure 4.19: DOC at 35 mg/L for all three coagulants

The initial raw water level was 4.2 mg/L. All three coagulants showed a reduction in organics with each trial resulting in a 50 to 60 % reduction in DOC. For the caustic and soda ash trials where pH of minimum solubility was maintained at 6.2 and 6.7 for the MB and HBPACl, respectively, both PACl coagulants showed slightly better removal over alum. The PACl coagulants showed slightly better removal of UV_{254} as well, as shown in Figure 4.20.
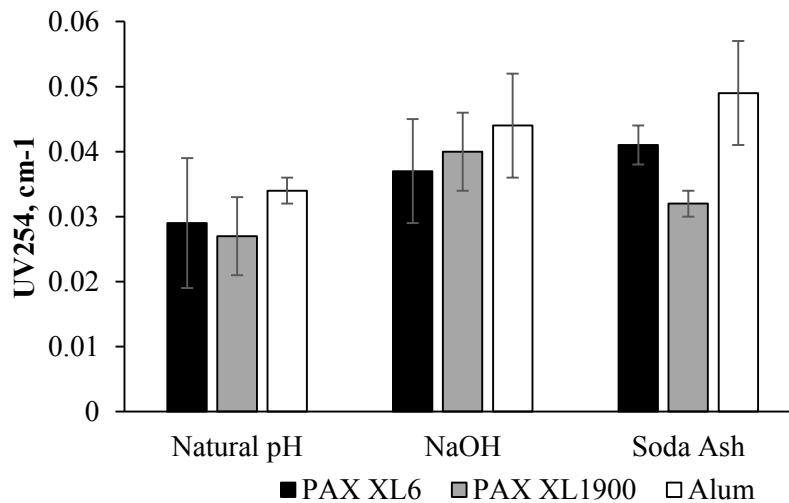
Figure 4.20: UV_{254} at 35 mg/L for all three coagulants

Figure 4.20 shows the UV$_{254}$ for each coagulant at a dose of 35 mg/L under the different pH conditions. Although the trial in which pH was not adjusted showed the lowest UV$_{254}$ for each of the three coagulants, the resulting concentrations in the treated water were approximately 3 to 4 times higher than that of the pH adjusted trials. There was little discernable difference in UV$_{254}$ removal for all three coagulants for the two trials that were pH adjusted (caustic and soda ash). This shows that all three coagulants are capable of removing this fraction of organics. For the trial adjusted with caustic, the MBPACl product achieved a slightly lower UV$_{254}$ value whereas the HBPACl product achieved a slightly lower value for the soda ash trial. In comparison to the full-scale analysis, where UV$_{254}$ remained at approximately 0.130 cm^{-1} throughout each stage of treatment, the addition of a coagulant in bench-sale trials showed reduction in such numbers, bringing the average of the two pH adjusted trials within the range of 0.030 to 0.040 cm^{-1}, which leads to a reduction between 65 and 75 %. Reduction to this level would result in a reduction of DBPs formed in the finished water. When comparing colour, the caustic trials showed slightly better removal over soda ash, as shown in Figure 4.21.
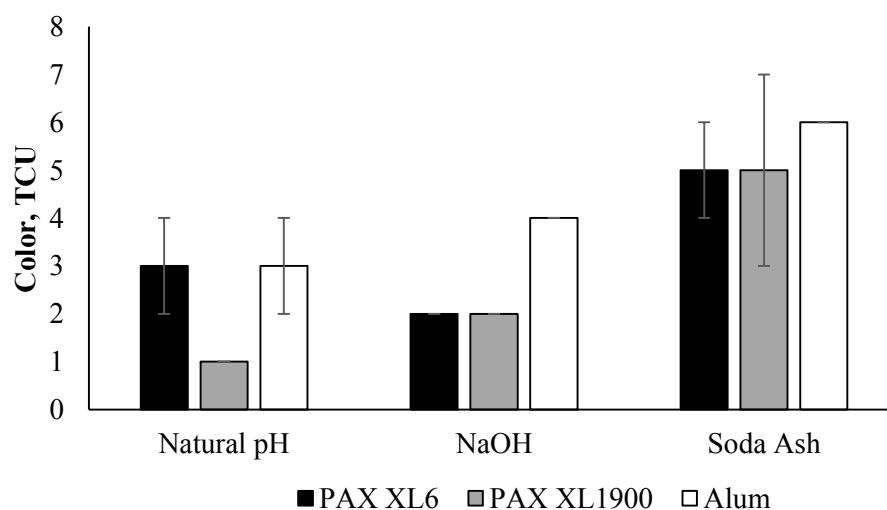
Figure 4.21: Colour at 35 mg/L for all three coagulants

Initial raw water colour for was 25 TCU. All three coagulants were shown to reduce the colour. The caustic trial showed slightly better removal over the soda ash trial for all three coagulants, especially the two PACl products, with 92 % removal shown with caustic and 80 % removal with soda ash.

For the pH adjusted trials, the pH of minimum solubility was maintained at 6.2, 6.7 and 6.0 ± 0.2 for the MBPACl, HBPACl and alum, respectively. For the natural pH trial, aluminum concentrations in the finished water were 3 to 4 times that of the pH adjusted trials. This is shown in Figures 4.22.
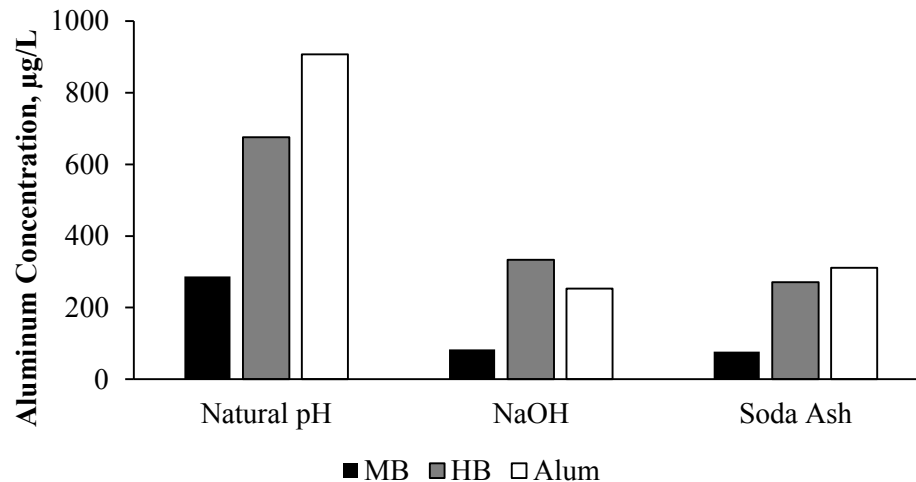
Figure 4.22: Aluminum concentrations in the treated water at 35 mg/L for all three coagulants

The MBPACl product produced lower aluminum concentrations for the caustic trial and soda ash trials. The operational guidance (OG) value for aluminum, as shown by the grey line, is < 0.1 mg/L as set by the *Guidelines for Canadian Drinking Water Quality* (Health Canada 2012). The MBPACl coagulant met these guidelines for both pH adjusted trials. Maintaining the pH of minimum solubility throughout treatment results in decreased aluminium concentrations in the treated water.

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Bench-scale tests showed that when comparing optimal dose of MBPACl, HBPACl and alum, both PACl coagulants showed higher NOM removal over alum in terms of DOC, UV_{254} and true colour. Of the two PACl products, the MBPACl also showed high turbidity removal (~98 % removal) and low aluminum concentrations in the treated water (< 0.1 µg/L). Caustic and soda ash trials for the MBPACl showed similar results for turbidity, DOC, UV_{254} and aluminum concentrations. A slightly higher removal of true colour was found using caustic (80 vs. 92 %). Similar findings were found for the MBPACl using caustic and soda ash at other doses (10 and 60 mg/L).

4.5 Conclusions

A full-scale audit of removal capabilities at each stage of treatment at the SWTP was conducted. Bench-scale experiments were also completed to determine the impact of different coagulants, doses and varied pH on coagulation performance using a surface water source with low alkalinity and variable NOM and turbidity.

Based on both full-scale and bench-scale results collected during the SWTP audit, use of coagulant is necessary for removal of NOM. Without removal of NOM, DBP concentrations will continue to exceed the MAC set by the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012).

Using a jar test apparatus, experiments to determine optimal coagulant dose showed that when pH was adjusted to the pH of minimum solubility, reductions in turbidity and NOM in the form of DOC and UV_{254} were noted with low aluminum concentrations in the finished water. When pH was not adjusted aluminum concentrations in the finished water

were three to four times higher and did not meet the MAC as set by the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012).

Optimal coagulant dose was determined based on the point of diminishing returns for turbidity and NOM removal. The optimal dose for each coagulant was verified using charge analysis, specifically, zeta potential. Although only three doses were trialed, a 10, 35, and 60 mg/L dose, optimal dose for the source water was found to be around 35 mg/L for each coagulant with zeta potentials ranging from -15 to 5 mV. When pH is controlled, the use of charge analysis at bench-scale can be used to determine optimal coagulant dose.

The three plants involved in the study are located in the Atlantic Provinces and have similar source water characteristics. Although the bench-scale were experiments conducted at the SWTP, they results are indicative of coagulant conditions at all plants described in this study. NOM within the water sources has been shown to be primarily in the dissolved phase. Bench-scale experiments have showed the addition of coagulant under pH control, dissolved NOM, represented in the form of DOC and UV_{254}, can be effectively removed. Furthermore, the use of charge analysis can be used to determine optimal dose of such NOM.

Determination of coagulant dose based on removal of dissolved NOM and charge analysis shows promise. Further investigation at full-scale at two other WTPs within the Atlantic Provinces with similar source water characteristics is described in Chapter 5 and Chapter 6. For this study, online instrumentation, including a SCM and UV_{254} monitor, are set up for a duration of three to four months at each plant.

Chapter 5: Preliminary Assessment of Online SCM and UV$_{254}$ Monitors

An audit of the Falmouth WTP was conducted to determine coagulation process operations under normal source water quality conditions. The FWTP is a conventional filtration plant that uses a BCA conventional upflow tube settler clarifier. The plant is equipped to dose with PACl (SternPAC) and pH adjust with soda ash at the influent into the plant. During the operation of the plant, the plant goes offline several times on a daily basis. Currently, plant operators do not use jar tests to determine optimal coagulation conditions. The coagulation dose is usually held between 14 and 16 mg/L. During the duration of the study, the coagulation pH was held between 7.5 and 8.5 during normal operating conditions. When the raw water quality begins to change, the coagulant dose is not increased, instead, the coagulation pH is decreased to 6.0.

Installation of the SCM and UV$_{254}$ monitor were set up for a duration of four months to determine the capabilities of the online instrumentation to aid in coagulation processes under rapidly changing raw water quality. Three rain events are highlighted during the instrument setup, however SCM and UV$_{254}$ data for only the first rain event are reported.

5.1 Materials and Methods

5.1.1   Plant Audit Data Collection

Water samples were collected prior to each stage of treatment at the FWTP including raw water, rapid mix, clarifier effluent and sand filter filtrate. Each sample was analyzed for pH, turbidity, TOC, DOC, UV$_{254}$, true colour, THMFP and HAAFP. The audit also consisted of a plant tour and an interview with the plant's head operator discussing current plant operations.

5.1.2 Analytical Methods

All analytical methods used in this chapter for plant audits and bench-scale experiments are outlined in Section 3.2.1 in Chapter 3: Materials and Methods.

5.1.3 Full-Scale

An online SCM (AF7000, RealTech) and UV_{254} monitor (M3000, RealTech) were set up at the FWTP from November, 2013 to February, 2014. Streaming current and UV_{254} measurements on the raw and filter effluent water were logged every minute on an external data logger. Data from the FWTP SCADA system, including raw, filter effluent and clearwell turbidity as well as raw and coagulation pH, was also gathered in 10 minute increments. Coagulant dose was not tracked on the plants SCADA system therefore a dataset was created by compiling dose changes as documented in the operator log books.

5.2 Falmouth Water Treatment Plant Audit

A three day site visit to the FWTP consisted of training the operators on jar test procedures, review of operator logs and plant operations as well as an audit of the treatment train. The audit was conducted on August 5th, 2014. For the audit, water samples were collected prior to each stage of treatment including raw water, rapid mix, clarifier effluent and filter effluent from the plants two filters. Each sample was analyzed for turbidity, TOC, DOC, UV_{254}, pH, THMFP and HAAFP as outlined in Section 3.2. Figure 5.1 shows the turbidity measurements for each stage in treatment.
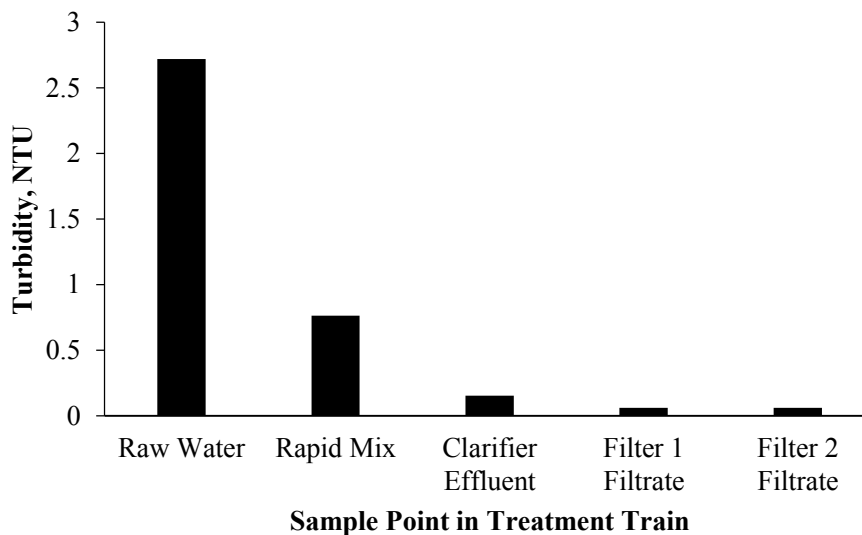
Figure 5.1: Profile of FWTP turbidity removal (August 5th, 2014)

The raw water turbidity for August 5th, 2014 was 2.7 NTU. Turbidity was reduced throughout the treatment train with both filters achieving 0.06 NTU. The *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) require that all treated water have a turbidity of less than 0.1 NTU. During the time of the audit, the FWTP was achieving acceptable filter effluent levels.

