Coupled Chemically-Assisted Filtration (CCAF) Approaches for Increasing Filter Resilience and Performance During Drinking Water Treatment

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

The paramount objective of drinking water treatment is the prevention of acute waterborne disease. Filtration remains a critical barrier for ensuring that *Cryptosporidium* spp. and *Giardia* are removed during drinking water treatment. During periods of source water quality change is when water treatment systems have the highest likelihood of process upsets that can result in pathogen transport through the water treatment systems.

The goal of this research was to develop an approach for rapid detection of filter performance degradation and methods to assist with prediction of coagulant dosages for increased filter resilience. Four objectives were studied to achieve this goal.

Full-scale water treatment plant filtration data were analyzed to determine periods of process deviations leading to upset conditions. Filter performance dashboards were developed to summarize water quality parameters on a monthly basis to identify emerging or chronic issues impacting filtration performance. Real-time filter performance control charts were developed to detect filter breakthrough prior to reaching filter run termination criteria. Zeta potential was assessed as a potential critical control element through investigations on a direct-filtration pilot plant.

The study found that development of filter performance dashboards can be used to detect underlying conditions that can lead to filter upset conditions, such as early breakthrough or other correctable process oscillations that lead to reduced operational resilience to upset. Real-time control charts were found to be capable of detecting filter breakthrough well before exceedance of internal alarm limits for filter run termination. Finally, measurement of online zeta potential was found to be a promising tool to assess and to control coagulation chemistry to meet water quality needs, and to prevent chemical over- or under-dosing conditions that can lead to pathogen transport through the filtration process.

Data driven analytics and the addition of online zeta potential monitoring is recommended as tools to improve water treatment plant resilience against pathogen breakthrough under changing water quality conditions.

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Most importantly, this thesis would never have been possible without the unfailing patience and encouragement of my wife Lori and kids Kian and Tayo, in supporting the long years and endless nights to put this document together.

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LIST OF ABBREVIATIONS

AEP	Alberta Environment & Parks
ALUM	Aluminum Sulphate
CAF	Chemically Assisted Filtration
CCAF	Coupled Chemically Assisted Filtration
CCP	Critical Control Point
CCME	Canadian Council of Ministers of the Environment
CFM	Cubic Feet Per Minute
CoC	City of Calgary
DAF	Dissolved Air Flotation
DALY	Disability Adjusted Life Year
DBP	Disinfection By-Product
DF	Direct Filtration
DOC	Dissolved Organic Carbon
FTW	Filter To Waste
IESWTR	Interim Enhanced Surface Water Treatment Rule
IPCC	Intergovernmental Panel on Climate Change
GCDWQ	Guidelines for Canadian Drinking Water Quality
GWUDI	Groundwater Under the Direct Influence of Surface Water
HC	Health Canada
KPI	Key Performance Indicator
LT1SWTR	Long-Term 1 Surface Water Treatment Rule
LT2SWTR	Long-Term 2 Surface Water Treatment Rule
MCLG	Maximum Contaminant Level Goal
NOM	Natural Organic Matter
NP/mL	Number of Particles Per Milliliter
NTU	Nephalometric Turbidity Unit
PAC	Powdered Activated Carbon
PTF	Pretreatment Facility
QMRA	Quantitative Microbial Risk Assessment
RTF	Residuals Treatment Facility
SBF	Sand-Ballasted Flocculation
SDWA	Safe Drinking Water Act
SPC	Statistical Process Control
SWP	Source Water Protection
SWTR	Surface Water Treatment Rule
TOC	Total Organic Carbon
TOF	Top of Filter
UCL	Upper Control Limit
UFRV	Unit Filter Run Volume
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
WHO	World Health Organization
WTP	Water Treatment Plant
ZP	Zeta Potential

1 Introduction

The paramount objective of drinking water treatment is the prevention of acute waterborne disease (Hrudey 2004; Jalba et al. 2010). Drinking water-associated disease outbreaks remain a persistent concern, as they continue to occur globally (Schuster et al. 2005; Mason et al. 2010; Widerström et al. 2014; Efstratiou et al. 2017). Human-infectious protozoa, which include *Cryptosporidium* spp. and *Giardia duodenalis* (also referred to as *Giardia lamblia* or *Giardia intestinalis*), are of particular concern. *Giardia* is the most commonly reported intestinal protozoan worldwide, and the cause of most waterborne infectious disease outbreaks in North America (Adam 1991; Hrudey et al. 2004). In North America, regulatory policies focus on reducing infection risk by requiring drinking water system owners to implement treatment by granular media filtration (or equivalent technology) and disinfection (USEPA 1998, 2002, 2006; AEP 2012). Notably, source water concentrations of protozoan parasites are not monitored because of impracticalities and costs associated with routine monitoring. Impracticalities include time-consuming sample collection due to low environmental concentrations of protozoa, laborious analytical methods, and often highly variable analytical recovery (Health Canada 2019b). As a result, American and Canadian regulations for treated water quality rely on indirect measures of treatment system performance and provide pathogen removal credits based on indicators of "well-operated" treatment (USEPA 2006; AEP 2012; Ontario Regulation 2020). While *Giardia* is the most commonly reported enteric protozoan globally (Adam et al. 2016), *Cryptosporidium* is often a focus because it is relatively more difficult to remove by filtration because of its smaller size. Further, *Cryptosporidium* cannot be adequately treated by traditional oxidant-based disinfection processes such as chlorination (Hanbin Li et al. 2001). Although UV irradiation can effectively inactivate *Cryptosporidium* spp., filtration remains a critical, required treatment barrier for preventing its passage into distributed water supplies (USEPA 2006; AEP 2012; Ontario Regulation 2020).

Filtration, more formally described as physico-chemical filtration and sometimes referred to as "chemically-assisted" filtration (CAF), remains a critical barrier for ensuring that *Cryptosporidium* spp. and *Giardia* (oo)cysts are removed during drinking water treatment. Critically, CAF processes are not size exclusion processes—to work, they require adequate destabilization of the small, colloidal particles suspended in source water (Edzwald 2011; Lee et al. 2021). Particle

destabilization enables particles, which include protozoa, to aggregate as flocs that range in size from microscopic to visible, and therefore enables their removal by subsequent sedimentation and filtration processes. The critical role of coagulation for ensuring adequate particle and protozoan removal by filtration is widely recognized (Amirtharajah et al. 1982; Amirtharajah 1988; Tobiason et al. 1988; Patania et al. 1995; Emelko 2001; 2003; Huck et al. 2001). Despite this and widespread general understanding of CAF process optimization approaches, reported removals of *Cryptosporidium* spp. by CAF are quite variable (Tobiason et al. 1988; Nieminski et al. 1995; Patania et al. 1995; Edzwald et al. 1998; Emelko 2001; 2003; Huck et al. 2001; Emelko et al. 2004; 2005; Brown et al. 2009; Hijnen et al. 2010). As a result, it is generally believed that "well-operated" conventional CAF processes can achieve at least 3-log reduction of *Cryptosporidium*. It should be highlighted that systems with source waters relatively high in turbidity (>~2 NTU) and dissolved organic carbon (DOC) concentrations (>~3mg/L) (Edzwald et al. 2000; Valade et al. 2009; Efstratiou et al. 2017) are generally expected to have higher source water concentrations of *Cryptosporidium* spp. oocysts (Dechesne et al. 2007; Srisuphanunt et al. 2010; Health Canada 2019b). As a result, *Cryptosporidium* removal by filtration has been predominantly studied in such systems (Patania et al. 1995; Emelko et al. 2005; Hijnen et al. 2010), for which several tools are available for optimizing coagulant dosages prior to clarification (typically by sedimentation) and filtration.

In contrast, it can be challenging for utility operators to ensure that adequate particle destabilization is achieved prior to filtration in systems treating high quality source water. Although these systems regularly meet the filtered water turbidity targets of the suite of U.S. Surface Water Treatment Rules and analogous international regulations, turbidity following coagulation and sedimentation (when present) can often be higher than in the source water because low applied coagulant doses result in the formation of micro-flocs that are not especially settleable (Culp 1977; Treweek 1979)—this underscores a common lack of connectivity between coagulant dosing, clarified turbidity, and filtration performance in systems treating high quality source water. Direct filtration (DF) plants (i.e., those with coagulation and flocculation, but not sedimentation processes prior to filtration) are designed to ensure particle removal through filtration by optimizing chemical coagulant addition for particle destabilization (Treweek 1979; Mccormick et al. 1982; Valade et al. 2009). However,

although DF is a CAF process, it only receives 2.5-log treatment credit for removal of protozoan parasites because of the assumption that conventional CAF processes that incorporate clarification (typically by sedimentation) will achieve 0.5-log of parasite removal in addition to that achieved by filtration alone (Edzwald et al. 1998; AEP 2012). Notably, these beliefs about process design and protozoan pathogen removal by various treatment process configurations are believed to be precautionary. Critically, however, they are also potentially concerning because implementation of conventional treatment (i.e., coagulation, flocculation, sedimentation, and filtration) may provide a false sense of security regarding protozoan pathogen removal by CAF in systems that treat high quality source water and assume that coagulant dosing is adequate when the filter effluent turbidity requirements of the suite of Surface Water Treatment Rules are met (Batista et al. 2021; Lee et al. 2021).

The importance of protozoan pathogen removal by CAF cannot be underscored enough. All drinking water systems, and especially those that treat high quality source water, are vulnerable to episodic, increasingly extreme source water quality deterioration resulting from climate change-exacerbated landscape disturbances such as fires, floods, and hurricanes (Emelko et al. 2011; Stone et al. 2011; IPCC 2018). While UV irradiation provides an additional treatment barrier against the passage of infectious protozoa into treated water supplies, increasingly variable source water quality, which can be expected as a result of these climate change-exacerbated landscape disturbances (Stone et al. 2011), can lead to conditions that potentially challenge particle removal by filtration (Emelko et al. 2011; Kundert et al. 2014), thereby potentially reducing the efficacy of disinfection by UV irradiation (Mamane 2008). Thus, there is an urgent need to ensure that critical treatment processes such as CAF are both well-operated and resilient to sudden changes in source water quality through the application of sufficient coagulant addition. This need is further emphasized by observations that both isolated cases and outbreaks of cryptosporidiosis and giardiasis have been linked to weather-related factors that also may be exacerbated by changing climate (Casman et al. 2001; Semenza et al. 2012).

1.1 Research Goals and Objectives

To address the lack of connectivity between source water quality, coagulant dosing, clarified water turbidity, and filtration performance with respect to particle and pathogen removal in systems treating relatively high quality source water, the overall goal of this research was to develop an approach for rapid detection and prediction of filter performance degradation to assist in coagulant dosing. Meeting this goal thus also provided a way to increase treatment resilience in response to water quality changes and operational upsets, such as those that can be increasingly expected as a result of climate change-exacerbated landscape disturbances. The following objectives were developed to address this goal:

1. To identify the operational conditions at which turbidity is an inadequate indicator of connectivity between coagulant dosing, clarified turbidity and filtration performance;

2. To evaluate monitoring tools and data-driven analytics to ensure optimal CAF performance for maximizing particle and protozoan pathogen removal by CAF;

3. To develop an approach for application of monitoring tools to achieve filter effluent turbidity and pathogen reduction targets; and

4. To evaluate the implications of operational configuration (e.g., conventional CAF, direct filtration, inline filtration) on application of monitoring tools to achieve filter effluent turbidity and pathogen reduction targets.

1.2 Research Approach

The research study was conducted in two phases. Phase 1 addressed objectives 1, 2 and 3, through a literature review and evaluation of historical data from a high-quality source water system in Calgary, Alberta, Canada. Historical data from the full-scale Glenmore Water Treatment Plant were examined and periods of sub-optimal treatment, as indicated by filter effluent turbidity, were identified. A framework for anticipating/rapidly identifying poor filtration events was developed based on analysis of three key water quality parameters: post-coagulation zeta potential, filtered

water turbidity, and total filtered water particle counts greater than 2µm. Phase 2 of the study addressed objective 4, which included a series of pilot-scale, direct in-line filtration investigations to assess the feasibility of direct filtration at stable, high-quality water conditions to meet turbidity and particle count filtered water quality goals. The use of zeta potential as a key indicator of particle destabilization and predictor of optimized pretreatment performance in response to coagulant and polymer adjustments was also investigated.

1.3 Thesis Structure

The thesis is organized into five chapters, a reference list, and appendices.

Chapter 1 contains the thesis introduction, thesis goal and thesis objectives.

Chapter 2 contains key background information and a literature review of relevant information regarding drinking water treatment, physico-chemical filtration, treatment of protozoan parasites, and associated regulatory considerations in a predominantly North American context.

Chapter 3 summarizes the environmental setting of the full- and pilot-scale drinking water treatment plants that were utilized in this investigation, with a focus on source water quality. The research methodology is detailed, including experimental development and rationale. The various materials and methods developed and utilized through the research are also specified.

Chapter 4 provides the thesis research observations and results.

Chapter 5 provides a synthesis of the literature review and discussion of the research results.

Chapter 6 provides conclusions, implications, and recommendations for further investigation.

2 Background & Literature Review

2.1 Health Risks Attributable to Enteric Protozoa in Drinking Water

The paramount objective of drinking water treatment is the prevention of acute waterborne disease (Hrudey 2004; Jalba et al. 2010). While the combination of effective filtration and disinfection have reduced the frequency and severity of waterborne illnesses over time (Paul et al. 2006), drinking water-associated disease outbreaks have unfortunately persisted over the past several decades (Schuster et al. 2005; Mason et al. 2010; Widerström et al. 2014; Efstratiou et al. 2017). Human-infectious *Cryptosporidium* spp. and *Giardia duodenalis* (also referred to as *Giardia lamblia* or *Giardia intestinalis*), are of particular concern. *Giardia* is the most commonly reported intestinal protozoan worldwide, and the cause of most waterborne infectious disease outbreaks in North America (Adam 1991; Hrudey et al. 2004).

To ensure the provision of adequate amounts of safe drinking water, a multi-barrier approach is often utilized. It is "an integrated system of procedures, processes and tools that collectively prevent or reduce the contamination of drinking water from source to tap in order to reduce risks to public health" (CCME 2004). Specifically, the multi-barrier system applies controls or barriers at several points to increase its efficacy against threats such as passage of human-infective microorganisms into treated and distributed water supplies. As shown in Figure 2.1, the main elements of a multi-barrier approach to the provision of safe drinking water are: source water protection, drinking water treatment for physical removal and disinfection of pathogens, and distribution system operation to maintain water quality to the customer (CCME 2004; WHO 2017). These elements are managed in a necessarily integrated manner through water quality monitoring; source-to-tap water supply management; legislative and policy frameworks; guidelines, standards and objectives; public engagement; and research and development of science and technology solutions (CCME 2004).

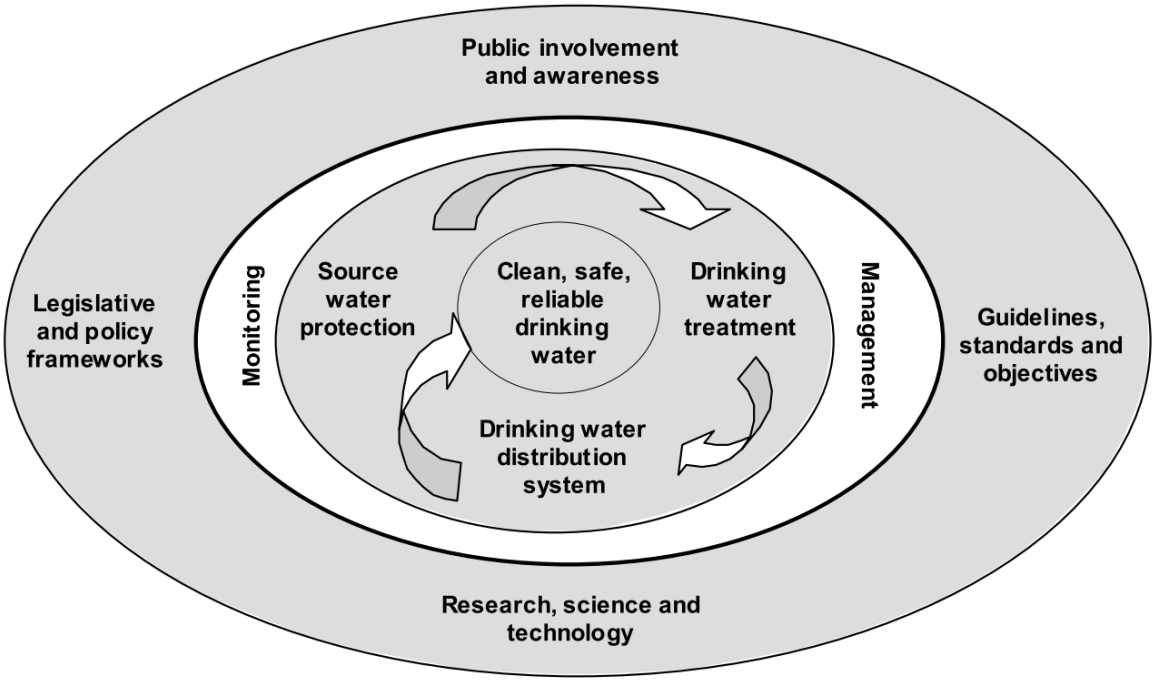

Figure 2.1 Components of the multi-barrier approach to safe drinking water (CCME 2004).

The key breakdowns within the treatment barriers that can result in the passage of waterborne pathogens into treated and distributed drinking water supplies, and possibly lead to human infection, most typically revolve around human error (Tang et al. 2013), natural hazards, equipment failures, intrusion of contaminants into the distribution system, or lack of treatment resilience in in responding to source or treated water quality changes (Schuster et al. 2005). Although waterborne pathogens reaching consumers in sufficient quantities to cause illness remains unlikely, the likelihood of infection is greatly increased when multiple failure scenarios occur concurrently (Hrudey et al. 2006; Wu et al. 2009).

The primary microbiological contaminants associated with outbreaks of waterborne disease are viruses, bacteria, and protozoan species. Viruses and bacteria are effectively treated through a combination of physico-chemical removal and disinfection processes, which typically involve chemical oxidation or ultraviolet irradiation. The human infective protozoa (*Giardia duodenalis* and

Cryptosporidium spp.) are amongst the highest-risk pathogens for waterborne outbreaks of disease because of their ubiquitous presence in surface water (Health Canada 2019b) and resistance to disinfection by oxidants traditionally used in drinking water treatment. Waterborne *Giardia* and *Cryptosporidium* are respectively found in water supplies as resilient cysts and oocysts that can infect hosts upon ingestion, causing severe gastrointestinal complications and even death (Thompson et al. 2016; Health Canada 2019b). *Giardia* cysts are highly resistant to chlorine disinfection, while *Cryptosporidium* oocysts are nearly impervious to chlorine disinfection at concentrations used for drinking water treatment (WHO 2017). Disinfectants such as UV and ozone can also reduce concentrations of infective cysts and oocysts, but only at certain operational conditions that include low turbidity (Korich et al. 1990; Bukhari et al. 2000; Clancy et al. 2004; Keegan et al. 2007; Health Canada 2019b). In contrast, both CAF and pressure-driven membrane filtration are effective in removing (oo)cysts of *Giardia* and *Cryptosporidium* from water (Patania et al. 1995; Letterman 1999; Emelko et al. 2005; Hijnen et al. 2010). If source water concentrations are extremely elevated, however, further treatment may be required (USEPA 2006); notably, this level of source water quality deterioration has not been widely reported outside of wastewater/stormwater reuse applications (Schoen et al. 2015; Walker et al. 2016; Domenech et al. 2018).

2.1.1 Quantification of health risk

Drinking water quality is managed through preventive measures to limit harmful exposures. It is critical to note that the provision of "safe" drinking water does not necessarily mean the complete absence of risk. In practice, the provision of "safe" water means that the infection risk is so low that consumers do not need to be worried about becoming ill from ingesting it (Hrudey et al. 2006). More specifically, this implies that the probability of illness should be negligible when compared to other sources of illness. For example, in the case of pathogenic protozoa, the United States Environmental Protection Agency (USEPA) has defined an upper limit of exposure, such that there is less than a 1 in 10,000 (10^{-4}) risk of infection from ingestion of potable water—this is achieved by achieving a minimum 3-log (i.e., 99.9%) reduction of protozoa during treatment. Higher levels of treatment may be required based on the presence and concentration of these pathogens in source

waters (USEPA 2006). Agencies such as the World Health Organization (WHO) and Health Canada (HC) have proposed Quantitative Microbial Risk Assessment (QMRA) modelling approaches to estimate the risk of infection and illness, or disability life adjusted years (DALYs), to consider both the probability of experiencing an illness and the impact of the associated health effects resulting from exposure to pathogens in water (LeChevallier et al. 2004; Health Canada 2018).

QMRA is widely used to inform water safety management decisions, such as provision of adequate amounts of treatment to reduce the risk of waterborne illness to acceptable levels. Thus, QMRA can assist with prioritizing hazards, selecting appropriate interventions, and setting health-based performance targets. The probability that disease may occur is based on water quality and treatment capacity information—this process can be reversed to calculate treatment requirements derived from health-based targets and source water quality (Schmidt et al. 2011, 2013; Schoen et al. 2015; Emelko et al. 2019). The WHO, USEPA and Health Canada have published guidance documents on utilization of QMRA assessments to quantify health risks for several reference pathogens (USEPA 2010; WHO 2016; Health Canada 2018, 2019b). Accordingly, QMRA approaches have been widely used to assess the treatment capabilities of several types of water treatment systems (Medema et al. 2009; Elliot 2015; Tfaily et al. 2015; Razzolini et al. 2016; Health Canada 2018).

2.1.2 Regulatory oversight

In the United States, the USEPA sets national maximum contaminant limits through the Safe Drinking Water Act (SDWA, 1974, 1986) and associated rules and their amendments. To reduce illnesses attributable to pathogens in water, a suite of rules was developed to guide treatment requirements for public systems using surface water and groundwater under the direct influence of surface water (GWUDI). In 1989, the Surface Water Treatment Rule (SWTR) established maximum contaminant level goals (MCLGs) for viruses, bacteria, and *Giardia duodenalis* (referred to as *Giardia lamblia* at the time). The SWTR also established minimum treatment requirements of filtration and disinfection for surface water and GWUDI systems without filtration avoidance permission. It also included treatment technique requirements in which approved treatment processes were assigned removal or inactivation “credits” to protect against the adverse health effects from exposure to

specific waterborne pathogens (USEPA 1989). In 1998, the Interim Enhanced Surface Water Treatment Rule (IESWTR) set a maximum contaminant level goal (MCLG) of zero for *Cryptosporidium* and a 2-log (99%) *Cryptosporidium* removal requirement for filtered systems (USEPA 1998). The protozoan removals were to be achieved by meeting a combined filter effluent turbidity limit of <0.3 NTU. In 2002 and 2006, the IESWTR was respectively supplemented by the Long-Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) and the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR); conventional drinking water treatment plants (i.e., those with coagulation, flocculation, sedimentation, and filtration) received 2-log (99%) and then 3-log (99.9%) *Cryptosporidium* treatment credits, respectively, under these rules (USEPA 2002, 2006).

In Canada, Health Canada publishes the Guidelines for Canadian Drinking Water Quality (GCDWQ) on behalf of the Federal-Provincial-Territorial Committee on Drinking Water (Health Canada 2019c). Provincial environment ministries typically follow Health Canada's recommendations for maximum contaminant levels and health-based treatment targets, amended regularly to incorporate new standards or updated treatment targets (AEP 2012; Ontario Regulation 2020); these regulatory criteria are generally analogous to those in the United States. Local water utilities are then responsible for the day-to-day operation of the water treatment systems. Some Canadian provinces also utilize the water safety planning approaches recommended by the World Health Organization (WHO 2017). Water safety plans build on the GCDWQ and help utility managers and operators ensure that treated water of consistently excellent quality is delivered to consumers by providing a framework for decision-making based on (1) collecting and evaluating critical information available about the water supply and treatment system, (2) analyzing and understanding potential risks, (3) assessing risk mitigation to correctly reduce risks to an acceptable level, and (4) determining what resources and actions are necessary to ensure that the identified risks are reduced.

2.2 Particle and Pathogen Removal During Water Treatment

2.2.1 Treatment of surface water – Overview

As a result of either natural events or human activities, a variety of particles including microorganisms, organic materials, and inorganics are present in the source waters that enter water

treatment plants (WTPs). Conventional drinking water treatment systems use chemical pretreatment (i.e., coagulation, flocculation, and sedimentation) and subsequent filtration to remove particles, including microbial contaminants (Edzwald et al. 1998). These treatment steps are critical to subsequently ensuring effective disinfection of bacteria, viruses (Templeton et al. 2007), and protozoa (WHO 2017).

Most particles and microorganisms that are suspended in water have a negative surface charge, so they tend to repel each other and therefore remain largely dispersed in the water. This negative surface charge is typically because of natural organic matter (NOM) adsorption on the particle surfaces (Drozd et al. 1996; Sharp et al. 2004; Sharp, Parsons, et al. 2006). Without chemical pretreatment, particles will remain in a "stable" state, in which they electrostatically repel one another, thereby preventing attachment and removal. Thus, coagulation and flocculation processes are designed to "condition", or "destabilize" suspended particles to encourage their aggregation into larger floc particles for more efficient removal during subsequent processes, such as sedimentation and filtration (Tobiason et al. 1988).

Addition of positively charged cations and/or polymer chains are used in pretreatment to destabilize and bind particles together. Chemical pretreatment also enhances the removal of organic molecules found at elevated concentrations in some source waters (Pernitsky et al. 2006). Removal of natural organic matter prior to chemical disinfection is important for minimizing the formation of disinfection by-products (DBPs) that form upon its reaction with chlorinated disinfectants; some DBPs are associated with higher rates of some cancers (e.g., bladder cancer) after long-term exposure, though those linkages remain "questionable and likely small" compared to other risk factors (Cotruvo et al. 2019).

Surface water quality varies widely between environmental settings. Water treatment process selection and sizing is based on site-specific physical, chemical, microbiological, and radiological water quality; source water particle/suspended solids and total or dissolved organic carbon (TOC/DOC) concentration and character, as well as the presence of anthropogenic contaminants, are especially critical to treatment process design (MWH 2012). Where particle concentrations and

coagulant requirements (also referred to as coagulant "demand") do not provide enough material to flocculate and settle effectively ahead of the filtration process, the sedimentation step can be eliminated. The resulting treatment scheme is referred to as direct filtration (DF); it relies on effective particle destabilization for particle removal exclusively by deposition on filter media surfaces. DF occurs where coagulants are dispersed with mechanical mixing/flocculation prior to filtration; direct in-line filtration (often simply referred to as "in-line filtration") occurs without the mixing step, where contact flocculation occurs at the surface of the filter media (Hutchison et al. 1974; Culp 1977; Mccormick et al. 1982; MWH 2012). As filters are constrained by the number of effective particle attachment sites that are available on the media that they contain, this limits the mass of particles that can be removed before the filter media are fully utilized and particles begin passing into subsequent treatment processes. For direct or inline filtration systems to function, high quality source waters are typically required to have turbidity of less than 10 NTU and TOC or DOC concentrations of less than 2-4 mg/L (Valade et al. 2009; MWH 2012).

Other pretreatment adaptations have been developed to deal with specific issues that challenge conventional pretreatment systems, such as high turbidity swings (e.g., during runoff periods) or high TOC/DOC loads. For managing rapid shifts in turbidity, solids contact units such as sand-ballasted flocculation (SBF) have been developed. SBF incorporates a microsand and polymer to increase the density and sedimentation characteristics of the coagulated water, and greatly enhances the sedimentation rates (Ghanem et al. 2007; Sieliechi et al. 2016; Lapointe et al. 2017, 2018). Powdered activated carbon (PAC) can be integrated into pre-treatment processes to remove synthetic and natural organic matter (Bhatnagar et al. 2017; Sillanpaa et al. 2018). Dissolved air flotation (DAF) uses the properties of finely dispersed air bubbles to float particles to the water surface for skimming and removal. DAF has proven particularly effective in systems with high organic and low particle content which makes traditional settling of low density floc particles problematic (Edzwald et al. 1999, 2001). Enhancements such as these improve pretreatment resilience to changes in source water quality and character that can challenge treatment. To illustrate the increasing complexity of treatment process requirements as source water quality

deteriorates and/or becomes more variable, simplified process flow schematics depicting DF, conventional treatment, and SBF are presented in Figure 2.2.

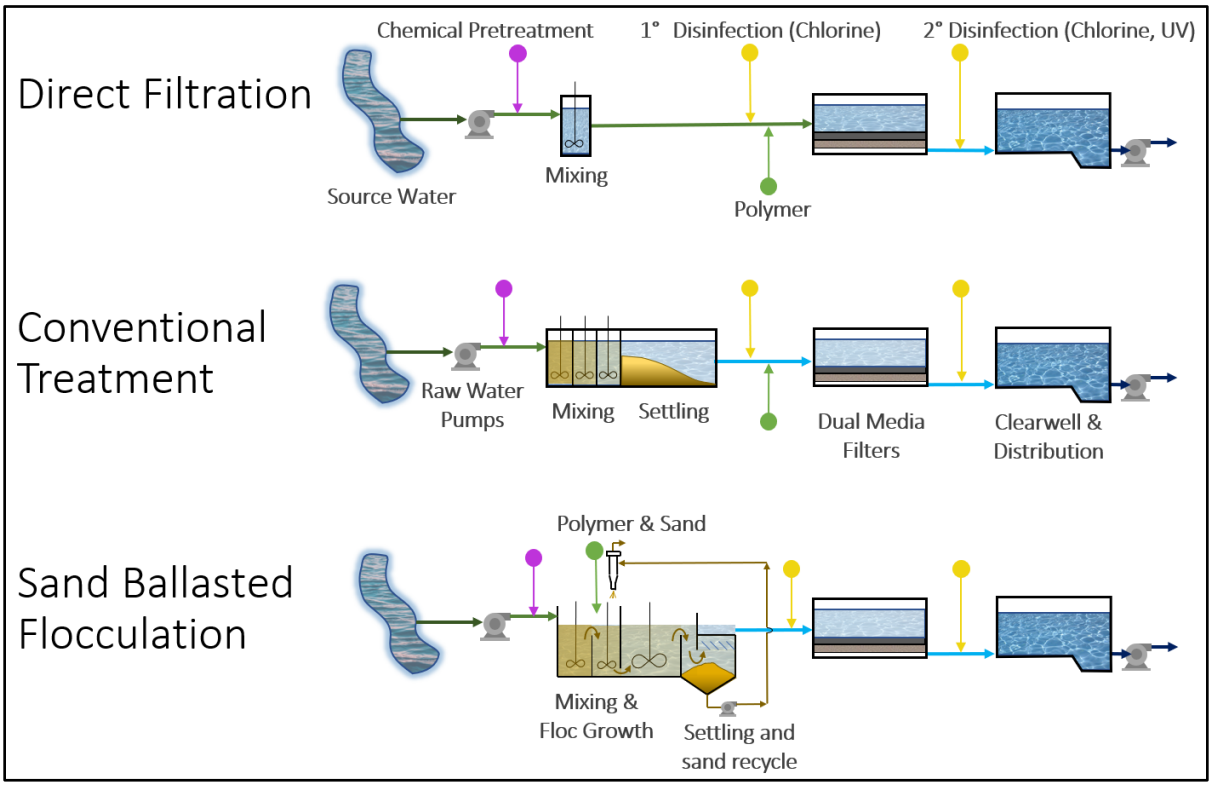

Figure 2.2 Simplified direct filtration (DF), conventional, and sand-ballasted flocculation (SBF) water treatment process flow diagrams illustrate the increasing complexity of treatment process requirements as source water quality deteriorates and/or becomes more variable (Adapted from MWH, 2012).

2.2.2 Coagulation

Chemical coagulants comprised of positively charge cations and/or polymer chains are typically added to destabilize and aggregate particles by four mechanisms: (1) double layer compression, (2) adsorption and charge neutralization, (3) enmeshment in precipitate (sometimes referred to as sweep floc coagulation), and (4) interparticle bridging (by polymers); notably, double layer

compression, adsorption and charge neutralization occur concurrently and cannot readily be differentiated in practice (Edzwald 2011); thus, they are discussed in Section 2.2.2.1 below.

2.2.2.1 Double layer compression

Attraction forces exist between all types of particles. The intermolecular force, termed Van der Waals forces, are comprised of weak London Dispersion Forces and stronger dipole-dipole forces; they are attractive forces that act on particles at close separation distances (Hamaker 1937; Shen et al. 2017). Repulsive electrostatic forces associated with the overlapping ion clouds that surround like-charged particles limit how closely particles can interact with one another, thereby creating an energy barrier to aggregation (or adhesion on surfaces) (Edzwald 2011).

Coagulation reactions and subsequent particle flocculation depend on the neutralization of electrostatic surface charge between particles and compression of the electrical double layer that surrounds each particle (Figure 2.3). Negatively charged suspended particles accumulate ions of opposing charge in the region immediately surrounding their surface; this fixed layer is called the Stern layer. Beyond this layer is a "diffuse region" of freely moving positive and negative ions that are present in a "cloud", in which there is a gradient of counterions. The concentration of this gradient decreases with distance from the particle surface. The combination of ions in the stern and diffuse layers forms the electrical double layer at the particle-liquid interface. The counterions near the particle surface will move with it through the fluid. The distance from the particle surface to the edge of the diffuse layer is called the "plane of shear", or "shear-plane" (MWH 2012).

As there is a change in electrical charge between the surface of the particle and the shear-plane, an electrical potential is formed, called the zeta potential (ZP). For particles to aggregate, sufficient counterions must be added to the water matrix to compress the width of the diffuse layer (Gregory et al. 2003; Davis et al. 2014). In general, a higher density of counterions in solution will mean that a higher number of counterions will be in the vicinity of the negatively charged particles surfaces to neutralize overall particle charge over shorter distances. Once coagulant addition has added sufficient volumes of counterions to the bulk suspension to minimize interparticle separation distances, the energy barrier is lowered, and Vander Waals forces are sufficiently attractive so that the particles remain aggregated as flocs (or deposited on filter media surfaces).

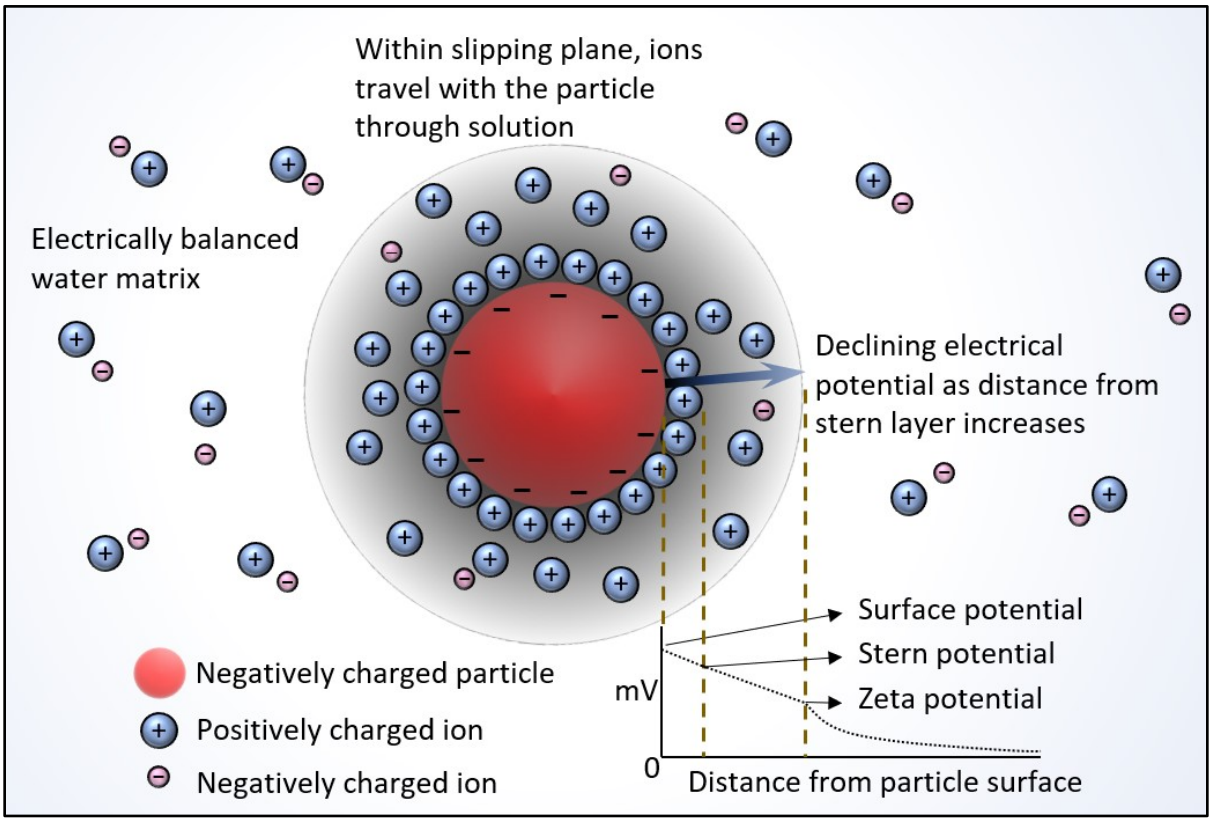

Figure 2.3 Illustration of negatively charged particle and associated electrostatic double layer. Attraction of the predominantly positive charged ion cloud next to the negatively charged particle surface creates an electrical potential, with charge density declining with increasing distance from the particle surface. Ion cloud thickness compresses (i.e., double layer compression) as ionic strength of the water increases and surface charge is neutralized over a shorter distance (adapted from MWH, 2012).

Zeta potential measurements during water treatment have been shown to follow a distribution. That distribution is caused by a variety of factors, including particle shape and angularity (Kim et al. 2008). The implication from presence of a charge distribution is that process trains within the water industry can operate over a range of zeta potential values. Each source water will contain a non-homogenous mixture of particles with varying surface charges driven by pH of solution, reactivity of surface function groups, temperature, NOM and inorganic ions (Jefferson et al. 2004).

2.2.2.2 Charge neutralization, adsorption and sweep flocculation

When coagulant is mixed into water, its chemical solubility limit will eventually be exceeded (Davis et al. 2014). At the solubility limit, further addition of chemical will drive equilibrium reactions to form coagulant solids. The newly formed solids can form weak attachments to both themselves and to other particles in the water (Gregory et al. 2003). Depending on the chemical and water conditions, the solids will chemically transition into more complex forms of varying surface charge, allowing for adhesion to the naturally occurring particles in the raw water stream (Edzwald 2011). As floc density surpasses that of the surrounding water matrix, the floc particles settle via gravity. Sweep floc formation and settling is a fundamental process required in naturally occurring surface waters with high chemical demand, to ensure that the downstream filtration processes are not overwhelmed with solids.

Alum coagulant used in water treatment systems is generally purchased in liquid form. Typically denoted as Al^{3+}, concentrated liquid alum exists in its hydrated form as $\left[Al_2(SO_4)_3{}^{3+} \bullet (H_2O)_n\right]$ (Pernitsky et al. 2006). Once added to water, the highly positive aluminum ions separate from the sulphate ions to form aluminum tetrahedron structures $\left[Al(H_2O)_4{}^{3+}\right]$ (Dentel 1991), with strong bonds to the surrounding oxygen atoms of the water molecules (Figure 2.4).