Raw water TOC and DOC measurements for the raw water were 2.7 and 2.6 mg/L, respectively. This demonstrates that NOM are primarily in the dissolved form, and is a typical characteristic for surface water in Atlantic Canada. Figure 5.2 shows the removal of TOC and DOC at each stage of treatment of the FWTP.
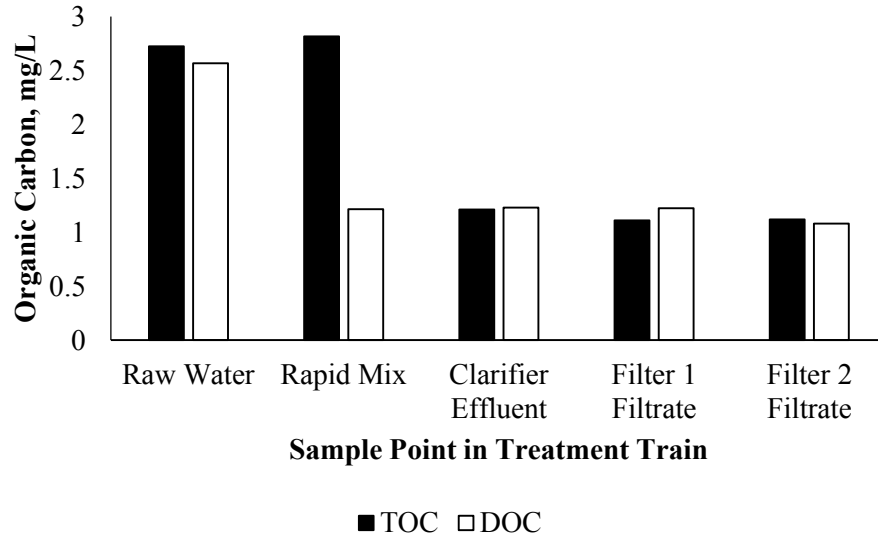
Figure 5.2: Profile of FWTP TOC and DOC removal (August 5th, 2014)

From the graph it can be shown that DOC levels are reduced between 55 and 60 %

throughout treatment. Likewise, UV_{254} was significantly reduced, as shown in Figure 5.3.
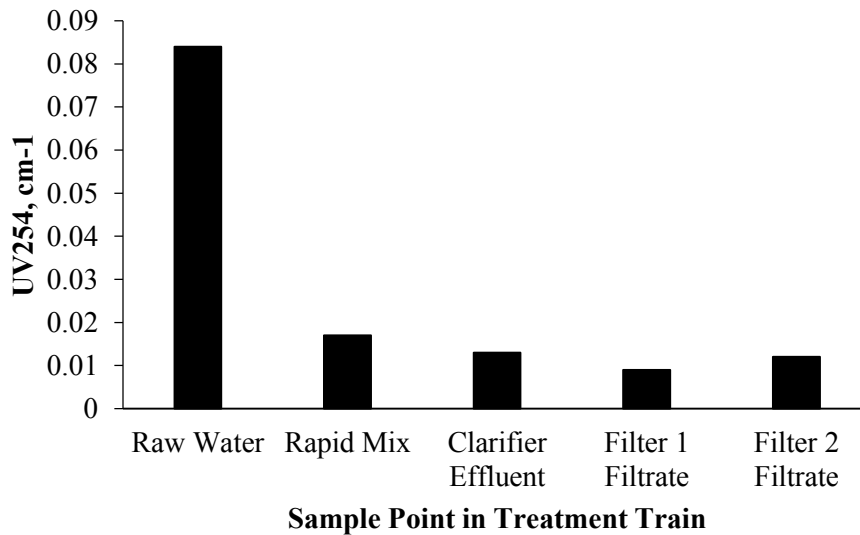
Figure 5.3: Profile of UV_{254} turbidity removal (August 5th, 2014)

Raw water UV_{254} was 0.084 cm^{-1}. This number was significantly reduced after

rapid mixing by 80 %. This reduction was also noticed in DOC, as shown in the previous

graph. Studies have shown that a reduction in raw water UV_{254} can reduce the amount of DBPs in the treated water. To compare disinfection by-product formation potential (DBPfp) between each stage of treatment at the FWTP, the UFC test was employed. Results from the test are shown in Figure 5.4.
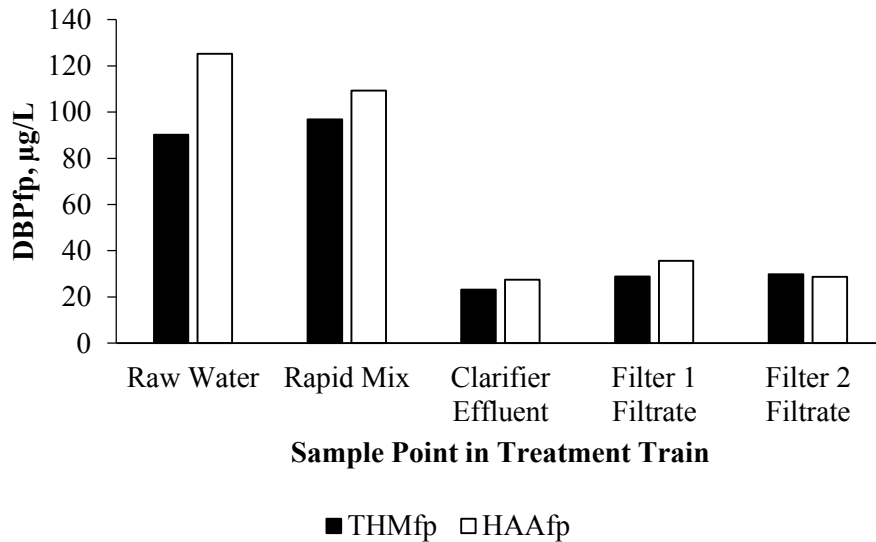
Figure 5.4: Profile of FWTP THMFP and HAAFP (August 5th, 2014)

Results from the UFC test showed that DBPFP was greatly reduced from raw water concentrations. Raw water concentrations were 90.1 and 125.2 µg/L for THMFP and HAAFP, respecively. These concentrations were reduced by approximately 68 and 75 % each. Although the UFC test results for DBPFP cannot be directly compared to the set guidelines, the results show that levels were being reduced at any stage of treatment at the plant. Ultimately, the test is indicative that the fraction of NOM responsible for DBP formation was being removed with current treatment practices on August 5th, 2014.

At the time of the audit, raw water pH was 7.2 and coagulation pH was maintained at 6.5. The coagulant dose was 24 mg/L of PACl. Aluminum concentrations in the finished

water were minimal with an average value of 5.0 µg/L between the two filters. The full-scale audit results showed that when maintaining the pH of minimum solubility during coagulation, NOM can be effectively removed with treatment while also reducing turbidity and aluminum concentrations in treated water. The removal of NOM was shown by reductions in TOC, DOC and UV_{254}. Specifically, TOC and DOC showed 55 to 60 % reductions, whereas UV_{254}, a known precursor for DBP formation, was reduced by 80 %. This was verified by the 68 and 75 % reductions in both THMFP and HAAFP from the raw water.

Although the operators were able to maintain a pH close to the pH of minimum solubility, there appeared to be discrepancies between the full-scale inline pH meter, which values were logged on the SCADA system, and the bench-scale pH meter. Operator logs documenting both these values from May to August, 2014 were reviewed. The discrepancies between the two readings are shown in Figure 5.5.
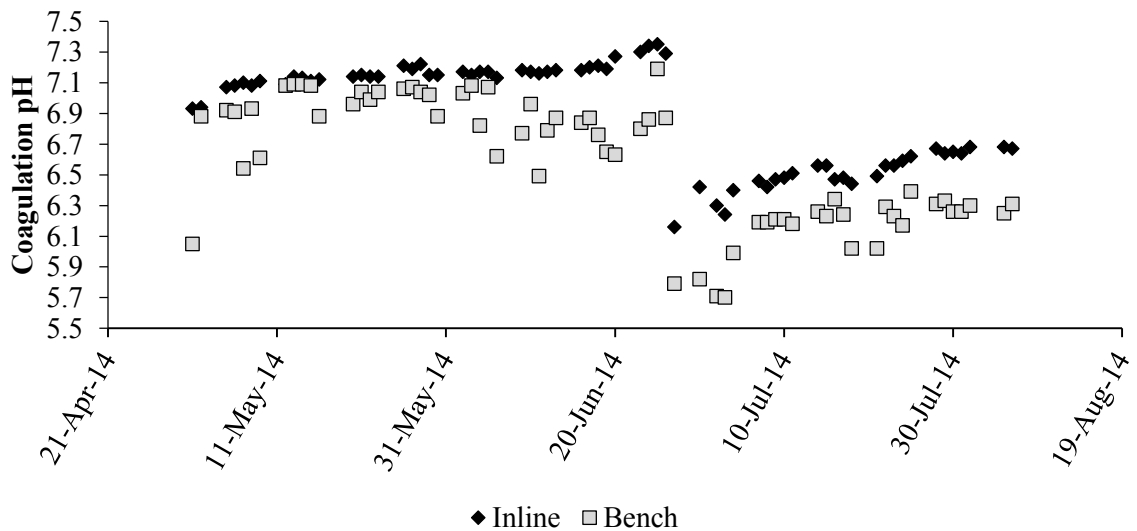
Figure 5.5: Full-scale inline and bench-scale pH measurements at the FWTP from May to August, 2014

From the graph, it can be seen that on June 27th, 2014, the operators reduced the coagulation pH, as read from the bench-scale measurement, from approximately 7.0 down to 6.0. From June 27th to August 4th, this coagulation pH remained between 6.0 and 6.4. The full-scale inline pH measurements during this time were higher and measured between 6.3 and 6.7 during this time frame. A paired t-test at the 95 % CI was run on the data set to determine whether there was a statistically significant difference between the bench- and full-scale pH measurements. The test showed that two measurements were statistically different ($p < 0.05$).

5.3 Online Instrumentation Study

Online instrumentation was set up from November, 2013 to February, 2014. However, due to calibration and maintenance issues, only data from December 1st, 2013 to February 22nd, 2014 were analyzed. Data from the SCADA system at the plant was also analyzed for this time frame. Figure 5.6 shows that the coagulation pH during the study varied between 5.8 and 8.7. However, the recommended pH for the minimum solubility of PACl is 6.2.

Figure 5.6: Coagulation pH and PACl dose for December 1st, 2013 to February 22nd, 2014 at the FWTP

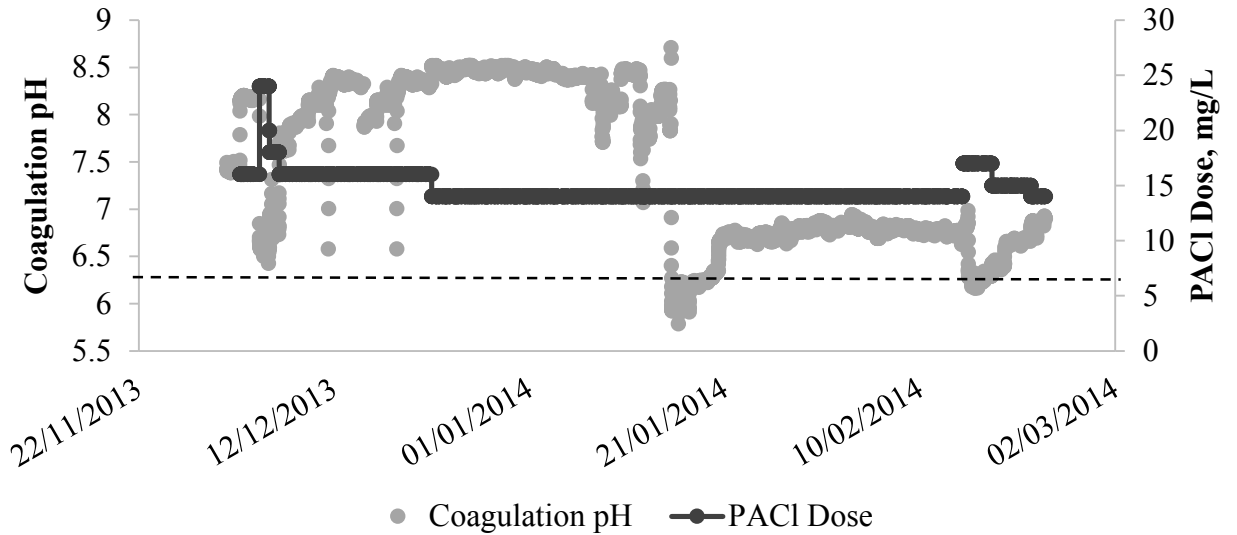The PACl dose was shown to be held between 14 to 16 mg/L for the majority of the study. The significant drops in the coagulation pH correspond with increases in the raw water turbidity that can be seen in Figure 5.7.
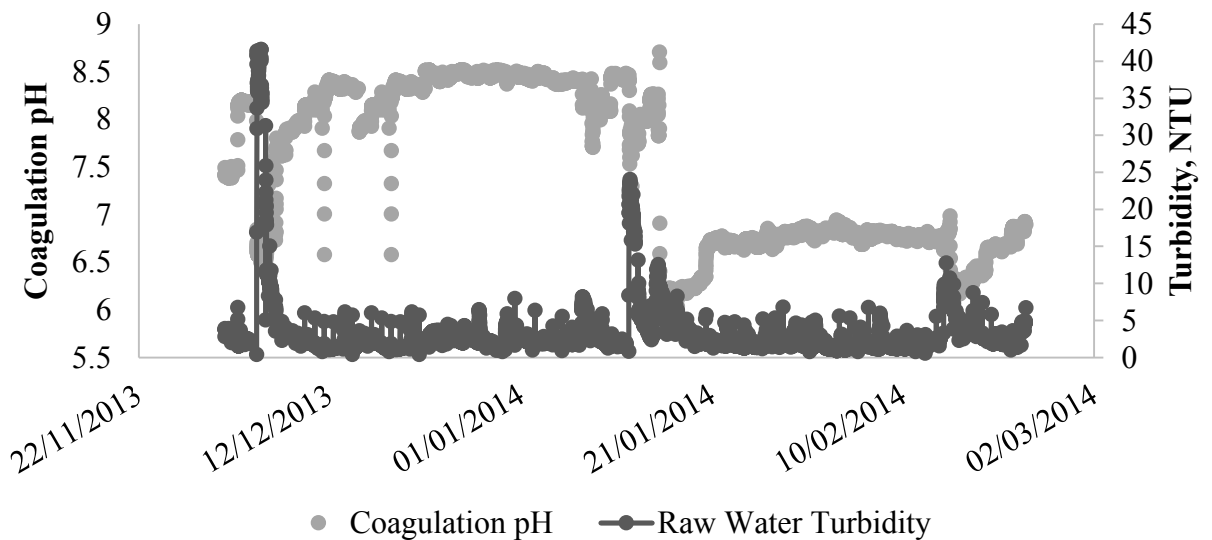
Figure 5.7: Coagulation pH and raw water turbidity for December 1st, 2013 to February 22nd, 2014 at the FWTP

During the study, there were three notable spikes in the raw water turbidity; December 4th, January 12th and February 14th. For the first rain event on December 4th, the turbidity peaked at 41 NTU. During the rain event, the PACl was increased from 16 to 24 mg/L while the pH was decreased from 8.2 to 6.4. The rain event on January 12th saw a peak raw water turbidity of 24 NTU. The PACl dose was held constant through this rain event at 14 mg/L with the pH decreasing from 8.5 to 5.8. The peak turbidity for the third event on February 14th was 12 NTU. The PACl dose was increased from 14 to 17 mg/L for the event and the pH was decreased from 6.9 to 6.2.

Each of the three rain events, classified by spikes in raw water turbidity, were each further analyzed. For each event, raw water turbidity, coagulant dose, apparent colour, coagulation pH and filter effluent turbidity were all analyzed. For the first rain event, raw water UV_{254} was also analyzed. The events are described below.

5.3.1 Water Quality Event 1: December 4th, 2013

During the December 4th event, the raw water turbidity spiked from 2 to 41 NTU, as shown in Figure 5.8.
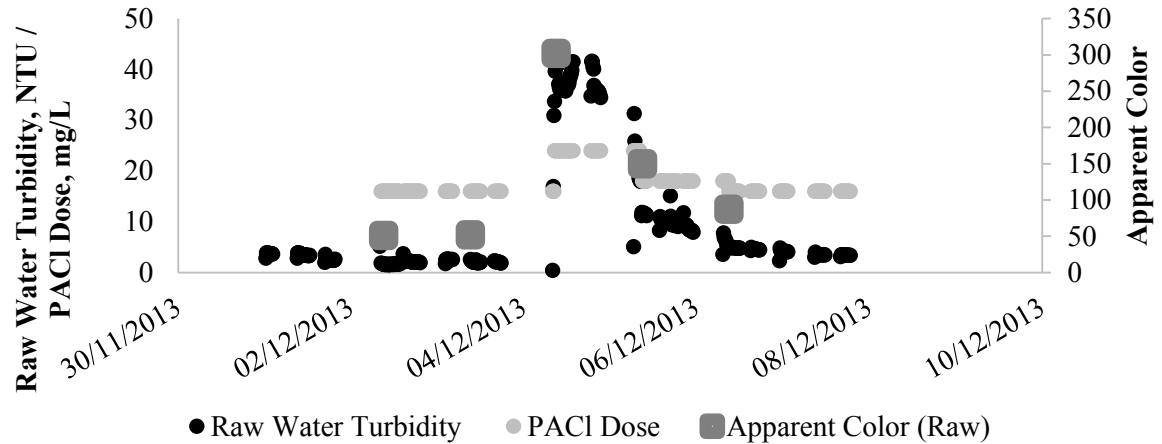
Figure 5.8: Raw water turbidity, PACl dose and raw water apparent colour for the December 4th event

The spike in raw water turbidity corresponds with heavy precipitation on December 3rd and 4th, 2013. With the spike in turbidity, raw water samples had an increase in apparent colour from 52 to 302 TCU. The apparent colour was measured via grab samples and analyzed in the plants laboratory. Prior to this rain event the clarifier effluent apparent colour was 14 TCU. This number spiked up to 302 at the peak of the event. The apparent colour appeared to drop off with raw water turbidity readings, however, there was no reading at the end of the event to verify whether the colour of the raw water returned to pre-event levels. There was no apparent colour reading on the clarifier effluent during the time of the event.