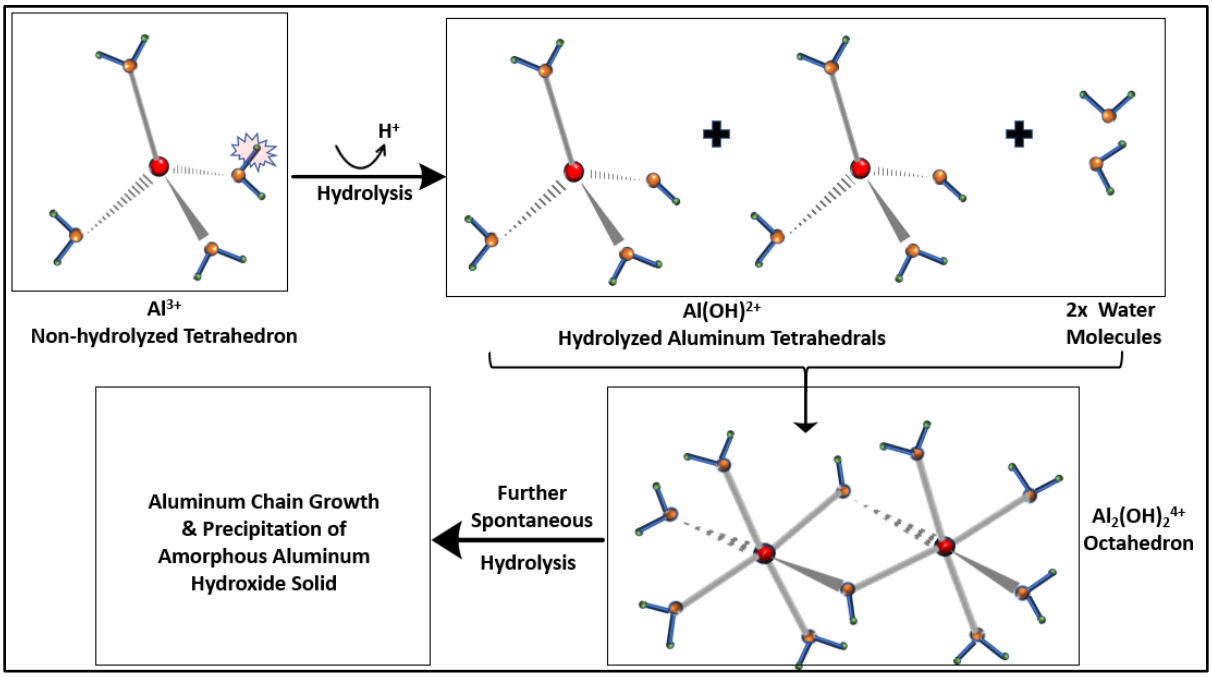

Figure 2.4 Aluminum sulphate hydrolysis reactions, dimerization, and growth (Adapted from Ruiz, McAdon, et al. 1997).

The strong aluminum-oxygen bonds result in a weakened interaction between the oxygen-hydrogen bonds of the water molecules, resulting in hydrolysis, or the release of protons into the surrounding water matrix under the pH conditions typical of surface water treatment systems. With the loss of each proton, the total positive charge of the tetrahedron declines by one, as described in the following reaction (1):

$$\left[Al(H_2O)_4{}^{3+} \xrightarrow{Hydrolysis} Al(OH)(H_2O)_3{}^{2+} + H^+\right] \quad (1)$$

For alum, the first hydrolysis reaction occurs within seconds of injection into the water matrix, and requires a rapid-mix step to distribute the aluminum ions evenly into the water matrix for first-stage charge neutralization (Letterman 1999). The positively charged aluminum tetrahedral monomers will attach preferentially to negatively charged species in the water matrix with the highest charge affinity. With more alum addition, the total metal ion in the system will allow remaining single Al^{3+} monomers to combine with additional water molecules to form complex polynuclear species (i.e.,

$Al_2(OH)_2^{4+}$ octahedrons) and undergo further hydrolysis reactions (Georgantas et al. 2006). At sufficient concentrations and longer reaction times, in the order of minutes, solid aluminum hydroxide floc will begin to form. At high pH conditions, the solid hydroxide will undergo further hydrolysis to reform a highly soluble and negatively charged aluminate ion (i.e., $Al(OH)_4^-$). The aluminate ion represents an undesirable product for water treatment; it will remain dissolved in solution, passing through the filtration process and adding to the total aluminum concentration of the final potable water product (AEP 2012; Health Canada 2019a). In contrast, if the water pH of the subsequent treatment units (i.e., typically clearwells or reservoirs) become more acidic, the reversible hydrolysis reaction can occur, and solid hydroxide floc can reform and deposit within the distribution system. Thus, pH control after coagulant addition is a critical component of any treatment process.

The release of positively charged hydrogen atoms through hydrolysis is buffered by the presence of alkalinity in source waters, where the released protons combine with carbonates to consume alkalinity (Edzwald 2011). In low alkalinity waters, the pH of solution quickly drops, requiring the addition of alkalinity to maintain pH levels within optimal ranges.

Based on the presence of first-order hydrolysis products and subsequent formation of solid hydroxide floc, distinct coagulation and flocculation mechanisms can be considered; they depend on the raw water quality, including organic and inorganic particle compositions. Source water NOM can vary widely in structure and charge density depending on its origin, and often varies seasonally (Sharp, Parsons, et al. 2006). Organics with surfaces containing carboxyl (COO^-), amino (NH_3^+), or hydroxyl (OH^-) functional groups, for example, are strongly attracted to the aluminum monomers, and exert high coagulant demand (Thurman 1985; Sharp, Parson, et al. 2006). Inorganic particles, such as clay, are typically formed from layered silica-based sheets. Silica atoms within the clay sheets can be substituted with other atoms, such as aluminum, to create a weak negatively charged framework; the resulting colloid contains a weaker surface charge relative to organic molecules and exerts a comparatively lower coagulant demand (Henderson et al. 2006). In the absence of significant source water organics, turbidity forming particles will drive coagulant demand. Figure 2.5 summarizes the typical hydrolysis reactions and coagulation regimes for a given water source.

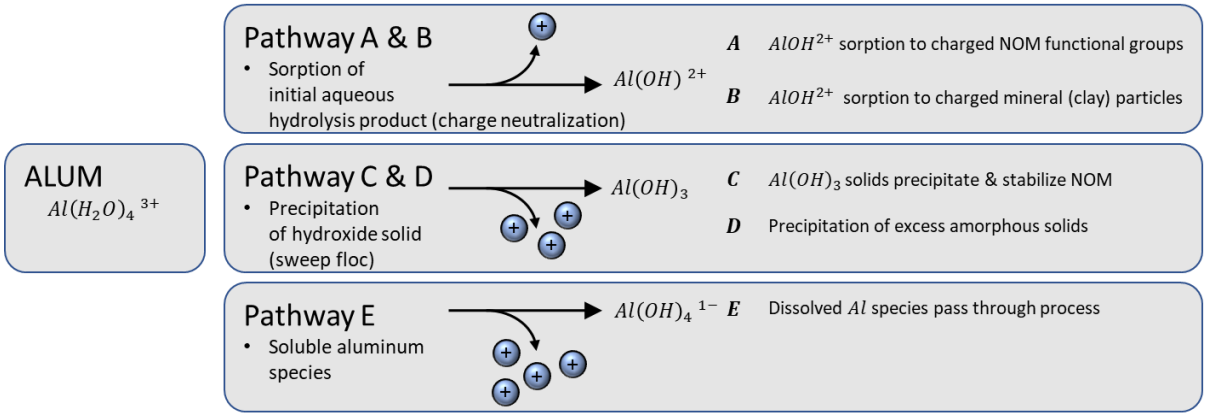

Figure 2.5 Reaction pathways of hydrolysis products, following coagulant addition to water (modified from Letterman 1999).

As detailed by Letterman (1999), pathways A and B in Figure 2.5 represent reactions between the first order alum hydrolysis product and binding sites on contaminant particle surfaces. Pathway C occurs where the solubility limit of aluminum is exceeded, and hydroxide floc is subsequently formed. The hydroxide solids collect and enmesh waterborne particles into larger agglomerations that are capable of settling or attaching to filter media. Pathway D occurs where excess alum is added, to form a large amorphous floc particle. Pathway D can lead to an over-coagulation condition, where particles re-stabilize within the water matrix to impede sedimentation and effective filtration. Pathway E represents the soluble aluminum species formed during coagulation, which can pass through filtration processes. This can be minimized by controlling pH to the point of minimum solubility prior to filtration; it also depends on temperature and reaction times. In high quality source waters with very low organics and particle loads, the overall coagulant demand produces so little hydroxide floc that a sedimentation step is not required to remove the coagulated flocs prior to filtration (Letterman 1999).

Amirtharajah & Mills (1982) analyzed numerous coagulation studies to generate a generic solubility diagram to describe the dominant mechanisms of alum coagulation. That diagram is reproduced in Figure 2.6 and illustrates the regions of suspension pH and applied alum concentration that correspond to each mechanism. Water treatment system operators can utilize the generic solubility

diagram to target treatment system pH to minimize soluble aluminum levels and to maximize (or minimize) floc formation based on their unique source water characteristics and the removal mechanisms that are relevant to the treatment processes utilized (Amirtharajah et al. 1982).

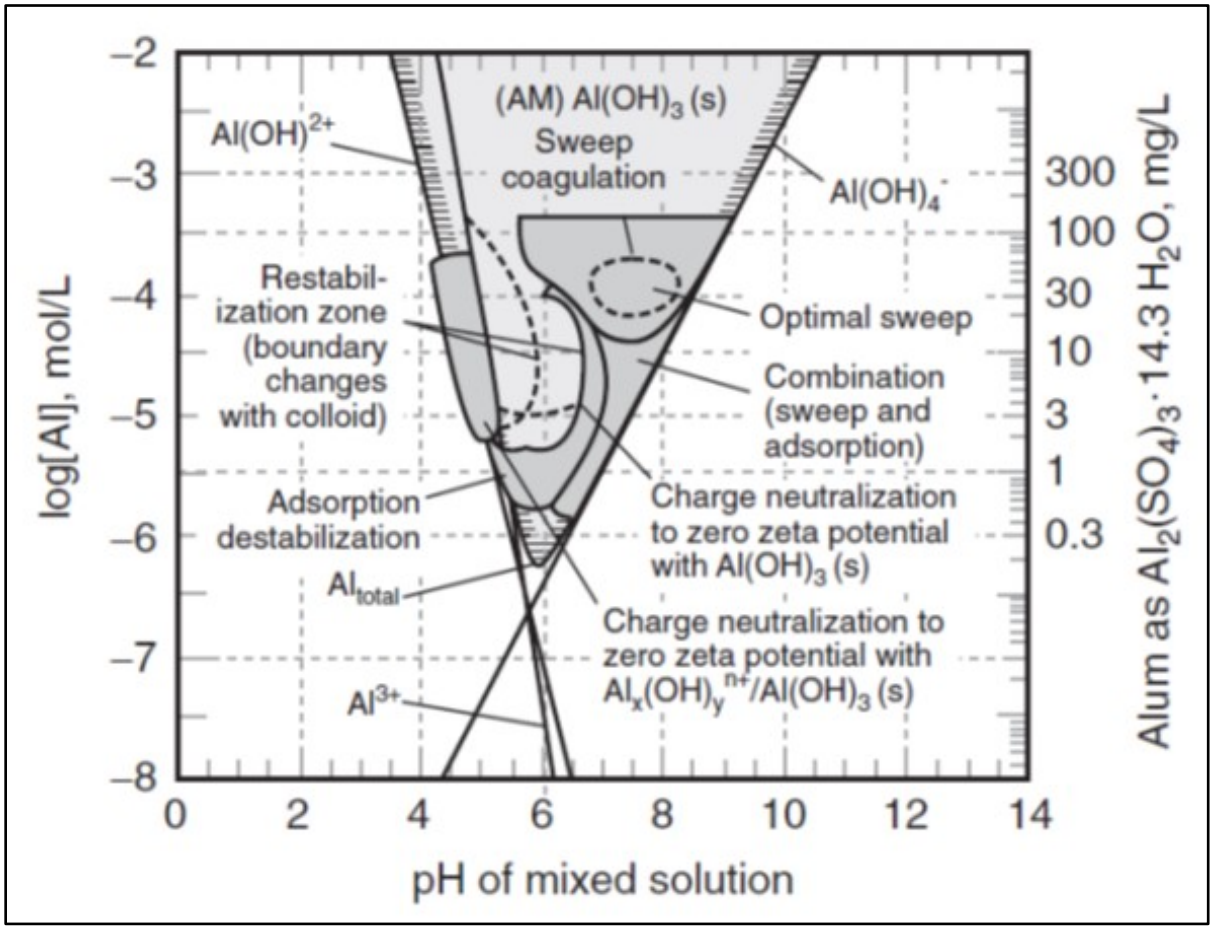

Figure 2.6 Aluminum hydroxide solubility diagram (MWH 2012).

In general, for water treatment processes that require additional coagulant beyond the minimum aluminum solubility levels (sweep floc), operators will endeavor to minimize the amount of hydroxide floc produced for sedimentation. In addition, as alum is added beyond the optimal sweep floc boundary, continued growth of the amorphous floc results in a large particle with low density and poor settling characteristics. The increased turbidity and formation of excess solids requires additional processing to collect, thicken and dispose, all of which drive total treatment costs up. pH

control can both maximize the amount of floc formed per unit of alum addition and neutralize surface charge of certain functional groups within the organic structures susceptible to re-hydrolysis, thereby reducing overall coagulant demand (Ashery et al. 2010; Naceradska et al. 2019).

2.2.3 Sedimentation

Conventional water treatment systems generally require sufficient coagulant addition for precipitation of the coagulant/metal salt hydroxide solids. In particular, high quality source waters (i.e., water with low numbers of naturally occurring particles) may require the additional solids to increase the collision frequencies and attachments necessary to grow floc to a sufficient size for settling. In drinking water treatment, high coagulant demands result in an increased mass of generated solids for neutralization, typically through enmeshment (sweep floc), resulting in removal of colloidal NOM and particles (Edzwald 2011). Sedimentation is necessary at the higher coagulant loading conditions associated with sweep floc coagulation so that subsequent filtration processes are not overloaded with carried-over particles generated during pretreatment. In DF systems, sedimentation is avoided through the addition of sufficient coagulant to neutralize particle surface charge to enable attachment to the filter media surfaces, with minimal generation of excess solids (Culp 1977; Carns et al. 1985). Thus, in DF, the goal of coagulant addition is to form very small "pin flocs" that may only be microns or tens of microns in size so that they can be efficiently removed by filtration, without causing excessive headloss accumulation.

2.2.4 Chemically assisted filtration (CAF)

In drinking water treatment, granular media filtration is used to remove fine and/or colloidal particles from water; the filter media act as collectors. Particles entering the filter beds typically range in size from 0.01 μm to 100 μm (Boller et al. 1995). Given that pore spaces between filter media grains are almost always much larger than the particles to be filtered, two key steps must both occur for effective particle removal by physico-chemical filtration: (1) particles must be transported to the vicinity of the filter media surfaces (or the surfaces of previously deposited particles), and (2) particles must attach to filter media surfaces with sufficient strength for retention (McDowell-Boyer et al. 1986; Boller et al. 1995). Thus, the particle surface chemical conditions must

be suitable to retain the particles, and that shear forces do not exceed the strength of the bonding sites, which would detach particles and wash them into the clearwells (Moran et al. 1993; Kim et al. 2004). "Filterability" refers to the ability of clarified water to meet water quality limits (at expected production volumes) through CAF processes. In contrast, "un-filterable" water refers to the clarified water streams that are unable to meet water quality limits through CAF.

Removal of particles through granular media filtration is typically achieved through a combination of three separate capture mechanisms, including: cake filtration, straining filtration, and physico-chemical attachment (Figure 2.7) (McDowell-Boyer et al. 1986). Cake filtration (Figure 2.7-A), often referred to as size-exclusion, occurs where particles larger than the pore spaces between media grains are prevented from passing through the filter by physical size exclusion. Where the ratio of colloid to collector diameter exceeds 0.154, the colloids will be too large to pass through the filter pore spaces and are collected on the surface of the filter media (Herzig et al. 1970). Straining filtration (Figure 2.7-B), also a form of size-exclusion, occurs where colloids are physically restrained, but trapped within the smaller regions of pore spaces adjacent to the grain-to-grain contact points throughout the filter (Bradford et al. 2005). The third mechanism is physico-chemical attachment of particles to filter media (Figure 2.7-C). Destabilized suspended particles remaining within the water matrix following pretreatment will have had their surface charges electrostatically altered during coagulation, thereby enabling deposition on the media or other particles and polymers already attached to the media surfaces (Boller et al. 1995).

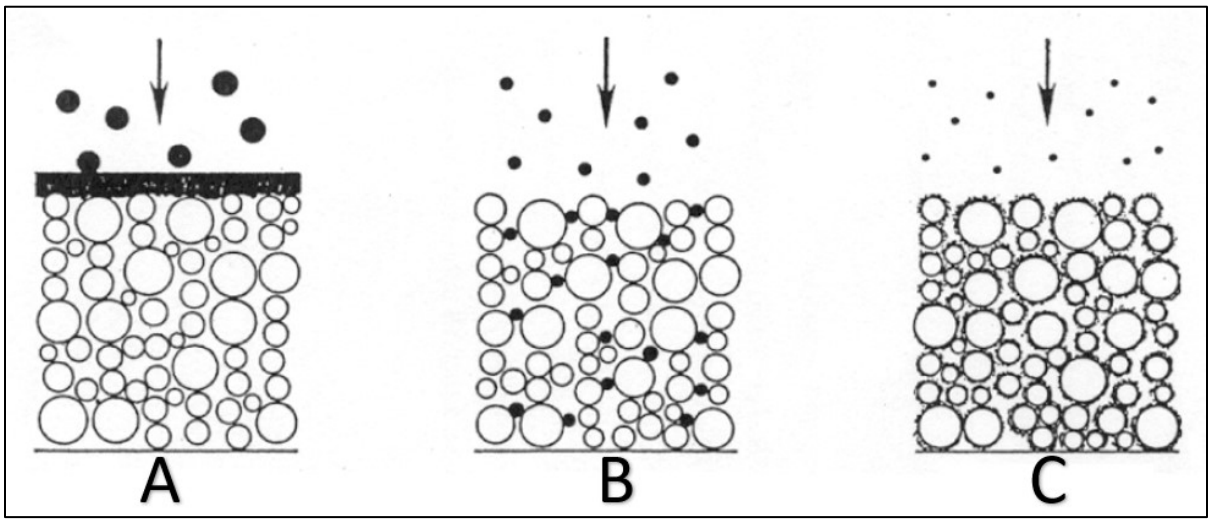

Figure 2.7 Porous media filtration mechanisms: cake (A), straining (B) and physico-chemical attachment (C), (reproduced with permission from McDowell-Boyer, et al. 1986). In drinking water treatment, the pore spaces between filter media are typically 100 to 1,000 times larger than the particles being removed, generally precluding straining.

Effective removal of particles and pathogens by physico-chemical filtration requires both the transport of particles/pathogens to the vicinity of filter media/collector surfaces and attachment on those surfaces (Tobiason et al. 1988). As illustrated in Figure 2.8, particles deviate from the fluid streamlines due to gravitational forces (i.e., sedimentation), diffusion gradients, hydrodynamics, and inertial effects of momentum (O'melia et al. 1967); interception in laminar boundary layers is generalized to include the effect of inertia (Fernandez De La Mora 1986). Each mechanism describes how the particles move across the fluid streamlines to reach the filter grain surfaces. The mechanisms illustrated in Figure 2.8 depend on velocity, particle size, density and fluid viscosity for the particle to exit the flow streamlines and pass close enough to an attachment point to be retained through electrostatic attraction forces (Ives 1970; Amirtharajah 1988).

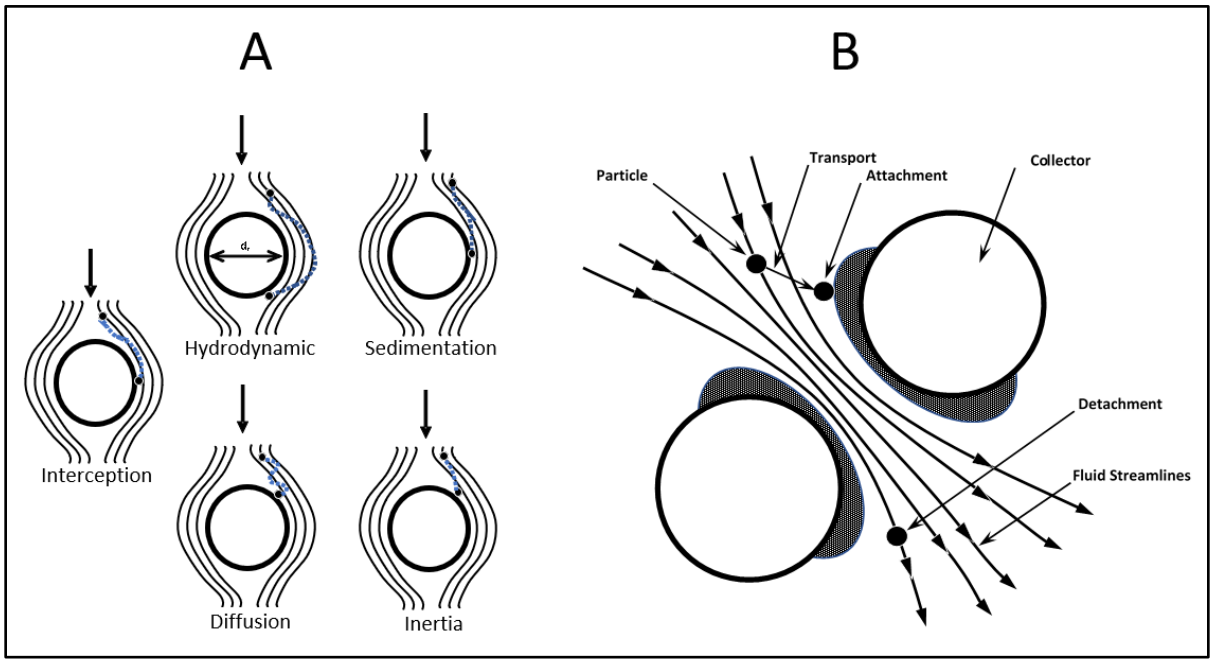

Figure 2.8 Particle removal during physico-chemical filtration (A), which requires both particle transport (B) and attachment to media surfaces (reproduced with permission; Panel B: Amirtharajah, 1988 and Panel A: Ives, 1970). Attachment is possible because the particle surfaces are adequately destabilized by coagulant addition (O'melia 1985).

2.2.4.1 Filter ripening and operation

Filter operation is made up of repeating cycles of conditioning or "ripening" (i.e., the initial period of rapid filtered water quality improvement during which particles deposit on filter media surfaces and act as additional collectors, Amirtharajah 1988), operation, termination, refresh and return to service. These phases of typical filter cycles are illustrated in Figure 2.9, and include a filter-to-waste (FTW) period (i.e., the period of time that water is sent to waste until water quality limits are reached), a stable operating period, a breakthrough period, a run termination period, a backwash period and a return to service for the next filter run cycle (Edzwald 2011).

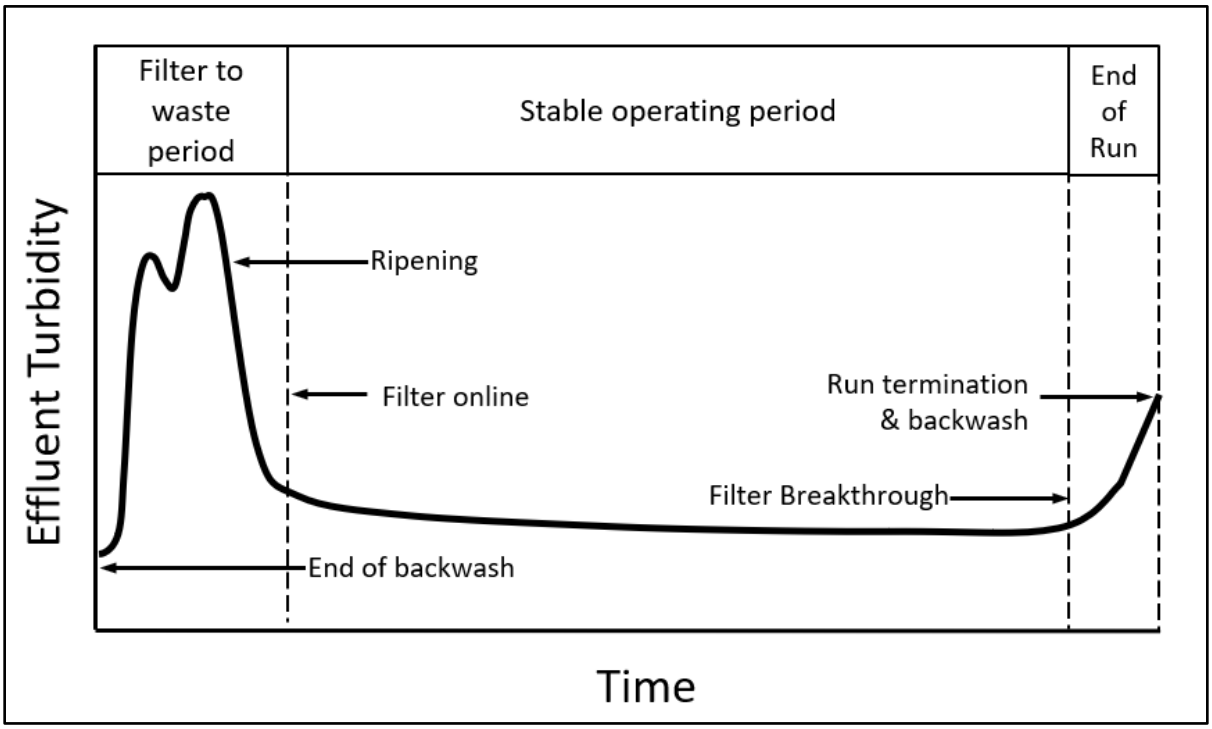

Figure 2.9 Typical filter run profile (Adapted from Amirtharajah et al. 1980).

The phases of the filter run are defined as follows:

- **Ripening/Filter-to-waste (FTW)**: Phase of the filter cycle during which water is passed through the filter, but has not yet reached specified water quality targets. The intensity and duration of this phase could be affected by several parameters, including raw water quality characteristics, coagulation efficiency, and backwash regime (Amburgey et al. 2005). FTW water is directed away from subsequent treatment, to be re-treated or discharged with the other waste streams. Notably, not all systems have the capability to FTW.

- **Stable operation**: Phase of the filter cycle during which pre-treated water passes through the filters and on to subsequent treatment processes; typically, a clearwell. The filtered water meets specified water quality targets. Deposition of particles slowly constricts pore spaces between media grains and causes fluid velocity and hydraulic shear forces to increase over time.

- **Breakthrough**: Period in the filter cycle during which the onset of degradation in filtered water quality is evident. It is caused by reduced deposition and/or detachment of particles.

Breakthrough is not always observed at the end of a filter run, especially where common utility practice is to terminate runs early based on either headloss criteria or time/operational practice.

- **Run termination**: Point in the filter cycle at which water passed through the filter has exceeded end-of-run criteria for any of the following: turbidity breakthrough, particle count breakthrough, maximum allowed loss of head, or maximum allowed run time.

- **Backwash**: Period during which the filter is removed from service and refreshed. Retained solids within the filter are separated from the media through the actions of air scour and reverse flushing of potable water prior to returning to the FTW period and start of the next filtration cycle.

The filter ripening sequence is distinguished by five different stages (Figure 2.10), which may not be observed for all filters as a result of operational details. The lag phase is associated with the clean backwash water that exists when filters are first put back into service. The intramedia remnants stage is observed next and reflects particles detached from the filter media during backwash that have remained in the water matrix trapped between the filter media grains. Backwash remnants that remain in the water column above the filter media are observed during the third phase of filter ripening. Thereafter, the second peak in filter effluent turbidity is observed during the fourth phase of filter ripening; it occurs as a result of filter influent water mixing with the backwash remnants. Finally, the fifth stage of filter ripening includes the improvement in the filtration efficiency as newly attached particles serve as collectors of other particles (Amburgey et al. 2005).

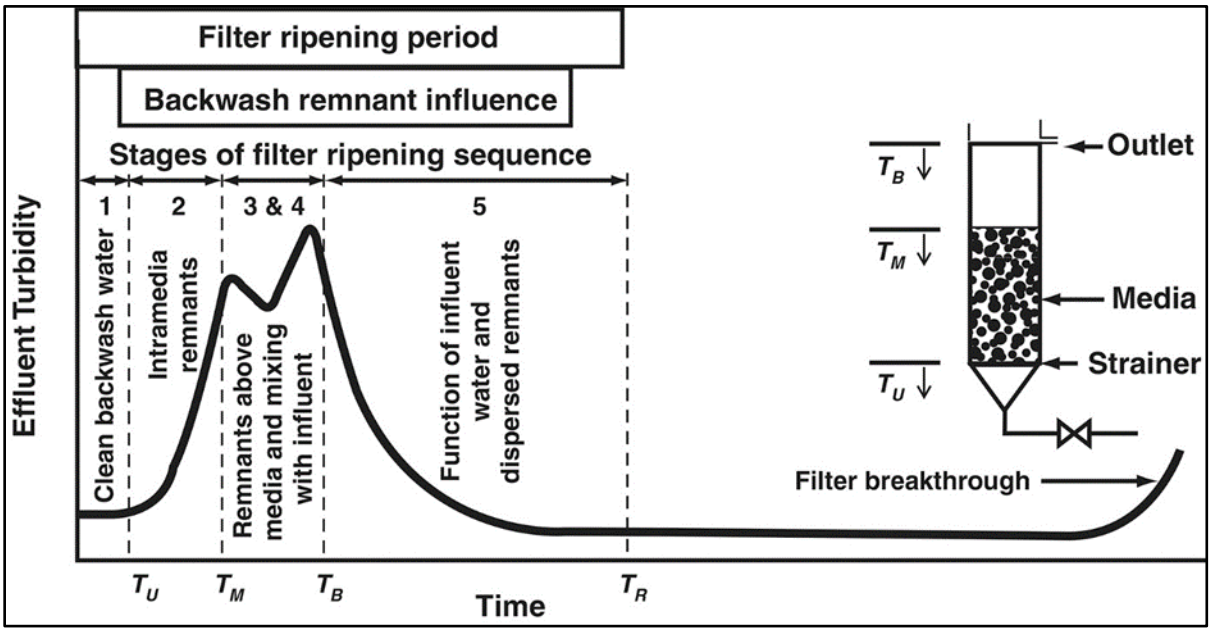

Figure 2.10 Typical filter ripening sequence (Amirtharajah et al. 1980; Amburgey et al. 2005).

2.2.4.2 Filtered water turbidity

Turbidity is a measure of the relative visual clarity of water, based on the extent to which light is scattered or absorbed by suspended particles within the water matrix. Turbidimeters operate by detecting the intensity of light scattered at one or more angles by particles within the sample. The measure of light scatter is referred to as nephelometric measurement, and turbidity is measured in nephelometric turbidity units (NTU) (Hart et al. 1992; AWWARF 2002). Use of standardized calibration suspensions between turbidimeter models allows for direct comparison between analyzers for regulation of potable water quality (Eaton 2005).

Particles of differing sizes, shapes and chemical compositions will reflect, absorb, or re-emit light to differing degrees. Consequently, turbidity does not necessarily correlate to the number or mass of particles in a water matrix (Letterman 1999). Notably, light scattering of colloidal-sized particles (i.e., ranging from 1 nm to 1 µm) depends on their number, size, shape and refractive index, as well as the wavelength of the light used by the turbidimeter. As a consequence, large numbers of particles with very small or very large diameters may scatter very little light (and hence have a lower relative turbidity) when compared to smaller numbers of particles with the same diameter as the

incident light wavelength (Edzwald 1983). However, turbidity is an effective tool to indicate real-time removal of particulates or organic materials during treatment that would otherwise reduce the effectiveness of disinfection processes or support transport of harmful organisms (Sadar 2007).

Turbidity has been widely used in the water treatment industry for monitoring performance of treatment systems. Turbidity has also been adopted as a critical parameter for controlling the quality of filtered water (USEPA 2006; AEP 2012). Filter effluent turbidity has widely been shown to correlate to pathogen log-reduction levels (Patania et al. 1995; Emelko et al. 2005; Health Canada 2016), with filter effluent turbidities of <0.3 NTU and <0.1 NTU commonly cited as the maximum and optimal filtered water turbidity targets for reduction of protozoa pathogens in drinking water treatment (Campbell et al. 2014; Health Canada 2019b). As such, turbidimeters provide a surrogate indicator to presence of microorganisms in treated drinking water (Sethi et al. 1997).

However, Batista et al. (2021) found that turbidity alone was not always sufficient to predict adequate pathogen removals at all conditions. Sub-optimal particle destabilization, under certain source water quality conditions, resulted in filter effluent water quality less than 0.1 NTU, but with *Cryptosporidium* log reductions approximately half that of filters with optimized particle destabilization. Log-removals reached less than 1-log removal in certain cases that exhibited poor particle destabilization prior to filtration (Figure 2.11). This result reinforces the extreme importance of ensuring adequate particle destabilization to ensure safe drinking water quality under all source water quality conditions.

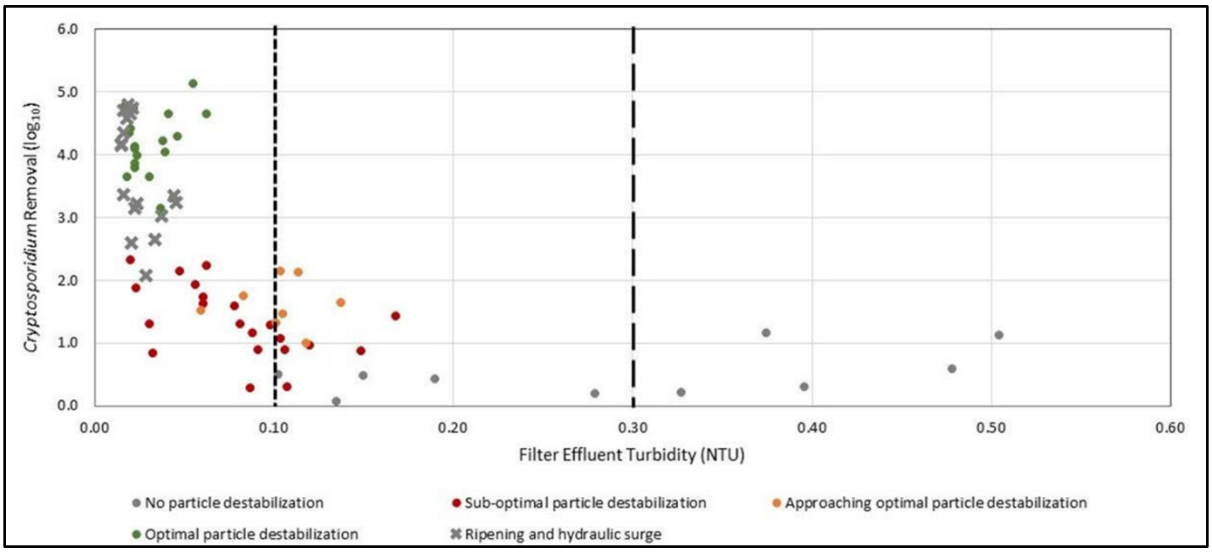

Figure 2.11 Comparison of *Cryptosporidium* removals during filtration under both optimized and sub-optimal particle destabilization conditions (Batista et al. 2021).

2.2.4.3 Filtered water particle counts

Particle counters provide a different and complementary measure to turbidity for monitoring filter ripening and detecting filter particle breakthrough. Particle counters used in water treatment measure the number and size range of suspended particles within a sample stream. The measurement is accomplished by light obscuration. Shadows cast by particles are counted by a photodiode detector and converted to a number of particles per mL of sample (NP/mL), and shadows used to categorize particles by size range (Lewis et al. 1992; Kochevar 2006). Due to the particle counters ability to detect particles in size ranges outside of the normal turbidimeter response zone, they provide redundancy to turbidimeter readings, and provide indication of filter breakthrough for the larger-sized particles, of which protozoa species belong to (Kochevar 2006). Particle counter response is sensitive to changes in filter performance; it is also sensitive to coagulant overdosing conditions that would not normally be picked up by turbidimeters (i.e., where lower amounts of light scatter is generated from particles of increasingly larger size than the wavelength of the turbidimeter light source) (Guminska et al. 2015). Particle counters on filtered water also tend to be more sensitive, as a percentage of change, when compared to turbidity

meters. For example, during onset of filter breakthrough conditions, particle counts may increase by a factor of 10 to 50, while turbidity may only change by 20% (i.e., from 0.025 NTU to 0.030 NTU).

Particle counters are limited in their ability to directly correlate filtered water particle numbers to either pathogen concentrations or their removal efficiency by filtration processes. Although particle counters are capable of counting cyst- and oocyst-sized particles, protozoan parasite concentrations remain too low to be differentiated from background particles. For example, a very high source water concentration of oocysts, such as 100 oocysts/100L, would correspond to only 0.001 oocysts/mL on the particle counter. Assuming that pretreatment and CAF processes achieve a 3-log reduction in oocyst concentration, and a filtered water particle counter detection limit is 1 NP/mL (i.e., very good filtered water quality), the source water oocyst concentration would need to be several orders of magnitude greater to provide a measurable (detectable) value on the particle counter. Additionally, because metal salt coagulation actually adds particles to water as a result of the hydrolysis and precipitation reactions that occur upon coagulant addition, reductions in particle count between raw and filtered water streams do not provide meaningful or reliable quantitative indication of microorganism removal by CAF processes (Edzwald et al. 1998). Particle counters can also have difficulties achieving consistent results between sensors, or even between particle counters that are of the same model from the same manufacturer (Sethi et al. 1997). These limitation are important considerations when evaluating performance between filters. Despite these limitations, particle counts remain a good qualitative measure of treatment performance in response to unoptimized coagulation conditions and for detection of filter breakthrough (Hargesheimer et al. 1995, 1998).

2.2.4.4 Filtered water headloss

Filter headloss refers to the change in pressure between the top and the bottom of a granular media filter. As filtration proceeds, particles accumulate on the filter media grains, causing the pore spaces to become restricted. As pore spaces constrict, increasing pressure is required to force the same volume of water through the filter media to maintain flow rates (MWH 2012). The increase in pressure required to force the water through the filter is referred to as headloss. Headloss is continuously monitored and helps to determine when a filter should be backwashed. In extreme

cases, when headloss increases beyond the water level available above the media, suction conditions can be formed. When that occurs, a vacuum is created at the particle surface, forcing dissolved gasses in the fluid to come out of solution and to form bubbles that remain attached to the filter media. The bubbles further restrict the pore spaces, and result in velocity increases that can shear particles away from the media and into the clearwell (Ireland Environmental Protection Agency 1995). For this reason, maximum headloss limits are placed on filters to trigger a backwash.

2.2.4.5 Unit filter run volume (UFRV)

Unit filter run volume (UFRV) is a filter operation metric that normalizes the number of water volumes passed through a unit area of the filter. For granular media filters, UFRV represents the throughput per unit area (following ripening) and allows for comparison of production between filters of different dimensions and total area. UFRV is calculated by dividing the accumulated flow by the surface area of the filter in m^3/m^2 (or gallons/ft^2). Efficiency of filter operation can then be assessed by comparison of results to optimized systems. Filtration systems that are preceded by clarification should produce 400 m^3/m^2 or more for optimal filtration efficiency, whereas a DF process should be capable of achieving 200 m^3/m^2 (AWWA 2011).

2.2.4.6 Electrokinetic measurements

Electrokinetic surface charge measurements are used to assess the effect of coagulants on particle surface chemistry (or electric potential at the plane of shear of the electric double layer). The two primary types of electrokinetic measures used in water treatment are streaming current detection and zeta potential analysis (Letterman 1999).