To understand how the plant performed during the rain event, raw water and filter effluent UV_{254} were examined. These levels are shown in Figure 5.9 along with raw water turbidity.
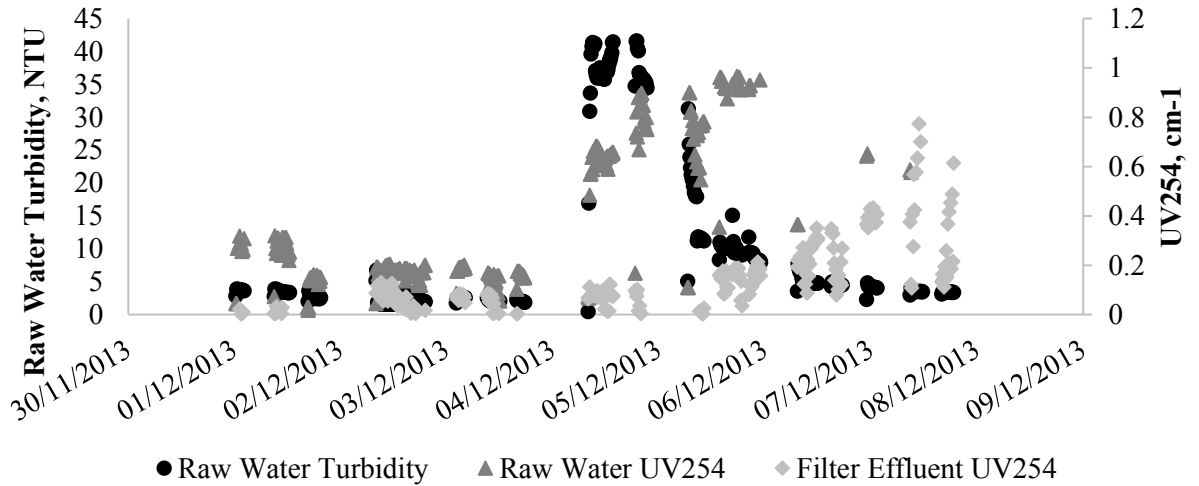
Figure 5.9: Raw water turbidity, raw water UV$_{254}$ and filter effluent UV$_{254}$ for the December 4th event

Prior to the rain event, the UV$_{254}$ measurement on the raw water was approximately 0.2 cm^{-1}. During the event, the raw water UV$_{254}$ spiked as high as 0.95 cm^{-1}. There was also a noticeable increase in filter effluent UV$_{254}$ from 0.05 to 0.5 cm^{-1} after the event. The may be representative of a coagulant under dose thus not allowing the increase in organics to be removed during treatment. At the time of the event, the coagulant dose was increased from 16 to 24 mg/L, this is shown in Figure 5.10. The coagulation pH during this time is shown in Figure 5.10.
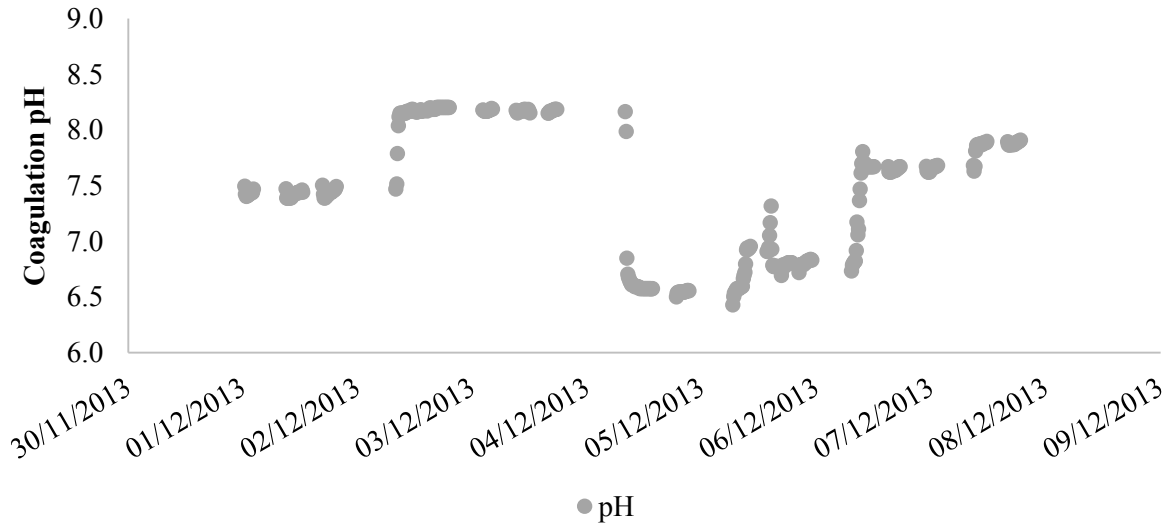
Figure 5.10: Coagulation pH for the December 4th event

Before the rain event, the pH was approximately 7.5. During the event, the pH fluctuated from a high of 8.1 to a low of 6.4. The pH was dropped to help manage the effects of the event. After the event the pH was brought back up to approximately 7.7. Streaming current during the rain event is shown in Figure 5.11.
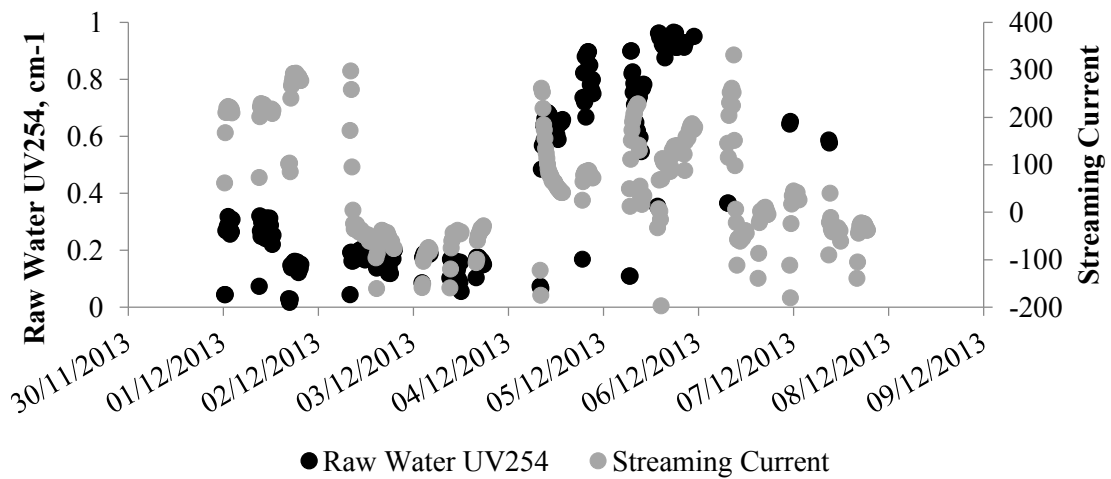
Figure 5.11: Raw water UV_{254} and streaming current for the December 4th event

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Due to the fluctuations in pH during the rain event, streaming current data did not show any discernable trend. Streaming current requires a stable pH. During the rain event, the pH fluctuated between 7.4 and 6.4.

To understand the quality of the finished water, filter effluent turbidity was examined. The filter effluent turbidity for the two filters is shown in Figure 5.12 with raw water turbidity.
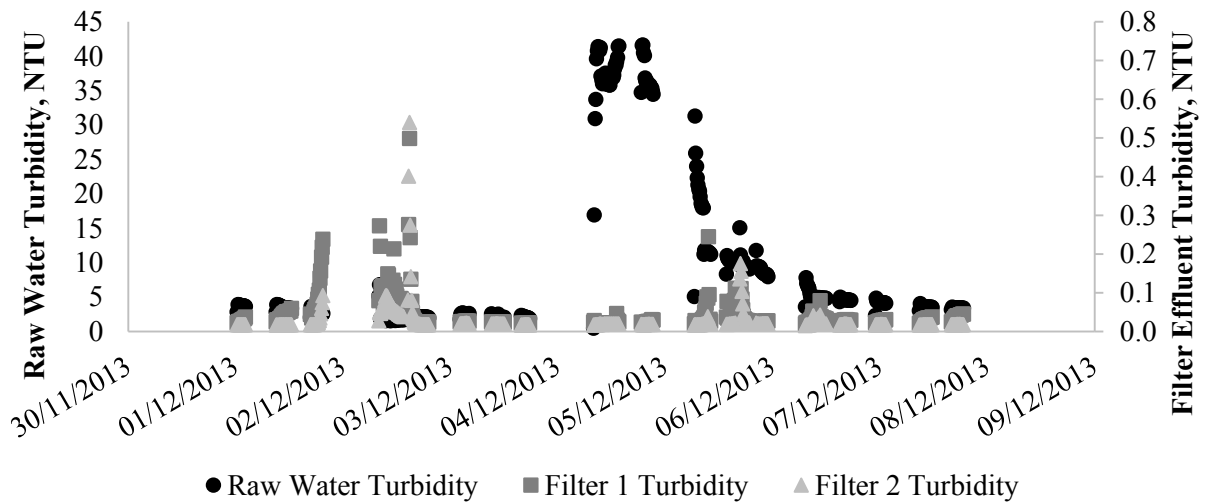
Figure 5.12: Raw water and filter effluent turbidity for the December 4th event

As previously mentioned, the raw water turbidity spiked from 2 to 41 NTU during the event. After the event, both Filter 1 and Filter 2 saw an increase in effluent turbidity with Filter 1 spiking to 0.244 NTU and Filter 2 spiking to 0.175 NTU. The *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) require that all treated water have a turbidity of less than 0.1 NTU. During the spikes in filter effluent turbidity, the treated water during this event was not meeting this standard.

5.3.2 Water Quality Event 2: January 12th, 2014

For the event on January 12th, there was a spike in the raw water turbidity from 2 to 24 NTU. This is shown in Figure 5.13.
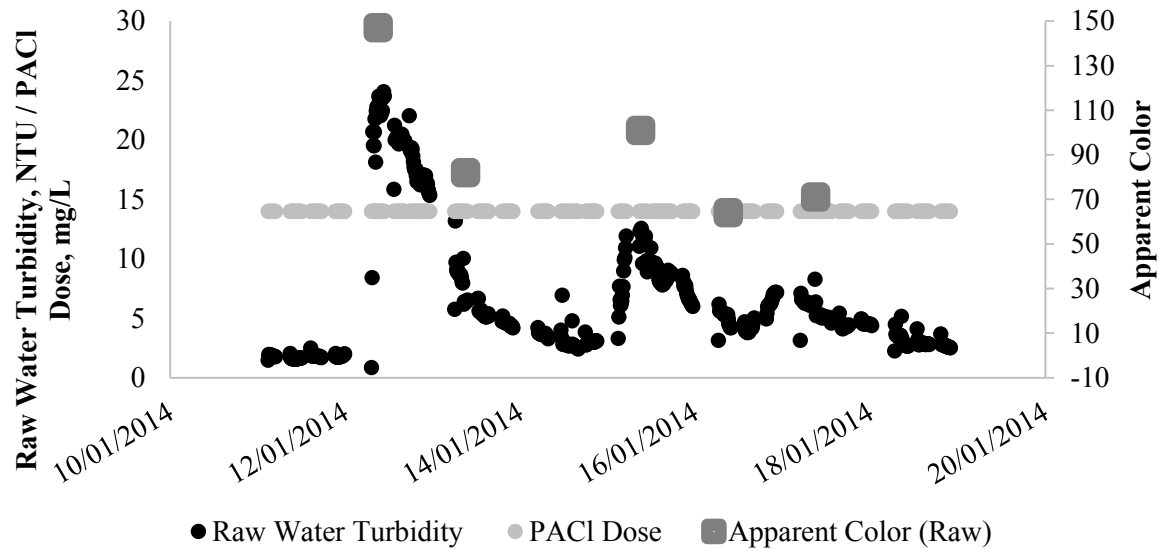
Figure 5.13: Raw water turbidity, PACl dose and raw apparent colour for January 12th event

The spike in raw water turbidity corresponds with a rain event on January 11th. The apparent colour measurements that were taken during the event reached a high of 147 TCU. Apparent colour readings for the clarifier varied between 10 to 13 TCU from January 13th to 18th. The PACl dose was kept constant throughout the event at 14 mg/L. pH was however decreased when raw water turbidity began to increase. This is shown in Figure 5.14.
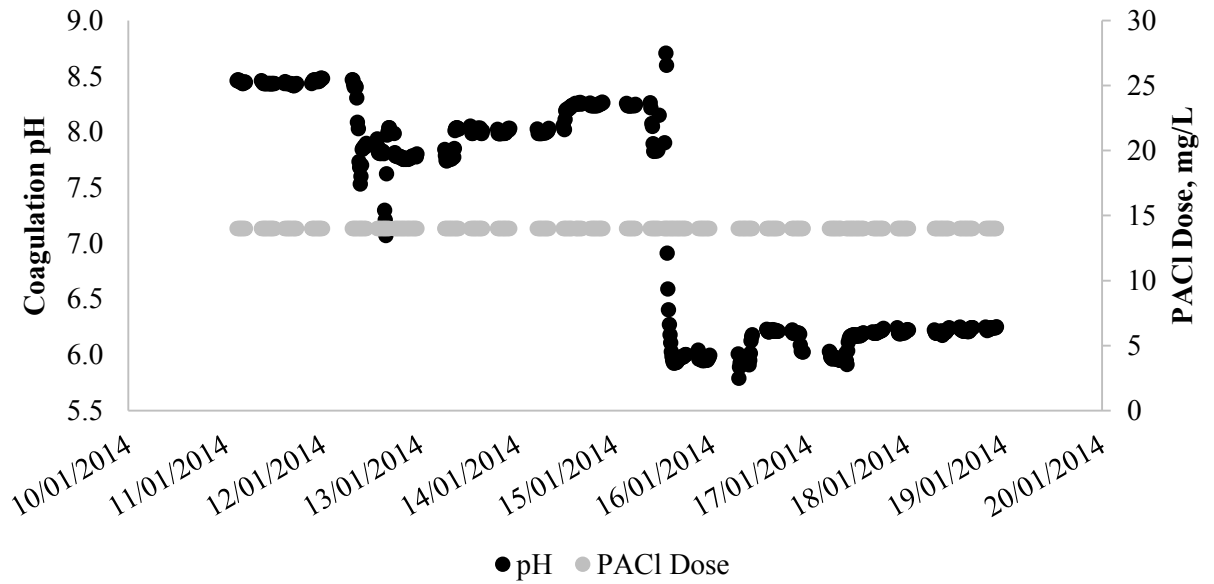
Figure 5.14: Coagulation pH for January 12th event

As stated above, there was no change to the PACl dose for the duration of the event. However, there was a drop in the pH from 8.5 to 7.7 corresponding to the first spike in raw water turbidity from 2 NTU to 24 NTU. The pH dropped again to 5.8 when the turbidity spiked the second time from 3 NTU to 12 NTU. Filter turbidity during this time is shown in Figure 5.15.
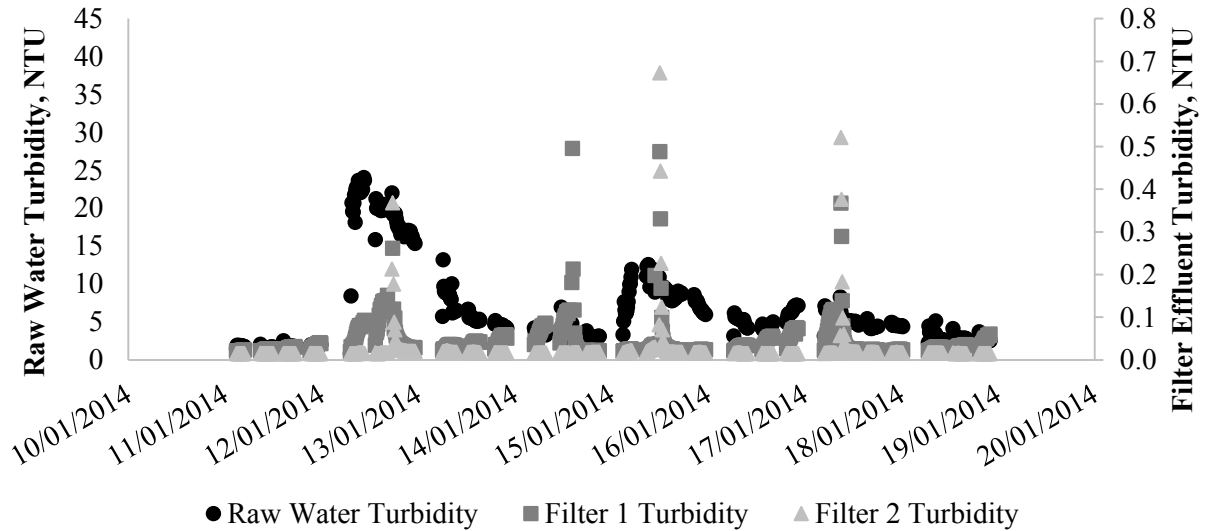
Figure 5.15: Raw and filter effluent turbidity for January 12th event

For both filters, the effluent turbidity increased for each peak in raw water turbidity. For the first spike on January 12th, Filter 1 effluent turbidity increased from 0.03 NTU to 0.26 NTU while Filter 2 saw the effluent turbidity increase from 0.03 NTU to 0.37 NTU. Corresponding to the increase in raw water turbidity on January 16th, Filter 1 effluent turbidity increased from 0.03 NTU to 0.48 NTU and Filter 2 effluent turbidity increased from 0.03 to 0.67 NTU. During the events, the treated water was not meeting the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) as stated previously.