Streaming current is a measure of electrical current developed as a reciprocating piston moves up and down within a sample cell. As the wall and piston pass across one another the test fluid moves in between to generate a measurable electrical current, which is detected by electrodes at opposite ends of the flow path (Dentel 1991; Abu-Orf et al. 1997). Once an ideal coagulant dosage is set, an operator will set the analyzer output to zero. Any shifts in streaming current output can then be attributed to changes in the solution chemistry (i.e., coagulation interruption, changing source water quality, etc.). Unfortunately, because the analyzer output represents a value relative to when the

unit was “zeroed”, the values become arbitrary and cannot be correlated to water quality parameters over time.

Zeta potential is measured directly via electrophoretic mobility of particles, where the velocity of particles subjected to an electric field is converted to an electrical potential (in millivolts, or mV). Electrophoretic mobility is correlated and converted to an electric potential (zeta potential) through application of Henry’s function (Sumner et al. 1931; Jefferson et al. 2004).

Monitoring of zeta potential during water treatment provides a direct assessment of charge neutralization for effective coagulation of particles. Zeta potential measurements for optimization of drinking water pretreatment processes in literature have focused primarily on settled (clarified) water turbidity, with the optimized zeta potential correlated to the minimum settled water turbidity, or DOC removal efficiency rather than filtered water quality (Dentel 1991; Ravina et al. 1993; Jefferson et al. 2004; Sharp, Parsons, et al. 2006; Morfesis et al. 2009; Wu C.D. et al. 2011). However, to ensure that coagulation results are optimized for the removal of particles (including waterborne pathogens) through filtration, zeta potential values should also be correlated to filtration efficiency. Consideration of zeta potential impacts on filtered water quality is an important aspect to fully link source water quality through pretreatment and CAF processes to ensure effective pathogen removal (i.e., by achieving a minimum filtered water turbidity and particle count).

2.2.5 Critical control points (CCPs) for filter performance monitoring

Critical control points (CCPs) are locations within the drinking water treatment process at which hazards can be prevented, eliminated, or reduced to acceptable levels; they are often determined from a thorough review of associated hazards (Jagals et al. 2004). Water treatment systems are designed around critical control points (Hellier 2000). The CCPs are monitored continuously, to ensure that unit processes feedback (i.e., such as filtered water turbidity) operate at all times within pre-set boundaries (Jagals et al. 2004; Hamilton et al. 2006; Damikouka et al. 2007; Walker et al. 2016). CCPs are located where operators can influence treatment through manipulation of process elements, such as chemical dosages or flow rates, to correct system performance (Jagals et al. 2004). Feedback from CCPs associated with coagulation and filtration processes are required to ensure that any given filter is optimized to meet regulatory and/or operational objectives at all

operating conditions. Most WTP supervisory control and data acquisition (SCADA) systems do not include modules that enable either integrated viewing of CCP data or their statistical analysis—these capacities are needed to enable filter performance optimization, especially in real or near-real time. These limitations are further complicated by the number of discrete unit processes, including filters, that are present in typical conventional WTPs—visualization and analysis of all of the requisite data streams that must be considered to identify potential concerns on a continuous basis is complicated and impossible in near-real time without automated support in generating summary statistics.

Without adequate real-time feedback to alert operators of changes to process influent or effluent water quality, the performance of treatment processes such as CAF can become compromised. In CAF, non-optimized coagulation chemistry, in conjunction with poorly controlled operating regimes, can lead to pathogen breakthrough by allowing solids to pass through the filter and into the clearwell during vulnerable periods of the filter run cycle (Huck et al. 2002).

To ensure that CAF processes are achieving optimal pathogen and particle removals, development of process metrics around CCPs is necessary to detect and to quantify impacts on filtration. Early and automated detection of process degradation provides an added layer of resilience under changing conditions, such as those imparted during unit process alterations, operational adjustments, or source water quality changes. Monitoring of CCPs allows for real-time feedback on operational decisions and provides a basis for continuous improvement (Damikouka et al. 2007). As well, process metrics can be used to summarize and to simplify the complex data streams for interpretation and action by the operator. The development of such tools can be expected to increase process resilience, decrease costs attributable to over-treatment, and provide safeguards to operational upsets.

2.2.6 Statistical process controls (SPCs)

Processes are monitored and maintained “in control” by gathering and using data. Alarm setpoints that define minimum or maximum operational thresholds for individual processes are the most basic forms of control used in water treatment systems. For filtration, exceedance of alarm setpoints alerts operators and triggers corrective action. A high alarm limit would normally be set at

a value below a compliance or safety threshold to allow time for intervention and correction. For example, if filtered water turbidity breakthrough is detected near the end of a filter run, the operator will place the filter offline for backwashing. Basic alarm setpoints provide the minimum feedback necessary to keep processes or equipment operating within safe limits. The next layer of resilience is the incorporation of automated control system intervention if a process crosses a critical alarm limit, indicating that the system is about to enter a non-compliant or unsafe state. Automated shutdowns will override the operator in the event that they missed the initial alarm beacon or were unsuccessful in returning the process to a compliant state.

Statistical process controls (SPCs) provide a basis to differentiate between the causes of variation during any process operation. When certain causes of variation are present that result in excessive process upset, the process would be classified as "unstable" or "out-of-statistical-control". An out-of-control process represents system responses that our outside of expected random variation (Jelali 2013). Through understanding of normal process variation, an acceptable control limit can be statistically determined (Mahmoud et al. 2010; Qiu 2017). Control charts can be generated to detect changes in the performance of a process. Control charts compare the current process performance against historical norms, and prompts for corrective actions when an upset limit has been detected (Shah et al. 2010).

One method of applying statistical controls is the use of "six-sigma" methodology (Liebermann 2011; Aldowaisan et al. 2015; Pohlmann et al. 2015; Rimantho et al. 2017). Six-sigma is a quality management program developed in the 1980's to control the variations in process environments to reduce the number of non-conformities and to close the gap between actual process performance and desired performance. Under six-sigma, a process metric which exceeds ±3 standard deviations from the mean would indicate an out-of-control process that must be investigated to determine and to correct the cause of the deviation (Liebermann 2011; Aldowaisan et al. 2015; Pohlmann et al. 2015; Rimantho et al. 2017). The upset limit is also defined as an Upper Control Limit (UCL) to define the distribution or spread of data points considered to be within the normal variability. A UCL at ±3 standard deviations from the mean represents that approximately 99.7% of the data

points within a normally distributed bell curve fall within acceptable variability and are not considered data outliers.

Six-sigma approaches are not common in the water treatment industry, but they are common manufacturing industries, where process inefficiency can negatively impact production capability and profitability (Liebermann 2011).

2.3 Climate change influences and impacts on treatability

As discussed in Section 2.1.2, the USEPA (USEPA 1998, 2002, 2003, 2006), Health Canada (Health Canada 2013a), and the Canadian Council of Ministers of the Environment (CCME 2004) all rely on the "multi-barrier approach" to "prevent or reduce the contamination of drinking water from source to tap" to reduce risks to public health (Emelko et al. 2014). All variations of this framework identify source water protection (SWP) for risk prevention and in-plant treatment technologies for risk management; all barriers in this framework must be effective to ensure drinking water security. Recently, it has been recognized that this reliance on traditional SWP approaches and in-plant treatment technologies is inadequate (Sham et al. 2013; Emelko et al. 2014). While it is effective for preventing and managing risks from anthropogenic landscape disturbances such as urbanization, climate change-associated disturbances have revealed alarming inadequacies in current implementations of the multi-barrier approach. Specifically, climate change undermines the basic assumption of stationarity, "the idea that natural systems fluctuate within a stationary envelope of variability" that has historically been the foundation for managing water supplies, demands, and risks (Milly et al. 2008).

Climate change is impacting hydrological cycles globally (IPCC 2018). For example, shifts in the timing and quantity of precipitation are resulting in increased rainfall and flooding in some regions and drought in others (Mirza 2011; IPCC 2018). Hotter and drier atmospheric conditions have resulted in the increased frequency of larger, more severe wildfires (USEPA 2016), which can be especially "hard" on water. For example, they can alter the timing of snow melt and increasing net precipitation (Williams et al. 2019). Post-fire stream temperatures can be elevated (Wagner et al. 2014) and significant amounts of suspended slides/sediment (Kunze et al. 2006; Silins et al. 2008;

Silins, Stone, et al. 2009; Bladon et al. 2014), nutrients (Ranalli 2004; Bladon et al. 2008; Aiken et al. 2011), heavy metals (Wolf et al. 2008), and other contaminants (Crouch et al. 2006) can be released to receiving streams. Associated water quality shifts can be long lasting (i.e., decades or longer) and far-reaching (i.e., propagating downstream for tens of kilometers, or farther) (Stone et al. 2014; Emelko et al. 2016); even at large basin scales with already deteriorated source quality, once believed unlikely to be markedly impacted by wildfire (Emmerton et al. 2020). Wildfires can also lead to significantly more variable source water quality (Stone et al. 2011) and alter stream ecology (Silins, Bladon, et al. 2009; Silins et al. 2014; Martens et al. 2019). Most importantly for drinking water operators, greater variability and deterioration in source water quality can challenge water treatment operations—especially coagulant dosing—thereby threatening filtration performance and pathogen removal (Emelko et al. 2014; Shams 2018) and increase treatment costs (Emelko et al. 2011, 2014; Price et al. 2017; Skwaruk et al. 2020).

3 Materials and Methods

3.1 Research Approach

As outlined in sections 1.1 and 1.2, the goal of this research was to develop an approach for rapid detection of filter performance degradation and methods to assist with prediction of coagulant dosages for increased filter resilience. Four research objectives were developed to reach the overall goal, including; (1) identification of operational conditions at which turbidity is an inadequate indicator of connectivity between coagulant dosing, clarified turbidity and filtration performance, (2) evaluation of monitoring tools to assist in achieving filter effluent turbidity and pathogen reduction targets, (3) development of data-driven analytics to ensure optimal CAF performance (through faster, partially automated analytics and identification of opportunities for potential operational response), and (4) to evaluate implications of operational configuration on monitoring tools in achieving filter effluent turbidity and pathogen reduction targets. Two project phases were required to meet all of the objectives.

Phase 1 of this research addressed Objectives 1, 2 and 3 through an analysis of historical filter performance data from a full-scale WTP in Calgary, Alberta, Canada (Glenmore Water Treatment Plant). Objective 1 included a historical review of filter performance data to identify periods during which filter performance was likely stressed or challenged. Identification of time periods where filter stress was likely, followed by a more in-depth analysis of water quality and operational information to determine the root cause of identified issues and identify how the process was brought back into control. Objective 2 was addressed by assessing whether the zeta potential of coagulated water could be used to inform filter performance (i.e., particle removal), by comparison to observed filtered water quality metrics (i.e., turbidity, particle counts). Objective 3 was achieved by examination of over 100 full-scale, “in good operational control” filter runs over a 1-year period to develop data-driven analytics (i.e., “control charts”) to ensure optimal CAF performance. These approaches were designed to rapidly identify filters that deviated from expected treated water quality value/ranges so that they could be investigated and removed from service before exceeding internal alarm setpoints or regulated water quality limits.

Phase 2 of this research addressed Objective 4 through a series of pilot-scale, direct in-line filtration experiments that were conducted to determine the optimal combinations of coagulant and polymer chemical concentrations needed to maximize filter yield (i.e., UFRV), while meeting or exceeding regulated filtered water quality criteria (i.e., turbidity). In addition to meeting or exceeding filtered water quality requirements, the utility of zeta potential analysis prior to filtration to indicate or possibly predict filter performance in removing particles (and therefore pathogens), thereby increasing treatment resilience, was also investigated.

3.2 Research Site

3.2.1 Site characteristics

The City of Calgary (CoC), Alberta, Canada is reliant on a generally high-quality source water that is derived from forested, snowmelt-dominated landscapes on the eastern slopes of the Rocky Mountains; it has generally low raw water turbidity and total organic carbon content (Valeo et al. 2007). Water quality can deteriorate annually during spring freshets originating in the foothills and high mountains; during these periods, source water turbidity and natural organic matter concentration and character reaching the City's water treatment plants can change rapidly. Notably, the exposure of the CoCs forested watersheds to wildfire hazard is high (Robinne et al. 2019); thus wildfire risk is substantial with significant potential for source water quality deterioration in the event of severe wildfire (Emelko et al. 2011).

One of the main factors driving treatment process selection at the study site has been the historically low source water concentrations of protozoa. A long history of routine (i.e. large bi-weekly) *Giardia* and *Cryptosporidium* monitoring has indicated either low or non-detectable protozoa levels over at least nine years (Schmidt et al. 2019). Under the existing regulatory frameworks for protozoa treatment in Canada (or the U.S.), the CoC must only achieve the minimum 3-log reduction of *Cryptosporidium* oocysts, and up to 5-log reduction of *Giardia* cysts (USEPA 2006; AEP 2012; Health Canada 2019b). Prior to the wider adoption of UV systems for protozoa treatment, the treatment system at the study site had been upgraded to significantly increase chlorine contact for treatment of *Giardia*. Thus, public health risk attributable to waterborne

protozoa is very low in the CoC and additional disinfection such as UV irradiation is not required. However, since the treatment of *Cryptosporidium* relies entirely upon filtration mechanisms at the study site, the utility requires that its filtration mechanisms be able to meet or exceed its regulated filtered water quality limits at all times.

Capacity upgrades at the CoCs Glenmore Water Treatment Plant occurred between the years 2003 and 2012. During that time, the chemical pretreatment processes were changed from conventional flocculation and sedimentation systems to a high rate SBF process. The upgraded processes were housed in a newly constructed Pretreatment Facility (PTF), which includes four separate treatment trains to respond to a seasonally wide range of flow demands. The original sedimentation tanks were re-purposed as flow-through chambers to maintain chlorine contact time for *Giardia* disinfection. The hydraulic retention time from the exit of the PTF to the filters, via the chlorine contact tanks, ranged from 4-hours to 8-hours depending on seasonal WTP flow rates.

Waste residuals from backwash processes are sent to a new Residuals Treatment Facility (RTF) for further processing. The residuals treatment processes are designed to concentrate and separate the solids into thickened sludge and clarified supernatant streams. Supernatant is subsequently returned back to the head of the PTF. Thickened sludge streams are sent to holding tanks for centrifugation and offsite disposal of the solid wastes. The residuals treatment process averted the prior need to dechlorinate and release the solids-laden waste streams back to the Elbow River. The updated PTF and RTF processes allow the treatment facilities to treat water at full plant capacity, regardless of time of year or source water variability.

The WTP processes at the research site includes pH correction with carbonic acid, rapid mixing of coagulant (alum), flocculation and sedimentation through a high rate SBF process using a fine (85 µm microsand) ballast and medium density cationic polymer, chlorine disinfection from onsite generation of sodium hypochlorite, dual media filtration (anthracite and sand supported by a stainless-steel underdrain), and final chlorine disinfection prior to pumping water into the water distribution system (See Appendix A, Figure A.1). The overall treatment process meets the demands of a seasonally variable raw water source. However, the added resilience afforded by the newer

processes at the study site was accompanied by the higher costs of higher energy and chemically intensive treatment processes.

3.2.2 Source water quality

The CoCs source water originates in the eastern foothills of the Rocky Mountains, from the Elbow River and Bow River Watersheds. Watershed drainage into the surface river network originates primarily from glacial and groundwater sources (Valeo et al. 2007), and as such, experience periods of stable raw water conditions through the winter, punctuated by intense seasonal water quality fluctuations in the spring and summer. The source waters are generally low in turbidity (<2 NTU) and total organic carbon (<2 mg/L), with brief spring freshets resulting in a temporary seasonal run-up and run-down of turbidity (up to 4,200 NTU) and total organic carbon (up to 30 mg/L) (Kundert et al. 2014). Freshets at the research site have historically occurred in two distinct phases. Early runoff from the localized foothills (March-April), associated with rising temperatures, mobilizes localized snowmelt into the river system. Since the underlying soils remain frozen, the accumulated organics wash into the receiving waters with minimal erosion. As a result, source water organics and color increase at the WTP, but turbidity remains low. The late spring snowmelt (May-June) occurs when the high mountain snowpack melts and flows into the river systems. The large runoff water volumes increase the depth and velocity of the river resulting in increased erosion of the primarily glacial till deposits (Jackson et al. 1987) and mobilization of trapped sediments in the riverbed. The late runoff period results in high turbidity and high organics at the WTP. The high seasonal variability in turbidity, organics and temperature during these periods (Beers et al. 1993; Bladon et al. 2012) enabled extensive assessment of filter performance during periods of rapid and significant water quality change, whereby sub-optimal particle destabilization and increased potential for protozoan pathogen passage through filtration processes would be most likely (Rizak et al. 2007).

Figure 3.1 illustrates the monthly variability in source water turbidity over a five-year period (2013-2018). Aside from the spring and summer freshets, the median turbidity was less than 2 NTU for the remainder of the year. Less variability occurred between August and March, with a median turbidity of less than 1 NTU.

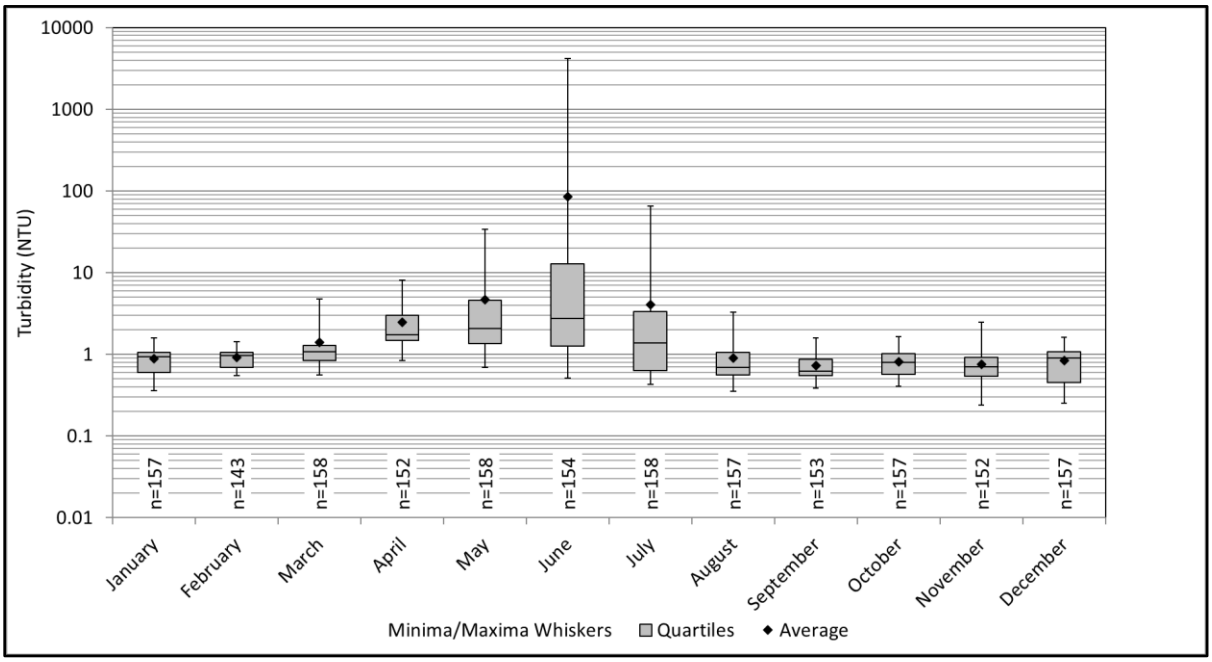

Figure 3.1 Source water turbidity at the Glenmore WTP in Calgary (2013-2018). The figure illustrates median, quartiles, maxima, minima, and average monthly values.

Figure 3.2 illustrates the monthly source water TOC and DOC concentrations at the Glenmore WTP over a five-year period in Panels A and B, respectively. Median TOC and DOC values were typically less than 2 mg/L for the late summer and fall months. Variability in source water TOC and DOC concentrations was lowest during the winter months; median values ranged between approximately 0.8 and 1.5 mg/L and 0.7 and 1.2 mg/L, respectively, thereby leading to stable coagulant demand conditions.

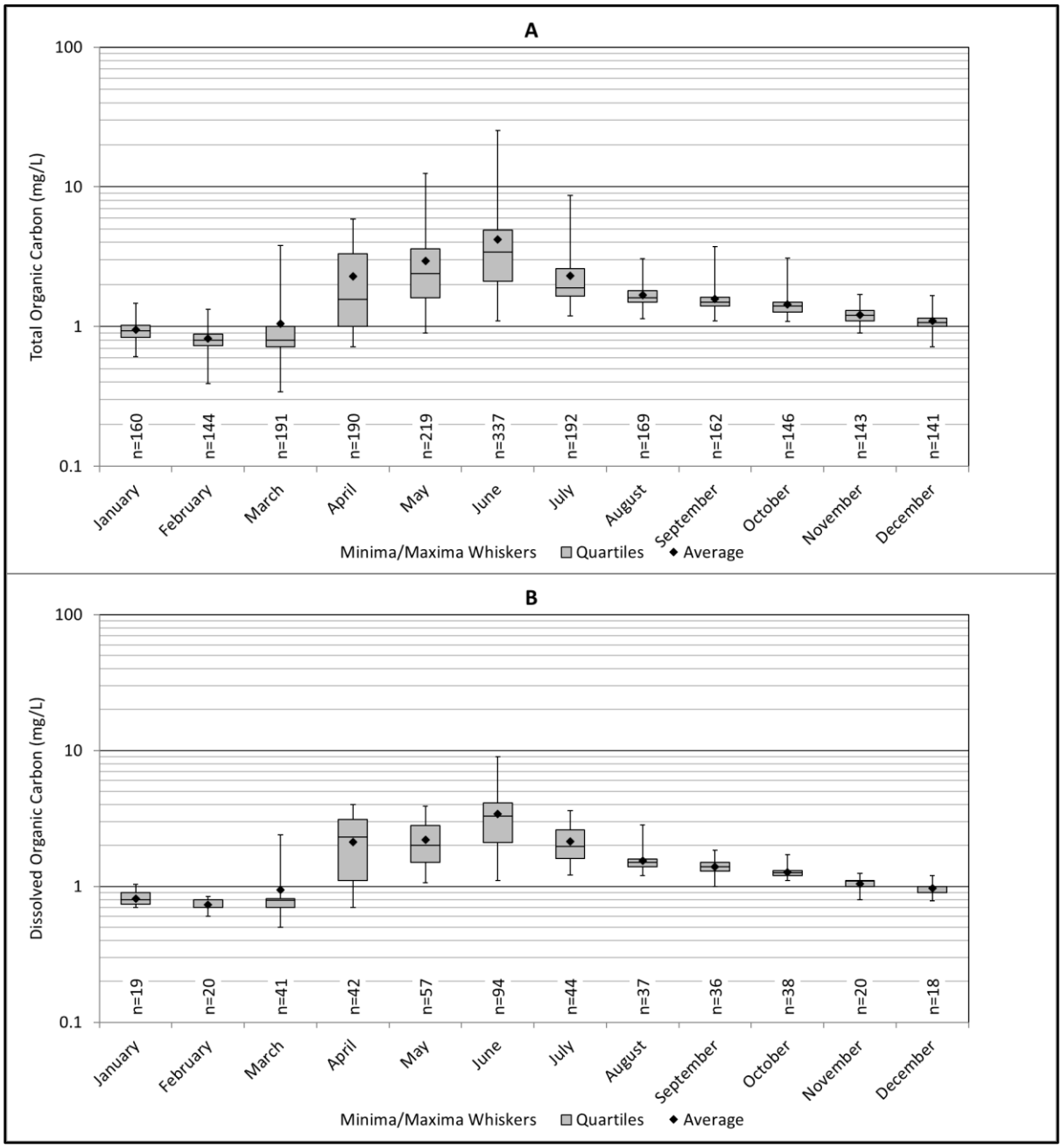

Figure 3.2 Source water Total Organic Carbon (Panel A) and Dissolved Organic Carbon (Panel B) concentrations at the Glenmore WTP in Calgary (2012-2018). The figures illustrate median, quartiles, maxima, minima, and average monthly values.

Figure 3.3 illustrates the monthly ranges for source water pH. Soils high in glacial and sedimentary deposits impart high hardness and alkalinity to the regional groundwater networks. The source water exhibits a relatively high raw water pH throughout the year, due in large part to the geology of the area (Jackson 1980). As a greater fraction of the water originates from overland flows during the spring and summer months, source water pH is increased, likely as a result of the transport of carbonate-rich surficial materials to receiving streams. The variability of source water pH also increased, especially between April and July, as a result of frequent summer storm events.

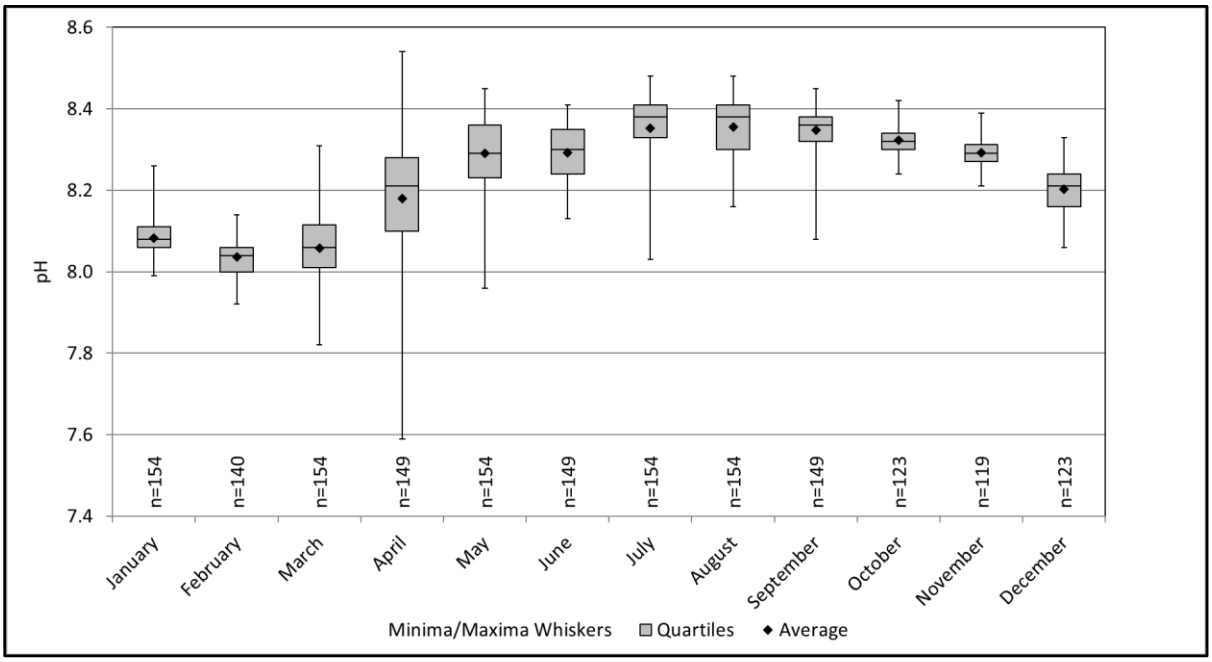

Figure 3.3 Source water pH at the Glenmore WTP in Calgary (2013-2018). The figure illustrates median, quartiles, maxima, minima, and average monthly values.

Seasonal atmospheric temperature variations contribute to a wide range of surface water temperatures in the CoC, as reflected in the source water temperature profile (Figure 3.4). In November through April, the median source water temperatures are less than 5 °C. Between December and March, source water temperatures are typically less than 2 °C.

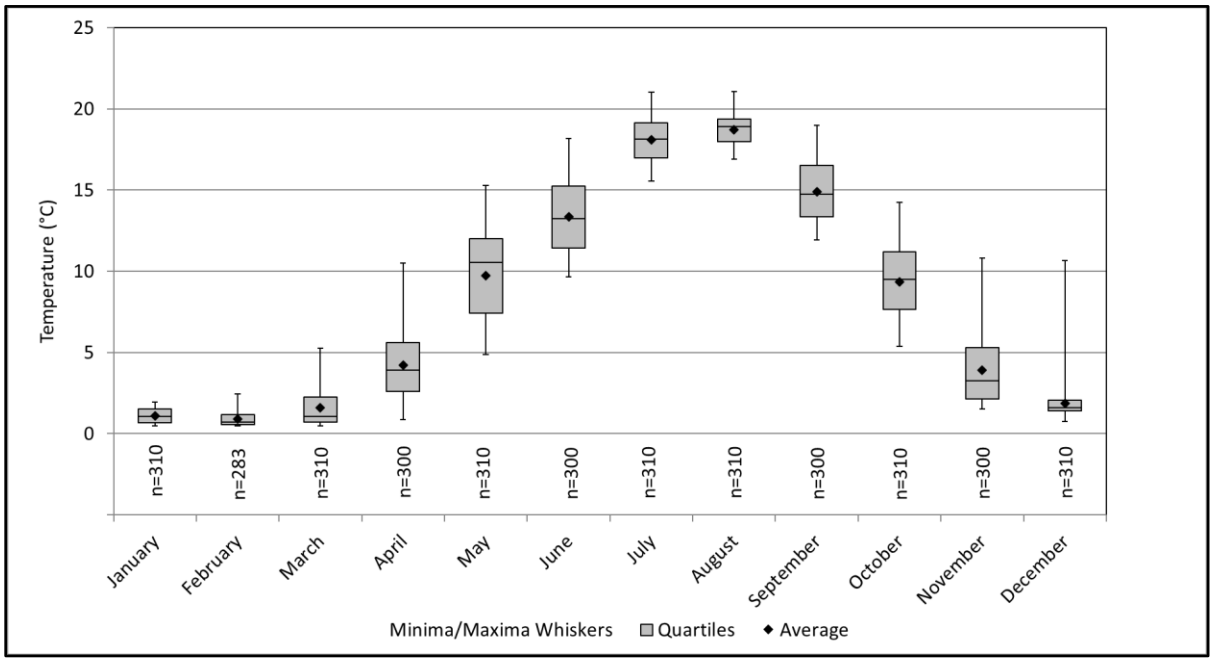

Figure 3.4 Source water temperature at the Glenmore WTP in Calgary (2013-2017). The figure illustrates median, quartiles, maxima, minima, and average monthly values.

Several important generalizations about source water quality and its relationship to treatment needs can be made based on the overall raw water quality trends exhibited at the study site and discussed above. They are:

- Source water characteristics display substantial seasonal trends in aspects of source water chemistry (i.e., TOC/DOC, pH, and turbidity) that typically drive coagulant demands (Gregory et al. 2003; Davis et al. 2014; Sillanpaa et al. 2018);
- High and variable turbidity and organic loadings during the spring and summer periods require operation in the sweep-floc coagulation regime to achieve metal salt coagulant hydroxide precipitation. The incoming particle loads, as well as the precipitated floc generated, would quickly exceed filtration capacity without sedimentation and solids removal processes; thus, the source water is not well-suited for DF during these periods (Valade et al. 2009); and

- Long, stable periods of low turbidity, low organics and stable pH levels during the winter periods indicate that the source water is optimally suited to seasonal DF (Valade et al. 2009), as long as 3-log removal of protozoan parasites is reliably achieved.

3.3 Phase 1 Framework Development for Improved Control of CAF Processes

3.3.1 Introduction

As discussed above, maintaining high quality, low turbidity filter effluent quality is considered essential to protecting public health from waterborne pathogens, especially protozoan parasites; this is mandated by both the USEPA and Health Canada, through the U.S. LT2ESWTR and its international equivalents (AEP 2012; Ontario Regulation 2020). Thus, the filtration process is a "critical control point" (CCP) because hazards associated with waterborne protozoan parasites can be prevented, eliminated, or reduced to acceptable levels at this point in the treatment process (Hellier 2000; Jagals et al. 2004; Damikouka et al. 2007; Walker et al. 2016; WHO 2017). Common metrics used to inform filtration control and performance that were used include filter effluent turbidity and differential pressure across the filters (i.e., loss of head); affiliated filter control elements allow for limited control of filter effluent water quality, and included water level and flow controls (AWWA 2011). Particle counters were also used because they can provide additional information regarding filter effluent quality and process performance (Hatukai et al. 1997; Hargesheimer et al. 1998).

As system complexity increases, utilities require a means to summarize and to present operational performance metrics in an efficient manner to ensure processes remain within control limits, relative to internal operational thresholds and regulatory requirements. Process monitoring is typically achieved through application of alarm setpoints to alert operators when internal operational limits are exceeded. Here, investigations were undertaken to improve operational resilience options through application of data analytics to assess and optimize filter performance at all operational conditions, in real-time. Rather than solely relying on reactive approaches to adjust coagulation chemistry following exceedance of pre-set internal alarm setpoints for filter effluent turbidity or head loss accumulation, zeta potential analysis was investigated as an indicator for

detecting sub-optimal coagulation and particle destabilization issues that would impact subsequent filtration performance.

3.3.2 Objective 1. Identification of operational conditions to connect coagulant dosing to filtration performance

Data trending allows for visualization of system performance over selected periods of time. Time-series analysis can assist in detection of emerging conditions that would trigger early intervention before an alarm is received. However, manual monitoring of multiple processes with trending charts, on a continuous basis, is untenable in a highly complex treatment system with limited operator resources. Added metrics are therefore necessary to consolidate available data streams, and to present relevant data to operators in a form that is quickly digestible and can be acted upon when the system is trending out of compliance (i.e., through generation of summary dashboards and key performance indicators).

Here, nine years (i.e., 3,285 days) of filter operation and performance data from 24 individual filters were utilized to generate key performance indicators (KPIs), which included filter effluent turbidity, filter effluent particle counts, headloss, filter ripening time, and UFRV. All data points within the historical database (typically recorded in 30-second intervals for filter CCPs) were used to generate the KPIs based on the average or maximum daily values from the analyzers. The KPIs were plotted in monthly intervals, thereby enabling rapid scanning of process performance to detect periods of non-ideal performance. Examination of large data sets enabled quick identification of process deviations (and their associated time of occurrence) in large batches, rather than reliance on the time-consuming method of viewing time-series filter runs one at a time.

The following tasks were conducted to generate the KPI dashboards:

(1) Online historical data were cleansed to remove blocks associated with backwashing or FTW periods, so that only water sent to the filtered water clearwell was considered;

(2) Average, minimum, maximum, and standard deviation values for KPIs (filter effluent turbidity, filter effluent particle counts, headloss, filter ripening time, and UFRV) were calculated on a daily basis from each filter in operation;

(3) Data collected during the final 15 minutes of each filter run were extracted to determine filter run termination values for maximum turbidity and maximum particle count;

(4) Monthly summary charts were generated from the average daily values of each parameter, as well as daily average terminal turbidity and terminal particle count;

(5) Monthly summary charts were generated for daily turbidity and particle counter standard deviations on individual filters, to illustrate daily variability of results; and

(6) Monthly summary charts for the KPIs were used to identify periods of potential filter stress (i.e., sub-optimal performance) for further investigation into root causes of the apparent performance issues.

3.3.3 Objective 2. Evaluation of zeta potential analysis to inform filterability

3.3.3.1 Equipment

To achieve Objective 2, an online zeta potential analyzer (Malvern Instruments Ltd., model Zetasizer WT, Worcestershire, UK), was used at the study site to assess how coagulation impacts on particle charge and destabilization could be linked directly to filter performance. Zeta potential data were collected to establish the optimal zeta potential range for optimizing filter effluent water quality and operational efficiency at the study site. Internal configuration settings for measuring frequency and operating modes were set according to Table 3.1.

Table 3.1 Malvern Panalytical online Zetasizer WT© instrument configuration.

SETTING	PARAMETER		SELECTION
Sample	Dispersant:		Water
	General Options:	Model:	Smoluchowski
		Viscosity:	Dispersant
	Temperature:	Auto:	Auto temperature sensor
	Cell:		Disposable capillary DTS 1070
Measurement	Duration:		Automatic
	Number of measurements:		3
	Delay between measurements:		0
	Advanced:	Auto attenuation:	Yes
		Auto voltage:	Yes
Data Processing	Analysis model:		Monomodal

The sample points for online zeta potential analysis were selected downstream of coagulant addition, but prior to polymer and microsand injection from the SBF pretreatment process. Samples were required to be free of abrasive microsand, which would act to scratch and compromise the integrity of the sample cells over a short period of time. The coagulated water sample points also avoided interference and charge uncertainty introduced from subsequent cationic polymer addition.

Continuous sample streams for raw and coagulated water were pumped at high rate (i.e., 350 Lpm) to the online ZetasizerWT to minimize sample transit time and to provide fresh sample for analysis. Flow control valves located on each sample stream were used to direct specific samples into the zetasizer for online analysis. Within the ZetasizerWT housing was a benchtop Zetasizer Nano Z analyzer, complete with an onboard computer and continuous sampling system. The onboard computer served to control sample flows through the zetasizer measuring cell, as well as to handle

the data transfer protocols to the main WTP control system. The ZetasizerWT was programmed to take three sequential zeta potential measurements from each sample aliquot, and to provide the averaged value back to the WTP control system and data historian.

Routine weekly, monthly, and annual maintenance was performed by licensed instrumentation technicians, based upon manufacturer recommendations for flow cell replacements, wear components replacements, and calibrations (Malvern Instruments Ltd., DTS1235 zeta transfer standard, Worcestershire, UK).

The following tasks were conducted to determine suitability of zeta potential monitoring for filter optimization.

(1) Online zeta potential results for both raw and coagulated water streams were cleansed via the online data historian, to remove data pertaining to calibration and internal system checks, and to correlate analyzer results to the active sampling points. Cleansed data were then imported into a spreadsheet for subsequent analysis.

(2) Assessment of normality was performed for stable raw water quality values to determine their range and standard deviation. Coagulated water zeta potential was analyzed for its ability to detect changing raw water quality conditions, and response to coagulant adjustment.

(3) The online data historian utilized at the study site has built-in analytics to generate statistical quality control (SQC) charts from time-series values of all of the KPIs, including zeta potential. Zeta potential time series data were plotted with the calculated standard deviations for the selected operational periods (i.e., those representing both stable operation and challenge periods), and a histogram chart was generated to compare values against a normal distribution. SQC charts were plotted for both stable and unstable/sub-optimal coagulated water quality conditions to assess the sensitivity of zeta potential results in signaling the need for coagulant dosage adjustments in response to changing water quality.

(4) Coagulated water zeta potential values were compared to filtered water turbidity to determine whether a performance linkage between the two parameters was evident, as would be expected according to classical filtration theory. To compare coagulated water zeta potential to filtered water performance, time series performance data (i.e., zeta potential, filtered water turbidity, and filtered water particle counts) were compared. Since the goal was to determine whether zeta potential could be used as a predictor of filter breakthrough, filter ripening peaks were removed from the filtered water turbidity and particle count data. Ripening peaks common to filter startup typically indicate backwash remnant water quality (Amirtharajah 1985) and would mask the quality of recently coagulated water entering the filter. Elimination of ripening peaks was achieved by suppression of data points corresponding to early filter run UFRV values of less than 50 m^3/m^2. Coagulant dose was also compared on the same plots to see how coagulant dose and coagulated water zeta potential conditions were reflected in filter performance.

(5) Online zetasizer results were compared to those obtained from grab samples, which were analyzed on a separate benchtop Zetasizer Nano. The benchtop zetasizer was configured to run five consecutive zeta potential measurements, using both fast-field and slow-field measurements to derive an average zeta potential for each sample aliquot. The ZetasizerWT analysis involved three discrete measurements as noted previously, but with slow-field measurements only. Temperature compensation on the ZetasizerWT was based on an integrated temperature thermocouple to select the proper internal temperature compensation settings on the zetasizer. Samples transported to the lab were cooled back down to the temperature recorded on the raw water stream at the time of sampling, and the temperature settings manually input into the benchtop zetasizer software to account for changes in viscosity due to temperature effects.