5.3.3 Water Quality Event 3: February 14th, 2014

For the rain event on February 14th, the raw water turbidity spiked from 2 NTU to 12 NTU, as shown in Figure 5.16.
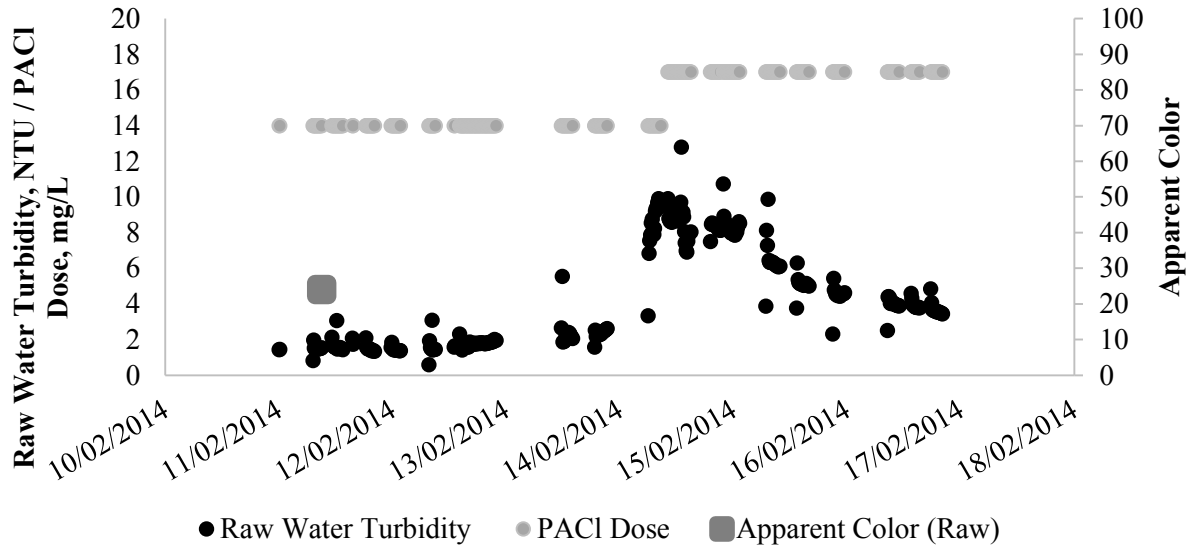
Figure 5.16: Raw water turbidity, PACl dose and raw apparent colour for the February 14th event

This spike corresponds with precipitation on February 13th and 14th. The raw water apparent colour prior to the event was 25 TCU, but there were no readings of apparent colour during the event. Also there were no apparent colour readings for the clarifier effluent during the event. The PACl dose was increased from 14 to 17 mg/L when the raw water turbidity spiked to 12 NTU. The coagulation pH for the event is shown in Figure 5.17.
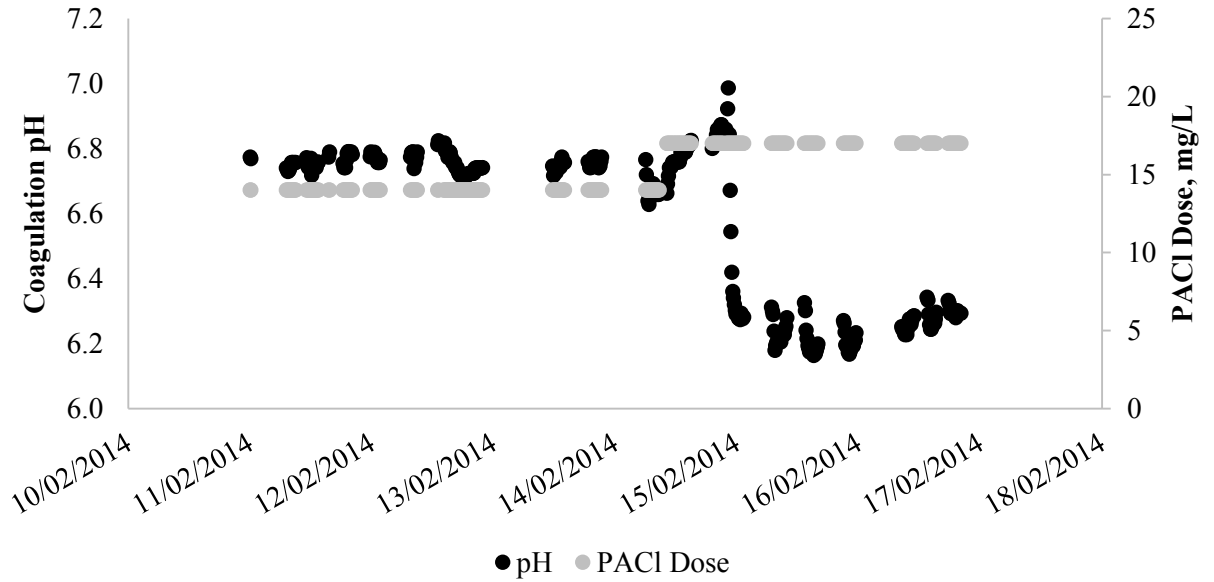
Figure 5.17: Coagulation pH and PACl dose for the February 14th event

As seen with the other events, the pH prior to the event was high and was dropped when raw water turbidity began to increase. For the event, the pH dropped from approximately 6.8 to 6.2. Filter turbidity is shown in Figure 5.18.
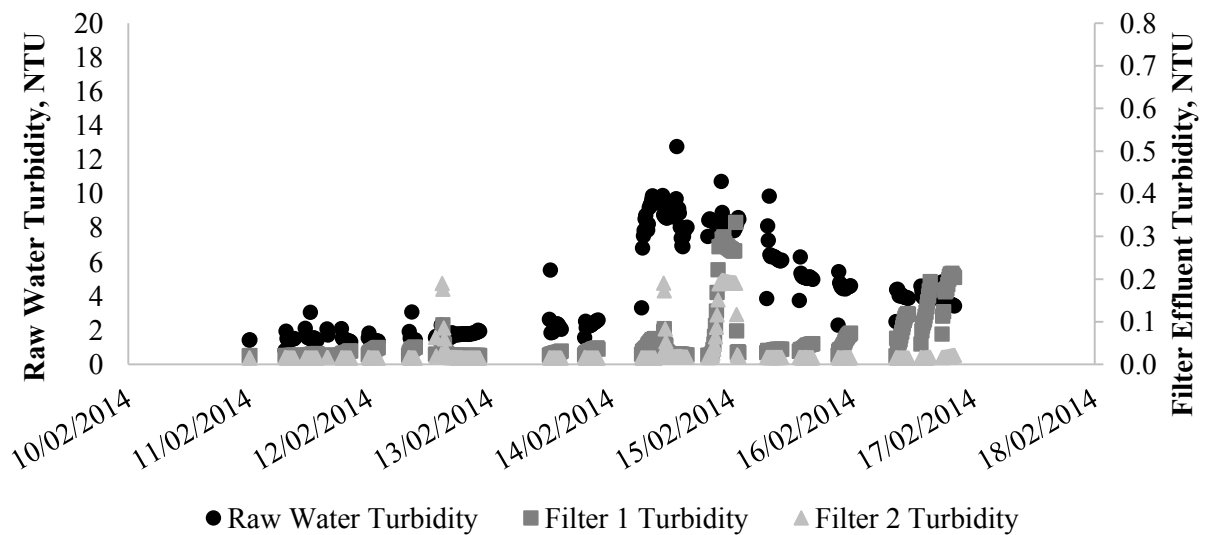
Figure 5.18: Raw water and filter effluent turbidity for the February 14th event

Again, the filter effluent turbidity increased after the raw water turbidity peaked. Filter 1 effluent turbidity increased from 0.018 to 0.33 NTU and Filter 2 effluent turbidity increased from 0.017 to 0.195 NTU. As was the case with the other two rain events, the spikes in the effluent turbidity did not meet the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012) standard for turbidity.

5.4 Conclusions

During the course of the study, the coagulation pH at the FWTP was held above the pH of minimum solubility for the coagulant used at the plant. During times of increased rainfall, the pH was lowered to 6.0. Due to the fluctuations in pH, no trends were shown with the streaming current data. This demonstrates the effect of not maintaining a stable pH on streaming current.

Online UV_{254} data was only available for the first rainfall event. This data showed that raw water UV_{254} increased with raw water turbidity. The data also showed an increase in filter effluent UV_{254} after the peak of the rain event. Although the online UV_{254} monitor showed ability to track changes in raw water quality, data was not available for the second two rain events due to lack of maintenance of the monitor. Because the plant goes on- and offline several times throughout the day, the lines into the monitor easily became clogged. When this occurred, the operators did not clear the lines to allow for a representative sample to be sent to the monitor for analysis. If the online instrumentation was to be considered for the FWTP, proper maintenance of the monitors would be necessary to ensure accurate readings.

Chapter 6: Evaluation of Performance Capabilities of Online SCM and UV$_{254}$ Monitors

The online instrumentation was setup at the BBWTP for a duration of four months. During the first two weeks of the setup, efforts were focused on calibrating the UV$_{254}$ monitor. Previous work had been completed at the BBWTP evaluating turbidity removal and efficiency of the DAF clarifier (Bickerton, 2012). This work illustrated that under normal source water quality conditions, the plant was able to maintain a relatively stable coagulation pH and achieve acceptable filter effluent turbidity.

The objective of this chapter was to highlight the performance capabilities of the online SCM and UV$_{254}$ monitors during rainfall events and to determine the viability of implementation of the online instrumentation at full-scale for coagulation process control when pH remains stable and the equipment was properly maintained and calibrated.

6.1 Materials and Methods

An online SCM (SCM2500, Chemtrac) and UV$_{254}$ monitor (UVM5000, Chemtrac) were set up at the BBWTP from May to September, 2013. The data collected from the online instrumentation as well as online data from the plants SCADA system was used to evaluate the performance capabilities of the online instrumentation. Streaming current and UV$_{254}$ measurements on the raw and filter effluent water was logged every minute over the course of the study. Data from the plants SCADA system, including raw water, filter effluent and clearwell turbidity, coagulation pH and coagulant dose were also logged every minute. A large dataset was compiled of both the online instrumentation data as well as the SCADA data and was analyzed for trends to identify performance capabilities.

6.2 Analysis of Normal Water Conditions

To ensure the BBWTPs coagulation processes were optimized under normal source water quality conditions (e.g. non-upset or rain event conditions), the coagulation pH and turbidity removal profile for the plant over the course of the study were first analyzed. The BBWTP uses polyaluminium chloride (PACl) and maintains pH with caustic. The pH of minimum solubility for PACl is 6.2. Figure 6.1 outlines the pH trend over the course of the study.
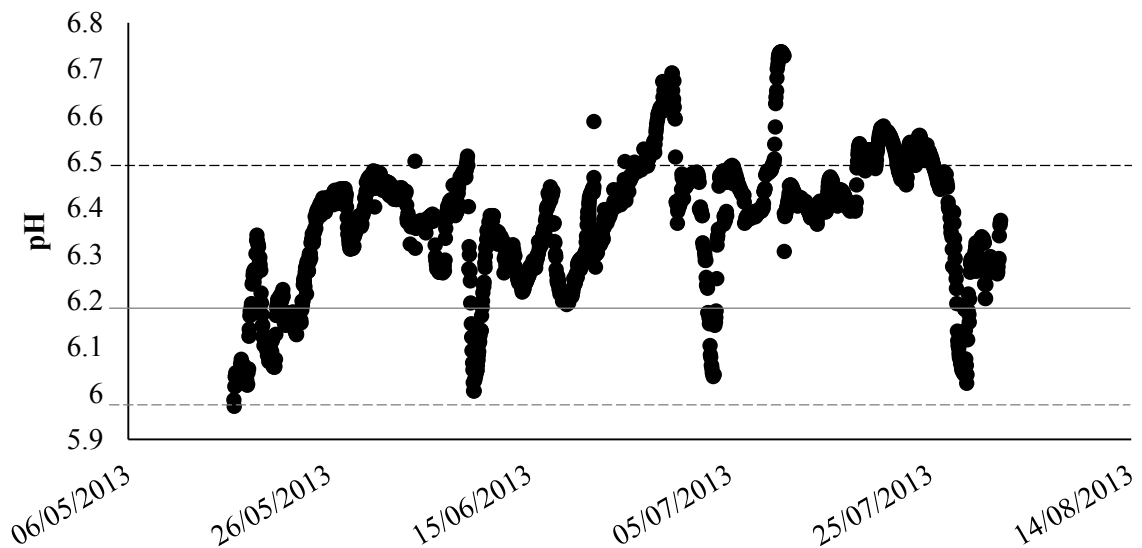
Figure 6.1: pH trend from May to August, 2013

The data shows the coagulation pH from May 16th to August 8th, 2013. Coagulation pH was found to average between 6.3 and 6.4 with highs reaching 6.7 and dropping as low as 6.0 during plant heavy precipitation events monitored during this study. If online instrumentation is to be considered for process optimization, pH must be kept constant with limited variability. Ability to maintain a constant pH is imperative not only during normal source water quality conditions but also under upset conditions.