3.3.4 Objective 3. Application of monitoring tools to achieve filter effluent turbidity and pathogen reduction targets

Objective 3 was focused on developing a method for early detection of particle and pathogen breakthrough from filters. To achieve Objective 3, control charts were developed that could be used

to link particle count process performance against an alarm threshold derived in real time (i.e., an upper control limit, or UCL). To detect filter breakthrough as early as possible, the UCL was established based on water quality performance data from prior filter runs. Particle count data used for control limit development were based on the outcomes of the analysis conducted to meet Objective 1 (Section 4.1.1), which indicated that observed filter effluent particle count values increased by orders of magnitude during filter breakthrough. To detect filter breakthrough in a timely manner, the filter runs were required to be segmented into smaller, discrete UFRV ranges within each filter run. The UCL for each filter run segment was then derived from the prior filter run particle count data corresponding to the same UFRV ranges. The UCL was calculated based on the average particle counts, plus three times their standard deviation. A three standard deviations-wide spread includes approximately 99.7% of data points within a normal distribution; thus, data within this range were considered within acceptable range of variability and were not considered as extreme values or outliers (Infinity QS n.d.; Mahmoud et al. 2010; Shah et al. 2010). Average particle count values outside of this range were thus considered as indicative of an out-of-control operating condition, which would signal the need for an operator to respond and investigate.

The following tasks were conducted to develop a real-time control chart for early filter effluent particle breakthrough detection:

(1) Data from individual filters were organized into discrete filter runs for analysis. Filter run start and end times were calculated based on control valve position and flow data;

(2) All individual filter runs were further partitioned into smaller segments, based on discrete UFRV ranges. The normalization of filter runs by UFRV segment, rather than run hours, accounted for both time and volume of water passed through the filter;

(3) Average particle count and standard deviation values were calculated for each UFRV segment;

(4) Prior ideal (or "well-operated") filter runs were identified to determine the typical range of filter effluent particle count values as the filter runs progressed;

(5) Particle count averages and standard deviations were calculated based on equivalent UFRV segments over sequential filter runs (of a single filter) to create a normal distribution;

(6) The UCL was calculated from the well-operated filter runs;

(7) Under the assumption that the test filter run particle counts would follow the same sample distribution as prior filter runs, the test filter effluent particle count values were used to calculate the number of standard deviations from the ideal mean of the "control" runs; and

(8) Filter effluent particle counts on the test filter runs were converted to a standard deviation (based on the mean and standard deviation of the prior in-control filter runs), and plotted as a function of UFRV for each filter run under investigation.

3.4 Phase 2 Pilot Scale Direct Inline Filtration Trials

3.4.1 Objective 4. Implications of direct inline filtration on application of monitoring tools to achieve filter effluent turbidity and pathogen reduction targets

3.4.1.1 Rationale

A pilot-scale filtration investigation was conducted to evaluate the effectiveness and resilience of direct inline filtration in removing particles and especially *Cryptosporidium* oocyst-sized particles from a typical high quality source water (i.e., low in organics and turbidity) at the study site. Given the relative lack of tools available for linking settled water quality indicators to filtration performance and the potential for zeta potential application for this purpose (Morfesis et al. 2009; Pernitsky et al. 2011), zeta potential analysis immediately following chemical addition was assessed to inform its utility as a tool for maintaining filter effluent water turbidity below regulatory thresholds, while concurrently maximizing water production (i.e., UFRV). Pretreatment chemicals were adjusted at the start of each experimental trial to determine the relative impacts of coagulant and polymer on filter influent zeta potential and filter effluent turbidity and particle counts; these impacts were evaluated with the objective of maximizing filter production capacity (UFRV). Constant chemical concentrations were applied during each filter run. Polymer (Magnafloc LT22S cationic polymer, prepared from dry polymer powder provided by BASF Canada Inc.) dosages ranged from 0 to 0.22 mg/L, and aluminum sulphate coagulant (Chemtrade Logistics Inc., 48.5% $Al_2(SO_4)_3 \bullet 18H_20$) dosages ranged from 0 to 18 mg/L. With two chemical agents used for pretreatment chemical adjustment, a high number of trials were required to determine optimal ratios of polymer to coagulant for filter optimization.

3.4.1.2 Design criteria

To successfully complete the experiments outlined in Objective 4 in a manner that would be meaningful for full-scale operations at the study site, a pilot filter apparatus was required that could meet the following criteria:

- Coagulant and polymer selected to match the existing Glenmore WTP pretreatment processes for particle destabilization. Consistency of applied chemicals was required because there would be no opportunity to substitute alternative coagulants or polymers on a seasonal basis at the full-scale WTP;
- The seasonal use of direct filtration would be required to function using the existing full scale filter media designs. Pilot filter media physical properties (i.e., effective size (ES), uniformity coefficient (UC) and density), filter media depths and filter underdrains were configured to match the full-scale WTP filters;
- Filter operating regimes were selected to minimize the potential for confounding factors or sources of errors between trial runs, including:
    - Filters operated in a declining rate mode, to eliminate issues associated with valve movements and flow pulsing through the filter media;
    - Backwashing regime selected to match full scale WTP operation for consistency (i.e., air scour followed by high rate backwash); and
    - Triplicate filter columns used to ensure repeatability and consistency at each alum and polymer chemical dosage combination.
- Pilot filtration system configured to provide continuous measurements for headloss, filter influent turbidity, filter effluent turbidity, filter influent particle counts and filter effluent particle counts for further analysis.

3.4.1.3 Source water

The winter period at the Glenmore WTP was selected for investigation to ensure stable source water pH, turbidity, and temperature conditions throughout all of the trial filtration investigations. Since the trial runs were to be compared against one another to determine the most suitable chemical combinations, consistent chemical conditions throughout the piloting period were essential to avoid potentially confounding sources of variation from unstable influent water quality. Source water entering the main WTP was pretreated with carbonic acid at full-scale for pH correction, which ensured stable pH values prior to chemical adjustment. Pilot plant feed water was therefore withdrawn from the full-scale WTP at pretreatment facility influent channels, just prior to

full scale coagulant addition. A centrifugal jet pump, complete with a manual flow control valve and inline rotameter were used to provide a stable feed water flow rate (i.e., 20 Lpm) to the pilot plant constant head tank for chemical dosage control (Figure 3.5). Excess water provided by the jet pump was diverted back to the main WTP through a separate flow control valve, in order to maintain adequate flow and pressure on the pump head for continuous operation.

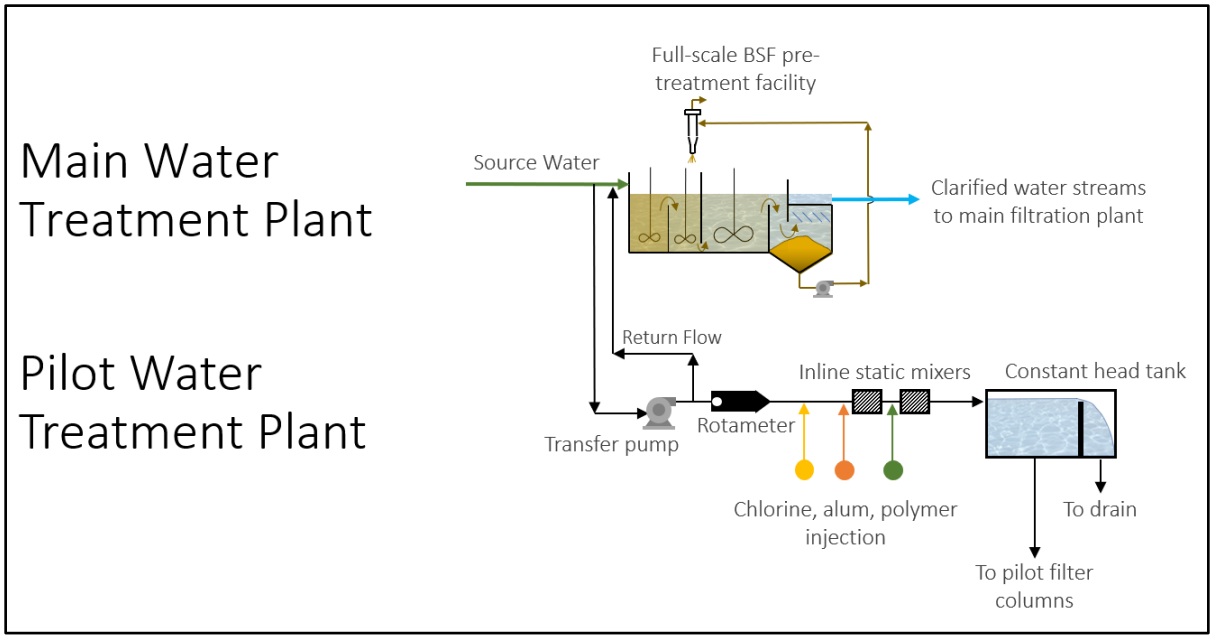

Figure 3.5 Pilot plant feed water withdrawal location in relation to main WTP.

3.4.1.4 Pilot-scale filtration process configuration

The configuration of the direct in-line filtration experiment is illustrated in Figure 3.6. It shows the general process flow and sampling locations for each experimental trial.

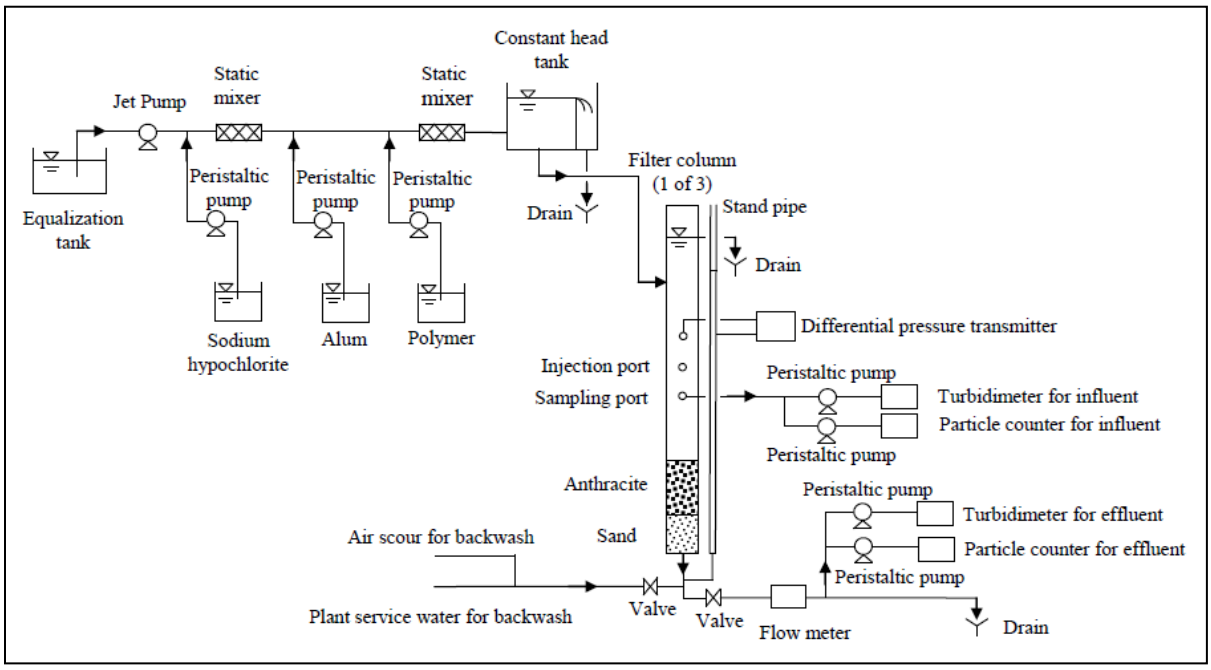

Figure 3.6 Direct in-line filtration experimental process flow diagram (modified from Wang, Kundert, and Emelko 2018).

3.4.1.5 Hydraulics

A constant head tank was fitted with an overflow weir to provide a constant static head to drive flow through the pilot filter columns. Water was passed from the constant head tank via gravity to the filter distribution header, where flow was split evenly to three parallel 3-inch acrylic pilot filter columns. From the distribution header, water was passed through a flow control valve and rotameter on each filter for flow balancing. Water was then directed through a side-wall penetration on each of the three-inch acrylic filter columns, where flow was directed downwards through the filter media and excess flow discharged upwards through an overflow pipe to provide a constant water level above the filter media.

3.4.1.6 Filter media

Filter media (sand and anthracite) were collected from the CoC full-scale WTP filters, to ensure that the physical material properties were matched between the pilot filter columns and the full-scale WTP. Media sizes and depths are detailed in Table 3.2. A stainless steel underdrain was

incorporated to match the full-scale water treatment plant underdrain design to provide media support and to distribute air scour and backwash flows evenly.

Table 3.2 Pilot column filter media configuration.

Layer	Depth (mm)	Effective Size, D_{10} (mm)	Uniformity Coefficient, D_{10}/D_{60}	Specific Gravity
Anthracite	457	1.0-1.1	1.35	1.33-1.40
Sand	305	0.45-0.50	1.40	2.65

3.4.1.7 Filter column wall effects

Filter performance can degrade at pilot-scale, especially when water short-circuits between the media grains and the inner wall of the filter column—termed "wall effects" (i.e., water passes more easily along the column wall than through the media). Wall effects on pilot filter columns occur where high-porosity grain arrangements, along the inner wall of filter columns, allows large particles and floc to pass deeper into the media than what would occur between adjacent media grains (Mcwhirter et al. 1997). Typically, the wall effects decline at a steady value within five media grain diameters from the column wall (de Klerk 2003). To reduce column wall effects, the ratio of the column diameter (*D*) to the media diameter (*d*) must be low (i.e., *D/d* ratios of 20 to 30) (Lang et al. 1993; Mcwhirter et al. 1997). The anthracite media used in this experiment had an effective grain size diameter of 1.1 mm (compared to 0.5 mm for the sand layer). With the filter columns inner diameter sized at 75 mm, the *D/d* ratio was greater than 50 for the larger anthracite grains, as recommended by Lang, et al. (1993). Thus, the pilot-scale filter design allowed for hydraulic loading rates of 15 m/hr without wall effects impacting filter performance.

3.4.2 Pilot filter column operation

3.4.2.1 Backwashing

Air scour and wash water were used during backwashing; pressurized air was passed upwards through the media, followed by a pressurized water backflush to simulate a normal backwashing sequence on a full-scale filter. Air was passed through the media at a flow rate of three cubic feet per minute (CFM) per square foot of media surface, which is typical of many full-scale filtration operations and matched the approach used in the full-scale WTP. Water backwash rates were monitored with rotameters and effective backwashing of the filter media visually confirmed (Colton et al. 1996). High rate backwash was set for an optimal media expansion rate of 30% (Amirtharajah et al. 1990). Following backwash, the filter columns were tapped with a rubber mallet to ensure media settled back to its original elevation, without mounding against the walls of the filter columns.

3.4.2.2 "Normal" operation

Filtration cycles were initiated immediately following a fresh backwash. The filters influent flows were fed from the constant head tank. The filters were operated with a constant hydraulic head set by the filter column overflow piping. Filtration rates were set at the start of each filter run and allowed to decline throughout the run as headloss accumulated and slowed the rate of filtration; this is also known as a "constant head, declining rate" mode of operation. The filtration rates started at approximately 15 m/h and declined to approximately 12 m/h throughout the filter runs, until the maximum headloss criterion (i.e., 2.0 m) was exceeded.

3.4.2.3 Chemical pretreatment

Influent water to the pilot plant was dosed with sodium hypochlorite solution (6%, W.E. Greer Ltd.) at approximately 1 mg/L as free chlorine to suppress microorganism growth, to act as an oxidant and promote efficient particle removal (Edzwald 2011) and to match typical chlorine levels on the full scale WTP. Chlorinated water was mixed via an inline static mixer, followed by concurrent addition of alum coagulant (Chemtrade Logistics Inc., 48.5% $Al_2(SO_4)_3 \bullet 18H_20$) and Magnafloc LT22S cationic polymer (0.25% or 0.30% by weight, prepared from dry polymer powder provided by BASF

Canada Inc.). The chemically adjusted water was then passed through a second static mixer, prior to discharging into an open-topped constant head tank (, Figure 3.6). The doses of each chemical were determined based on the varied experimental conditions.

Peristaltic pumps used for chemical dosing were calibrated for each chemical with daily drawdown tests utilizing a graduated cylinder, with the influent water flowrate set by the manual rotameter and needle valve downstream of the pilot plant feed centrifugal jet pump (Figure 3.5). When low coagulant dosages were required that the peristaltic pumps could not deliver in low enough volumes, dilution of concentrated alum was achieved by mixing equal volumes of deionized water, and pH maintained less than 3 to ensure hydrolysis would not occur prior to coagulant injection into the source water stream.

3.4.3 Water quality and filter parameters

3.4.3.1 Headloss

Filter headloss was continuously monitored with a differential pressure gauge (Omega Engineering Inc., Stanford, CT, model number PX771A-100WCDI). Headloss was manually verified by measuring the liquid differential level between the filter column overflow and liquid level in the filter effluent site glass located immediately upstream of the filter discharge flow control valves.

3.4.3.2 Filter column effluent flow rate

Pilot filter column effluent flow rates were continuously monitored downstream of the manual filter effluent flow control valves with an insertion magnetic flowmeter (Omega Engineering Inc., Stanford, CT, model number FMG 3001-PP). Flows were set at the start of each filter column test to reach the specified filter startup hydraulic loading limit (i.e., 15 $m^3/m^2/hr$). The selected loading rate represented a worst-case scenario for velocity and shear forces across the filter media grains, which would require ideal attachment mechanics to retain particles during the pilot filter trials.

3.4.3.3 Sample flow

Sample water was collected downstream of the filter effluent flow meters and transported to the filter effluent analyzers with peristaltic pumps, via flexible tubing connected to the drain header of

each filter. A single peristaltic pump fitted with a multi-head roller was used to send identical flows from individual filter columns to their respective turbidimeters. Similarly, a second multi-head peristaltic pump was used to send sample flows from each filter column to their respective particle counters. Filter influent water was intercepted above the filter media from filter column number two and sent to a dedicated turbidimeter and particle counter using the same peristaltic pump heads as the filter column effluent samples. Flow rates through each of the turbidimeters were set at 250 mL/min, and flows through each particle counter were set at 100 mL/min, as per the analyzer manufacturers recommendations.

3.4.3.4 Particle Counts

Filter influent and effluent particle counts were monitored utilizing continuous online analyzers. The particle counters (HACH 2200 PCX Particle Counter, Hach Co., Loveland, CO.) measured total particles from 2-750 µm, with the data reported as total number of particles ≥2 µm per mL (i.e., NP/mL). Data were collected by the main WTP control system via a 4 to 20mA signal loop, with data points stored every 30 seconds. Each particle counter was calibrated on-site by industry-certified instrument technicians. Standard protocols were used to calibrate and verify particle counters, as recommended by the manufacturer. Calibration was achieved by passing mono-disperse polymer microspheres (Duke Scientific Corporation, Palo Alto, CA.) through the unit. Calibration verification was achieved as per Hach document; "Analytical procedures 2200 PCX Particle Counter—particle counter performance verification", document number 28043-89.

3.4.3.5 Turbidity

Filter column influent and effluent turbidity was measured using online turbidimeters (HACH Model 1720E, Hach Co., Loveland, CO.) that were calibrated with dilute formazin suspensions to USEPA Method 180.1: Determination of Turbidity by Nephelometry, with reference to Standard Method 2130B (Eaton 2005). Validation of all turbidimeters was performed daily against a benchtop turbidity analyzer (HACH Model 2100N, Hach Co., Loveland, CO.).

3.4.3.6 Chlorine

Free chlorine residual was monitored at the constant head tank during each pilot filter run following equilibration of chemical feeds through the constant head tank (i.e., alum, polymer, and sodium hypochlorite). An amperometric titrator (Wallace & Tiernan, Series A790, Evoqua Water Technologies, Pittsburgh, PA.) was used to test for free chlorine residual, operated in accordance with Standard Method 4500-Cl D (Eaton 2005).

3.4.3.7 pH

Source water pH was recorded continuously from the full-scale WTP online pH probes (HACH Model DPD-2P1, Hach Co., Loveland CO.), with an accuracy of ± 0.02 pH units. The online pH probe was calibrated weekly based on Standard Method 150.1 (Eaton 2005), by certified instrument technicians with a measuring range of 0 to 14 pH units.

3.4.3.8 Zeta potential

The zeta potential of source and chemically pretreated water matrices was analyzed (Malvern Instruments Ltd., model Zetasizer Nano Z, Worcestershire, UK). Source water samples were collected at the pilot plant transfer pump. Chemically pretreated water samples were collected from the pilot plant constant head tank following equilibration of alum coagulant and polymer (for each of the tested chemical combinations), but prior to startup of chlorine dosing to the constant head tank. Sample collection for zeta potential analysis was performed prior to chlorination to match the chemical addition regime more closely at the online zeta potential sampling point on the full-scale pretreatment facility.

Samples were transferred to the onsite laboratory in 250 mL Nalgene bottles for analysis within one hour of sample collection.

Table 3.3 summarizes the internal settings of the benchtop zetasizer. The zetasizer was maintained and verified by the manufacturer's representative, at the frequency recommended by the manufacturer.

Table 3.3 Malvern Panalytical benchtop zetasizer Nano Z© instrument configuration.

SETTING	PARAMETER		SELECTION
Sample	Dispersant:		Water
	General Options:	Model:	Smoluchowski
		Viscosity:	Dispersant
	Temperature:	Manual:	Daily source water temperature
	Cell:		Disposable capillary DTS 1070
Measurement	Duration:		Automatic
	Number of measurements:		5
	Delay between measurements:		0
	Advanced:	Auto attenuation:	Yes
		Auto voltage:	Yes
Data Processing	Analysis model:		Mixed Mode (M3)

3.4.4 Data collection & analysis

3.4.4.1 Direct Filtration pilot column study data collection

In total, 48 direct inline filtration trials were conducted using varying dosages of coagulant and polymer (Appendix B). Filter run parameters were recorded from the pilot plant online analyzers for each filter run and automatically saved by the main WTP control system for later data extraction. Saved parameters included top-of-filter (TOF) turbidity, TOF particle count, filter effluent turbidity, filter effluent particle count, filter flow rate and headloss through each filter.

Filter runs were analyzed to determine basic filter run characteristics. Run characteristics included calculation of ripening times, ripening volumes, run termination times, UFRV at time of run termination, and cause of run termination (i.e., turbidity breakthrough, particle count breakthrough, or headloss exceedance). The stable operating period began once both filtered water turbidity reached ≤ 0.1 NTU and total particle counts greater than 2 µm reached ≤ 50 NP/mL. Run termination occurred when any of the following conditions were met: (1) headloss reached ≥ 2.0 m, (2) turbidity reached ≥ 0.1 NTU, or (3) total particle counts greater than 2 µm reached ≥ 50 NP/mL. Where filter runs were unable to reach the ripening criteria, a UFRV of zero was used.

To determine whether zeta potential could be used as a predictor of filter performance (in a direct inline filtration setting), filter runs were compared to determine relative performance at each chemical dose combination. The following analyses were performed:

(1) Comparison of alum dose versus UFRV, at constant polymer dose;

(2) Comparison of polymer dose versus UFRV, at constant alum dose;

(3) Assessment of normality and standard deviation for raw water zeta potential samples;

(4) Comparison of zeta potential versus UFRV, at constant polymer dose;

(5) Comparison of zeta potential versus UFRV, at constant alum dose; and

(6) Assessments of normality were conducted on source water zeta potential, pH and temperature to ensure minimal impact to coagulant demands throughout the trial period. This was done through least-squares and ANOVA analysis (Appendix C).

4 Results and Discussion

4.1 Phase 1 Results and Discussion

4.1.1 Objective 1. Identification of operating conditions to connect coagulant dosing to filtration performance

Combined filter performance trends were used to visualize average and terminal turbidity and particle count data. The green shaded zones within the Figure 4.1 charts represent the target filter performance criteria for each parameter (<0.1 NTU, or <50 NP/mL). Yellow shading represents the performance zone which exceeds the operational setpoints, but remains within regulatory limits up to the automated filter shutdown setpoint (<0.25 NTU). The red shading represents unacceptable filter performance values that will trigger a filter bed shutdown (>0.25 NTU, or > 50 NP/mL).

The dashboards provide a first step to quickly view and to identify periods of time where filter performance may be abnormal or trending towards an undesirable state. Because of data handling limitations, charts are constrained to 30-day increments. Thirty days allows for a reasonable amount of time to see longer-term trends in filtered water quality, where slowly changing source water chemistry could result in a gradual decline in filter performance, without correction by chemical adjustment. Figure 4.1 shows the composite time-series outputs for filter performance dashboard during a select 30-day window.

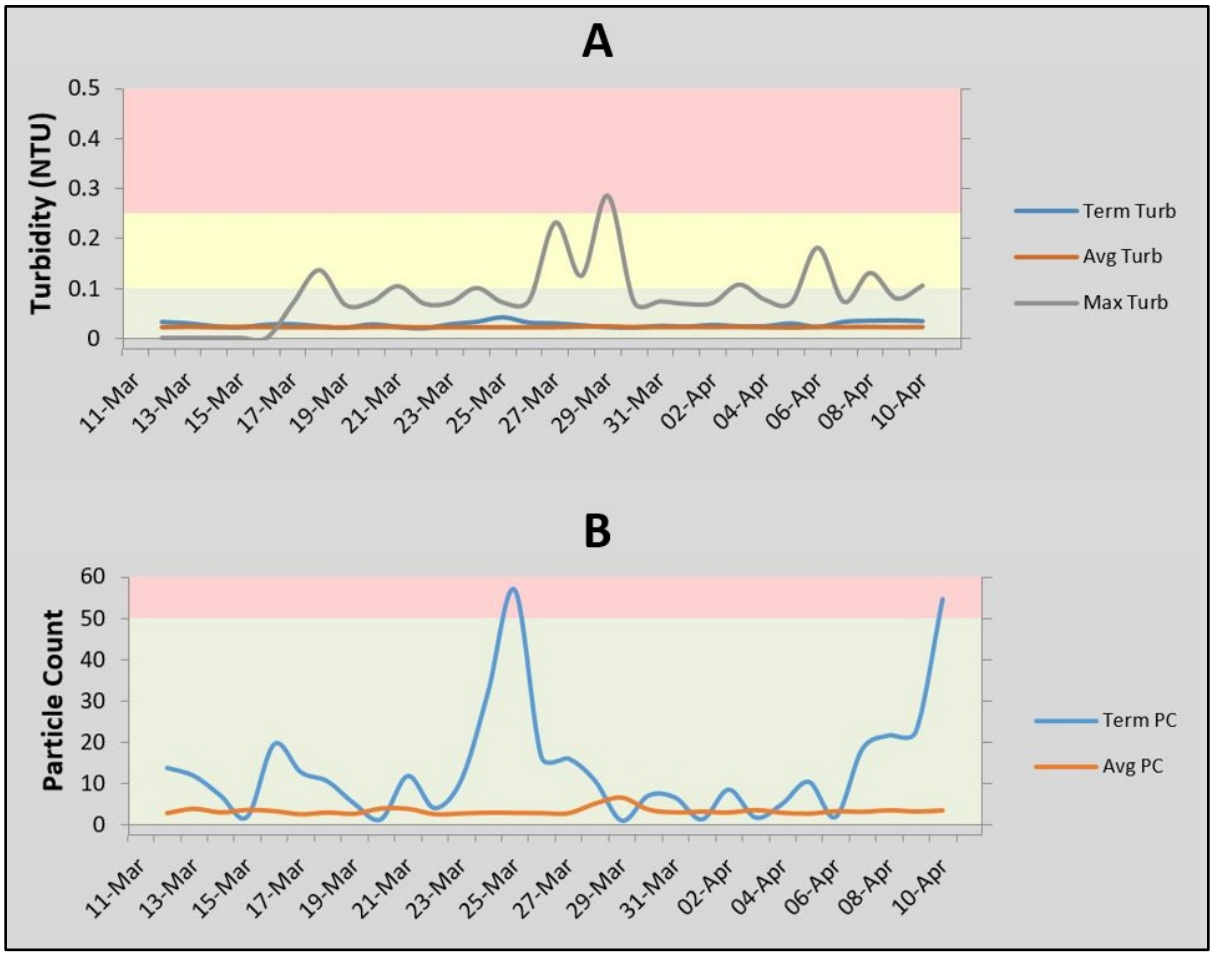

Figure 4.1 Combined filtered water performance results from all online filters. Daily average and terminal values for turbidity (Panel A) and particle count (Panel B) are illustrated over a 30-day period.

The dashboard shown in Figure 4.1 illustrates how a composite trend can be used to identify periods of potential filter stress for further investigation. In this example, terminal filtered water turbidity remained close to the average turbidity for the runs represented. However, terminal particle counts deviated significantly from the average run performance. The high terminal particle count would indicate the potential that certain filters experienced onset of breakthrough for those days. The maximum turbidity line from Panel A may be cause for concern, but may also represent intermittent data spikes from particles detaching from sample line walls to cause temporary increases in turbidity.

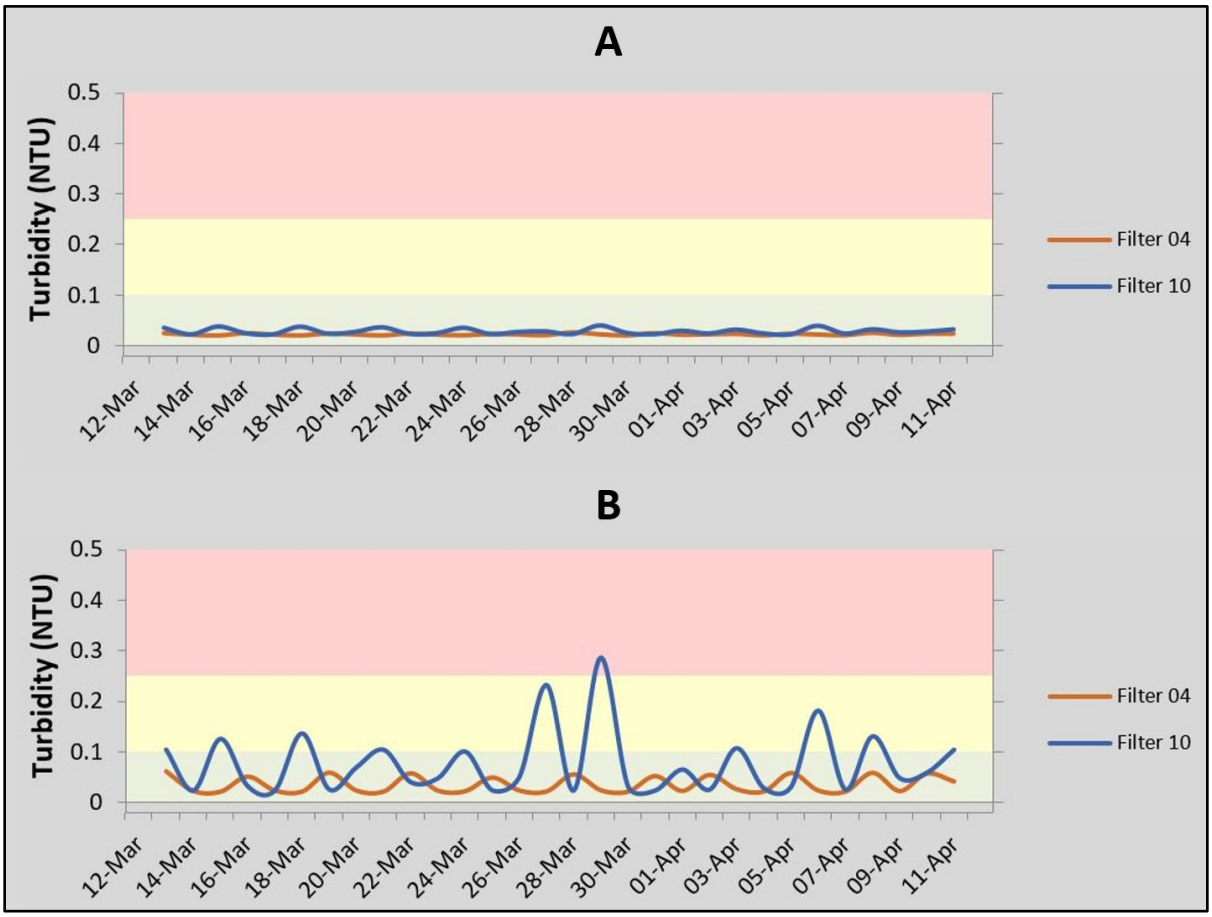

Figure 4.2 Average turbidity (Panel A) and maximum turbidity (Panel B) from individual filters over the evaluated period. Cyclical trending of daily average and maximum turbidity observed on alternating days corresponded to backwash periods. A limited number of filters are shown on each panel for clarity.

Compared to more typical combined filter effluent water quality charts such as those shown in Figure 4.1, individual filter effluent water quality charts provide a more detailed breakdown of run parameters for each filter on a given day, thereby allowing greater resolution of potential challenge periods. The trends in Figure 4.2 show a slight cyclical oscillation in the daily average filtered water turbidity. The maximum daily readings for filtered water turbidity (Panel B) illustrates a much higher apparent cycling than observed with the average filtered water turbidity (Panel A). The cyclical nature of the maximum turbidity trending would indicate issues with either filter ripening,

breakthrough, or recurring turbidity spikes passing through the analyzers, and requires further investigation to determine the root cause.

The daily standard deviation from individual water quality analyzers is captured in Figure 4.3. Analyzer variability provides a means to target specific filters (or analyzers) that exhibit higher than normal value changes throughout the day, which could be indicative of filter performance or analyzer quality control issues. High standard deviations which exceed values observed on adjacent filters, could be flagged for further investigation into the source of the variability.

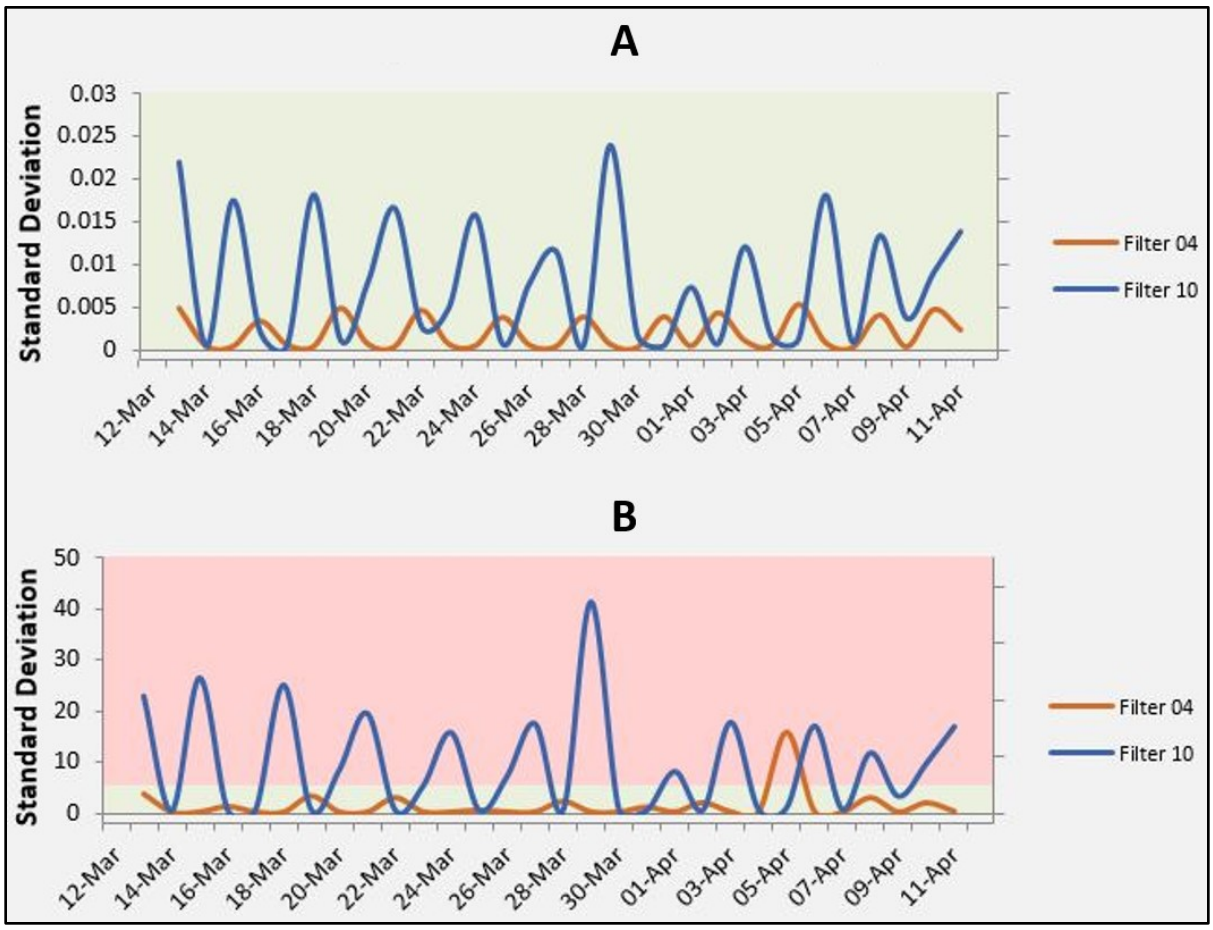

Figure 4.3 Daily analyzer standard deviations for filtered water turbidity (Panel A) and particle counts (Panel B). High analyzer standard deviations, when compared to adjacent filters, are illustrated for the selected time periods for further investigation.

The oscillations observed in Figure 4.2 for the combined filters, are also found in Figure 4.3 for standard deviation on individual analyzers. Examination of filtered water particle count and turbidity standard deviation can be used to identify specific filters for which KPIs are highly variable on a given day, when plotted alongside other filters. Although some oscillation is expected from filter ripening, where water quality improves steadily during the initial hours of the filter run cycle, the difference between the observed beds remains high. Heightened variability on both turbidity (Panel A) and particle count (Panel B) indicate a potentially problematic filter which requires further investigation to rule out or to confirm a filter performance-related issue.

Based on the time-frames of suspected water quality issues identified in the filter dashboards, Figure 4.4 represents filter trending directly from the WTP data historian. Recorded filter operating parameters are overlain on a time-series plot to visualize actual filter performance throughout the time range selected. Figure 4.4 illustrates an example of poor particle attachment to the filter media, as demonstrated by early and repeating turbidity and particle count breakthrough at the end of each filter run. Of note, is that although there is a rise in turbidity and particle count values near the end of the filter run, the regulatory parameters for filtered water turbidity were not exceeded (i.e., turbidity remained below the regulatory threshold of 0.3 NTU at all times). Subsequent changes to coagulant dosage were able to rectify the turbidity breakthrough by the time of the final filter run illustrated in Figure 4.4. Early filtered water particle count and turbidity breakthrough is a condition that requires correction before regulated limits are exceeded, as late-run turbidity and particle breakthrough correlates to increased pathogen transport through the filter media (Huck et al. 2002; Emelko et al. 2003; Campbell et al. 2014).