A snapshot of normal source water quality conditions from May 25th to May 28th, 2013 was selected for review of several parameters including turbidity, UV_{254} and streaming current. Figure 6.2 shows the raw water, Filter 3 effluent and clearwell turbidity during this time.
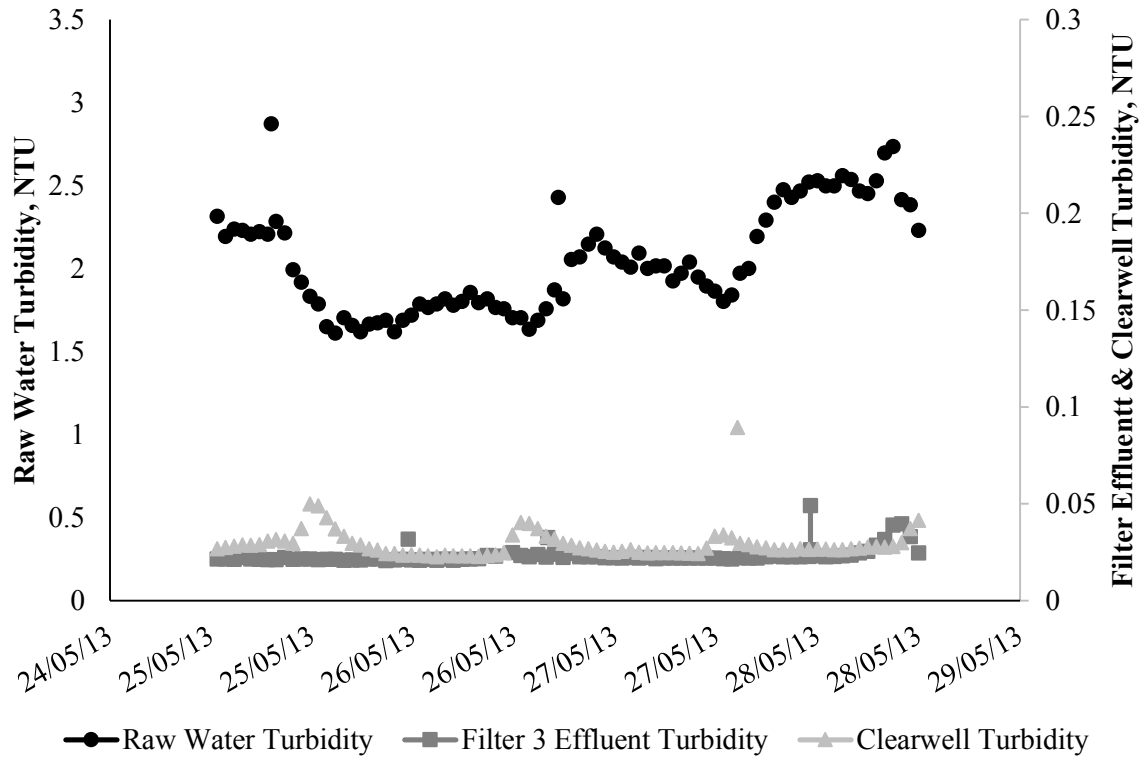
Figure 6.2: Raw water, filter effluent and clearwell turbidity from May 25th to 28th, 2013

From the graph, it can be seen that average raw water turbidity was stable and averaged a moderate 2.1 NTU. Filter effluent turbidity from Filter 3 was shown to remain around 0.02 NTU. Clearwell turbidity also remained steady at 0.02 NTU with slight fluctuations to 0.03 NTU. The overall trend shows stable turbidity. Turbidity was then compared with raw water UV_{254} during this time, as shown in Figure 6.3.
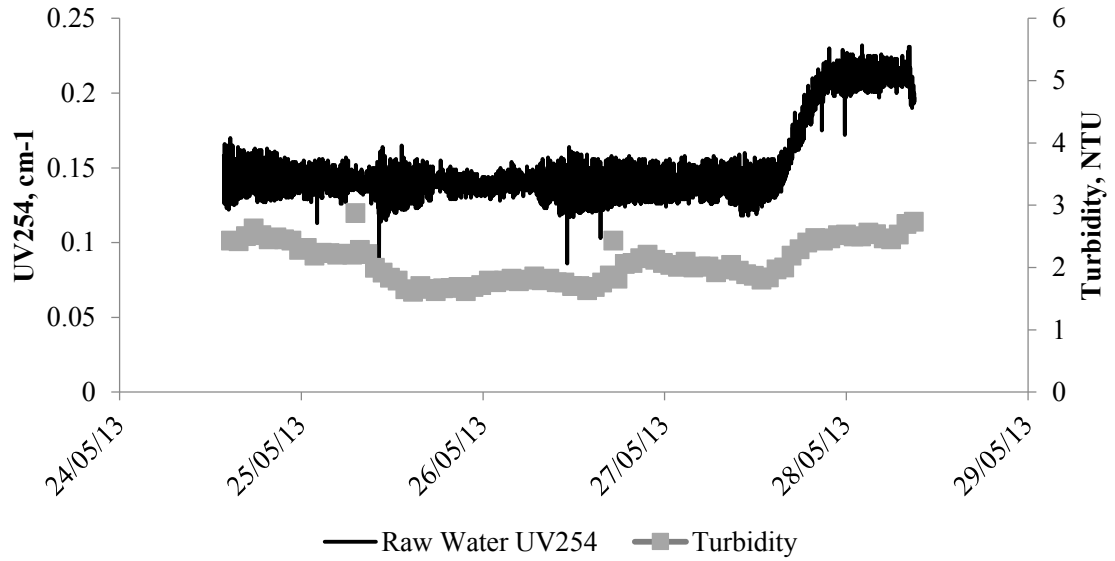
Figure 6.3: Raw water UV_{254} and raw water turbidity from May 25th to 28th, 2013

It can be seen that the raw water UV_{254} remains constant at 0.15 cm^{-1}, however, there was a slight increase to 0.21 cm^{-1} on May 28th. It should be noted that turbidity did not increase at this time, indicating that raw water UV_{254} levels can increase independent of turbidity. To further investigate the change increase in raw water organics, UV_{254} was plotted with streaming current. This trend is shown in Figure 6.4.
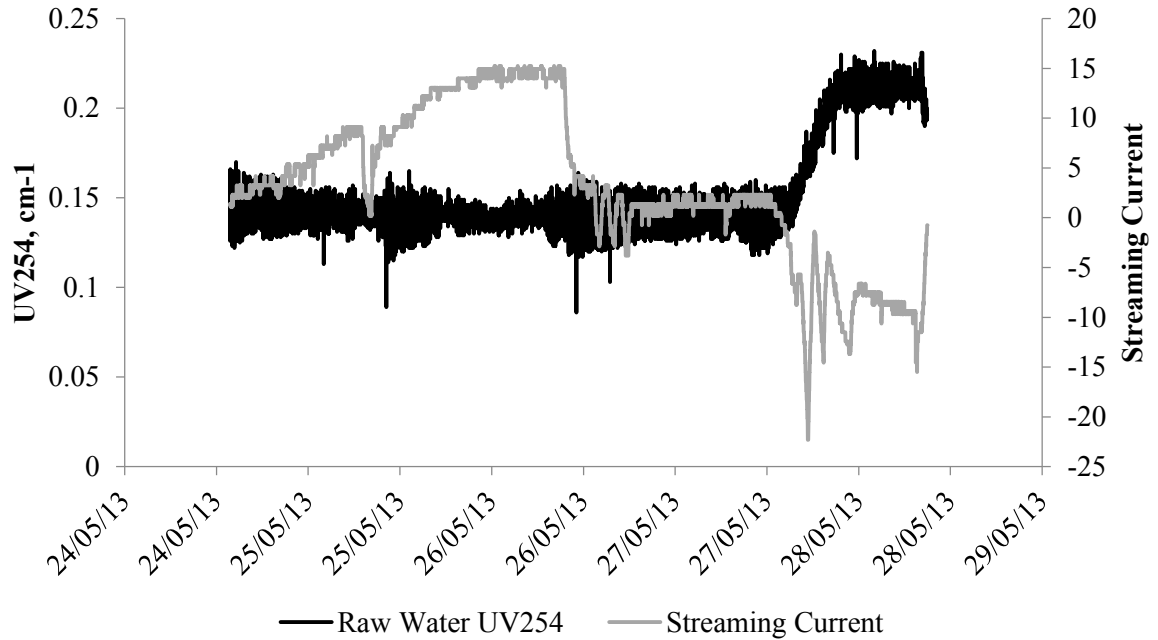
Figure 6.4: Raw water UV$_{254}$ and streaming current from May 25th to 28th, 2013

   The graph shows that when the raw water UV$_{254}$ increased in the water on May 28th (i.e. increase in negatively charged particles), the streaming current dropped. As mentioned, the operators at the BBWTP use the plant SCM to determine optimal coagulant dose. As the streaming current dropped, an alarm would have notified the operators of the change. It is therefore expected that the PACl dose was increased accordingly. The coagulant dose for the week is shown in Figure 6.5.
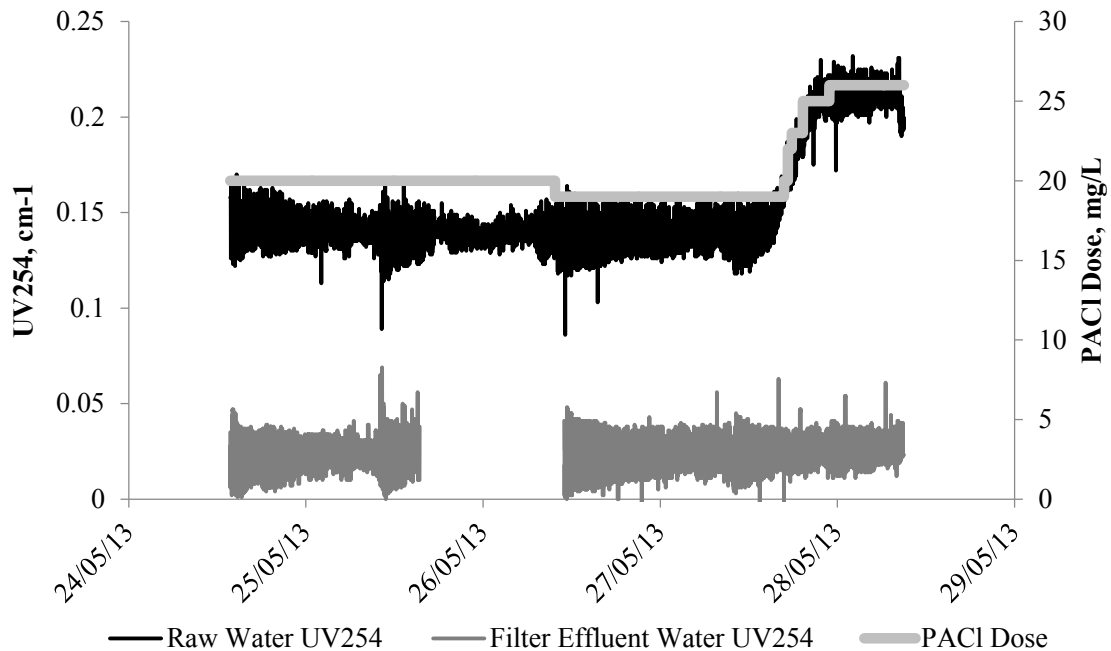
Figure 6.5: Raw water UV_{254}, filter effluent UV_{254} and PACl dose from May 25th to 28th, 2014

Figure 6.5 verifies that the PACl dose was increased based on the drop in streaming current. It can be seen that where the raw water UV_{254} increased on May 28th the PACl dose was also increased from 20 to 25 mg/L. The filter effluent UV_{254} did not appear to be effected during this increase in raw water UV_{254}. This indicates that coagulation was sufficient.

6.3 Analysis of Challenged Water Conditions

To assess the performance capabilities of the online instrumentation, three rain events at the plant from May 15th to August 8th, 2013 were evaluated. The three events were characterized by significant increases in raw water UV_{254}. The dates at which these events occurred are June 8th, July 3rd and July 29th.

6.3.1   Water Quality Event 1: June 8th, 2013

Raw water UV_{254} and raw water turbidity for the June 8th, 2013 event are shown in Figure 6.6.
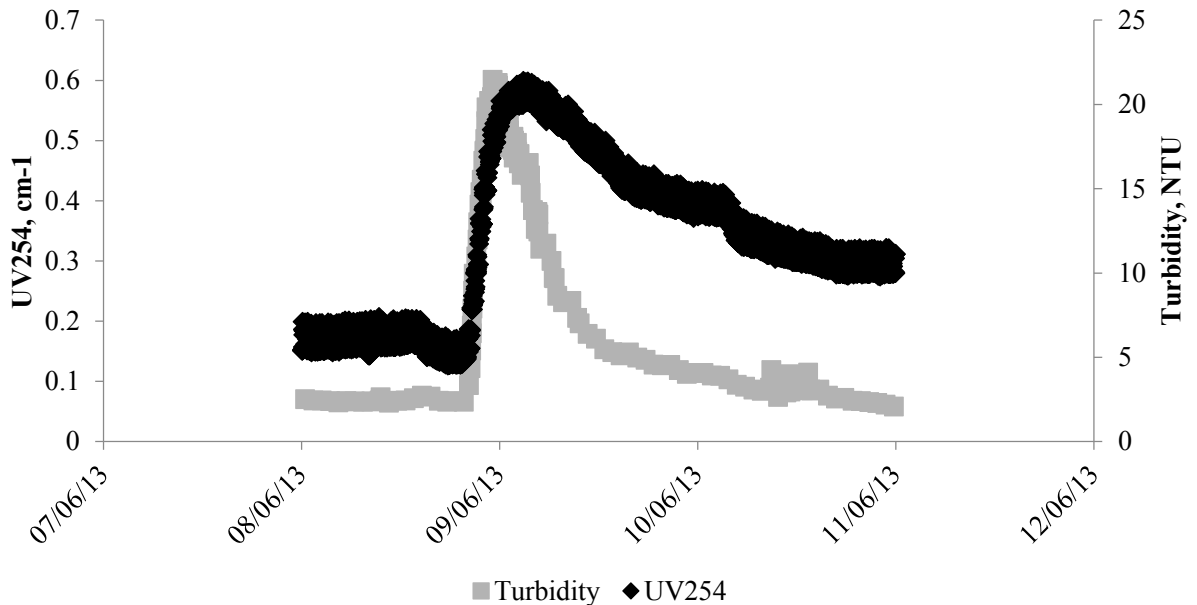
Figure 6.6: Raw water UV_{254} and turbidity for June 8th, 2013 event

From the graph, it can be seen that on the night of June 8th both raw water UV_{254} and turbidity increased sharply. UV_{254} increased from 0.2 to 0.6 cm^{-1} and turbidity increased from 2 to 20 NTU. Turbidity dropped off more quickly than the raw water UV_{254} and was back to normal levels 24 hours after the event. Raw water UV_{254} however, did not return to its previous levels as quickly. Levels were still double their original value two days after the event. Inability to maintain proper coagulation for removal of these organics during this time could lead to increases in DBPs in the finished water. To assess system performance, raw water UV_{254} is shown with filter effluent UV_{254} and PACl dose for the event in Figure 6.7.
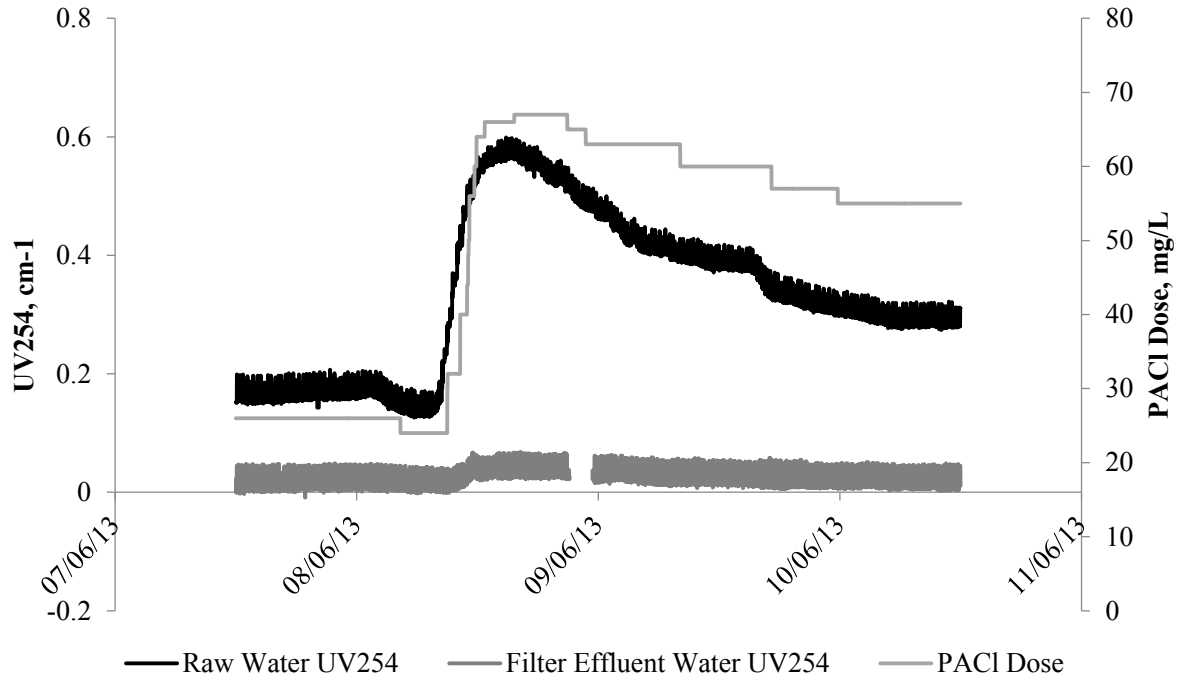
Figure 6.7: Raw water UV_{254}, filter effluent UV_{254} and PACl dose for June 8th, 2013 event

The PACl dose appears to trend with the raw water UV_{254}. Initially, the PACl dose does not increase as quickly as the raw water UV_{254}. The PACl dose also remains higher as the raw water UV_{254} begins to decrease. There also appears to be a slight increase in the filter effluent UV_{254} shortly after the time of the event. This increase suggests inadequate coagulant dosing to remove organics. The large gap at the end of the event suggests a possible overdose of coagulant. These trends can also be verified by analysing the streaming current, as shown in Figure 6.8.
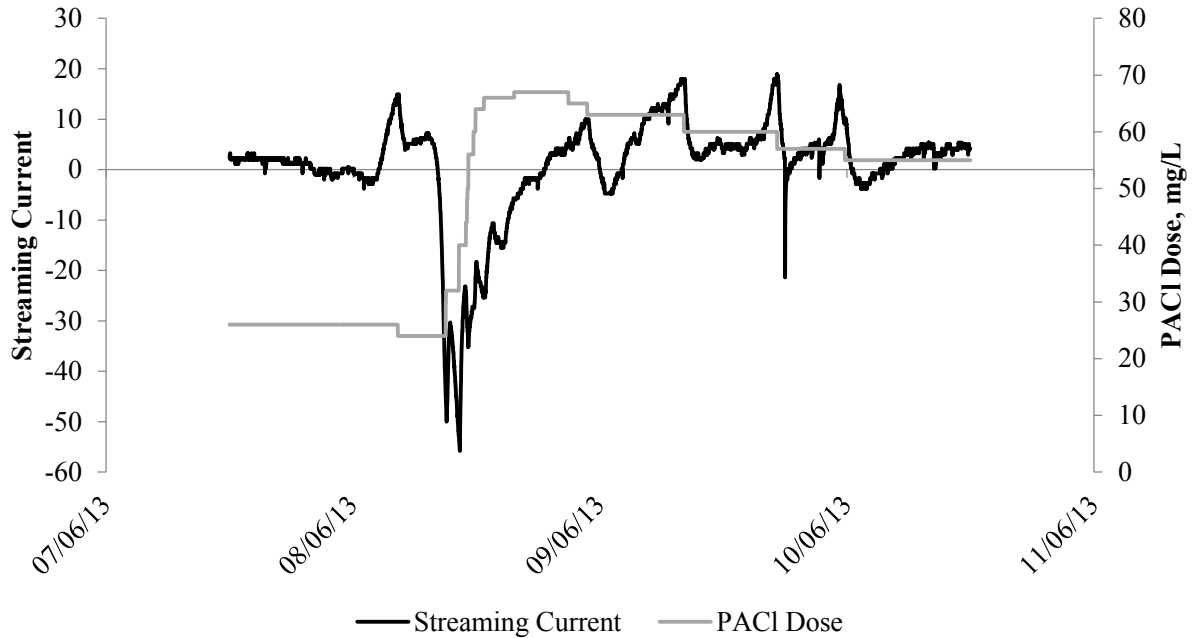
Figure 6.8: PACl dose and streaming current for June 8th, 2013 event

Prior to the event, the streaming current was reading slightly above zero. The sharp decrease in streaming current to -50 represents the start of the event. From the graph it can be seen that even though the PACl dose was increased quickly, the streaming current did not reach zero, its pre-event set-point, for another 8 hours. This indicates that the coagulant was not increased quickly enough to offset the increase in raw water UV_{254} which may have caused the increase in the filter effluent UV_{254} as shown in the previous graph. Furthermore, the streaming current remained between 5 and 20 over the next two days before leveling off back at its zero set-point on the night of the 10th. This may indicate a slight overdose during this time and increased cost of chemical usage.

The coagulation pH over the course of the study was shown to remain fairly stable averaging between 6.3 and 6.4 with highs reaching 6.7 and lows near 6.0 during events. A closer examination of pH during the June 8th, 2013 event is shown in Figure 6.9.
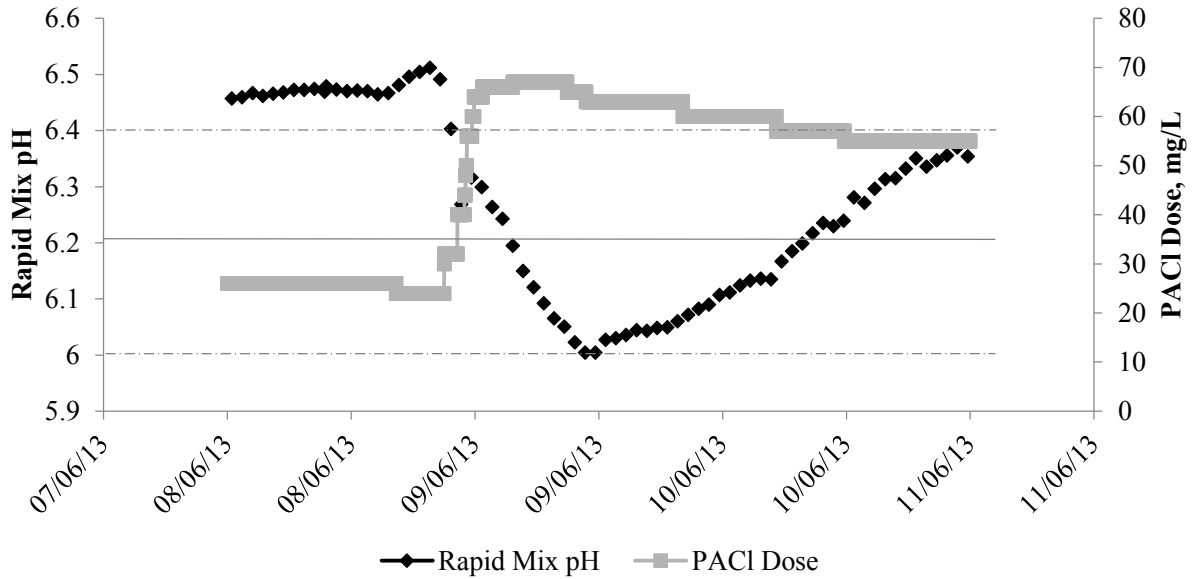
Figure 6.9: PACl dose and pH for June 8th, 2013 event

Prior to the event, the pH was approximately 6.5. During the event the pH dropped as low as 6.0. Ideally, the pH should be held constant around the pH of minimum solubility for the coagulant. Holding the pH constant is also necessary to reduce error in the streaming current. As the operators are currently adjusting the coagulant dose based on streaming current, maintaining a consistent pH will reduce the chance of inadequate or overdose. Changes in pH can shift the set-point of the streaming current that the operators may ultimately be trying to achieve.

6.3.2 Water Quality Event 2: July 3rd, 2013

Raw water UV_{254} and raw water turbidity for the July 3rd, 2013 event are shown in Figure 6.10.

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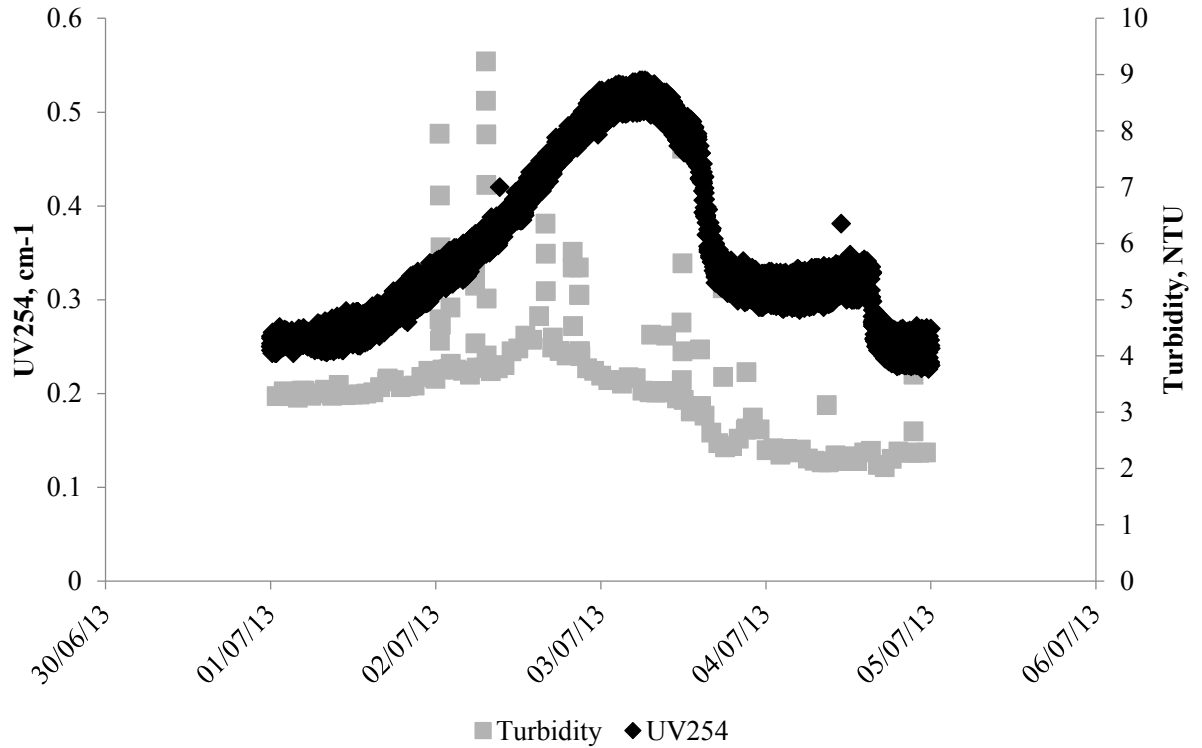
Figure 6.10: Raw water UV_{254} and turbidity for July 3rd, 2013 event

During this event, the raw water UV_{254} increases gradually from 0.2 to 0.6 cm^{-1} over the course of 24 hours. During this time, the raw water turbidity did not show a parallel and consistent increase. Aside from a few slight spikes, the turbidity remained stable between 2 and 4 NTU. This event shows that increases in raw water UV_{254} can be independent of turbidity. The performance of the plant was evaluated based on filter effluent UV_{254} as shown in Figure 6.11.
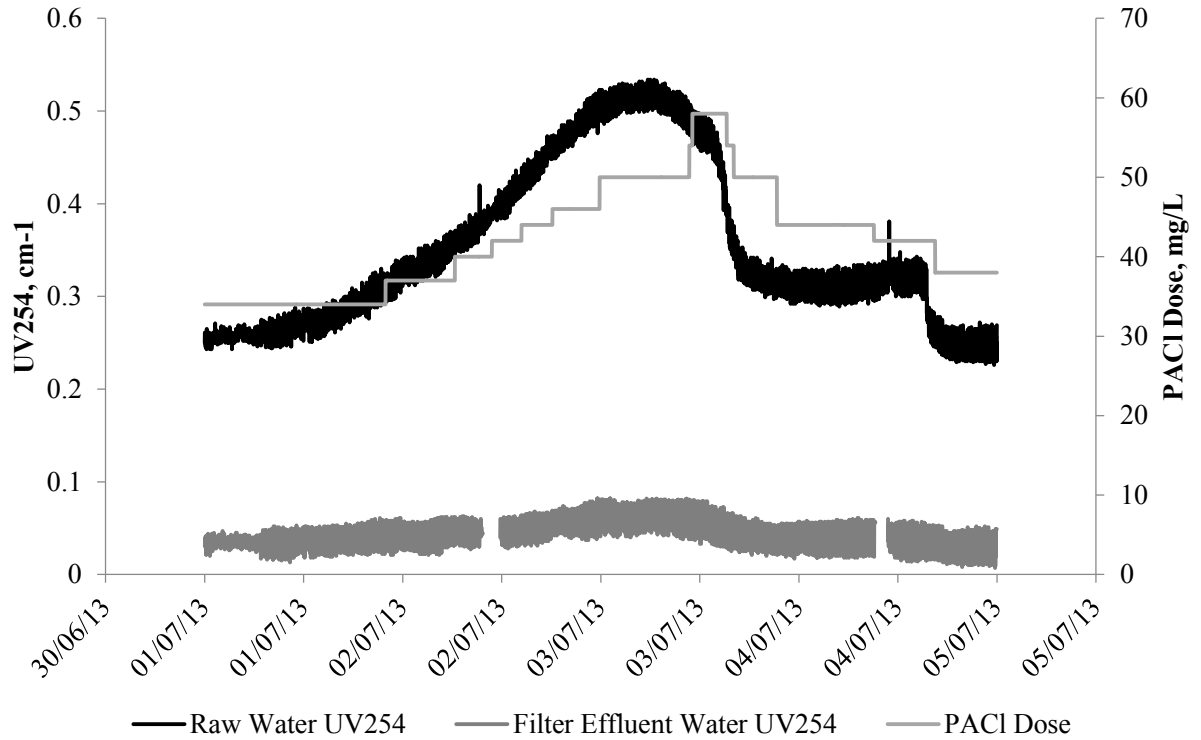
Figure 6.11: Raw water UV_{254}, filter effluent UV_{254} and PACl dose for July 3rd, 2013 event

Raw water UV_{254}, filter effluent UV_{254} and PACl dose for the event are shown in Figure 5.11. The same trend shown in the previous event is also shown here. There is a slight but noticeable increase in filter effluent UV_{254} indicating that coagulation was not optimized during the event with levels reaching as high as 0.08 cm^{-1}. Again, the PACl dose appears to follow the raw water UV_{254}, however, there is a lag in dose between July 2nd and 3rd. To determine whether coagulant doses were inadequate, streaming current was examined, as shown in Figure 6.12.
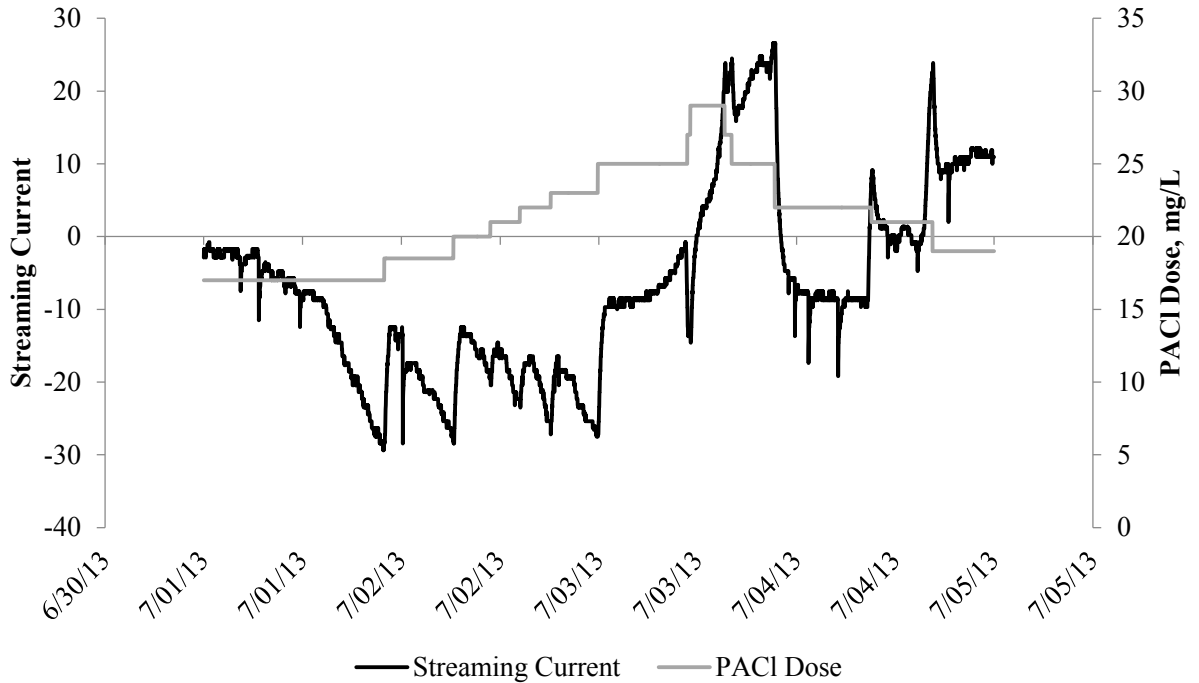
Figure 6.12: Streaming current and PACl dose for July 3rd, 2013 event

Prior to the event, streaming current was reading slightly below zero as the set-point. The graph shows how the streaming current begins to drift away from this set-point and drops as low as -30. Inability to maintain the set-point indicates inadequate coagulation at this time. This may also explain the increase in filter effluent UV$_{254}$ in the Figure 6.11.