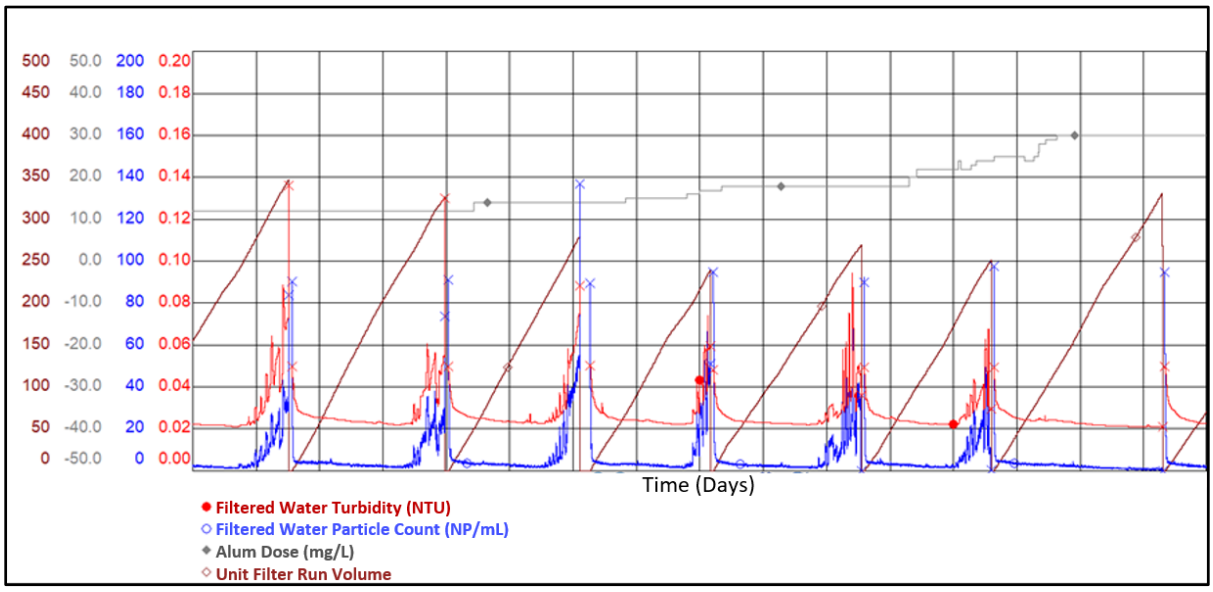

Figure 4.4 Online filter run data from the WTP SCADA system. Time range is based on the time series observed in Figure 4.3. End of run breakthrough was evident based on increase of terminal turbidity and particle counts. Subsequent increases to coagulant dosage eliminated the terminal breakthrough conditions and improved the UFRV results.

Figure 4.5 illustrates how additional issues can be identified by overlaying parameters other than just water quality indicators. Filter loading rate (or flowrate per unit area per hour, m^3/m^2/hour) is included to note how the impact of abrupt flow rate changes during the filter run can increase the severity of filter breakthrough events as filters near the breakthrough period of the filter run.

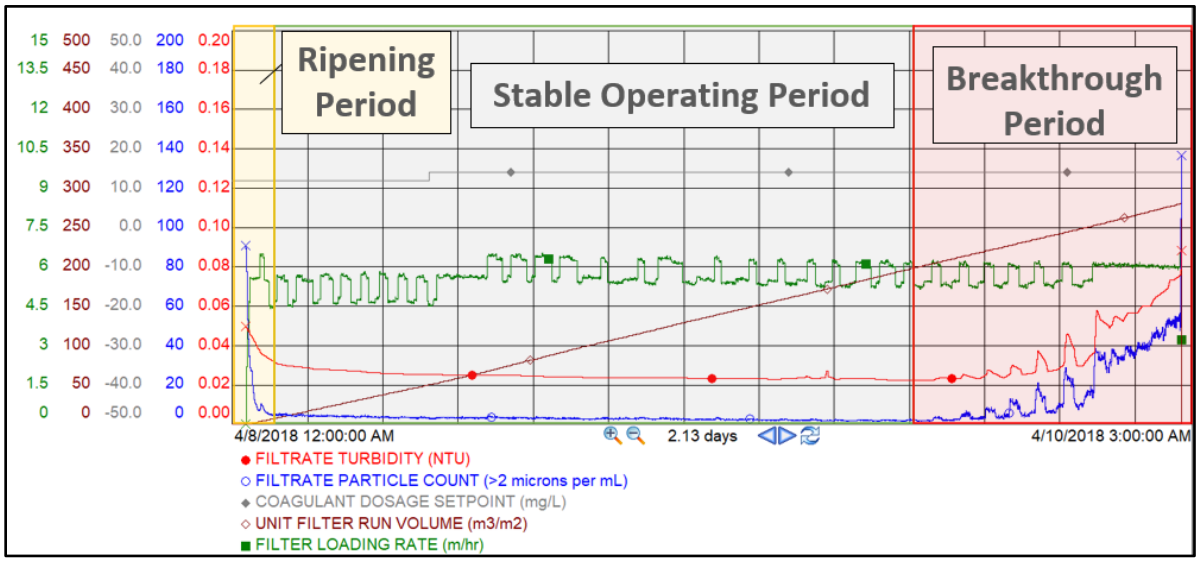

Figure 4.5 A Filter experiencing end-of-run turbidity and particle counts breakthrough is illustrated. Online analyzer time-series trending shows emerging breakthrough conditions, evident by the increasingly high turbidity and particle count values detected on filter effluent with each subsequent surge in filtered water flow rate.

The single filter run sequence illustrated in Figure 4.5 shows the impact of frequent filter flow control valve oscillations, as the control system attempts to automatically maintain a flow setpoint. Particle count and turbidity breakthrough are seen emerging near the end of the filter run. As onset of breakthrough begins, each valve movement and subsequent surge in filter flow rate displays increased turbidity and particle count passage into the filtered water clearwell. It should be noted, in this case, that turbidity changes at levels less than 0.1 NTU are more difficult to detect without detailed trending, when compared to particle count increases during filter breakthrough development. During the initial turbidity surges, the turbidity levels increased above stable operating levels by only approximately 0.01 NTU (i.e., from 0.025 NTU to 0.035 NTU), while particle counts surged by up to 30 NP/mL (i.e., from 1 NP/mL to over 30 NP/mL) for each flow surge. The higher relative change in particle counts make it easier to detect change than for turbidity.

Figure 4.5 illustrates the difficulty in reliance on turbidity alone to detect the onset of filter breakthrough, where both particle count and turbidity remain well below operational setpoints but

display increasingly more severe breakthrough peaks with each subsequent hydraulic disturbance through the filter.

4.1.2 Objective 2. Evaluation of online monitoring tools for use in prediction of filterability

4.1.2.1 Online zeta potential analysis

Zeta potential results from full scale WTP data were evaluated as a potential CCP for connecting coagulation and particle destabilization to filter run performance. In its most simplistic form, utility operators can monitor zeta potential trends to identify whether coagulation chemistry has shifted, or chemical dosing has been interrupted, and bring the system back to an optimal zeta potential state.

Zeta potential observations on the test site coagulated water demonstrate high variability between individual sample results, where individual step changes often exceed one standard deviation from the mean (Figure 4.6). To enable further statistical analysis, conformance to a normal distribution can be evaluated on a statistical quality control (SQC) chart. A non-normal distribution would render the zeta potential data unusable for statistical analysis, without further manipulation to transform them into a normal distribution.

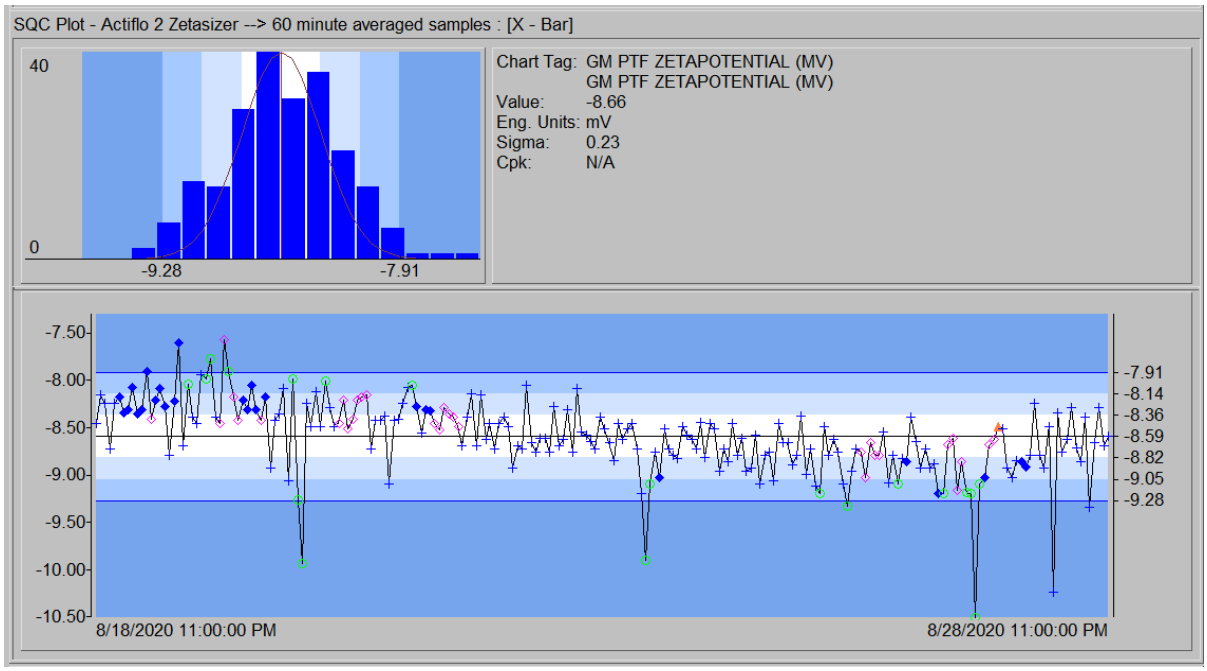

Figure 4.6 Statistical Quality Control (SQC) plot generated by the WTP SCADA system for coagulated water zeta potential during stable water quality conditions. Each of the horizontal colored bars overlain on the trendline represent 1-standard deviation from the mean. A normal distribution of results is illustrated during stable water quality conditions over the selected time period based on the inset histogram plotted with the expected ±3 standard deviation normal distribution curve.

Figure 4.6 shows a histogram and trendline of coagulated water zeta potential values, prior to polymer addition, taken during a window of stable operating conditions. Data from the selected time period appeared consistent and followed an approximately normal distribution, based on the histogram results. However, a high standard deviation was observed (i.e., where adjacent data points often exceed one standard deviation or more), which suggests that a large number of samples would be necessary to generate a more precise average zeta potential value over a longer time period. The zeta potential of both coagulated and uncoagulated (i.e., source water) samples had high standard deviation over all of the seasons that were evaluated.

Sharp, transient drops in coagulated water zeta potential were observed on several occasions. The low values represented periods during which the pretreatment trains were stopped and restarted,

thus impacting coagulation effectiveness for particle destabilization. The length of the coagulant dosing lines (i.e., distance between the chemical control valves and dosing points) resulted in several minutes of transit time, and hence a lag period, between coagulant system startup and chemical to reach the dosing point. These decreases in zeta potential values during treatment train startups closely matched the raw water zeta potential values and thus indicated under-coagulation. Further analysis showed that each of these startup periods resulted in a subtle, but measurable increase in filtered water turbidity when the poorly destabilized water passed through the filter media. The increased turbidity remained below regulatory limits for all filters impacted. Zeta potential monitoring, in this case, allowed for detection and correction of a potential risk to water quality and pathogen transport resulting from sub-optimal pretreatment chemistry (Figure 4.7).

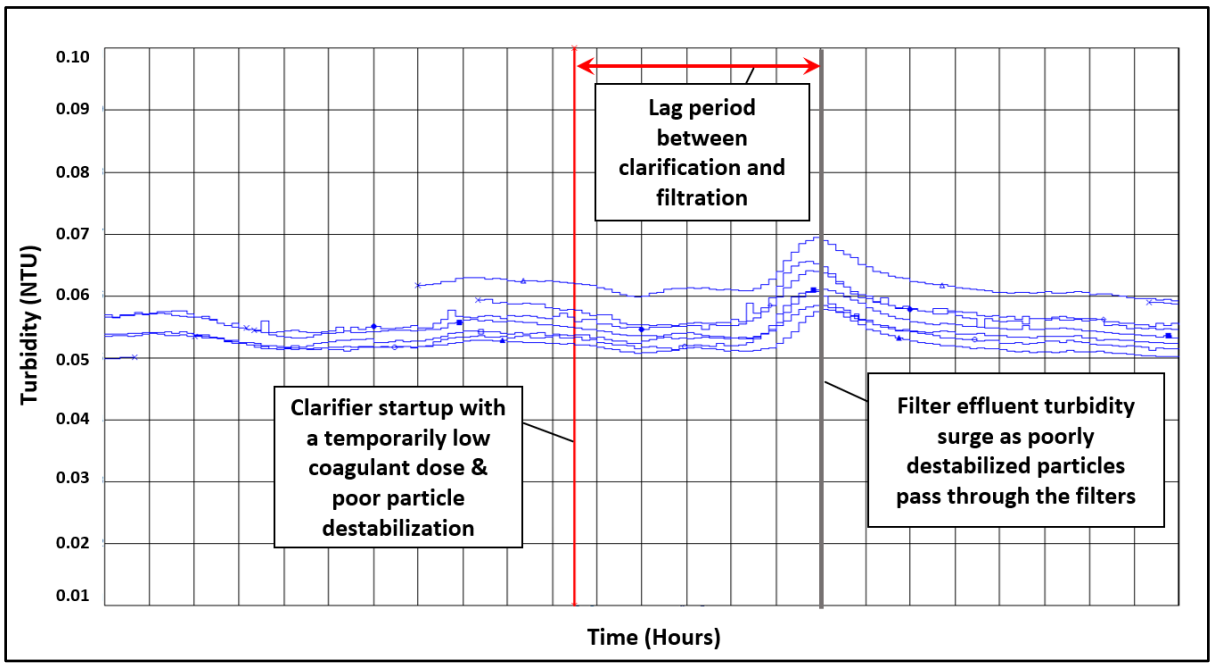

Figure 4.7 Time-series illustration (from SCADA) of impacts on filtered water turbidity due to temporary interruption of coagulant dosing, (i.e., during startup of individual SBF clarifiers—shown by the vertical red line), which resulted in a transient volume of water reaching the filters that exhibited poor particle destabilization. The time between clarifier startup and temporary surge in filter effluent turbidity matched the hydraulic transit time for the poorly destabilized particles to reach the filters.

The SQC plot shown in Figure 4.8 represents a period of source water quality chemical change which did not follow a normal distribution (illustrated by the histogram plot overlain with the six-standard deviation probability curve embedded within Figure 4.8), as coagulated water zeta potential increased by a measurable amount over a short period of time. The abrupt change in source water quality (i.e., without changes to pretreatment chemical dosing) resulted in a double-peak histogram for source water zeta potential, which resulted from the climb in zeta potential, represented by a nearly six-standard deviation change in zeta potential for the time period analyzed.

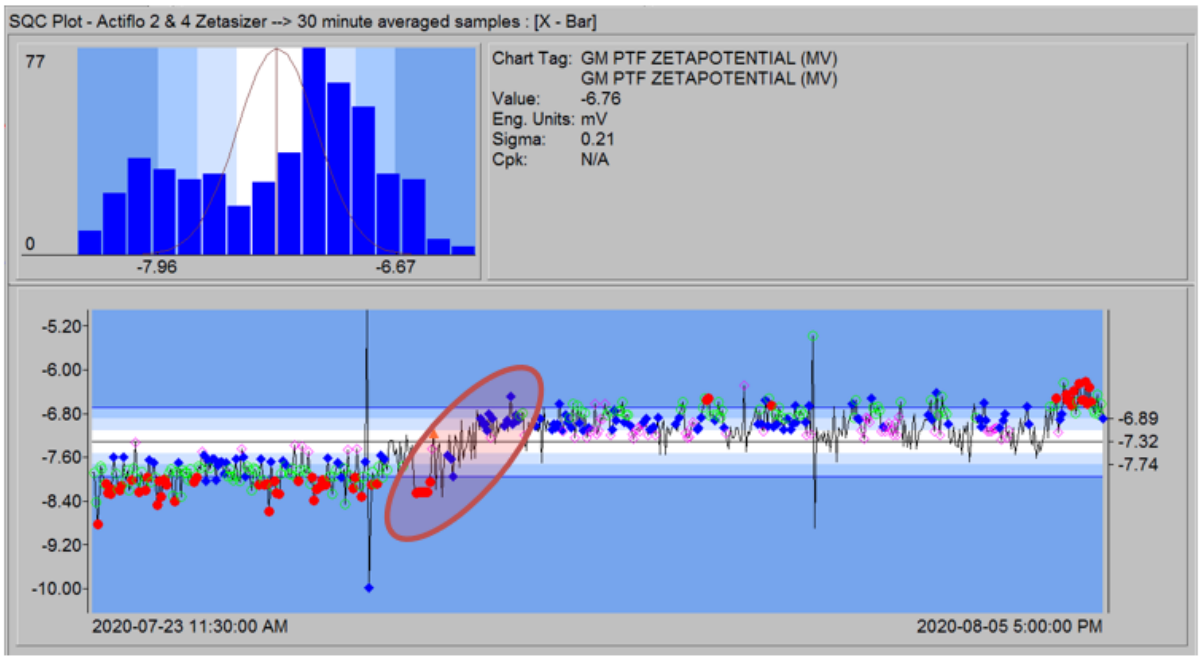

Figure 4.8 Statistical Quality Control (SQC) plot generated by the WTP SCADA system for coagulated water zeta potential during changing water quality conditions. Highlighted period in red illustrates increasing zeta potential during a source water quality change, in absence of pretreatment chemical adjustments. Without chemical adjustments during shifting source water quality, poor particle destabilization and early filter breakthrough can occur. The embedded histogram illustrates the deviation of zeta potential distributions away from the expected normal distribution shown by the solid line within the histogram. The shifting zeta potential pattern (i.e., away from normality) indicates that a change has occurred in the coagulated water chemistry not explained by normal variation.

For the same time period illustrated in Figure 4.8, zeta potential values for coagulated water were plotted alongside filter effluent turbidity and particle counts, in time-series, to detect filterability changes at varying coagulated zeta potential values (Figure 4.9). This was done to determine whether the changing zeta potential values would create a detectable change in filtration performance, under changing raw water quality conditions.

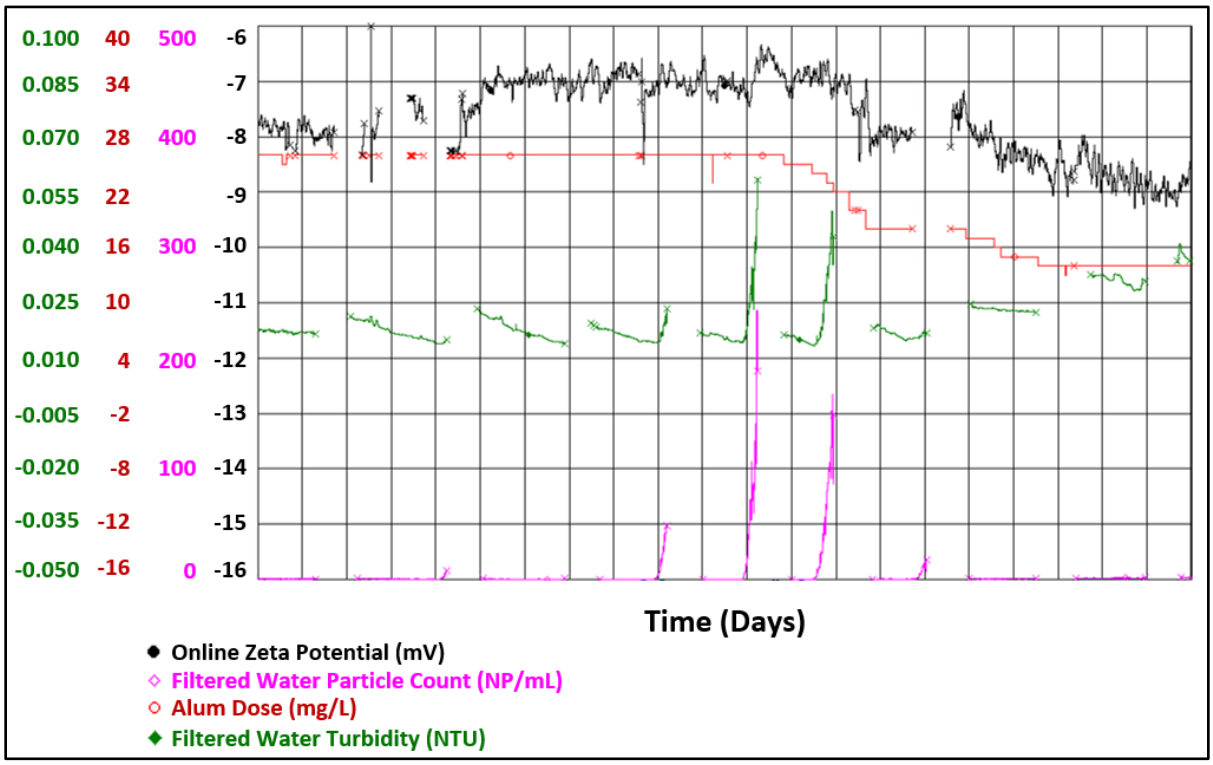

Figure 4.9 Time series SCADA schematic illustrating development of terminal filter breakthrough during periods of increasing coagulated water zeta potential. A single filter is shown, with turbidity and particle count ripening peaks removed for clarity. Filtered water turbidity remained below 0.1 NTU at all times for all filters during the onset of breakthrough, while particle counts exceeded 300 NP/mL, in some cases. Online coagulated water zeta potential values (black) ranged from -6.3 to -9.1 mV, while coagulant dosages (red) ranged from 26 mg/L down to 14 mg/L.

The evaluation of time-series filter performance data in Figure 4.9 indicated terminal breakthrough occurring over consecutive filter runs. Analysis of filter effluent turbidity found a marginal increase

in turbidity prior to filter run termination, at values well below 0.1 NTU. In contrast, filtered water particle counts during the terminal breakthrough periods exceeded 300 NP/mL in certain filters.

Examination of filter effluent turbidity and particle count data as a function of zeta potential provides a sharper illustration of zeta potential impacts on particle removal by filtration. Breakthrough conditions are pronounced at the more positive zeta potential values as indicated in Figure 4.10 and Figure 4.11.

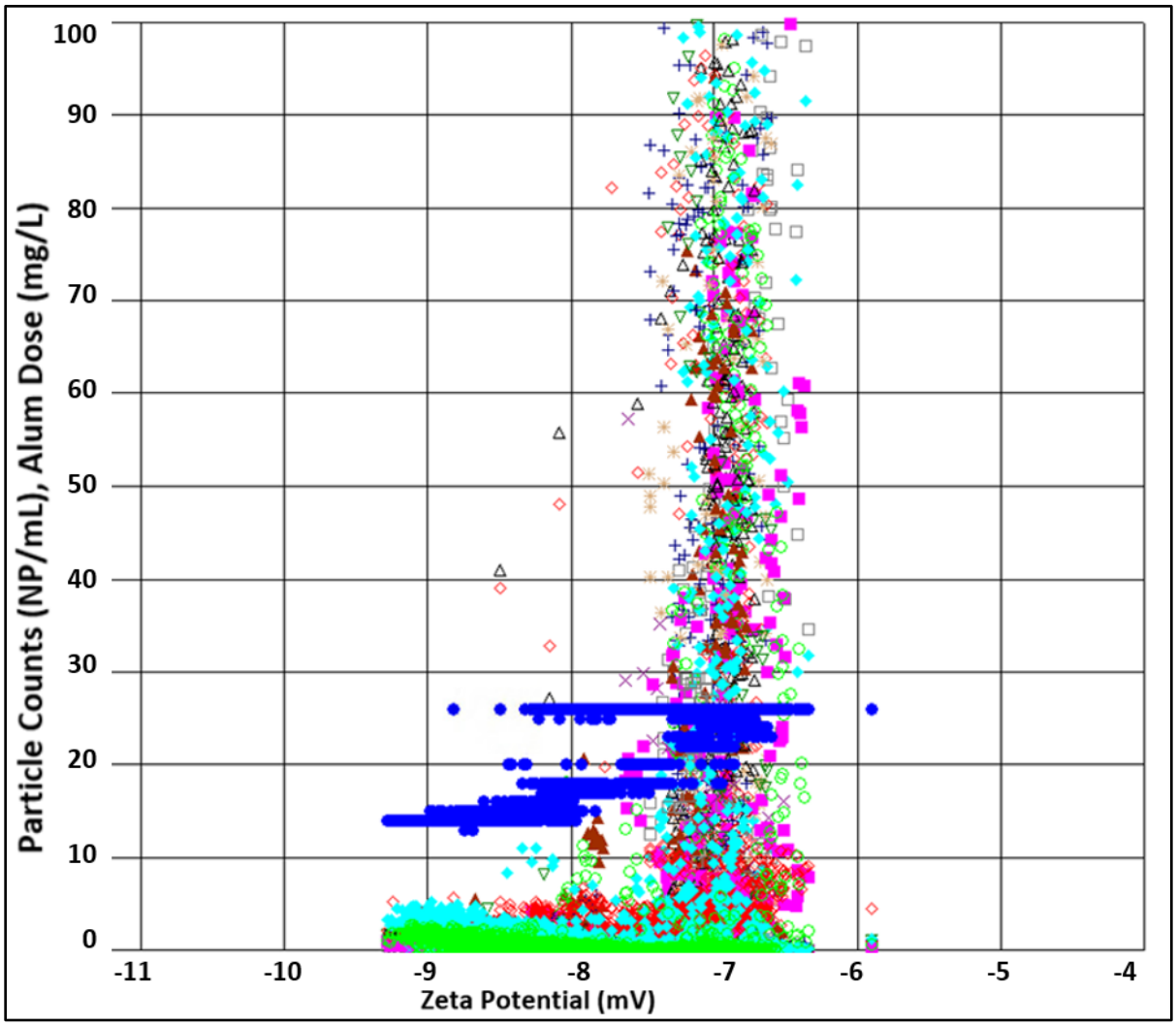

Figure 4.10 Filtered water particle counts (NP/mL, multiple filters, ripening peaks removed for clarity) plotted as a function of coagulated water zeta potential (mV). The chart, output by the WTP SCADA system, shows the coagulant dosage as blue circles. Reduction in particle counts was evident at the lower coagulant dosages, which corresponded to the more negative zeta potential values. Increased particle counts at higher zeta potential values indicate an over-coagulation condition, resulting in re-stabilization of particles and subsequent passage through the filters. This is corrected at the lowered coagulant dosages.

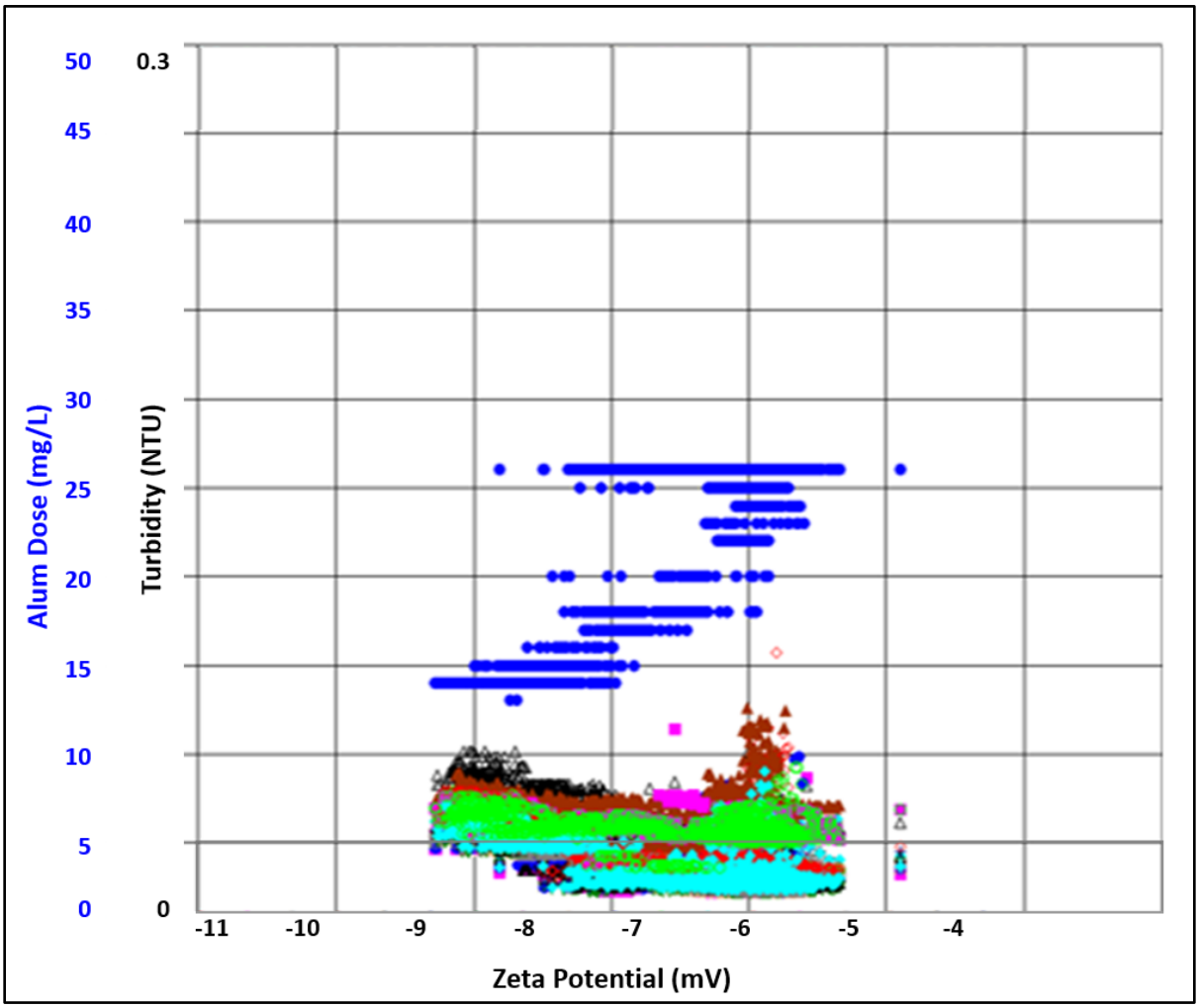

Figure 4.11 Filtered water turbidity (NTU, multiple filters, ripening peaks removed for clarity) plotted as a function of coagulated water zeta potential (mV), during the identical time period illustrated in Figure 4.10. The chart, output by the WTP SCADA system, shows the coagulant dosage as blue circles. The same surface charge conditions that had resulted in filtered water particle count breakthrough (Figure 4.10), resulted in nearly undetectable filtered water turbidity increases at similarly high (i.e., more positive) zeta potential values.

Based on the elevated particle counts found at higher coagulated zeta potential values, additional trends in filter effluent particle counts as a function of zeta potential were examined. Example trends obtained during the spring freshet season are shown in Figure 4.12.

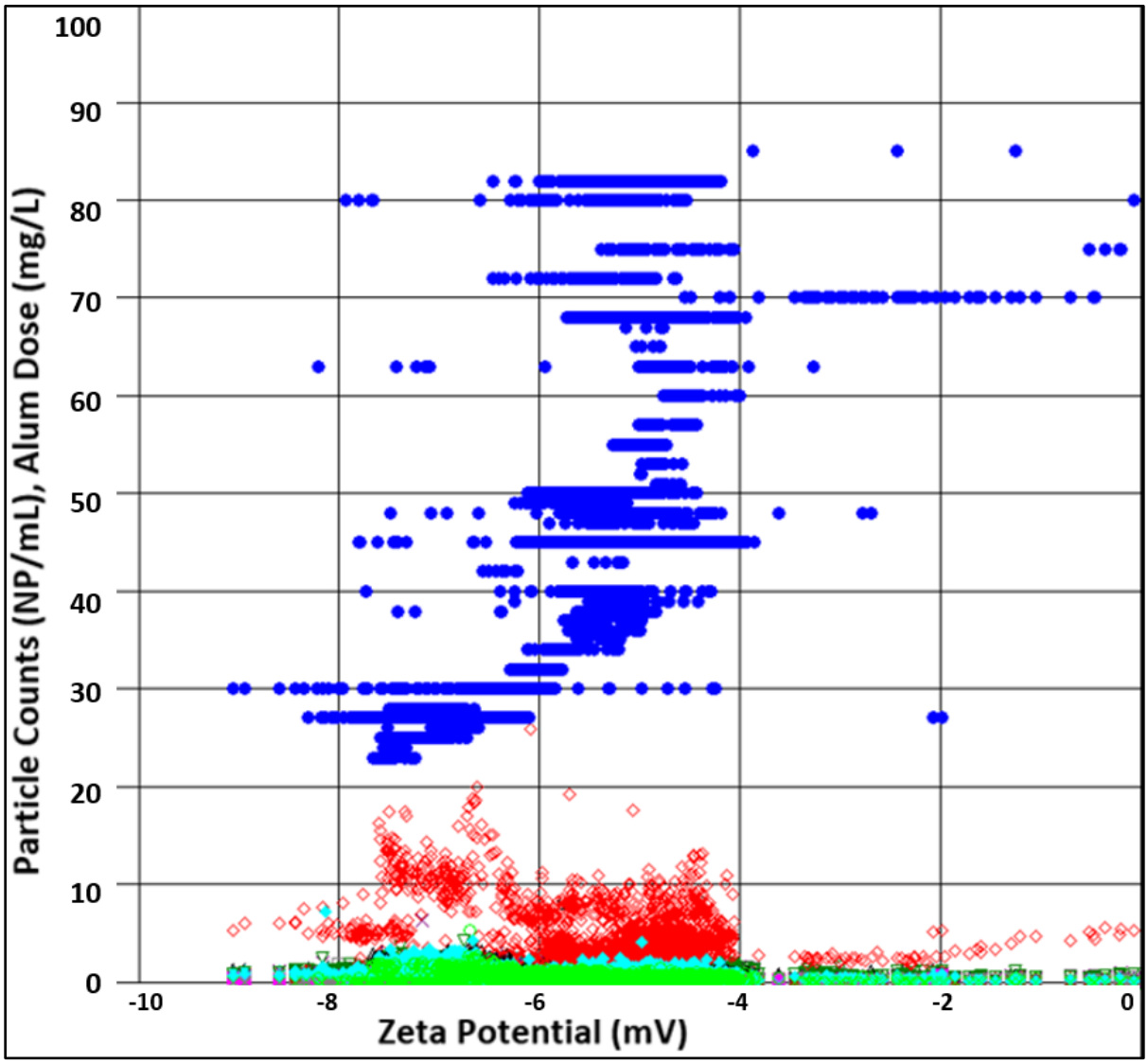

Figure 4.12 Filtered water particle counts (NP/mL, multiple filters, ripening peaks removed for clarity) plotted as a function of coagulated water zeta potential (mV), during the annual spring freshet. A wide range of coagulant dosages (blue) were required to maintain low filtered water particle counts. Optimized coagulated water zeta potential values ranged from between -8 mV to -4 mV. Optimum filter effluent turbidity during the freshet differed from results observed in Figure 4.10 and Figure 4.11, where early run termination via particle count breakthrough occurred as zeta potential values increased above -7 mV (Figure 4.10).

Coagulant demands varied widely throughout the period illustrated in Figure 4.12. Throughout all of the coagulant dosing adjustments, stable filter effluent particle counts were achieved over the entire range of zeta potential results encountered (-8 mV to -4 mV). There appear to be other mechanisms involved which allows for good filtration results in the Figure 4.12 time period, compared to the time period in Figure 4.10 which exhibited high particle counts and breakthrough at more positive zeta potential values. These data suggest that seasonal adjustment of coagulated water zeta potential target range is warranted to maintain filterability within acceptable limits.

4.1.2.2 Comparison of online zeta potential to discrete lab analysis

Online zeta potential results from the Malvern ZetasizerWT were compared to those obtained from grab samples, evaluated with a benchtop zetasizer. Figure 4.13 includes the monthly average values for online zeta potential alongside the monthly average for grab samples on coagulated water, prior to polymer addition. Both the online analyzer and laboratory analyzer incorporated the Malvern Zetasizer Nano for sample analysis.

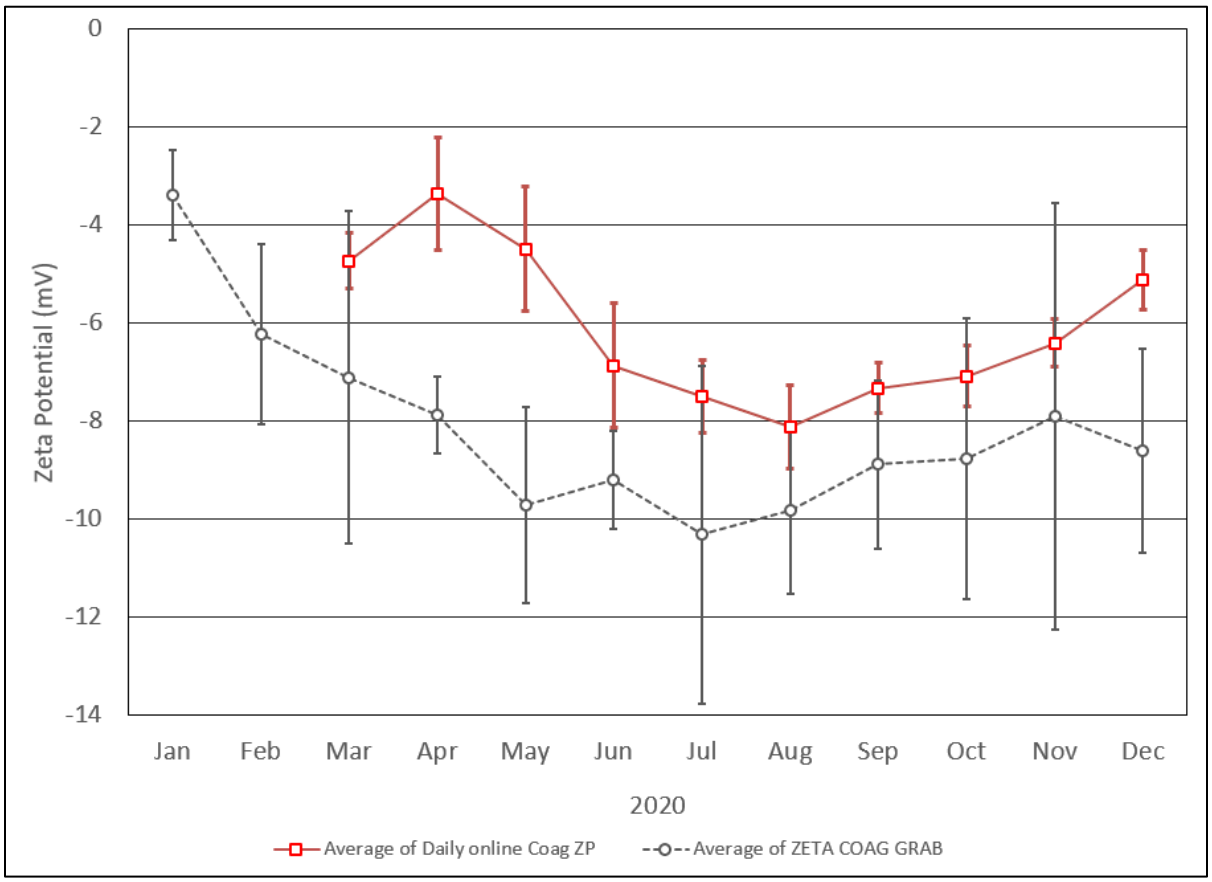

Figure 4.13 Monthly average zeta potential for coagulated water. Error bars indicate one standard deviation. Grab sample zeta potentials are contrasted with those obtained using an online zetasizer. Higher standard deviation and negative bias were observed in laboratory analysis of grab samples (as compared to online analysis).