Similar to the previous event, pH was maintained above 6.0. However, as shown from Figure 6.13, pH ranges from 6.0 to 6.5. Maintaining a constant pH is necessary if online SCM is to be used for coagulation control.
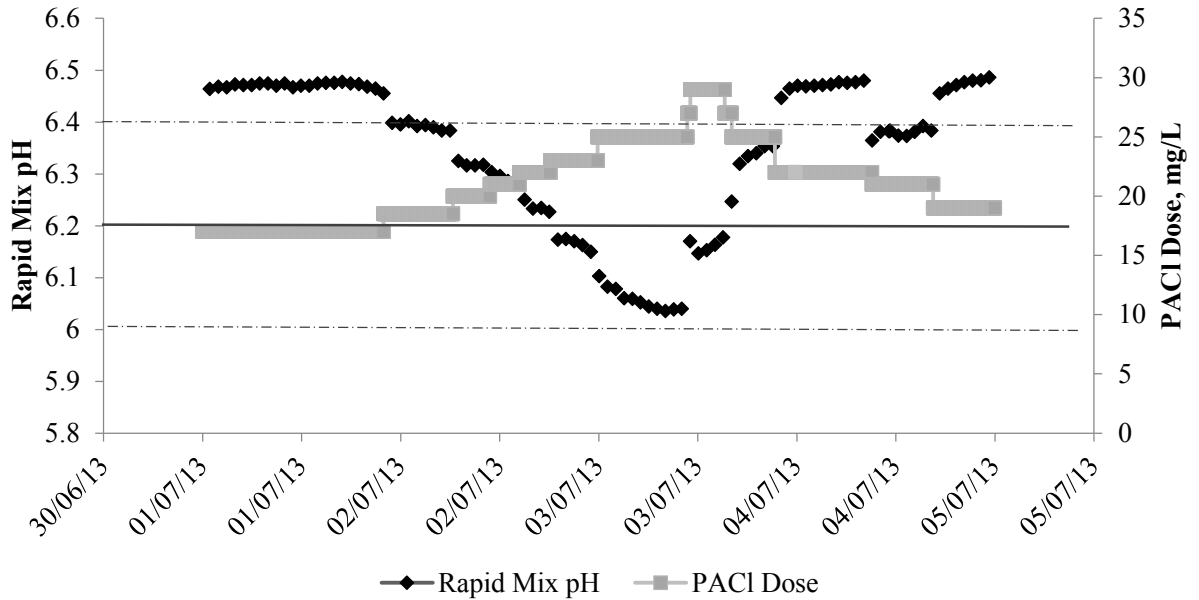
Figure 6.13: PACl dose and pH for July 3rd, 2013 event

6.3.3   Water Quality Event 3: July 28th, 2013

Raw water UV$_{254}$ and turbidity are shown in Figure 6.14 for the July 28th, 2013 event.
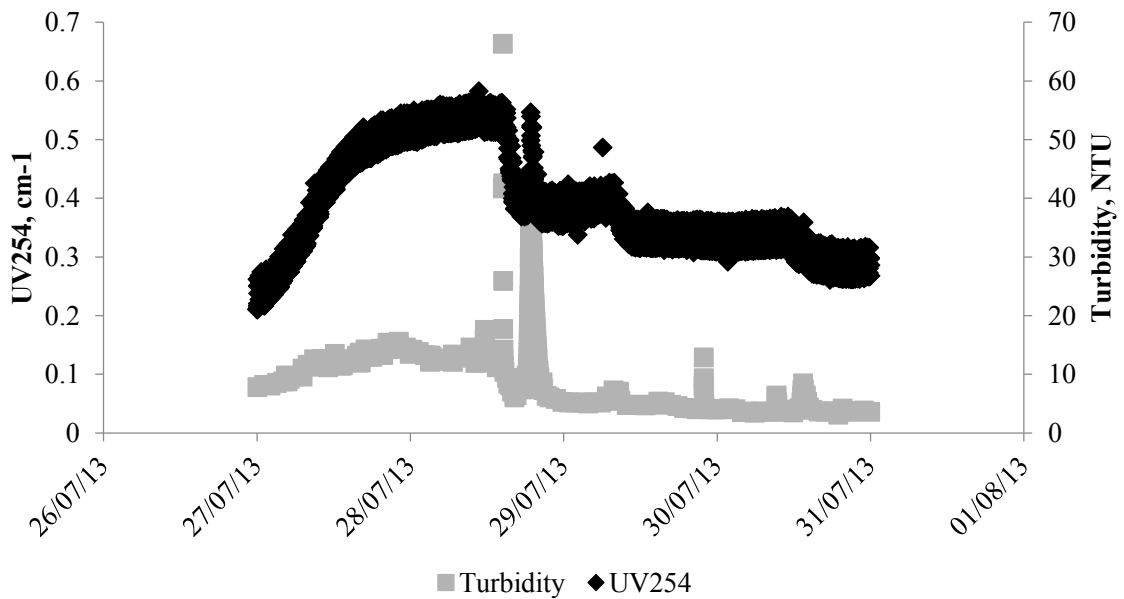
Figure 6.14: Raw water UV$_{254}$ and turbidity for July 28th, 2013 event

Raw water UV_{254} increased from 0.2 to 0.6 cm^{-1} whereas turbidity remained fairly stable between 5 and 10 NTU with a sharp spike to 40 NTU on the night of the July 28th. Figure 6.15 shows the UV_{254} removal capabilities of BBWTP for the event as well as the coagulant dose.
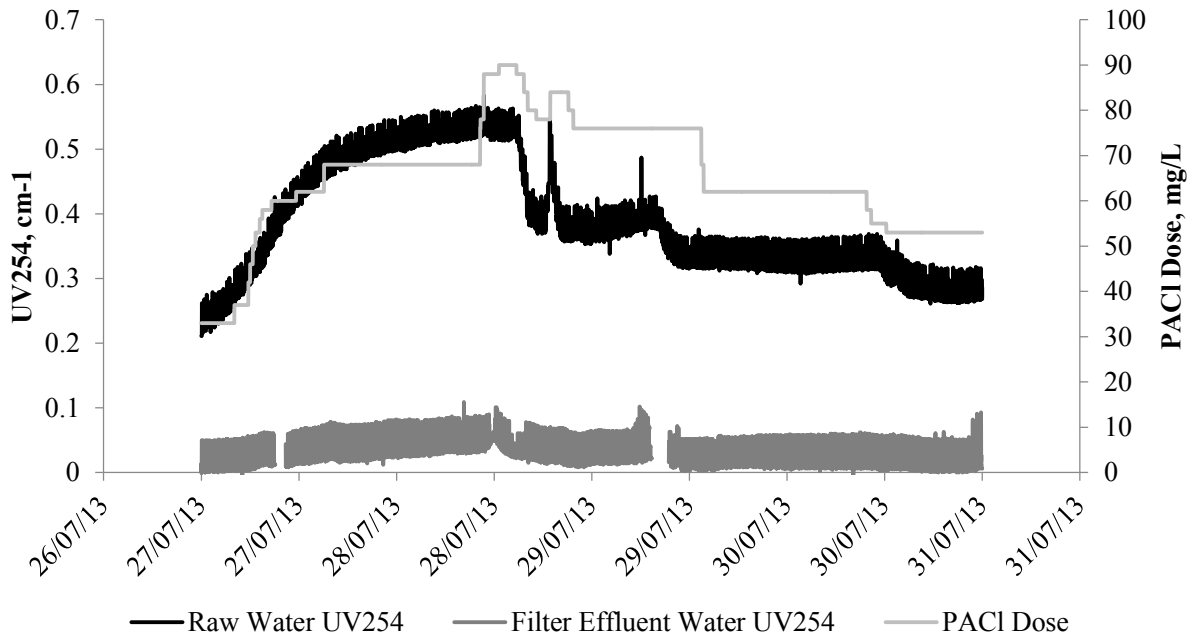
Figure 6.15: Raw water UV_{254}, filter effluent UV_{254} and PACl dose for July 28th, 2013 event

From the graph it appears that the PACl was not increased quickly enough at the start of the event. The slight increase in filter effluent UV_{254} is also shown, with the most noticeable increase shown on the night of the 28th. These values peak at 0.08 cm^{-1}. This increase in filter effluent UV_{254} shows that there is room to improve coagulation processes during times of rapidly changing raw water quality. Streaming current is used to verify whether there was inadequate chemical addition during the time of the event. This is shown in Figure 6.16.
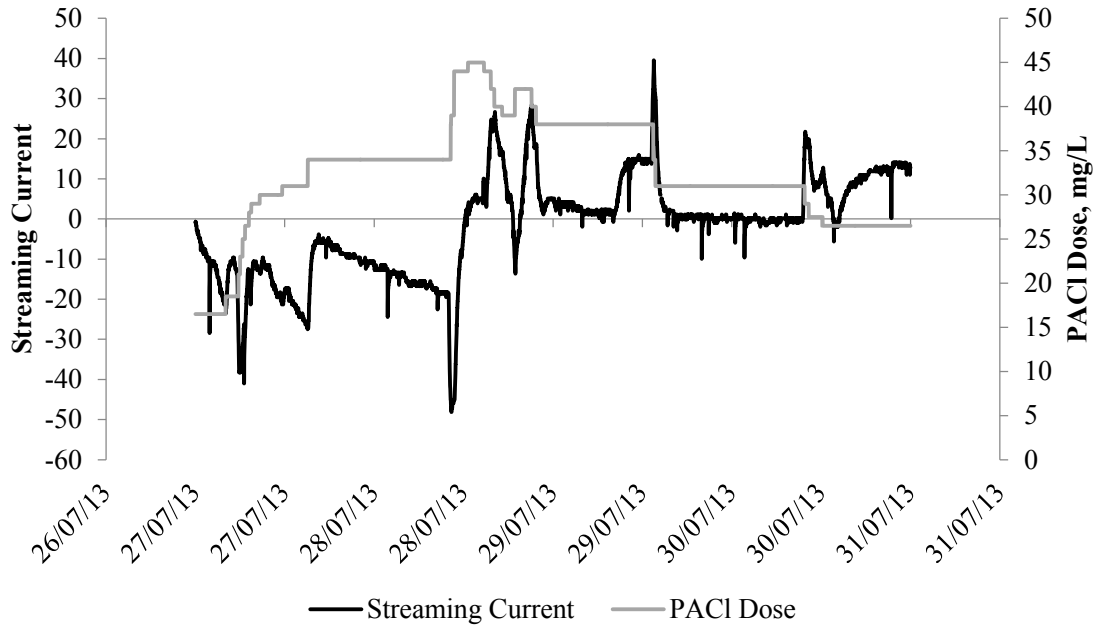
Figure 6.16: Streaming current and PACl dose for July 28th, 2013 event

Like the previous events, the streaming current was shown to drift from the set-point (-10) at the beginning of the event. The graph shows that the streaming current appeared highly negative for July 27th and 28th with lows reaching -50. The streaming current then increased and leveled out around zero. This may indicate a slight overdose as the pre-event set point was slightly negative around -10. To ensure that the set point did not drift due to changes in pH, the coagulant pH during the time of the event is considered and is shown in Figure 6.17.
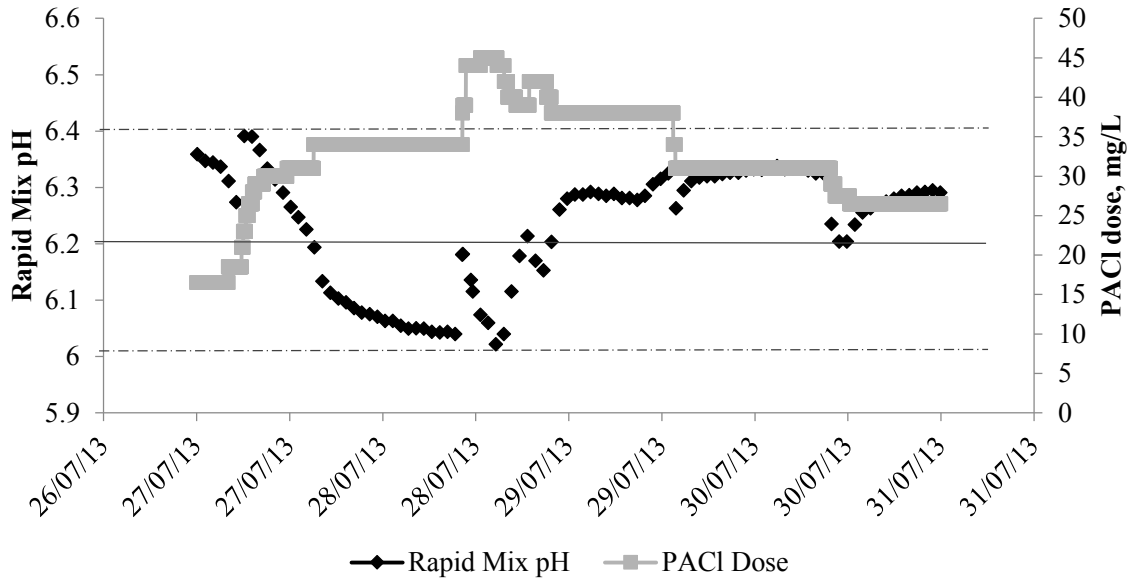
Figure 6.17: PACl dose and pH for July 28th, 2013 event

The pH follows the same trend as the previous two events with pH ranging from 6.0 to 6.4. The pH at the beginning of the event was around 6.3 and although it dropped to 6.0 during the peak of the event, it returned to its pre-event value by the end of the event. Ability to maintain a constant pH ensures that the streaming current set-point dose not shift.

6.4 Evaluation of Full-Scale Online Instrumentation Potential

Based on the performance capabilities during the three rain events, there appears room to further optimize coagulation practices, especially during times of rapidly changing raw water quality. In each of the three rain events monitored during this study, streaming current was shown to rapidly drop off during the initial stages of the event. This indicates that manual control of the coagulant dose was not increased fast enough to compensate for the sharp decline in raw water quality caused by the rain event. The inadequate coagulant dose does not allow for optimal removal of the organics and thus causes a slight increase

in filter effluent UV_{254}. Current plant practices show that manual increases in coagulant dose based on changing streaming current are not adequate or fast enough to keep up with the changing raw water quality. Thus, there exists the potential to benefit from online automated control of coagulation.

To assess the capabilities of an automated prediction model, a preliminary regression analysis was completed on the BBWTP data set and an equation to determine coagulant dose was developed. Based on the findings of the study, there existed a strong correlation between raw water UV_{254} and coagulant dose, as shown during the three rain events. Equations incorporating raw water UV_{254} both singly and combined with turbidity were evaluated for the ability to predict coagulant dose. Streaming current data was not included in the regression analysis due to the inherent bias associated with the existing practice of determination of coagulant dose by the operators based on changes in SCM readings.