Similar to the results observed for zeta potential and coagulant dose, both the online and grab sample zeta potential values reflected a decrease in zeta potential associated with optimal filtration performance between spring and summer periods—this may reflect shifts in bulk water quality and differences in the distributions of individual particle zeta potentials that yield instrument readings. Nonetheless, the grab samples and laboratory analysis here yielded consistently lower individual and monthly zeta potential values and higher standard deviations than the corresponding online ZetasizerWT. Factors that may have contributed to the lab sample analysis biasing low may include

unaccounted temperature effects, variable holding times between sample collection and analysis, and/or variable sample vial agitation & mixing during transport.

As coagulant hydrolysis reactions occur on the scale of minutes (Gregory 2009), the increased variability seen in the laboratory analyzed samples results is reasonable, as delays between sample collection and running the sample on the zetasizer are inherently variable. Extended holding times prior to zeta potential analysis allow additional time for successive coagulant hydrolysis reactions to proceed. Sample agitation and mixing during transport also act to increase particle collision frequency, which would be expected to enhance the progression of hydrolysis reactions (Amirtharajah et al. 1982), resulting in an increasingly more negative zeta potential value as the aluminum species become less positively charged. Conversely, the continuous sample line flow to the online analyzer provides consistent transit times and mixing energies for each sample ahead of analysis. As a result of the large number of samples required to calculate an accurate average zeta potential value when standard deviations are high, and given the uncertainty in transport and holding times from time of collection to running samples, this analysis demonstrates that reliance on infrequent zeta potential grab samples for fine tuning coagulant dosages is less optimal than reliance on online analysis.

The changes to optimal coagulation zeta potential readings over time suggest the need to either establish seasonal zeta potential targets to optimize filtration performance or obtain more accurate zeta potential distributions. Given the high level of effort to continuously create new zeta potential targets, it would be simpler to evaluate filter effluent turbidity and particle counts as a function of zeta potential to ensure that filter performance remains within operational goals and regulatory limits (Figure 4.10 – Figure 4.12). Thus, as source water quality shifts, WTP operators would be able to adjust coagulant dosages to maintain the zeta potential ranges optimized for that season. Of course, filter effluent turbidity and particle counts necessarily must serve as the primary metrics used to fine-tune coagulant dosing; however, this analysis demonstrates that zeta potential analysis can be a useful tool in expediting that process, especially during rapidly changing raw water quality conditions.

4.1.3 Objective 3. Application of monitoring tools to achieve filter effluent turbidity and pathogen reduction targets

To determine the suitability of filter effluent particle count values for UCL development, average particle count data for specified UFRV ranges were calculated over a series of filter runs spanning one year. Average particle count results for three selected UFRV ranges within individual filter run cycles were extracted and plotted in Figure 4.14.

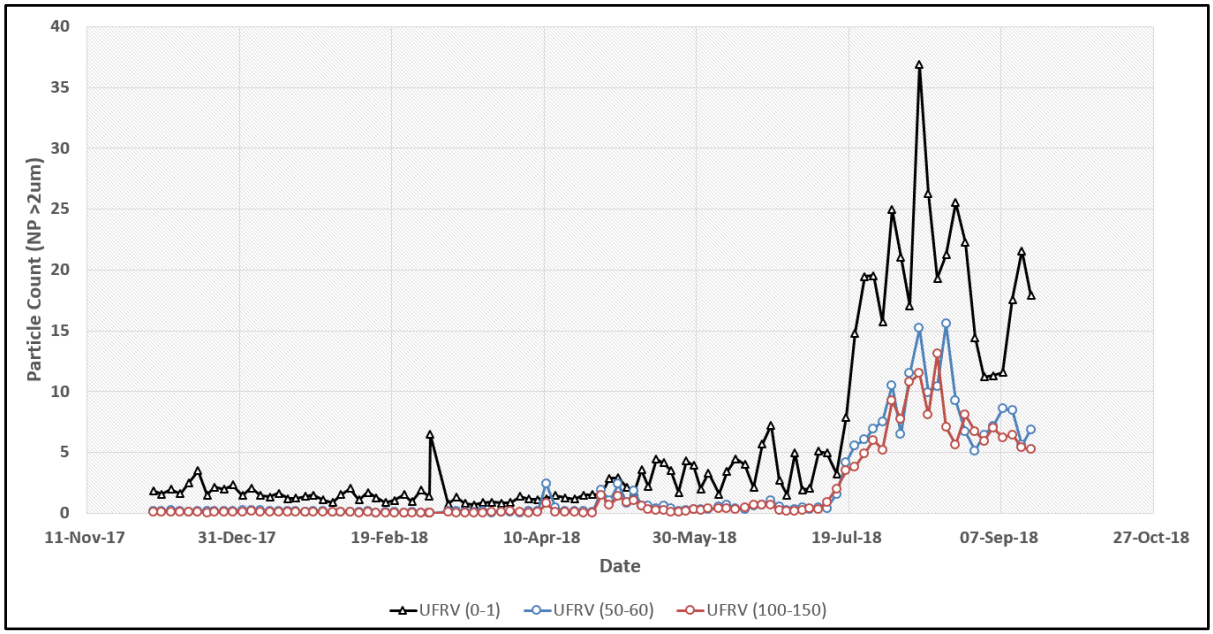

Figure 4.14 Seasonal variability observed for average particle count data within discrete UFRV segments over sequential filter runs spanning one year. Low particle count variability is observed during cold water winter conditions (i.e., November through April), with increasing variability evident through the warm water periods (i.e., May through October).

The variability in filter effluent particle counts for each of the UFRV segments investigated (and representing a one year period) is illustrated in Figure 4.14. In this figure, selection of the UFRV ranges (i.e., the spacing between the points on the ordinate for which variability in particle counts was evaluated) is arbitrary; three values were utilized to determine particle count consistency at different stages of the filter run cycle. Although not shown here, smaller run segments did not yield significant improvements to response characteristics or variability.

The Figure 4.14 trend illustrates a long period of consistent particle counts through the winter season (November to April), followed by fluctuation during the warmer spring and summer seasons (May to October). The higher particle count levels through the summer warm water conditions are typical at the study site. Higher overall variability appears to correlate to onset of early spring snowmelt, storm events and an annual freshet during the late June to July period. Each seasonal change would have triggered coagulant dosage changes, resulting in some particle count variability as dosages are optimized to the changing water quality conditions. Using these data, six-sigma methodologies were applied to generate an UCL, based on three standard deviations (or "3-sigma") above the mean particle count value, derived from sequential data points (Figure 4.15). For subsequent filter runs, any UFRV segment exceeding the 3-sigma boundary could be alarmed and investigated. Figure 4.15 illustrates how multiple filter runs are overlain to create a particle count envelope, from which the standard deviation (yellow & green bars), as well as the 3-sigma UCL (red bar) were derived.

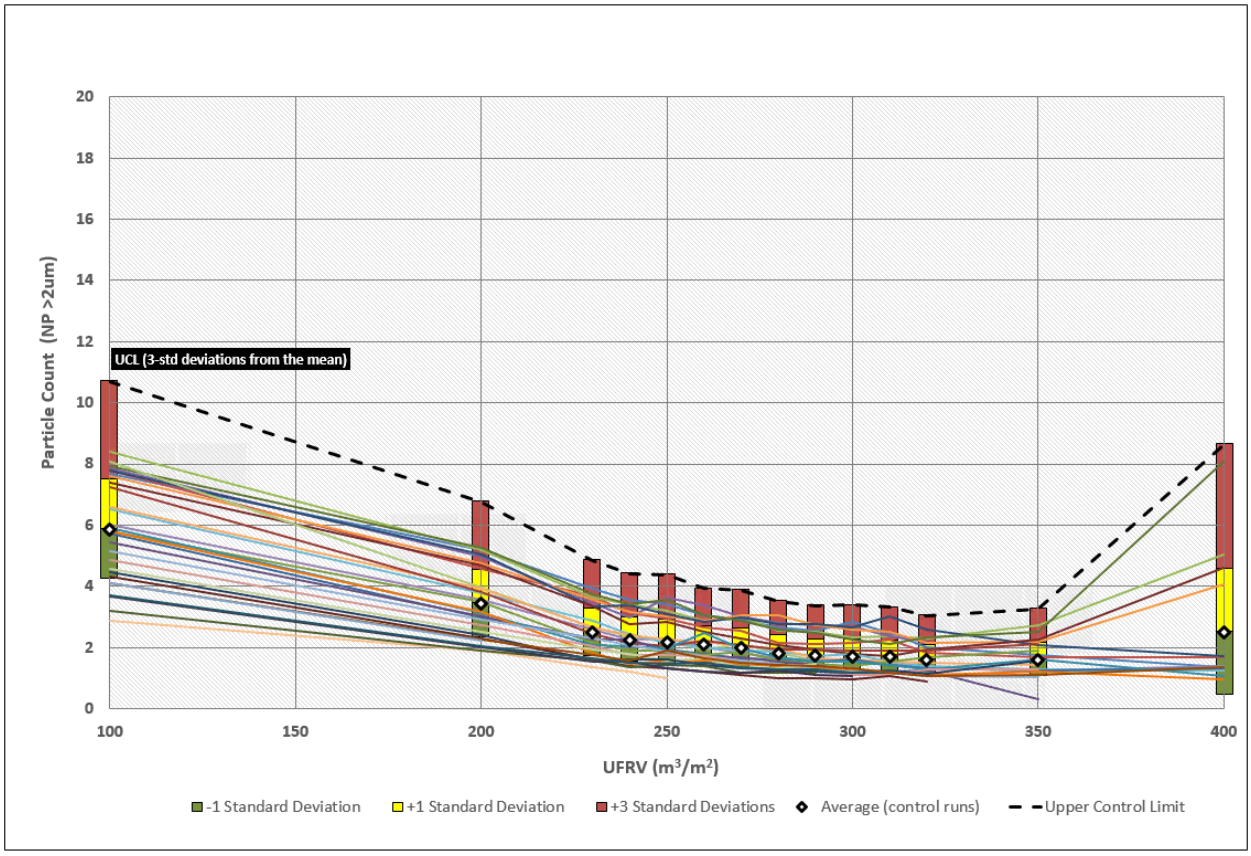

Figure 4.15 Statistical quality control chart development throughout a filter run cycle. A particle count envelope is built from prior in-control filter runs on a single filter bed. Mean particle count and standard deviation is used to calculate an upper control limit for future filter runs on each UFRV sub-range. Upper control limits are based on 3-standard deviations above the mean particle count of in-control runs.

Historical filter runs that exhibited terminal particle count breakthrough were used to test the modelling results for early detection of breakthrough formation. The stressed filter runs in Figure 4.4 (Section 3.3.2) were evaluated as a function of the UFRV-particle count relationship in Figure 4.16. Incorporation of smaller UFRV segments is used here to better define when onset of breakthrough was occurring between subsequent runs.

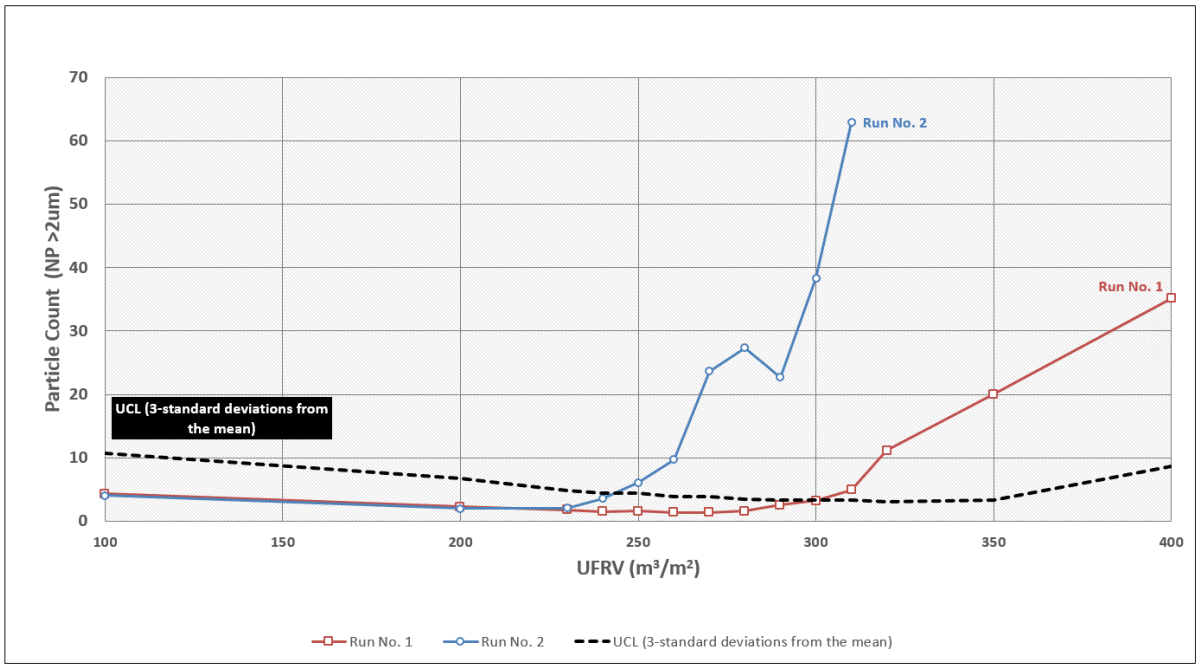

Figure 4.16 Application of particle count UCL's on stressed filter runs. Average particle count values between UFRV segments are illustrated. The UCL is exceeded for each of the illustrated filter runs, indicating a filter state that must be investigated prior to exceedance of regulated water quality thresholds.

Figure 4.16 illustrates the progressively earlier and more severe particle count breakthrough over two successive filter runs. The approximate point at which breakthrough starts is visible when average particle counts deviate from prior in-control filter runs and exceed the upper control limit. The earlier and more severe particle count breakthrough between run 1 and run 2 implies that the CAF process was worsening under the given water quality conditions and would require a chemical adjustment to recover control.

A key limitation with comparison of raw particle count data is that each analyzer has slightly differing calibration ranges and filter bed performance, which are not directly comparable. To overcome that limitation, the particle count data for the run under observation were converted to a standard deviation value, based on the particle count distribution of the prior ideal filter runs. The normalization of particle count data attenuates any differences in analyzer response or relative

differences in run performance between filter beds. With particle count data in Figure 4.17 converted to relative standard deviations for each UFRV segment, the normalized results could be directly compared against any filter bed, with an upper control limit represented as a straight line. Once the filter run standard deviation crosses the UCL threshold, the filter should be investigated or shut down for backwash.

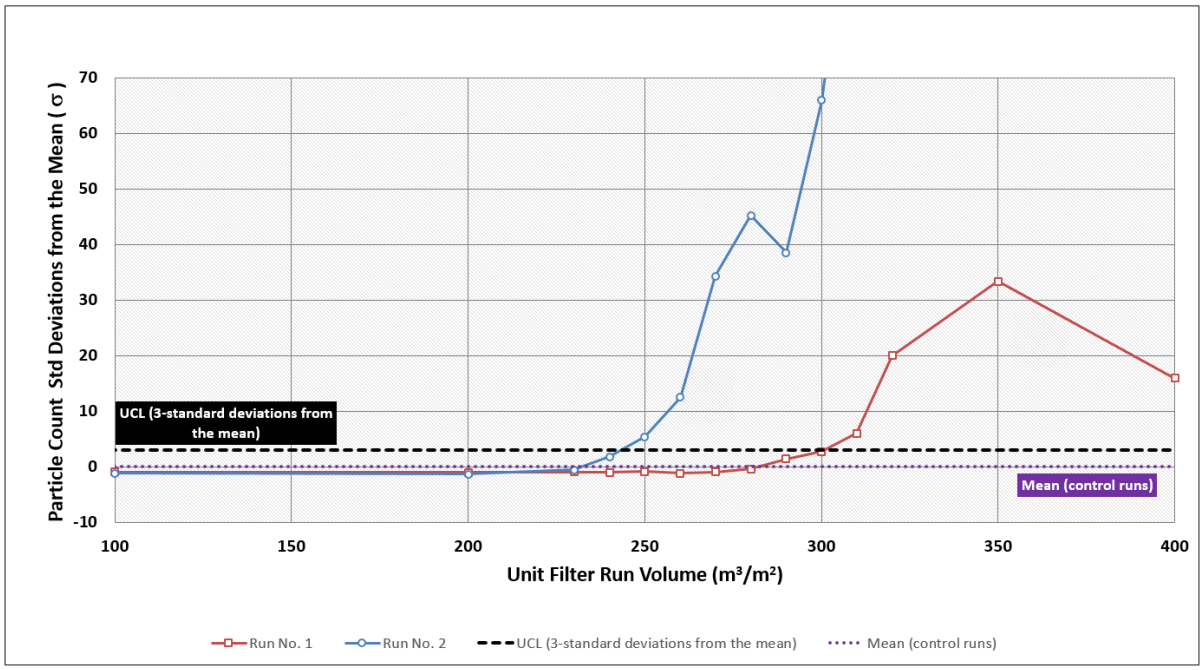

Figure 4.17 UFRV as a function of filter effluent particle count standard deviation between UFRV segments, based on data illustrated in Figure 4.15 and Figure 4.16. Results for each UFRV segment are normalized based on the distribution of particle count data of prior ideal filter runs. Normalization of particle counter data to standard deviation allows for comparison of performance between analyzers of varying calibration ranges, and filter beds with differing run performance.

A number of assumptions and limitations are evident from the analysis. As filter runs progress through their stable operating period, filter effluent turbidity and particle count continued to improve with time, as particles attach to one another more efficiently. As a result, a non-normal distribution of particle count data was formed within each UFRV segment. However, the improvement in water quality is generally inconsequential compared to the particle count variation

observed between ideal filter runs; therefore, it was ignored for this analysis. Additionally, with sufficiently small UFRV segments, the subtle improvement in water quality is insignificant compared to changes in filter effluent particle counts when filters experience terminal end-of-run breakthrough.

During selection of the ideal, or "control" runs, the particle count values observed near the end of each run may exhibit early signs of breakthrough, but remain within acceptable limits. Below the cut-off point triggering a backwash (i.e., <50 NP/mL), these runs were incorporated into the "ideal" run profiles to increase the 3-sigma threshold (i.e., although the increased variability of data points increased the standard deviation, and hence the UCL, they were included if they fell within the existing 3-sigma boundary). Of course, thresholds can be adjusted by tuning the allowed variability to be incorporated into the range of acceptable values. Additionally, in situations such as those shown in Figure 4.14, conditions such as seasonality of particle count data require that the particle count envelope for each UFRV range be updated on a routine basis. In such cases, the ideal filter run envelopes will require routine updates with optimized filter runs, either through continuous incorporation of filter run values within standard deviation limits, or by rebuilding profiles, such as when an analyzer re-calibration results in a step change in particle count values. This issue can lead to false alarms for the first several runs following analyzer recalibrations. Re-establishment of particle count ranges should resolve within a few backwashes, but alarms could be suppressed until at least three consecutive filter runs are available to establish a new UCL. Alternatively, the average standard deviation of adjacent filters could be used to determine an interim standard deviation for the affected filter until a minimal number of filter runs are completed to re-establish its own filter run particle count envelope.

Although the control charts developed for the completion of Objective 3 were successful in detecting filters which exhibited filter effluent particle breakthrough, the number of test runs were limited to the known periods of filter breakthrough illustrated through Figures Figure 4.1 through Figure 4.9, which exhibited filter effluent breakthrough. The large data sets and computer run-time required to (1) synthesize the in-control runs and (2) analyze each filter run segment over consecutive filter runs, limited the number of test scenarios able to be completed during this study.

With sufficient computing power, this approach may be used for continuous improvement of filter performance. Importantly, this type of control chart approach provides a compact and concise check on performance of the many critical control points monitored by operators, that may or may not have been picked up otherwise. As operators gain insight from the control charts, they will be able to see the immediate impacts of their control decisions on filter performance. The added resilience is especially important in systems susceptible to climate change, which can result in rapid or unforeseen swings in background chemistry and filtration performance that requires operator intervention to correct.

4.2 Phase 2 Results and Discussion (Objective 4)

4.2.1 Direct in-line filter column trials experimental observations

Pilot plant source water quality remained generally consistent throughout the DF trials, based on the following parameters in Table 4.1 (Wang et al. 2018).

Table 4.1 Source water quality ranges over duration of direct in-line experimental trials.

PARAMETER	VALUE	UNITS
Temperature	3.3 ± 2.9	°C
pH	7.7 ± 0.1	--
Turbidity	1.5 ± 0.3	NTU
TOC	1.2 ± 0.4	mg/L
(UV_{254})	0.013 ± 0.004	cm^{-1}
Zeta Potential	-11.8 ± 1.89	mV

Direct filtration trials for each alum coagulant and polymer dosage combination were run concurrently in triplicate filter columns. Zeta potential of water in the constant head tank, FTW volumes, FTW ripening times, filter run times, filter run termination criteria, and filter UFRV for all

pilot column chemical combinations were evaluated (Table 4.2). For comparison, full scale WTP water quality conditions and chemical dosages are also summarized in Table 4.2.

Table 4.2 Direct in-line filter column trial results summary

	Filtration conditions				Direct In-line Pilot Column Results				Main WTP Data						
RUN	Alum dose (mg/L)	Polymer dose (mg/L)	Effective Ripening Time (min)	Effective run time (hrs)	Run End Criteria	Effective UFRV (m^3/m^2)	Effluent Chlorine (mg/L)	TOF Zeta Potential (mV)	Influent Zeta Potential (mV)	Influent Turbidity (NTU)	WTP Alum dose (mg/L)	WTP Polymer dose (mg/L)	Influent pH	Influent Temperature (°C)	Sample Date (DD-MMM-YY)
1	0.0	0.000	DNR	0.0	Turbidity	0	0.9	-12.18	-12.00	1.3	12.0	0.11	7.55	0.9	29-Jan-16
2	0.0	0.024	DNR	0.0	Turbidity	0	1.0	-10.98	-12.70	1.3	12.0	0.11	7.70	0.9	12-Feb-16
3	0.0	0.048	DNR	0.0	Turbidity	0	0.8	-11.28	-11.90	1.7	12.0	0.12	7.84	3.5	18-Mar-16
4	0.0	0.072	DNR	0.0	Turbidity	0	0.8	NS	NS	1.3	12.0	0.11	7.83	3.2	15-Mar-16
5	0.0	0.096	DNR	0.0	Turbidity	0	0.9	-13.64	-14.30	1.7	12.0	0.12	7.85	3.7	19-Mar-16
6	0.0	0.144	DNR	0.0	Turbidity	0	0.8	-10.30	-11.50	1.6	12.0	0.12	7.85	3.7	20-Mar-16
7	0.0	0.216	DNR	0.0	Turbidity	0	0.8	-7.90	-11.40	1.9	12.0	0.12	7.85	3.7	20-Mar-16
8	1.0	0.024	DNR	0.0	Headloss	0	0.8	NS	NS	1.5	12.0	0.12	7.79	2.1	5-Mar-16
9	2.0	0.024	266	17.9	Headloss	225	0.8	-9.60	-12.10	1.6	12.0	0.12	7.80	2.2	6-Mar-16
10	2.0	0.048	38	15.3	Headloss	188	1.1	NS	NS	1.6	12.0	0.12	7.82	2.9	12-Mar-16
11	3.0	0.000	DNR	0.0	Particles	0	1.0	-10.30	-12.00	1.4	12.0	0.11	7.74	2.0	15-Dec-15
12	3.0	0.024	66	14.7	Headloss	193	1.4	-10.10	-12.00	1.3	12.0	0.11	7.71	0.9	16-Feb-16
13	3.0	0.036	44	13.5	Headloss	179	0.9	-10.60	-11.80	1.5	12.0	0.11	7.76	1.7	29-Feb-16
14	3.0	0.048	40	12.3	Headloss	166	0.9	-10.01	-11.10	1.3	12.0	0.11	7.74	1.4	24-Feb-16
15	3.0	0.072	14	11.9	Headloss	159	0.9	NS	NS	1.5	12.0	0.12	7.73	1.3	23-Feb-16
16	3.0	0.096	34	9.1	Headloss	122	0.9	-8.24	-12.20	1.4	12.0	0.11	7.74	1.4	25-Feb-16
17	3.0	0.144	17	6.3	Headloss	82	1.0	-4.56	-11.20	1.3	12.0	0.11	7.70	0.9	11-Feb-16
18	3.0	0.216	28	5.2	Headloss	70	0.8	-2.11	-11.10	1.4	12.0	0.11	7.75	1.5	26-Feb-16
19	6.0	0.000	DNR	0.0	Particles	0	1.0	-8.54	-12.50	1.3	12.0	0.11	7.34	0.9	9-Feb-16
20	6.0	0.024	25	3.1	Particles	44	0.8	-10.03	-13.20	1.3	12.0	0.11	7.71	1.0	17-Feb-16
21	6.0	0.048	16	7.0	Particles	90	1.3	-9.38	-10.90	1.6	12.0	0.12	7.82	2.8	11-Mar-16
22	6.0	0.072	13	9.8	Particles	124	1.2	-9.41	-9.87	1.5	12.0	0.12	7.78	1.9	3-Mar-16
23	6.0	0.096	12	8.6	Headloss	114	0.9	-9.13	-11.80	1.5	12.0	0.12	7.77	1.8	1-Mar-16
24	6.0	0.144	11	8.1	Headloss	102	0.8	-5.22	-11.50	1.4	12.0	0.11	7.56	0.8	1-Feb-16
25	6.0	0.216	10	5.6	Headloss	71	1.5	-4.15	-12.50	1.6	12.0	0.12	7.78	1.9	3-Mar-16
26	9.0	0.024	DNR	0.0	Particles	0	0.8	NS	NS	1.7	12.0	0.12	7.81	2.7	10-Mar-16
27	9.0	0.048	13	3.8	Particles	51	1.2	NS	NS	0.8	12.0	0.12	7.80	2.3	7-Mar-16
28	9.0	0.072	9	2.1	Particles	29	0.8	-7.79	-13.20	1.6	12.0	0.12	7.79	2.0	4-Mar-16
29	9.0	0.096	12	4.1	Particles	54	0.8	NS	NS	1.7	12.0	0.12	7.81	2.7	10-Mar-16
30	9.0	0.108	10	5.2	Particles	66	0.9	NS	NS	1.6	12.0	0.12	7.83	3.1	14-Mar-16
31	9.0	0.120	11	5.7	Particles	73	1.0	NS	NS	1.7	12.0	0.12	7.81	2.5	9-Mar-16
32	9.0	0.144	8	6.8	Headloss	87	0.8	NS	NS	1.4	12.0	0.11	7.75	1.5	26-Feb-16
33	9.0	0.216	9	5.8	Headloss	75	0.8	-4.14	-11.90	1.6	12.0	0.12	7.79	2.0	4-Mar-16
34	12.0	0.000	DNR	0.0	Particles	0	1.0	-6.61	-12.50	1.3	12.0	0.11	7.57	0.9	8-Feb-16
35	12.0	0.024	DNR	0.0	Particles	0	1.0	-7.96	-12.10	1.3	12.0	0.11	7.72	1.0	18-Feb-16
36	12.0	0.048	DNR	0.0	Particles	0	0.8	-8.44	-13.80	1.7	12.0	0.12	7.81	2.7	10-Mar-16
37	12.0	0.072	11	1.5	Particles	19	0.8	NS	NS	1.6	12.0	0.12	7.84	3.4	17-Mar-16
38	12.0	0.096	11	2.2	Particles	29	0.8	-6.92	-13.10	1.6	12.0	0.12	7.84	3.4	17-Mar-16
39	12.0	0.120	9	2.4	Particles	31	0.9	-5.34	-11.50				7.83	3.1	14-Mar-16
40	12.0	0.144	7	2.4	Particles	33	0.8	-4.56	-12.90	1.6	12.0	0.12	7.77	1.8	2-Mar-16
41	12.0	0.216	9	5.3	Headloss	70	0.8	-2.88	-11.50	1.6	12.0	0.12	7.77	1.8	2-Mar-16
42	18.0	0.000	DNR	0.0	Particles	0	1.0	-6.13	-13.10	1.4	12.0	0.11	7.57	0.8	5-Feb-16
43	18.0	0.024	DNR	0.0	Particles	0	0.9	-5.78	-12.40	1.3	12.0	0.11	7.73	1.2	21-Feb-16
44	18.0	0.048	DNR	0.0	Particles	0	1.0	-3.82	-11.30	1.3	12.0	0.11	7.73	1.3	22-Feb-16
45	18.0	0.072	DNR	0.0	Particles	0	0.8	NS	NS	1.6	12.0	0.12	7.83	3.2	15-Mar-16
46	18.0	0.096	DNR	0.0	Particles	0	0.8	-3.62	-11.40	1.6	12.0	0.12	7.83	3.2	15-Mar-16
47	18.0	0.144	11	0.7	Particles	10	0.7	-3.34	-13.40	1.8	12.0	0.12	7.86	3.9	21-Mar-16
48	18.0	0.216	20	1.3	Particles	19	0.9	-4.44	-11.20	1.5	12.0	0.11	7.76	1.7	29-Feb-16

TOF = Top of Filter
DNR = Did Not Ripen
NS = No Sample

4.2.2 Direct in-line filtration experimental results

Alum and polymer doses are the independent variables that were adjusted during the direct in-line filtration experiments, with the objective of maximizing filter yields (i.e., UFRV's). Trial results are trended in three dimensions in Figure 4.18 to visualize the impact of each chemical dosage change on maximum UFRV production.

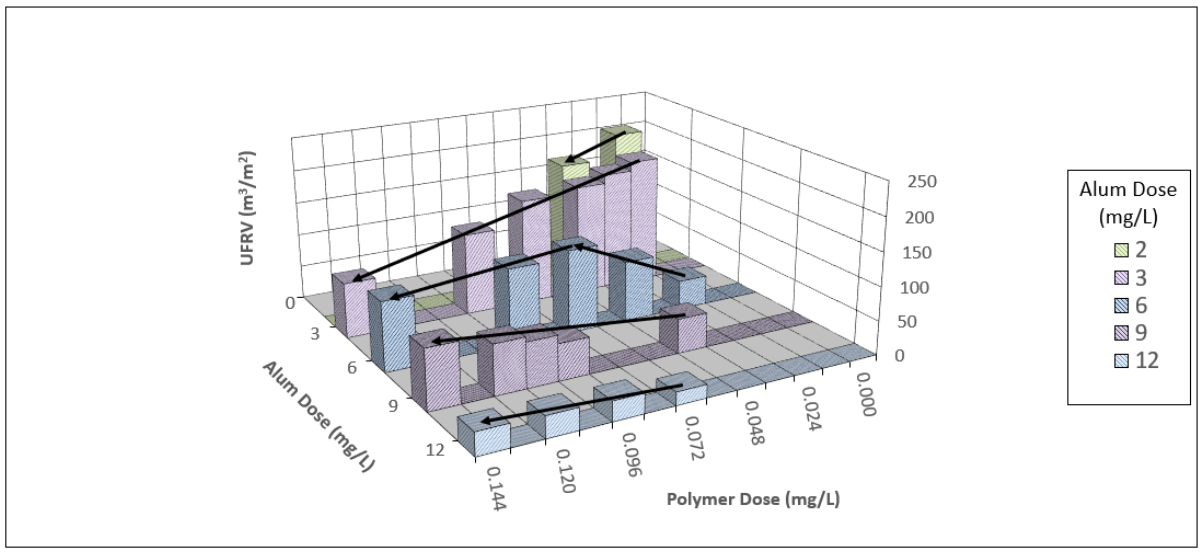

Figure 4.18 Direct in-line filtration trial summary. UFRVs obtained by pilot-scale direct in-line filtration of water pre-treated with various combinations of alum and polymer for particle destabilization. Each chemical pre-treatment combination was investigated in triplicate.

At the loading rates investigated, the filters were unable to ripen without some combination of both coagulant and polymer. Chemical combinations that were unable to reach the filter water quality performance criteria were assigned UFRV values of zero. Maximum UFRV values for all trial conditions were achieved at the lowest chemical dosage combinations that were able to meet the filtered water quality performance criteria.

Relative impacts on filter production were assessed separately for each independent variable (i.e., coagulant and polymer dose) with the opposing independent variable held constant (Figure 4.19 A-B and Figure 4.20 A-B). UFRV was then evaluated as a function of these independent variables to identify optimal filter performance, and to evaluate impacts on filter ripening times.

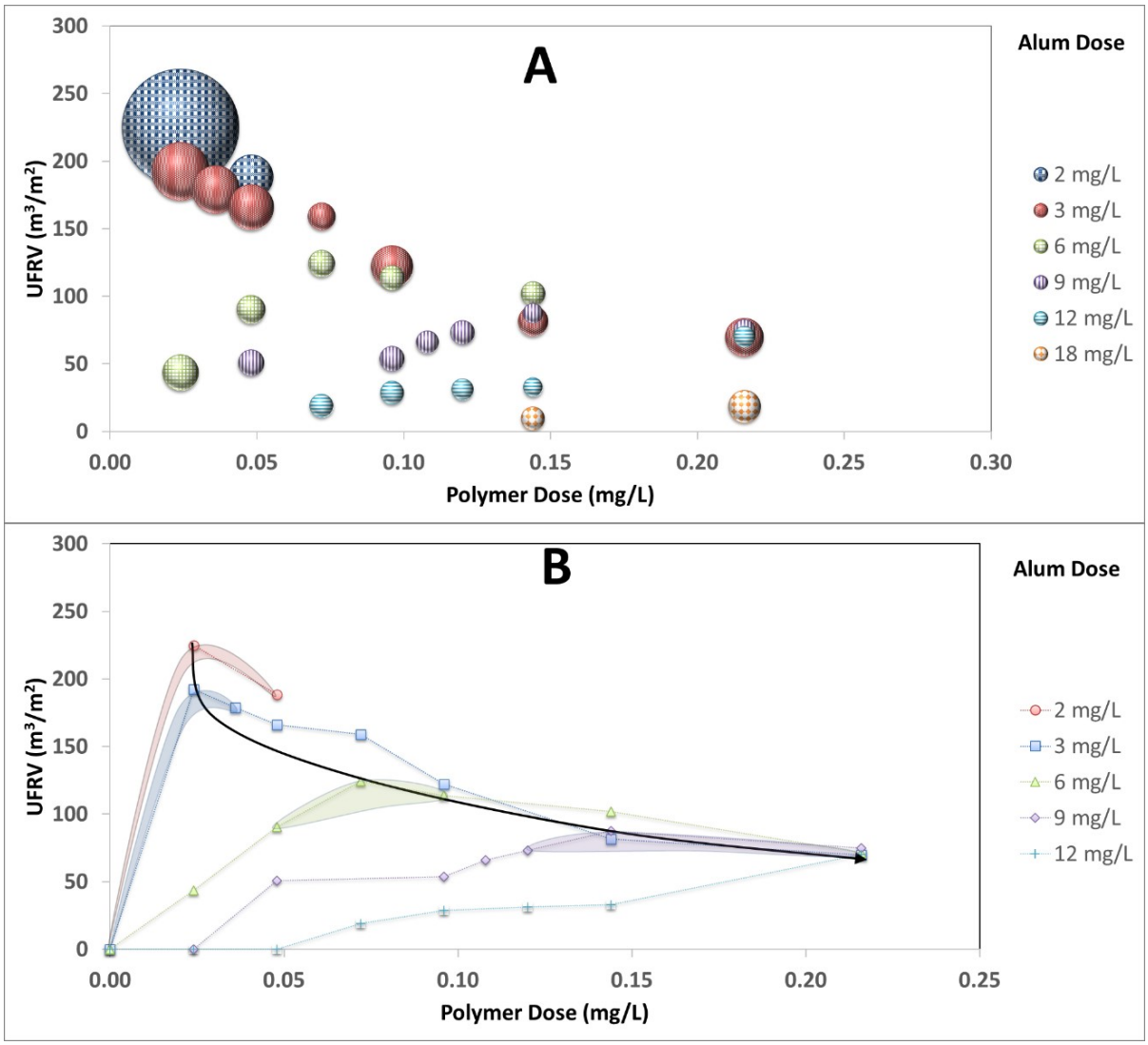

Figure 4.19 Direct inline filtration trial results, with polymer dose plotted as a function of UFRV, where alum dosages were held constant. Panel A illustrates impacts to relative ripening times, with larger circles representing longer ripening periods. Panel B illustrates the sensitivity of increasing polymer dosages. The shaded areas illustrate the range of chemical dosages required to maximize UFRV yield (i.e., the data points surrounding maximum UFRV for each coagulant dose). At low chemical dosages, UFRV is highest, but can sharply decline with minimal changes to particle destabilization. The ideal alum dose appears to occur between 3 mg/L and 6 mg/L to maximize production, minimize filter ripening time, and increase the stability of particle destabilization to changing conditions.

By viewing polymer dose as the independent variable in Figure 4.19-A and B, a maximum UFRV is visible for each coagulant dose profile. Under steady state and low coagulant dosage conditions (i.e., 2-3 mg/L), UFRV values increase quickly to their maximum observed yields with only minimal polymer added (<0.05 mg/L). Further increases to polymer dosage result in a decline in UFRV yield. Figure 4.19-B connects the maximum filter yields for each of the coagulant dose profiles to illustrate a loss in maximum filter yield above the minimum coagulant dose tested (i.e., 2 mg/L alum). As coagulant dose is increased, higher levels of polymer are required to achieve a maximum filter yield, at the expense of increasingly lower UFRV yields. The alum dose can be deduced from Figure 4.19 by following the shaded bands for each alum dose profile, which surround the maximum UFRV points for each coagulant dosage profile. Although the alum dosages at 2-3 mg/L yield the highest UFRV, the particle destabilization appears very sensitive to disruption, and requires tight control of polymer to maintain UFRV levels. A coagulant dosage between 3 mg/L and 6 mg/L appears to be optimal, where the shaded bands in Figure 4.19 widen out, such that increases or decreases in polymer have a smaller effect on UFRV values. Maximum filter production is somewhat reduced, but particle destabilization appears to be easier to control with polymer.

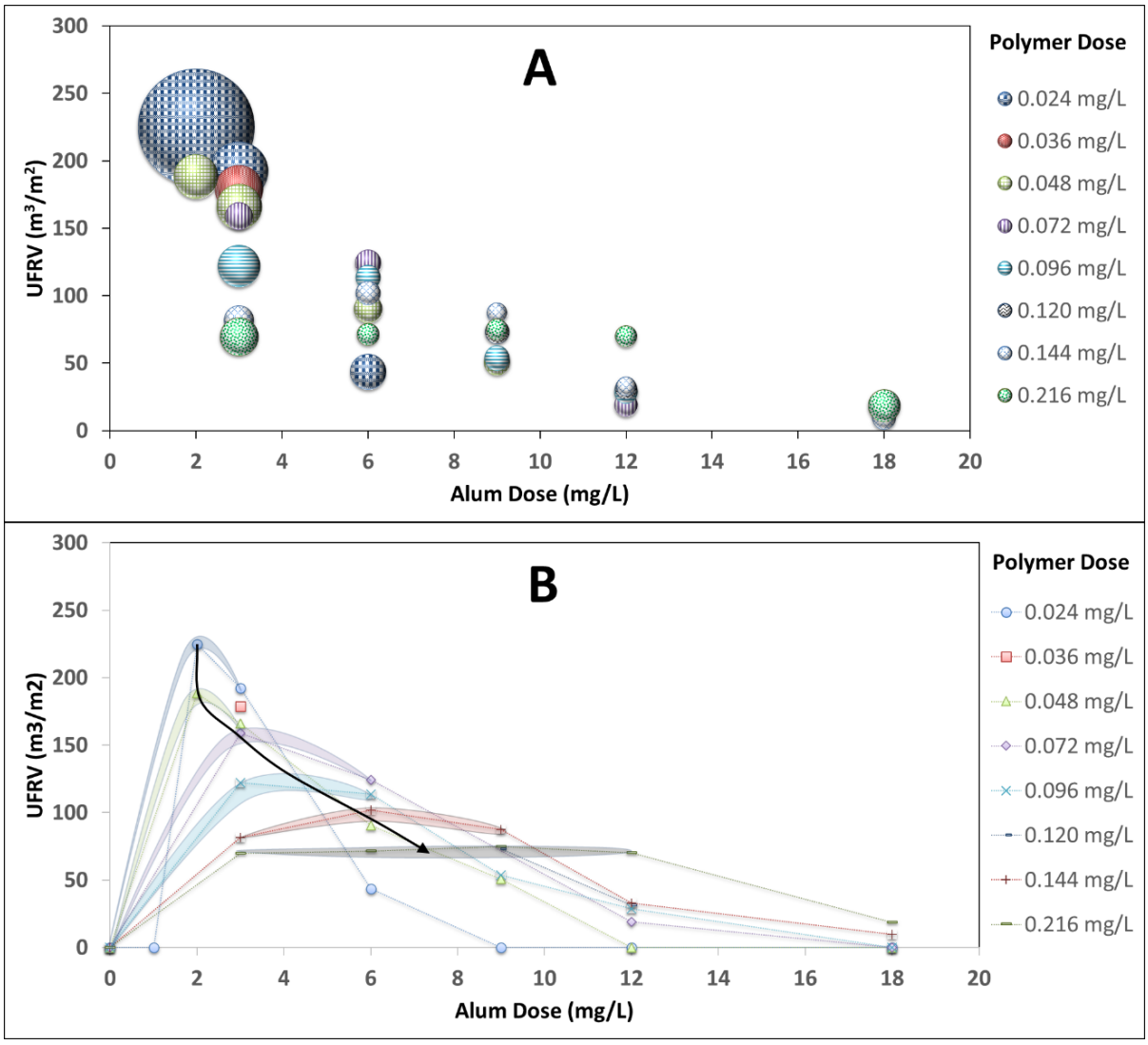

Figure 4.20 Direct inline filtration trial results, with coagulant dose (i.e., alum) plotted as a function of UFRV, where polymer dosages were held constant. Panel A illustrates impacts to relative ripening times, with larger circles representing longer ripening periods. Panel B illustrates the sensitivity of increasing coagulant dosages. The shaded areas illustrate the range of chemical dosages required to maximize UFRV yield (i.e., the data points surrounding maximum UFRV for each coagulant dose). Evident here is a UFRV plateau formed with increasing polymer dosage bands. The purple banding (i.e., 0.072 mg/L polymer) appears ideal to maximize UFRV at coagulant levels between 3-6 mg/L. Particle destabilization appears sensitive at dosages below 0.072 mg/L, resulting in narrow UFRV peaks, indicating susceptibility to subtle changes in source water quality.

By viewing coagulant dose (i.e., alum) as the independent variable in Figure 4.20-A and B, a maximum UFRV is visible for each polymer dose profile. Figure 4.20-B connects the maximum filter yields for each of the polymer dose profiles to illustrate a loss in maximum filter yield above the minimum polymer dose tested (i.e., 0.024 mg/L). Under low polymer dosage conditions (i.e., 0.024-0.048 mg/L), UFRV values increase quickly to their maximum observed yields with only minimal coagulant added (<3 mg/L). Further increases to coagulant dosage result in a decline in UFRV yield. As alum dose is increased, higher levels of polymer are required to achieve a maximum UFRV, until a UFRV plateau is reached. The optimal polymer dose can be deduced from Figure 4.20 by following the shaded bands for each polymer dose profile, which surround the maximum UFRV points for each polymer dose. Although the alum dosages at 2-3 mg/L yield the highest UFRV, particle destabilization appears very sensitive to disruption, and requires tight control of alum to maintain UFRV levels. A polymer dosage between 0.048-0.072 mg/L appears to be optimal, where the shaded bands in Figure 4.20 widen out, such that increases or decreases in coagulant have a smaller effect on UFRV values. Maximum filter production is somewhat reduced, but particle destabilization again appears to be easier to control.

Based on the pH ranges for coagulation, alum dosing ranges for both the DF runs and full-scale WTP are indicated on an alum coagulation phase diagram (Figure 4.21).

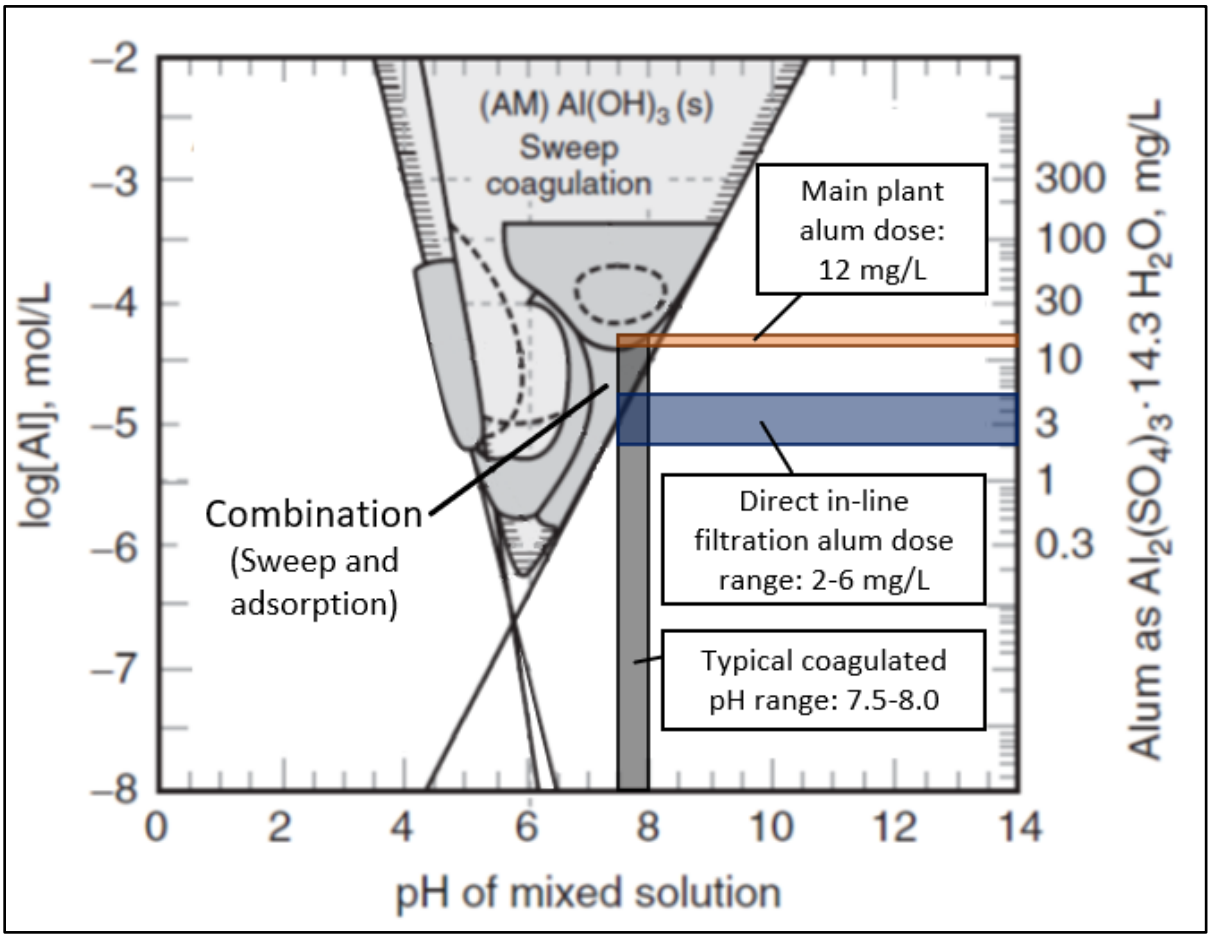

Figure 4.21 Alum coagulation phase diagram comparison. Coagulation pH and optimized coagulant dosing range for direct in-line filtration trials and full-scale WTP configurations are illustrated on the diagram. While the main plant operated at the low end of the sweep coagulation range, the direct-inline filtration was optimized when operated within the combination sweep and adsorption zone of particle destabilization.

Based on the operating pH range and coagulant dosages applied, the optimum DF trials put the coagulation regime within the combination sweep & adsorption zone. In this operating regime, suspended particles are destabilized through attachment to pin-sized aluminum hydroxide micro-flocs, which remain too small to settle, and carry directly onto the filters for attachment to the filter media. Comparatively, the full-scale WTP required coagulant dosing at levels in the sweep-coagulation zone to allow for capture, settling and recirculation of the microsand ballast. The result strongly suggests that the utility could save costs and improve efficiency by suspending SBF function

and operating the filters in a direct in-line filtration mode when treating high quality source water during the winter months. While evaluation of zeta potential and oocyst-sized microspheres should suggest that removals of *Cryptosporidium* and *Giardia* (oo)cysts by filtration would also be concurrently maximized, this confirmation was beyond the scope of the present investigation.

4.2.3 Assessment of zeta potential for optimization of in-line Direct Filtration

Prior to each trial, source water zeta potential was analyzed following full scale pH adjustment, but prior to coagulant and polymer addition. These zeta potential results were plotted as a function of time to verify raw water consistency over the duration of the filtration experiments, and to assess the variability/spread of data (Figure 4.22). The red squares in Figure 4.22 represent the average of five consecutive zeta potential measurements for each sample aliquot. The small gray dots represent each of the five consecutive measurements from which those averages were calculated. An approximately straight line (slope = 0.007; R^2=0.0051; α=0.05) is formed through the data, which represented the least-squares analysis on the pilot plant feed water throughout the entire testing period (Appendix C - Figure C.1). This analysis indicates that no significant or abrupt raw water quality changes (that would have resulted in changes in zeta potential) were experienced throughout the testing period—this was critical because such changes would likely have affected coagulant demand during the trials. Similarly, source water parameters which would impact raw water zeta potential, including temperature (Appendix C -Figure C.2) and pH (Appendix C -Figure C.3), were assessed for consistency throughout the trial period.

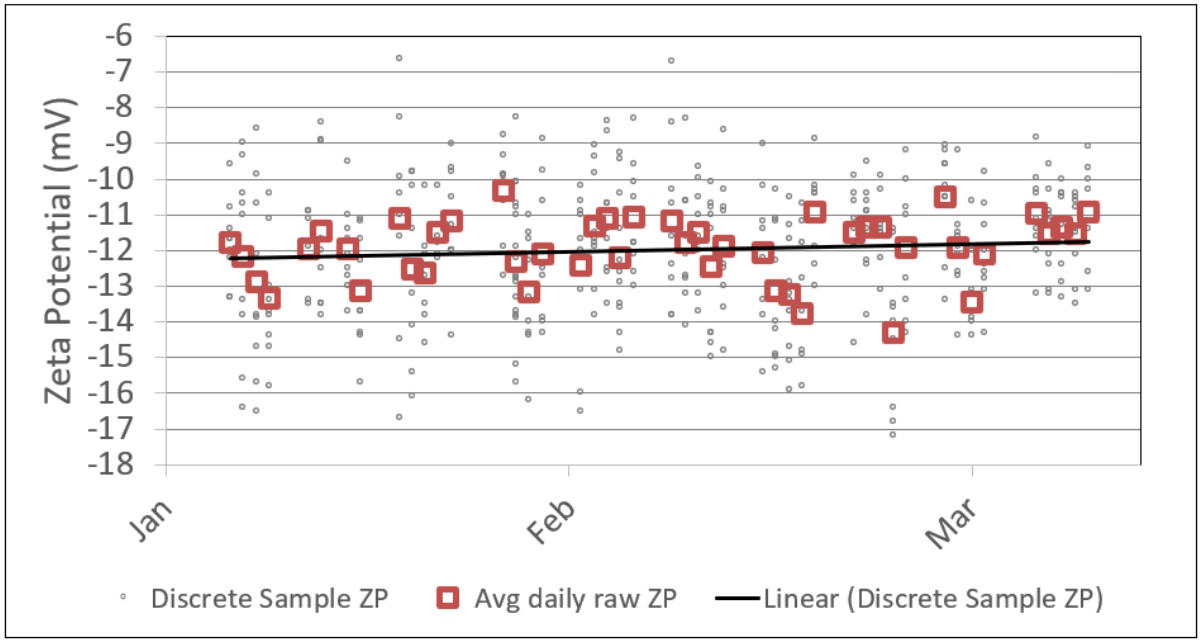

Figure 4.22 Zeta potential findings for pilot plant source water prior to coagulant, polymer, and chlorine dosing, but after pH adjustment. Individual sample results indicated a high spread of data between sampling events, while average zeta potential was relatively consistent over the length of the pilot trials. The average zeta potential over the duration of the pilot was -11.8, with a standard deviation of ± 1.89 mV.

Assessment of the raw water zeta potential data indicates that although the data were highly scattered, they fell within a normal distribution, based on a 5% significance level of expected Z-values (Figure 4.23).

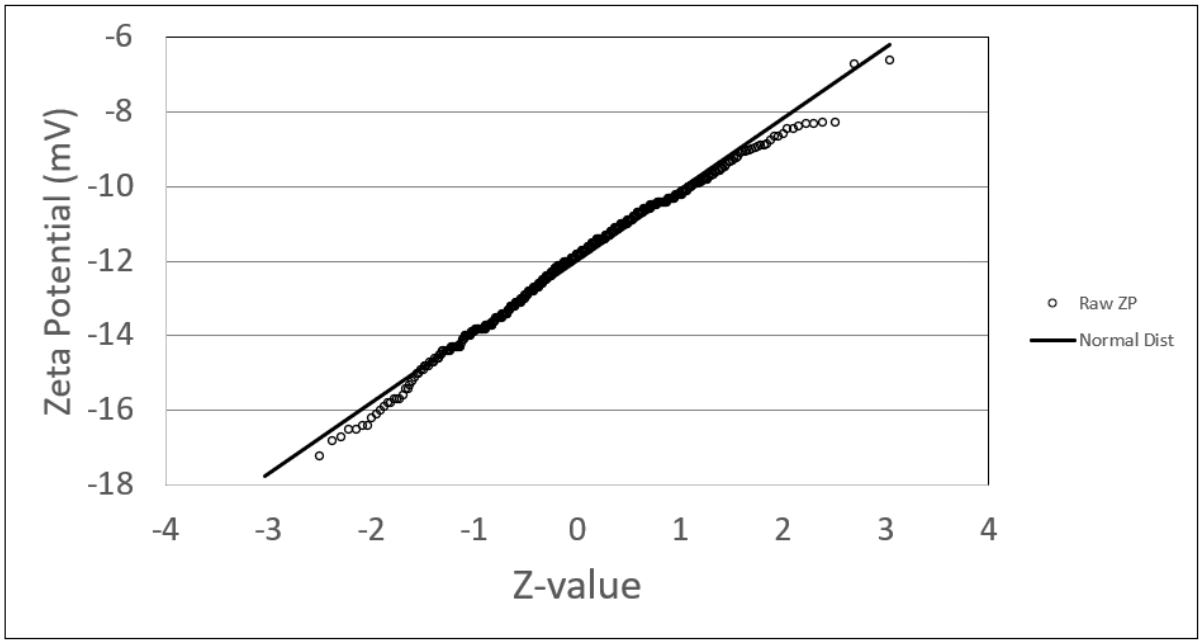

Figure 4.23 Comparison of raw water zeta potential values to the expected normal distribution at a 5% significance level.

The histogram illustrated in Figure 4.24 shows the sample frequency distribution against the expected normal distribution at a 5% significance level. This result implies an approximately normal distribution for raw water zeta potential data throughout the pilot filter testing period, when compared to the expected normal distribution (see Appendix C for detailed calculations for source water zeta potential normality).

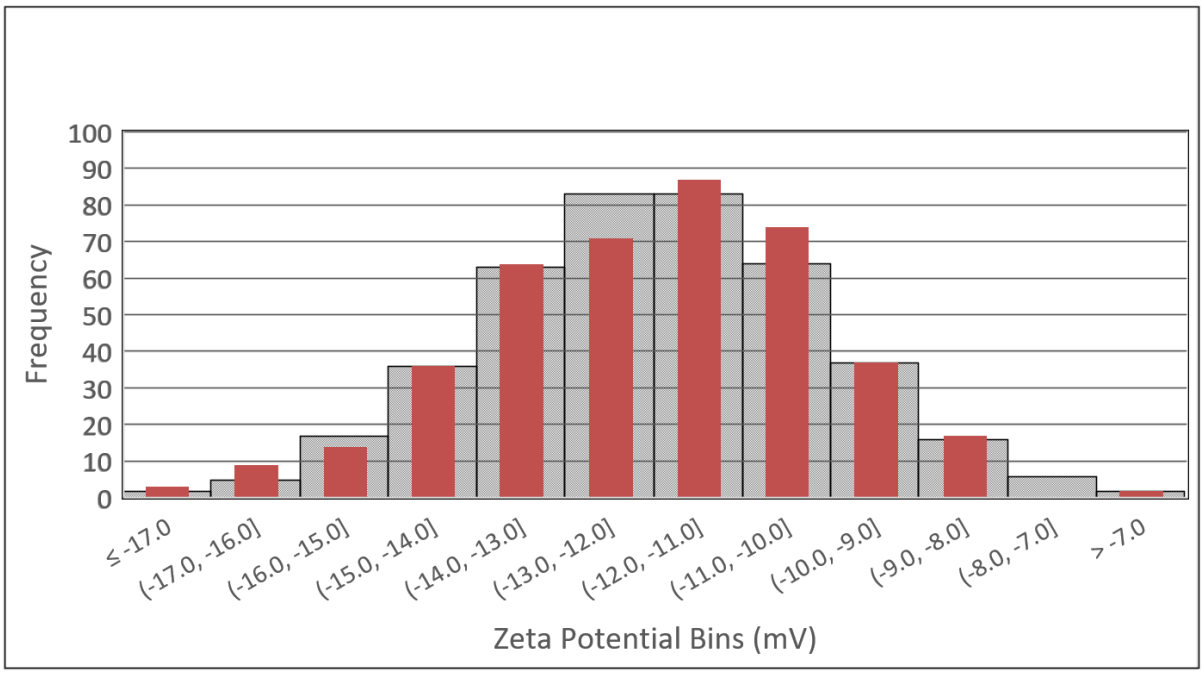

Figure 4.24 Histogram of raw water zeta potential with observed frequency (red) and expected normal distribution frequency at a 5% significance level (grey). Results confirm that zeta potential results were within the bounds of a normal distribution.

Confirmation of normality on the raw water samples implies that coagulated water zeta potential results would also be expected to fall within a normal distribution, where consistent water quality parameters remain stable (i.e., temperature, turbidity, NOM, pH, conductivity, and pretreatment chemical dosages).

Zeta potential was also analyzed on chemically pre-treated water, for most of the chemical combinations, and was sampled from the pilot plant constant head tank to ensure consistent reaction time and mixing energies prior to collection. The relationship between zeta potential and UFRV was evaluated, as shown in Figure 4.25 and Figure 4.26.

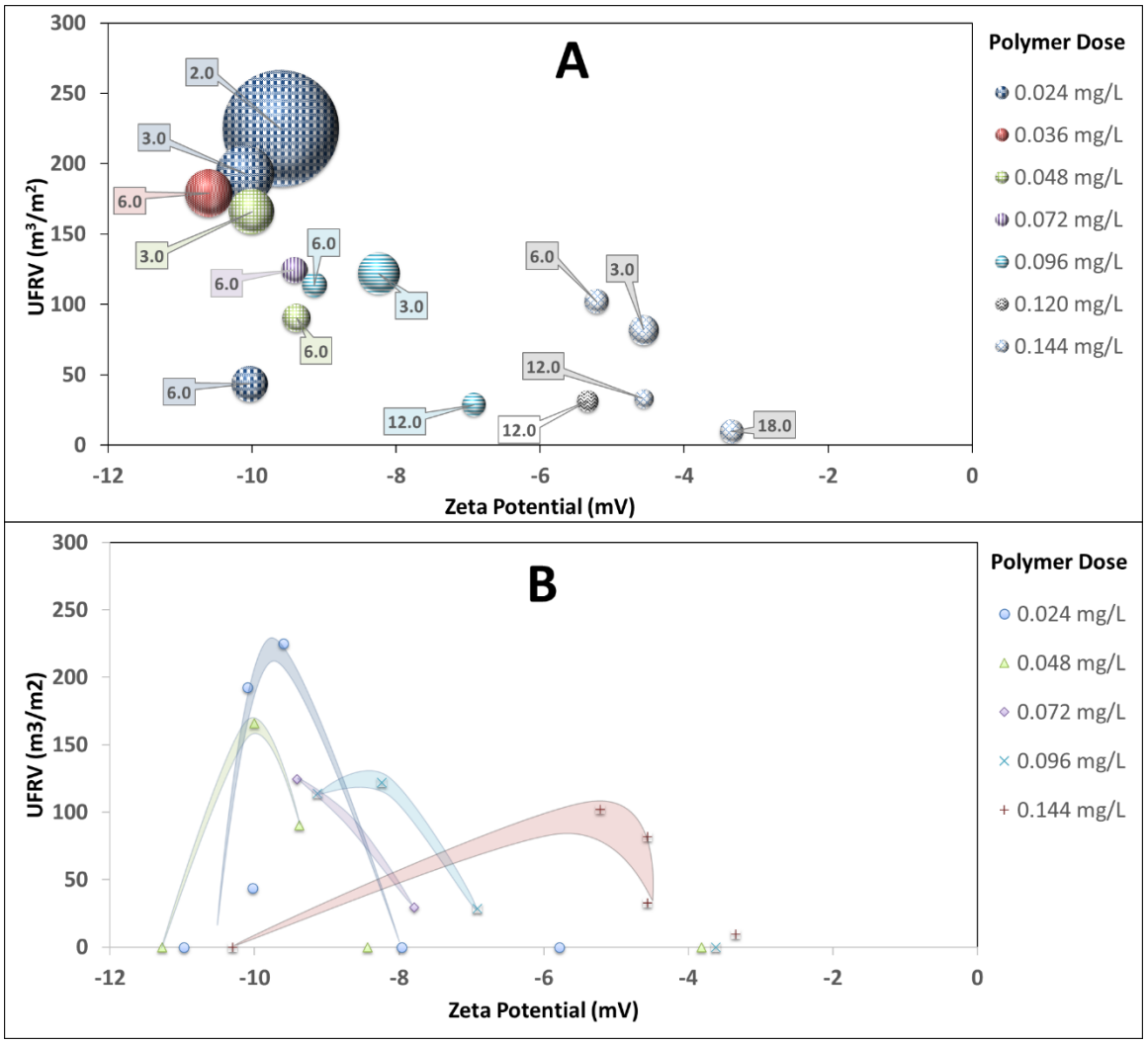

Figure 4.25 UFRV is illustrated as a function of zeta potential following chemical coagulant and polymer addition. Circle sizes in Panel A represent the relative ripening time for each chemical combination. Panel A shows coagulant impacts (indicated by the colored callout boxes) on zeta potential, with polymer dosages held constant. Panel B shows the relative maximum UFRV for each of the displayed polymer dosing bands. Optimal UFRV yield occurred at approximately -9 mV, based on maximum UFRV. However, the zeta potential values did not follow a curve consistent with increasing chemical dosages between points, as was seen where chemical dose was used as the independent variable. The discrepancy is likely explained by the high standard deviation in zeta potential results obtained during the trial period.

The zeta potential trending, as illustrated in Figure 4.25, is less clearly defined than with the chemical dose versus UFRV trends from Figure 4.19 and Figure 4.20. For instance, the zeta potential value (-4.6 mV) at 3 mg/L alum and 0.144 mg/L polymer is approximately equal to the zeta potential value (-4.6 mV) observed for the filter run at 12 mg/L alum and 0.144 mg/L polymer. That result was not expected, given the substantial difference in coagulant dosage between the two samples (i.e., a less negative/more positive zeta potential is expected at higher coagulant dosages). However, these results could not be excluded, given the substantial variability (i.e., high standard deviation) of the raw water zeta potential values (± 1.89 mV). Figure 4.26 illustrates UFRV as a function of zeta potential, while coagulant is held constant.

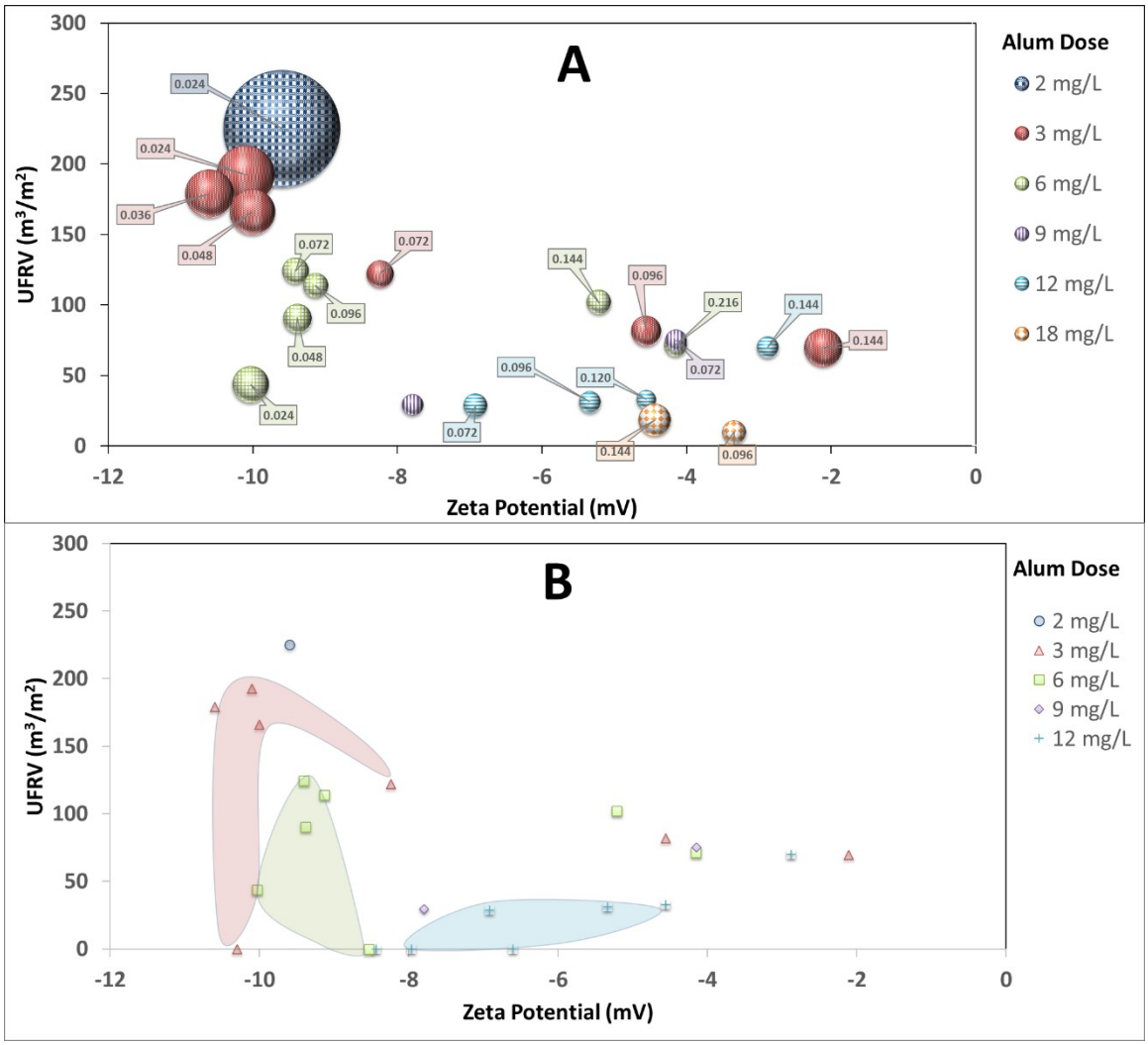

Figure 4.26 UFRV is illustrated as a function of zeta potential following chemical coagulant and coagulant addition. Circle sizes in Panel A represent the relative ripening time for each chemical combination. Panel A shows polymer impacts (indicated by the colored callout boxes) on zeta potential, with coagulant dosages held constant. Panel B shows the relative maximum UFRV, with shaded portions corresponding to each of the displayed coagulant dosing bands. Optimal UFRV yield occurred at approximately -9 mV. However, the zeta potential values did not follow a curve consistent with increasing polymer dosages between points, as was seen where chemical dose was used as the independent variable, making it difficult to determine the polymer dose responsible for the maximum UFRV. The discrepancy is likely explained by the high standard deviation in zeta potential results obtained during the trial period.

As with Figure 4.25, the results illustrated in Figure 4.26 for UFRV as a function of zeta potential were difficult to interpret, where increasing polymer dosages did not necessarily result in a less negative/more positive zeta potential value. Because of the variability in observed zeta potential results for both source water and chemically pretreated water, attempts to correlate UFRV and zeta potential while adjusting more than one chemical at a time is not recommended when relying on the accuracy of single zeta potential samples to represent the average zeta potential of the water matrix.

5 Discussion and Synthesis of Results

5.1 Chemically Assisted Filtration (CAF) in Literature and in Practice

It is recognized that the primary objective of drinking water supplies is to protect public health through removal or inactivation of human infectious pathogenic organisms such as bacteria, viruses, and protozoa. To achieve this objective, drinking water utilities are required to meet filtered water quality treatment objectives through a combination of physical removal of particles and microbial disinfection to bring health risks as low as reasonably practicable (USEPA 2006; AEP 2012; Health Canada 2013b; Ontario Regulation 2020). The unique characteristics of each watershed influences selection of treatment processes to meet these objectives.

Pathogens targeted for removal in water treatment systems are often associated or attached to colloidal particles. These particles and pathogens are predominantly negatively charged (Xagoraraki et al. 2004; Henderson et al. 2006; Edzwald 2011). Through electrostatic repulsion, particles in suspension are considered "stable", and will not attach to one another or to the filter media for removal. Because suspended particles are much smaller than the flow streams passing between the filter media grains, their physical removal is dependent on particle transport and attachment to the filter media surfaces, rather than through size exclusion and physical straining mechanisms (Amirtharajah 1988). Filters therefore rely on the destabilization of particles to electrochemically attach to the media for removal. This is achieved through addition of highly charged trivalent cations, such as Al^{3+} or Fe^{3+}, to shrink the repulsive zone surrounding particles. Once the repulsive charges are neutralized, particles can move close enough to overcome the energy barrier so that intermolecular attractive forces can draw and reversibly bind the particles to media surfaces. To achieve physical removals of pathogens and suspended solids through filtration, this particle destabilization is essential, and is generally referred to as physico-chemical or "chemically-assisted" filtration (CAF).

Flocculation, sedimentation, and filtration processes are dependent on attachment mechanisms to allow particles to aggregate or attach on media surfaces so that they are efficiently removed from water. As such, a direct link is created between adequate particle destabilization via coagulation,

and filter performance for removal of these pathogens. To ensure that water treatment systems are reactive to changes in particle surface charge affecting destabilization (under continuously changing water quality conditions), it is necessary to view the interrelations between source water quality, pretreatment, and filtration processes together. This concept is referred to here as "Coupled Chemically Assisted Filtration" (CCAF); it focuses on ensuring that filters remain as optimally operated as possible by coupling source water quality and chemical pretreatment directly with filtration performance.

As described in Chapter 2, natural organic matter and turbidity play a driving role in coagulant demand, which is required for particle destabilization and attachment mechanisms to work (Amirtharajah 1988; Xagoraraki et al. 2004). Based on the literature review and utility experiences, four primary water quality quadrants are identified that drive coagulation and filtration chemistry, as outlined in Figure 5.1.

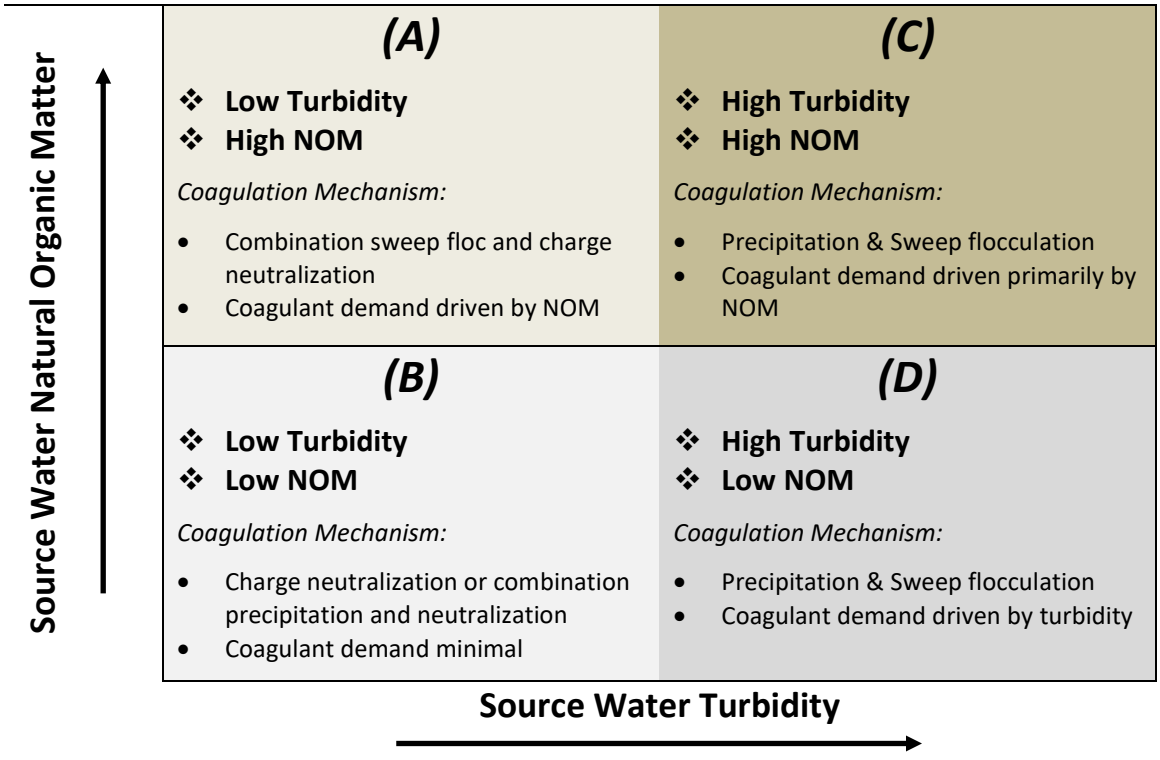

Figure 5.1 Primary source water quality quadrants which drive coagulant demand.

Prediction and monitoring of coagulant demand for treatment of high turbidity systems (Figure 5.1-Panel C & Panel D) are well documented (Dentel 1991; Gregory 2009), with a sweep flocculation treatment regime utilized to precipitate organics, and to enmesh and to settle particles prior to filtration (Saxena et al. 2018; Sillanpaa et al. 2018). Jar testing is normally predictive of required coagulant dosage at full scale for sedimentation purposes (Dennett et al. 1996). With optimized sedimentation, the clarified water is generally also destabilized sufficiently for effective filtration.

Rapidly changing source water quality complicates coagulant dosing in high turbidity or high NOM systems however, because frequent chemical adjustments are required as coagulant demands shift. Mountainous, snow-dominated regions provide a clear example of this phenomena through springtime freshets. Moreover, freshets often occur in two stages at the study site (Figure 3.1 - Figure 3.4). The first freshet, comprised of low elevation and localized warming, triggers snow melt above frozen soils, resulting in source water flows made up of dissolved organics high in color, but with minimal turbidity (Figure 3.1 - Figure 3.2). The second event, comprised of high mountain snowmelt, greatly increases the source water flow, and carries both high turbidity and high NOM material in a flashy event resulting in a sharp rise in coagulant demand, followed by a slower tail with dropping coagulant demand.

Each runoff condition requires a method to predict filtered water turbidity performance prior to water reaching the filters. During the rapidly changing source water conditions, jar tests are often inadequate because of the long testing times required, while the continuously changing water quality negates the jar test results before they can be utilized for process control. Settled water quality following pretreatment can also be an inadequate method to predict filter performance in such cases (Kundert et al. 2014). An example from the 2013 flooding in the City of Calgary found that as source water turbidity levels approached 4,000 NTU, the mass of suspended solids resulted in rapid sedimentation, even without adequate coagulation and particle destabilization. Settled water turbidity during a brief period of intense turbidity and NOM change remained below 5 NTU, which is normally within acceptable solids loading limits for filter processes to function. However, the resulting clarified water stream was under-coagulated and became “unfilterable”, where the granular media filters were unable to retain particles at sufficient levels to maintain filtered water

quality below 0.1 NTU (i.e., filters could not ripen to <0.1 NTU, though filtered water quality was still able to achieve <0.3 NTU to meet the regulatory turbidity limits). Following chemical adjustment, the settled water turbidity remained the same, but the filtered water quality improved as turbidity and particle count data returned to normal levels.

For low turbidity, high NOM source water systems (Figure 5.1-A), a moderately high coagulant demand is generally required for effective particle destabilization, depending on the nature of the organics present. The large, fragile amorphous flocs historically generated at the study site following coagulation to treat high organic carbon (but low suspended solids) source water conditions often results in floc structures with poor settling characteristics under the concurrent cold-water temperatures, due to a lack of suspended solids to form a dense floc. The cold-water temperatures which impact bulk fluid density and viscosity make it difficult to settle the hydroxide solids without addition of a polymer or ballast to increase floc density. Jar testing to determine settled water quality can also be a poor predictor of filter effluent water quality to meet regulatory turbidity limits without other means to assess charge neutralization or floc attachment and settling efficiency of the organic constituents.

Coagulant demands are generally low for high quality source water systems (Figure 5.1-B), with very low amounts of floc formed through hydrolysis reactions. Chemical addition under such conditions is dependent on whether sedimentation is practiced. The low turbidity, low NOM quadrant is largely driven by a combination of charge neutralization and/or precipitation (Amirtharajah et al. 1982). At pH ranges commonly used for water treatment, a true charge neutralization regime is not achieved, and some precipitation of alum floc will always occur. In such cases where sedimentation is required, some overdosing of coagulant is necessary to grow floc to sufficient size and density for settling.

Achieving appropriate coagulant dosing for sufficient particle and pathogen destabilization is challenging for utilities treating high quality source waters such as those with low turbidity and low NOM found in Figure 5.1-Panel B. When sedimentation is required to minimize solids carryover onto the filters (and resulting in low UFRV), some overdosing of coagulant may be required to

ensure that sufficient floc is formed to allow for sedimentation to work. It remains critical, however, that particles remaining in suspension are adequately destabilized (i.e., have not re-stabilized through over-coagulation), thus allowing them to pass through the filters. Historically, these high-quality systems have had the advantage of being chemically stable in terms of source water turbidity for long periods of time (Figure 3.1), which affords time to optimize coagulant dosages for maximum particle destabilization based on observed filtered water ripening times, turbidity, particle count and UFRV. The key challenge that remains for high quality systems is in monitoring and responding to changes in source water quality which affect filtration. There are few reliable indicators for clean water systems that are able to correlate coagulated water chemistry against filtered water performance indicators. Evidence from the direct filtration study and full-scale monitoring presented in this thesis has shown that a low settled water turbidity does not guarantee a high-quality filter effluent, as both over-dosing and under-dosing of coagulant can result in settled water that is insufficiently destabilized for effective filtration (Figure 4.10, Figure 4.11).