The regression equation based only on raw water UV_{254}, as shown in Equation 1, had an R^2 value of 75.4%.

$$Coagulant\ Dose = (118 * Raw\ Water\ UV_{254}) + 5.82 \qquad (1)$$

When turbidity was included in the equation, as shown in Equation 2, the R^2 increased only slightly to 76.5 % indicating that turbidity was an insignificant contributor to the dosage prediction model.

$$Coagulant\ Dose = (117 * Raw\ Water\ UV_{254}) + (0.281 * Turbidity) + 5.23\ (2)$$

This was further verified when turbidity was considered alone, showing poor fit with an R^2 value of only 31.7 %. Based on these values and the results from the online

study, it was determined that coagulant dose could be projected based upon raw water

UV$_{254}$. Traditionally, adjustments to coagulant dose are made in a discrete, step-wise

manner by the plant operator as opposed to a continuous dosage variation. The output of

the prediction model, being a continuous function, was adapted both to reflect this discrete,

step-wise approach consistent with manual dosage adjustments and allow for a clearer

visual representation of the deviations between actual and predicted coagulant dose. This

adaptation was performed via the use of an If/ Then function. Specifically, if the predicted

coagulant dose, as determined by Equation 1, changed by at least 15 % relative to the

previously outputted dose prediction, the new dose was then applied. Barring said change,

the outputted coagulant dose remained unadjusted. The If/ Then function is described

below.

$$If\ \ y_n = \frac{|y_{Eqn1} - y_{n-i}|}{y_{n-i}} \geq 15\ \%$$

$$Then\ report\ y_n$$

$$If\ not, report\ y_{n-i}$$

where y_n = new coagulant dose as determined by a 15 % change
y_{Eqn1} = coagulant dose as determined by Equation 1
y_{n-i} = last outputted coagulant dose

The projection of the step-wise model based on raw water UV$_{254}$ is shown for each

of the three rain events. The light grey line in each of the graphs (PACl Dose Model)

indicates the step-wise dose based on the 15 % change in coagulant demand. The dark grey

line represents the actual coagulant dose as administered by the plant operators. Figure

6.18 shows the projected PACl dose based on raw water UV$_{254}$ for the June 8th, 2013 event.
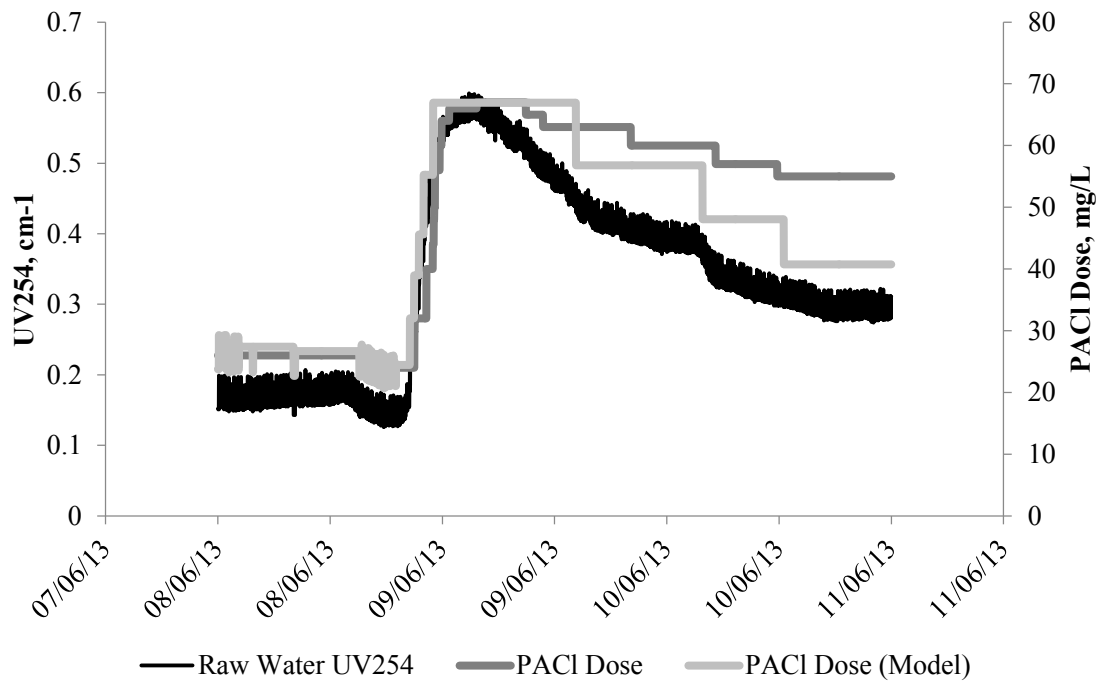
Figure 6.18: Projected PACl doses based on raw water UV_{254} (June 8th, 2013)

The model indicates that the PACl dose should have increased more quickly at the beginning of the event and decreased more quickly at the end of the event. This corresponds with what was shown in Figure 5.8 regarding the streaming current of the water which indicated inadequate chemical addition at the beginning of the event and possible overdose at the end of the event. If additional coagulant was added at the start of the event, there may not have been an increase in filter effluent UV_{254} as shown in Figure 6.9 and 6.18. A similar trend is shown in Figure 6.19 for the July 3rd, 2013 event.
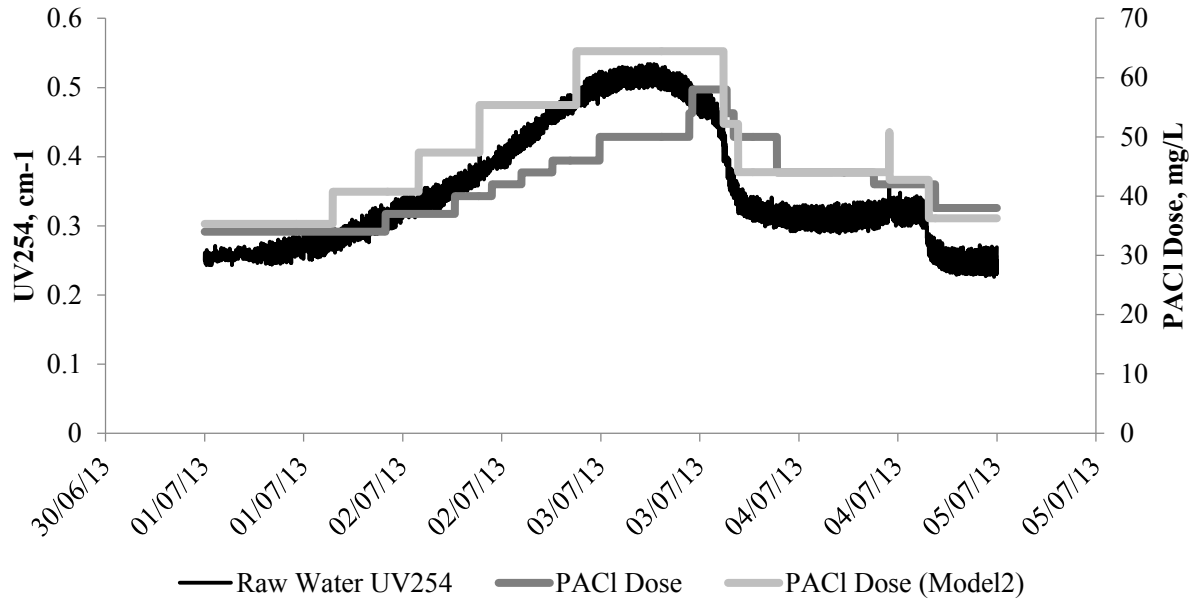
Figure 6.19: Projected PACl doses based on raw water UV_{254} (July 3rd, 2013)

The projected PACl dose is expected to increase more quickly at the beginning of the event. This agrees with the streaming current trend as shown in Figure 6.12. Again, if there was sufficient coagulant dose at the start of the event, there may not have been an increase in filter effluent UV_{254}. Finally, Figure 6.20 shows the projected PACl dose for the July 28th, 2013 event.
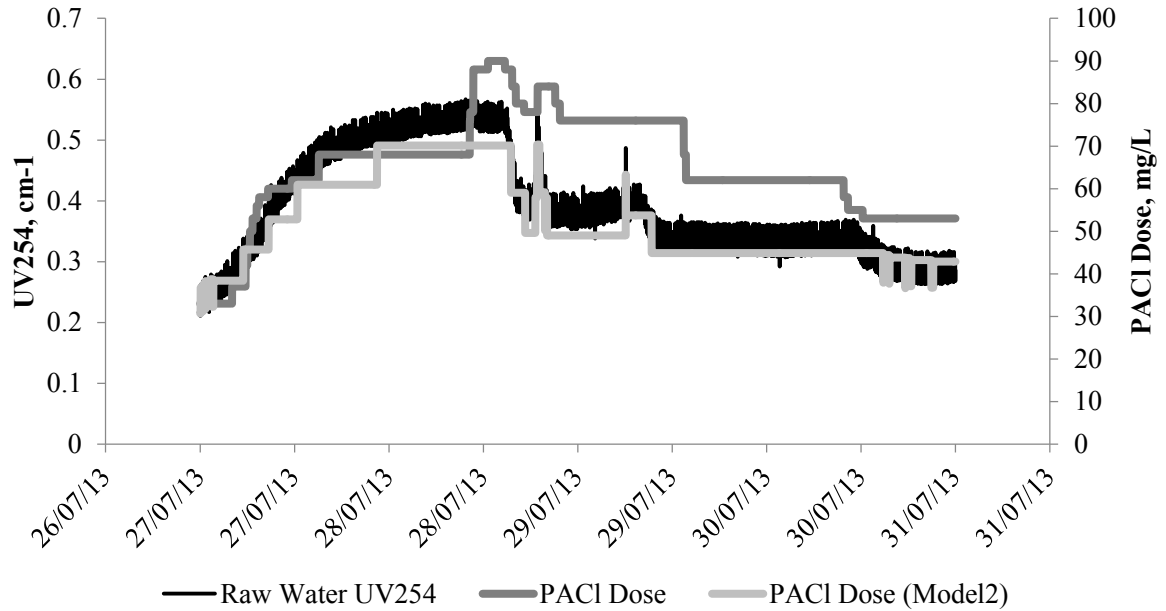
Figure 6.20: Projected PACl doses based on raw water UV_{254} (July 28th, 2013)

Although the model follows the actual PACl dose fairly closely at the beginning of the event, there is a noticeable difference at the end of the event where the projected PACl dose is approximately 10 mg/L lower.

Based on the projected PACl doses from the developed model, there exists two key potential benefits to online coagulation control. The first being an immediate reaction to rapid increases in organic concentrations within the feed water. NOM compounds have a greater coagulant demand compared to turbidity particles therefore basing adequate coagulant dosage upon measured increases in raw water UV_{254} would lead to more effective treatment over current plant practices.

The second benefit would be in cost savings on the tail end of a rain event. In the three events outlined, the projected PACl dose appeared to decrease more quickly than the actual PACl dose as raw water UV_{254} decreased. This is congruent with streaming current

trends during the rain events which indicated possible chemical overdoses at the end of the events.

6.5 Conclusions

During the course of the study, the BBWTP maintained on average a pH of 6.4 with fluctuations as high as 6.7 and as low as 6.0 during plant events. Ability to maintain a constant pH is essential if online coagulation control is to be considered.

Results from the online instrumentation set up showed that UV_{254} monitors could detect increases in raw water UV_{254} that were independent of raw water turbidity. These increases were also identified by the SCM which became more negative and drifted away from its set-point.

During a rain event, both raw water UV_{254} and raw water turbidity were shown to rapidly increase. However, the raw water turbidity was shown to return to its pre-event levels faster than raw water UV_{254}. Raw water UV_{254} required another 24 hours to return it its pre-event levels. NOM has a greater surface charge than turbidity. Basing coagulant dose on turbidity alone will not allow for proper removal of NOM, especially given that UV_{254} was shown to remain high after a rain event.

Streaming current was also shown to detect chemical inadequacies. At the beginning of each of the rain events, streaming current was shown to drop well below its set-point, indicating insufficient coagulant addition. Furthermore, as the raw water quality returned to its pre-event quality, the streaming current was shown to remain slightly above its set-point indicating possible chemical overdose.

Results from this phase of the study show that when the online instrumentation was properly maintained and pH was held within an acceptable range (i.e. ± 0.3 from pH of

minimum solubility), online SCM and UV_{254} monitors show ability to detect changes in source water quality. The regression model based on raw water UV_{254} demonstrated the relationship between raw water UV_{254} and coagulant demand which showed ability to avoid chemical inadequacies such as chemical under doses at the beginning of a rain event, and overdoses at the end of an event.

Based on the findings from the study, it is recommended that the online instrumentation be trialed during different seasons to track seasonal changes in NOM. It is also recommended that the prediction model based on raw water UV_{254} be trialed at full-scale for the determination of coagulant dose with SCM as a check for optimal coagulation control.

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

To investigate the viability of using online instrumentation to provide process control in response to rapid changes in source water quality, the treatment systems of three WTPs around Nova Scotia were reviewed. An audit of the each of the plants was conducted to determine current operating and coagulation process control treatment approaches and coagulation processes under normal source water quality conditions were examined. Online instrumentation was set up at two the WTPs to investigate the usefulness of online SCM and UV_{254} monitors during variable source water quality.

The importance of chemical addition for the removal of NOM from a water source was evident from the plant audit at the SWTP. Based on these results from the audit, it was determined that further experiments evaluating removal capabilities of three coagulants at varying pH was necessary. Bench-scale experiments were conducted to determine the impact of coagulant type, dose, and varied pH on coagulant performance. Due to the fact that the source water for the SWTP is low in alkalinity and highly variable in terms of NOM and turbidity, the results from the experimentation could be applied to other surface water sources with similar characteristics.

Results showed that when coagulant pH was held at the pH of minimum solubility, high reductions in turbidity and NOM in form of DOC and UV_{254} were observed with low aluminum concentrations in the finished water. The experiments were run using a jar test apparatus. Optimal dose was based on the point of diminishing returns for turbidity and NOM removal. This optimal dose was also verified by zeta potential results which ranged from -15 to -5 mV.

The results from the SWTP showed that determination of optimal coagulant dose could be determined using charge analysis for surface waters in the Atlantic Provinces that are primarily low in alkalinity and variable in turbidity and NOM. Specifically, the majority of the NOM within the source waters are in the dissolved phase (e.g. DOC, UV_{254}).

Online instrumentation was set up at two of the WTPs; FWTP and BBWTP. Results from FWTP showed the importance of maintaining a constant pH. When pH was not held constant, streaming current data could not be used. Preliminary online UV_{254} data showed that raw water UV_{254} increased with raw water turbidity during a rain event. Online data was only available for one rain event due to improper maintenance of the instrumentation. Results demonstrated the need for continuous care of the equipment including weekly draining of the process lines into the monitors to avoid clogging and allow for a representative sample to be sent to the monitor for analysis.

Results from the BBWTP showed that when the online instrumentation was maintained and calibrated, SCM and UV_{254} data can aid in coagulation process control. During rain events, both the online SCM and UV_{254} monitor showed ability to track changes in source water quality and indicate inadequacies in plant performance. During these events, rapid increases in raw water UV_{254} and turbidity were observed. However, it was shown that turbidity returned to its pre-event levels faster than raw water UV_{254}.

At the start of each event, streaming current was shown to decrease well below its set point at the beginning of the event. A sharp decrease from its set point indicated that there was inadequate coagulant addition to account for the decreased source water quality. These inadequacies may have been the cause for increases in filter effluent UV_{254}. During the end of the three events, streaming current was also shown to be slightly more positive

than its pre-event set-point indicating a chemical overdose. Based on the results from the study, there appears opportunity to improve current coagulation operations.

Results from the study demonstrated that both SCM and UV_{254} monitors could be used to aid in coagulation determination during rain events. Streaming current, however, was shown to be highly affected by shifts in pH. Furthermore, due to changes in raw water quality (e.g. seasonal shifts), jar tests must be frequently run to ensure the proper set-point. Raw water UV_{254} was not affected by changes in process (e.g. pH) and does not require a set-point. Furthermore, it gives a real-time indication on the amount of organics within the source water. Ability to base coagulant dose on changes in raw water UV_{254} shows opportunity to improve finished water quality by increasing coagulant as rapid changes in source water occur as well as cost savings by decreasing dose more quickly at the end of the event. Use of SCM as a check for optimal coagulation control would also allow for inadequacies.

7.2 Recommendations

Investigation into the use of online instrumentation for coagulation process control is becoming more important as drinking water regulations become more stringent. The ability to automatically control coagulation conditions using online instrumentation would reduce the frequency and severity of plant upsets as well as the need for the increase in staff during such times.

For this study, the online instrumentation was set up at the BBWTP for four months from May to September, 2013. To track seasonal changes in NOM and coagulant demand, it is recommended the instrumentation be set up over the course of a year. This would

allow for development of seasonal models as well as a general annual model to predict coagulant dose.

Newer models of SCM have been developed that incorporate an offset for shifts in pH. For plants that struggle with maintaining a stable pH, the newer SCM model would allow them to track changes of the charge of the particles within the source water without changes in pH affecting the readout.

Future work should include trialing the UV_{254} monitor at full-scale for the determination of coagulant dose. If possible, set up should allow for automatic chemical addition using the developed model as a starting point. The trial should include use of a model for prediction of coagulant dose under both normal source water quality conditions and upset conditions.

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