Many systems that treat high quality source waters require a secondary means to dose chemical at the filters (i.e., filter aid polymer) to account for subtle shifts in source water quality or persistent under- or over-coagulation leading to re-stabilization (Edzwald 2011). However, the addition of a secondary means of particle destabilization to improve filtration performance is site-specific. Addition of chemicals at the filter is often limited, as mixing opportunities and reaction times are not generally available at the filter influent. Use of coagulants is limited as a filter aid due to limited mixing options necessary for dispersion and effective particle destabilization. The added floc formation from coagulant filter aids would also act to potentially overload the filters with hydroxide floc, if overdosed. Polymers are therefore the most common chemicals used as filter aids; they are able to bridge between poorly destabilized particles and the filter media, and also enhance filter ripening when particle loading is low.

Beyond the source water treatment generalizations provided in Figure 5.1, other complicating factors can exist in natural systems which influence the efficiency of particle attachment to filter media. Biological components, for example, contain surface proteins and sugars that protrude from the cell wall membranes to create steric interferences (i.e., physical barriers), which prevent

particles from approaching one another at short enough separation distances to allow electrostatic adhesion. Sweep flocculation mechanics and addition of polymers can often overcome these separation distance limitations to allow for effective particle removals but can also concurrently change the coagulant concentrations necessary to achieve "filterable" water quality in clarifier effluents that feed filtration processes. Accordingly, further investigation of these issues is warranted; however, it is beyond the scope of the present investigation.

5.2 Development of Methods for Online and Offline Monitoring of Filtration Performance for Improved System Resilience

The development of filtered water quality dashboards and statistical control charts was investigated herein with the goal improving filter resilience to changing source water quality conditions. Two methods of filter monitoring were assessed, which included both an offline and online method of assessing filter performance over time. For offline performance monitoring, filter dashboards were developed based on a moving 30-day window of process feedback to detect slowly changing filter performance. An online means of filter monitoring was tested to detect early onset of filtered water particle count breakthrough, to ultimately be able to alert utility operators of degrading filtered water quality conditions in real-time before a regulatory exceedance occurs (Figure 4.17).

Overall filter health and scanning for periods of filter instability was assessed at the study site through the compilation of WTP data and incorporation into a summary filter performance dashboard (Figure 4.1). The resulting filter performance dashboard for effluent turbidity, particle count, loss-of-head and UFRV provides a high-level view of water treatment health over time. Performance indicator dashboards from historical WTP were shown to be a useful tool to detect and to troubleshoot the causes for filter performance issues (Figure 4.5).

Long-term trending allows drinking water utilities to assess treatment plant performance over time, and to detect issues affecting filter performance. Filtered water turbidity, headloss and (less often) particle counting are the common metrics amongst North American utilities to monitor filter performance, with turbidity as the regulatory measure of compliance. Data analysis on filter monitoring points is required to detect whether the underlying data show evidence of well-

controlled chemistry through stable, continuous adjustment of chemicals, or whether there is evidence of undesirable and correctable process fluctuations.

Filter performance dashboards also allow for detection of slowly emergent filtered water quality and efficiency issues. In addition to the summary filter performance metrics, individual analyzers can be assessed based on their relative standard deviations over time. Differences in relative stability provides insight into issues related to filter performance or analyzer reliability (Figure 4.3). Any observed standard deviations on turbidity and particle counters allows for faulty analyzers to be quickly flagged for service or calibration. The daily or monthly data compilations reduces review time for routine filter health checks and provides direction for investigation of filter upsets. However, a person is still required to physically review trends after a period of time, which will not capture issues occurring in real-time.

Real-time monitoring of filtration processes is reliant on pre-set alarm setpoints to trigger operator intervention or automated control sequences. The alarm setpoints provide a necessary level of oversight for maintaining filtered water quality within preset boundaries. However, without constant vigilance on the part of utility operators, risk of unoptimized water quality through repeated and undetected filter turbidity or particle count breakthrough can put a utility at risk of future pathogen breakthrough events.

The additional layering of computerized sentinel monitoring tools can provide an independent means to support operators and improve the resilience of water treatment systems against process upset. Provision of computerized sentinel monitoring systems reduces the reliance on people to continuously scan, interpret and act upon process upsets. The reality faced by utility operators, is that their attention cannot remain focused on any single system at all times. Flow balancing, management of secondary process, chemical batching, system checks and communication with other staff and contractors, for example, all provide distractions that limit any single operator's attention. System complexity and layout, in terms of physical size and number of unit processes to be monitored, can create risks of overlapping events occurring that require attention. With the

development of filtration performance metrics, resilience is increased while freeing up valuable operator time for other tasks.

5.3 Zeta Potential as a Critical Control Element

Cryptosporidium oocyst removal is of utmost importance for granular media filtration treatment processes, especially in absence of other disinfection mechanisms, such as UV irradiation. The surface charge of microorganisms is a primary driver that controls oocyst to surface interaction for flocculation to other particles, and for physico-chemical filtration (Tufenkji et al. 2006). Zeta potential provides a means to directly monitor the net surface charge of coagulated water to ensure adequate destabilization for filter optimization. Although zeta potential does not replace turbidity or particle counting for filter performance monitoring, it can be monitored at a critical control point upstream of the filtration process to improve reaction time to changing water quality conditions that affect colloidal surface charge and particle attachment efficiency to media surfaces during filtration.

Online zeta potential monitoring shows promise to adopt as a critical control element to assess adequate destabilization of particles during the coagulation process, particularly in cases where settled water turbidity cannot predict filter performance under all conditions (i.e., under very low source water TSS and turbidity conditions). For each of the four source water quality quadrants in Figure 5.1, only zones that require high alum dosages for sweep flocculation are typically able to predict filter performance with settled water turbidity (i.e., through jar testing). However, even in those cases, zeta potential can provide sensitivity to assist with coagulant optimization to minimize overdosing or underdosing of coagulants and polymers. Zeta potential can also allow for online optimization of coagulant dosing where the seasonal nature of NOM and TOC influences the coagulant dose to varying degrees.

Ideally, zeta potential would be measured directly ahead of the filtration process, to gauge the level of particle destabilization just prior to filtration. However, to function as a critical control, the sample point must be located where adequate response time is available to adjust chemical dosing and recover a process from an upset condition before filtration is compromised. Further to this,

with systems that employ polymers or secondary coagulants, the zeta potential results are highly impacted making the zeta potential values difficult to interpret (Figure 4.10, Figure 4.11). Depending on their respective dosing ratios, zeta potential measurements after both coagulant and polymer are added can result in equivalent zeta potential values, but with vastly differing results on filtration performance reflected in of ripening times, particle counts, turbidity and UFRV (Figure 4.25). Each chemical used during the pretreatment process will exert influence on the zeta potential of particles suspended in the water matrix. However, while coagulant alters the density of charged particles in suspension, polymers (with high cationic charge) will bind particles together over a longer distance, even under poorly coagulated conditions. A poor combination of coagulant to polymer ratios can result in a zeta potential equivalent to that observed for an optimized pretreatment system, but which instead causes rapid particle accumulation at the surface of the media, preventing particle penetration into the deeper filter media and resulting in early filter run termination from high headloss.

With zeta potential sample points situated immediately following coagulation, response time is improved to allow for rapid chemical adjustments to maintain zeta potential results for adequate and consistent particle destabilization. The ability to respond quickly with coagulant adjustments is advantageous during changing source water quality conditions, to ensure a resilient filtration process. Although zeta potential shows great promise as an indicator for effective particle destabilization ahead of the filtration process, several caveats exist which limits its reliability under the observed test conditions observed in this study. Raw and coagulated waters contain a random distribution of charged particles, with zeta potential values following a normal distribution (Figure 4.23, Figure 4.24). The random distribution of particle charge results in a trend with potentially high standard deviation and complicated interpretation. Operators should thus not rely upon a single zeta potential sample to drive coagulant decisions. Depending on the sampling conditions and treatment objectives, zeta potential analysis on its own, may be unreliable without multiple samples to provide an accurate mean value. It may also require validation with filtered water quality turbidity and particle count data, thereby coupling the analysis with the process performance objective. Seasonal impacts also appear evident with measured zeta potential values, based on the

observed coagulated water zeta potentials which appear to correlate to seasonal influences such as water temperatures and nature of organic particles in the source water (Figure 3.4, Figure 4.13). Substantial differences between laboratory-analyzed grab samples and online analyzer values observed in this study showed consistent discrepancies of approximately 2 mV in side-by-side comparisons. Issues such as these will require a utility to expend additional effort to ensure consistency over time, especially if the data are to be used for process control. At present, this seasonality of zeta potential values makes interpretation of specific zeta potential values difficult in absence of additional process performance information and precludes the use of a single year-round operational zeta potential targets in absence of corresponding filter performance understanding and indicators.

5.4 Use of direct filtration as a seasonal alternative mode of operation

Optimized coagulant and polymer dosing under direct filtration schemes were shown to be capable of achieving high quality effluent turbidity and particle counts, under the conditions tested. Results showed that more negatively charged coagulated water zeta potential values were required to optimize the filtration process, when comparted to the full-scale WTP (Figure 4.10 through Figure 4.13 and Figure 4.25 through Figure 4.26). The most likely cause for this phenomena follows that to achieve sweep floc conditions for the SBF process, excess generation of hydroxide floc is required for settling resulting in a higher net-positive zeta potential charge. Carry-over of particles in the clarified water stream would result in slight particle re-stabilization. However, with the addition of polymer required for the SBF process, the carryover of polymer would act as a filter aid to retain any over- coagulated particles within the filter bed.

Observations over time on the full-scale WTP has found that overdosing of polymer would improve settled water turbidity, but shortened filter run times through excessive headloss and thus lowered UFRV yields. Conversely, with use of a polymer for direct filtration, coagulant dose can be lowered to minimize hydroxide floc formation, which slows the depletion of available particle binding sites within the filter media. The added polymer has been necessary for the existing WTP filter

configurations to overcome the repulsive forces between filter media and micro-floc to meet water quality targets of less than 0.1 NTU.

In changing production seasonally from CAF to direct filtration, limitations exist on filter media designs and WTP configurations that limits chemical selection and mixing systems that would provide more optimal characteristics for direct filtration. To successfully switch to a DF mode of operation, a utility needs be able monitor source water quality for changes that would require rapid conversion back a conventional coagulation/flocculation/sedimentation operating regime. This study addressed the site-specific limitations with chemical dosing systems by applying the same chemicals utilized at full scale, as well as matching the filter media designs to ensure that the two operating regimes would remain compatible.

5.5 Implications of climate change impacts

While high quality source water systems may require minimal treatment processes to destabilize particles for filtration, they remain susceptible to minor variations in source water quality to cause process upsets. Climate models typically predict alterations to weather patterns that result in increasingly variable, larger, and more frequent deteriorations in water quality, depending on location and local geography. Changes at the watershed scale that create risk for increased variability in source water chemistry needs to be accounted for at any given water treatment plant. During changing water quality conditions, where chemical adjustments are needed to accommodate the change, is where water treatment process resilience is most required. Application of Coupled CAF and sentinel water quality monitoring systems can improve resilience to climate change impacts through improved understanding and detection of the key metrics affecting water quality and system performance.

6 Conclusions and Recommendations

6.1 Conclusions

1. The concept of "Coupled CAF" was developed to emphasize that chemical pretreatment (i.e., coagulation/flocculation/sedimentation) serves two equally important purposes in drinking water treatment: (1) removing sufficient solids for efficient subsequent filtration and (2) achieving sufficient particle destabilization for ensuring adequate removal of particles/pathogens remaining in filter influent streams. Reliance solely on turbidity is inadequate for ensuring that both of these objectives are met.

2. Zeta potential analysis shows great promise as a tool for indicating that sufficient particle destabilization has been achieved for optimal filtration performance. However, limitations exist that require increased scrutiny and analysis to develop seasonal zeta potential targets for effective particle destabilization. Particular care is required when using zeta potential to predict filter performance when both coagulant and polymers are employed for particle destabilization.

3. In the absence of UV irradiation, well-operated Chemically Assisted Filtration (CAF) is the most critical treatment barrier for reduction of pathogenic protozoa resistant to chlorine disinfection. CAF processes need to specifically link mode of filter operation, operational controls, source water quality and treatment objectives. Through improved understanding of CAF processes, utilities can improve filtration performance as measured by particle, organic and protozoan pathogen removals.

4. To ensure that CAF processes are achieving optimal pathogen and particle removals, development of process metrics around critical control points is necessary to detect and to quantify impacts on filtration. Early and automated detection of process degradation provides an added layer of resilience under changing conditions, such as those imparted during unit process alterations, operational influences, or source water quality changes. Monitoring of

critical control points allows for real-time feedback on operational decisions and provides a basis for continuous improvement. As well, process metrics can be used to summarize and simplify the complex data streams for interpretation and action by the operator. All of the above will result in increased process resilience and cost avoidance from over-treatment and provides additional guards to operational upsets.

5. Direct Filtration, when applied under suitable conditions, is capable of meeting regulated filtered water quality limits. Similar to CAF, particle destabilization during direct filtration must be achieved prior to filtration. Use of zeta potential can improve the reliability and performance of direct filtration systems. However, site-specific protozoa challenge studies should still be conducted to ensure that low filtered water turbidity and particle counts correlates to effective pathogen removals.

6. During episodes of water quality change is where the greatest risk occurs for getting coagulant dosing wrong and increasing health risks. Coupled CAF approaches can serve as climate change adaptation and mitigation tools, especially in systems experiencing landscape disturbances, which can lead to significant variability in source water quality.

6.2 Recommendations

The following research goals are recommended for further study:

For water treatment systems generally, the following recommendations can be used to improve resiliency of water treatment plants:

- Employ particle counting to monitor filtered water effluent quality, in addition to turbidity. Particle counting provides complementary, but different information to turbidity analyzers. This is especially relevant to high quality source water systems, and to those that practice oxidation ahead of filtration (i.e., chlorination). However, particle counters do require proper installation and routine maintenance to ensure good results over time.

- Develop use of online zeta potential analysis to monitor coagulation effectiveness under changing source water quality conditions, especially for utilities with low source water NOM and turbidity.
    - Although routine grab sampling for zeta potential analysis can provide some insight into the water treatment plant performance, real-time control of coagulation has the potential to greatly reduce over-coagulation costs and prevent filtration process upsets.
    - Zeta potential analysis needs to be done in the proper location, and requires interpretation to be successful. Not all source water systems will necessarily be able to target the same coagulated water zeta potential values, or under all water quality seasons, for effective filtration.

- Pursue advancement of online data analytics to improve response time to conditions leading to early filter breakthrough.
    - Time-series analysis with identification of KPIs allows for improved insight on filtration performance.

- Development of data handling protocols and data archiving for extraction and analysis by third party software systems is essential to allow for future troubleshooting and optimization exercises.
- Development of site-specific analytical tools requires significant resources to set up initially but holds great potential to improve resilience of water treatment systems.
- Work is required to integrate sensors data for incorporation into KPIs and dashboards. Use of particle counters for this function may be case-specific.

Further research into the following areas will improve the utility of zeta potential analysis to allow for more predictive control of coagulant dosing:

- Correlation of zeta potential to source water quality (i.e., by linking source water NOM structure and particle surface charge to coagulant demand). Understanding landscape influences on coagulant demands can improve response time for chemical adjustments and minimize frequency and severity of potential process upsets.
    - Source water zeta potential, in conjunction with other online analyzers such as TOC, UV254 absorbance and pH can provide additional insight in predicting coagulant changes before water reaches the water treatment plant in real-time.

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Appendix A : Additional Figures

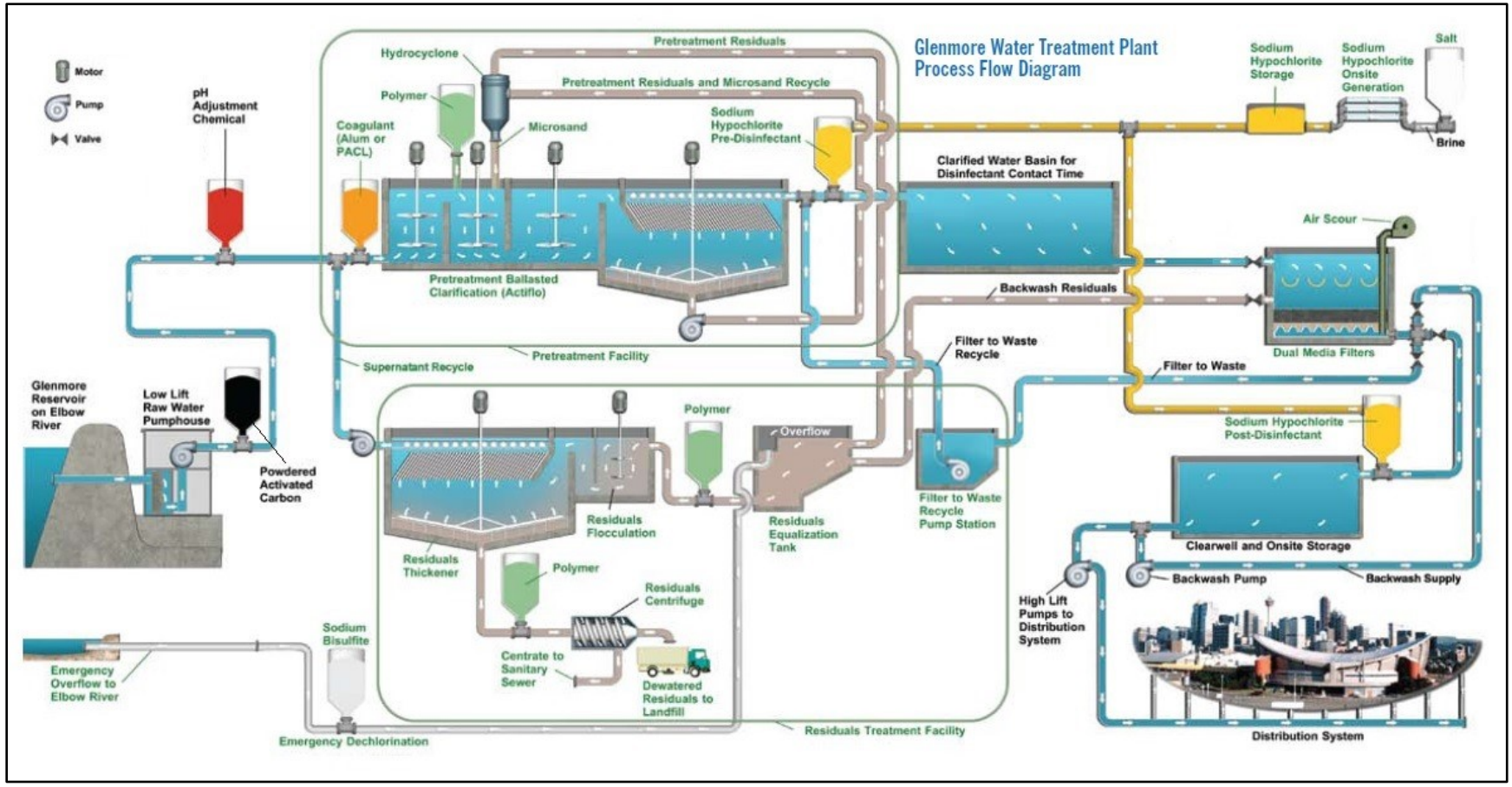
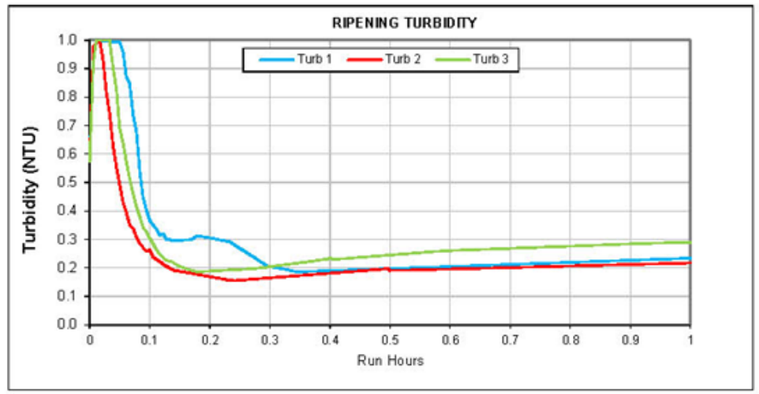
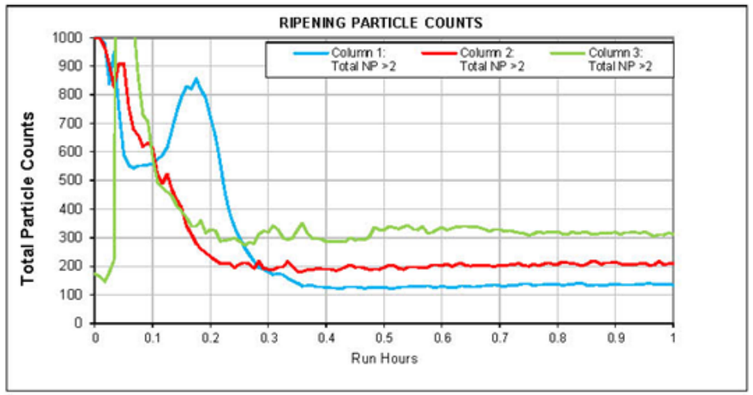
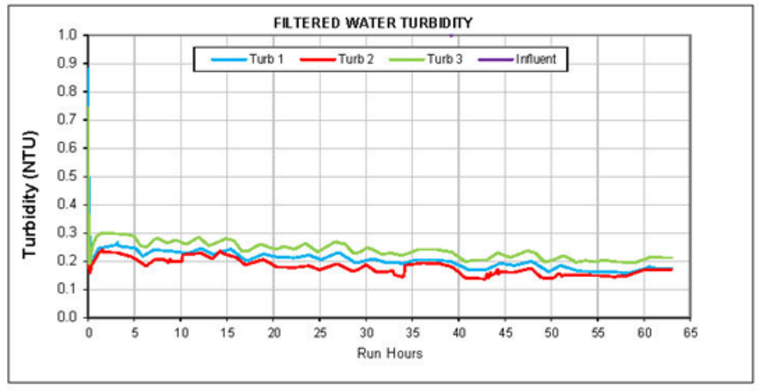


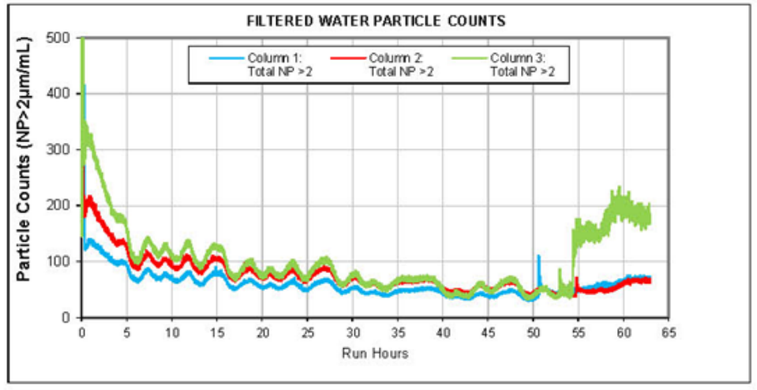
Figure A.1 The City of Calgary's Glenmore Water Treatment Plant study site process flow diagram. Pretreatment mechanisms illustrated include Sand-Ballasted Flocculation (SBF). (Process flow diagram courtesy of the City of Calgary upgrade program public pamphlet).

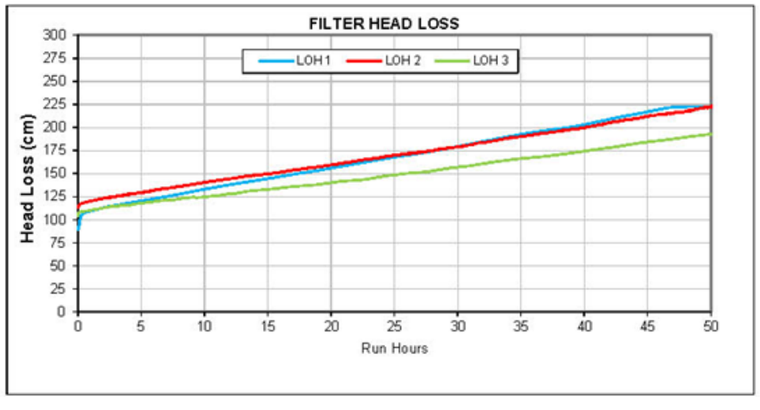
Appendix B : Direct In-line Filtration Pilot - Run Summaries

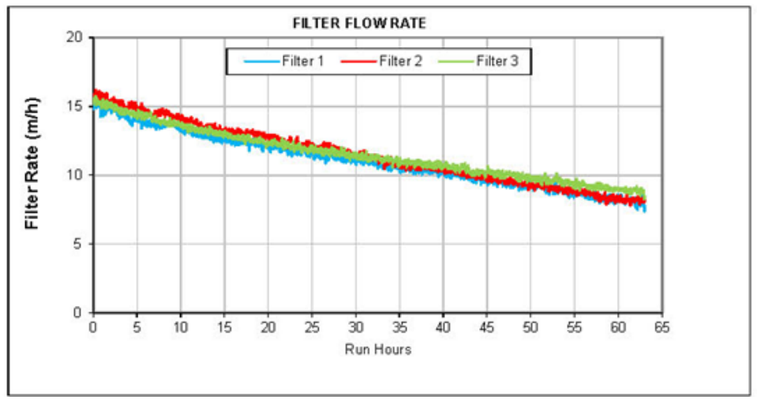












RUN SUMMARY

Run Started	29-Jan-16 16:47
Run Ended	01-Feb-16 7:47
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	0		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.00		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.90	0.90	0.90

ONLINE DATA SUMMARY

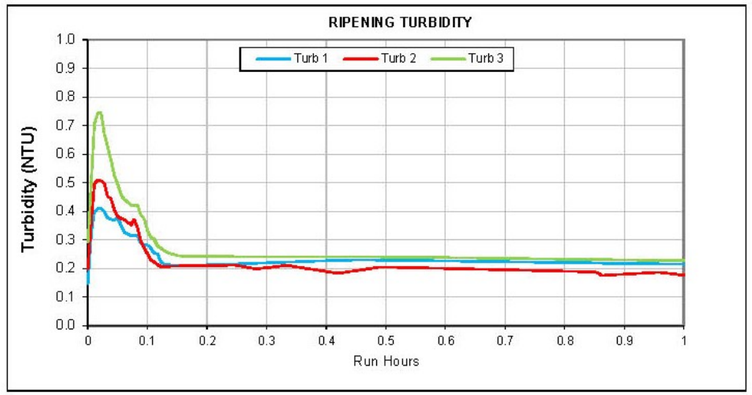
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.24	1.39	1.29
Column Influent	0.98	1.75	1.12
Filter Column 1 Effluent	0.16	1.00	0.20
Filter Column 2 Effluent	0.14	1.00	0.18
Filter Column 3 Effluent	0.19	1.00	0.24
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

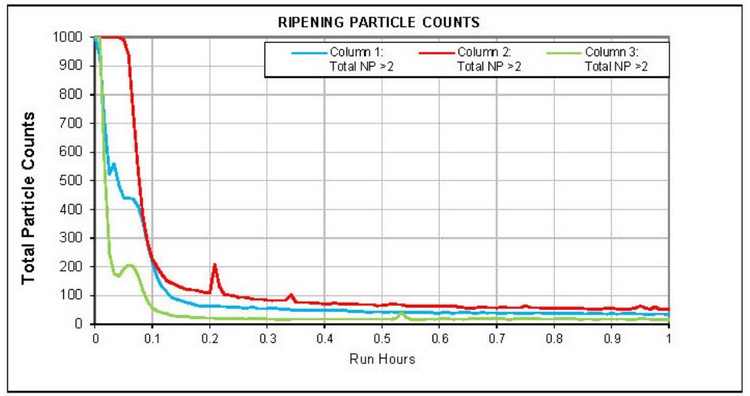
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	47	52	49
Filter Column 2 Effluent	43	51	47
Filter Column 3 Effluent	36	53	42

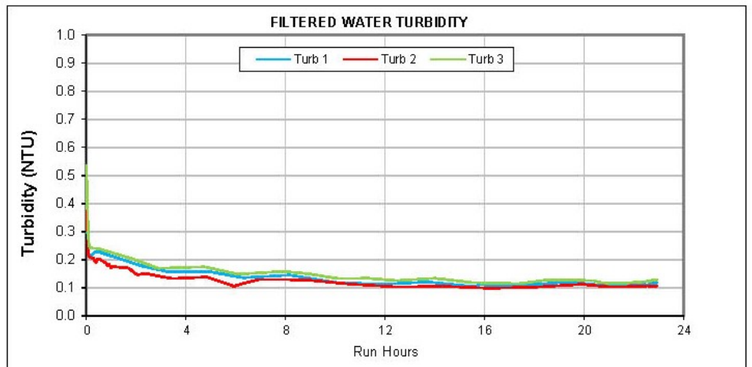
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.89	1.50	0.035
Filter Column 2	0.97	1.50	0.034
Filter Column 3	0.93	1.50	0.022

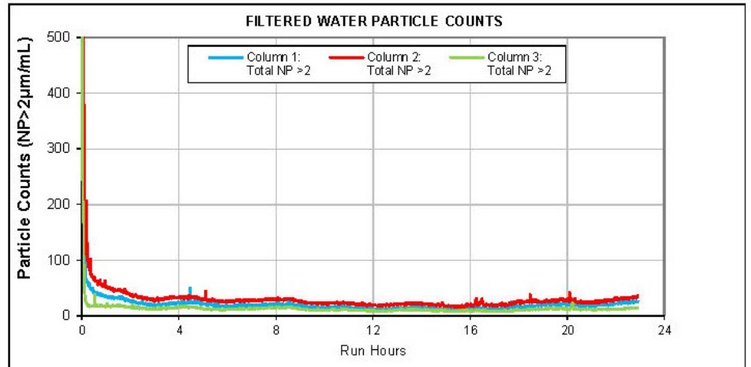
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	13	11.07	0
Filter Column 2	14	11.48	0
Filter Column 3	14	11.51	0

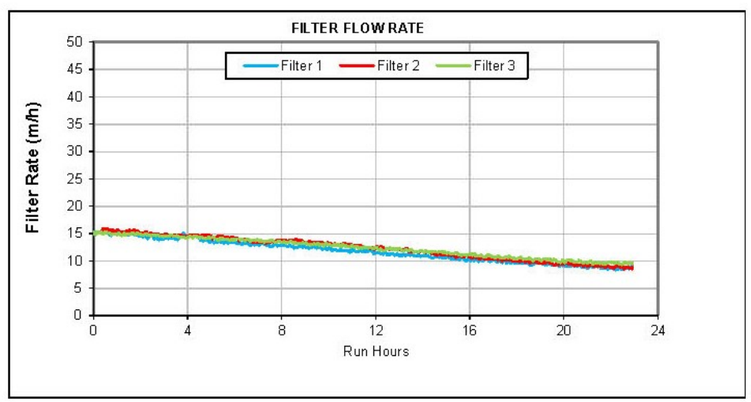
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	12-Feb-16 12:24
Run Ended	13-Feb-16 11:20
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	0		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.02	1.02	1.02

ONLINE DATA SUMMARY

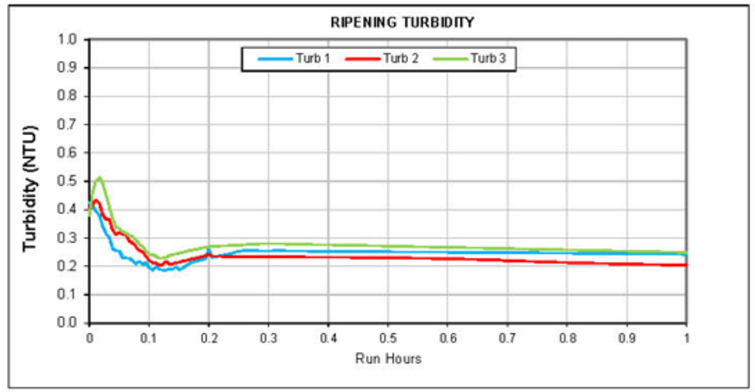
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.27	1.36	1.32
Column Influent	0.82	1.16	0.94
Filter Column 1 Effluent	0.10	0.41	0.13
Filter Column 2 Effluent	0.10	0.51	0.13
Filter Column 3 Effluent	0.11	0.75	0.15
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

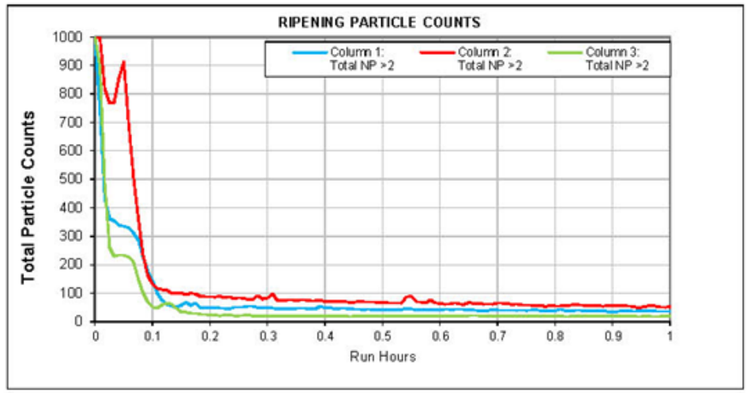
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	11	41	19
Filter Column 2 Effluent	16	47	26
Filter Column 3 Effluent	8	20	12

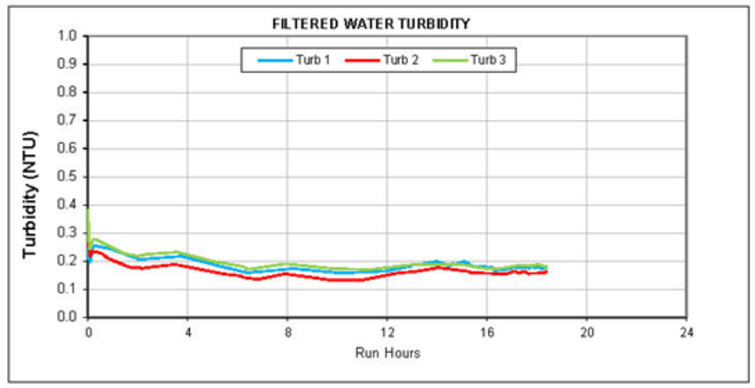
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.86	1.50	0.082
Filter Column 2	0.94	1.50	0.073
Filter Column 3	0.87	1.50	0.062

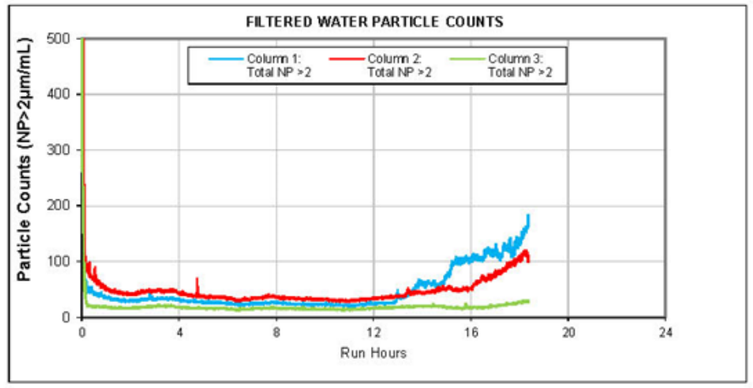
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	14	11.75	0
Filter Column 2	15	12.33	0
Filter Column 3	15	12.39	0

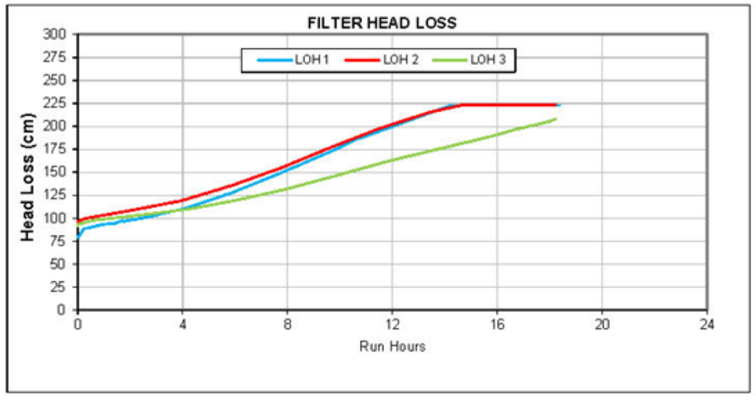
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

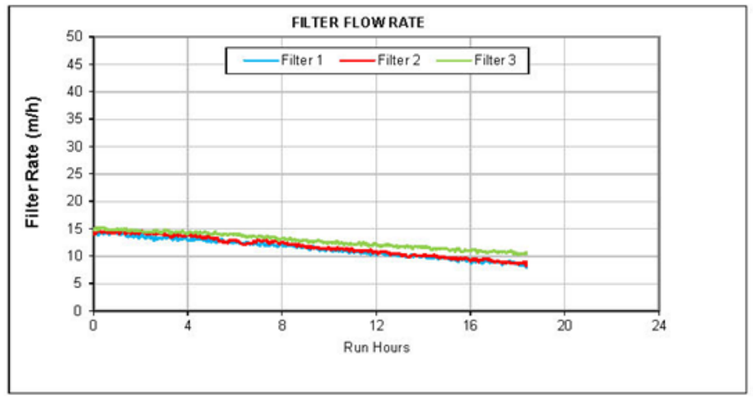












RUN SUMMARY

Run Started	18-Mar-16 16:57
Run Ended	19-Mar-16 11:20
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	0		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.048		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.82	0.82	0.82

ONLINE DATA SUMMARY

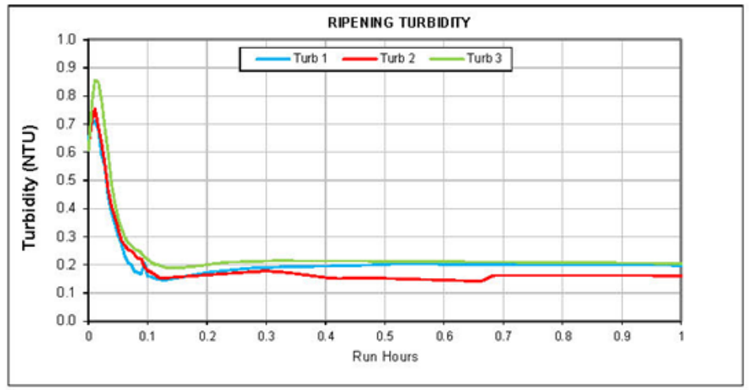
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.68	1.84	1.71
Column Influent	0.76	0.98	0.87
Filter Column 1 Effluent	0.16	0.42	0.19
Filter Column 2 Effluent	0.13	0.43	0.16
Filter Column 3 Effluent	0.17	0.51	0.20
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

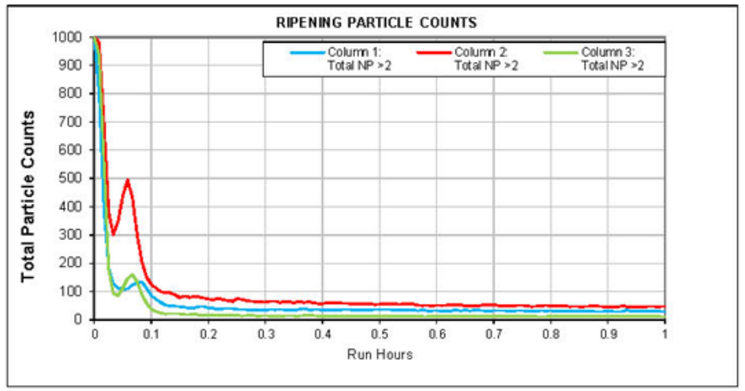
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	21	48	28
Filter Column 2 Effluent	29	52	38
Filter Column 3 Effluent	13	28	17

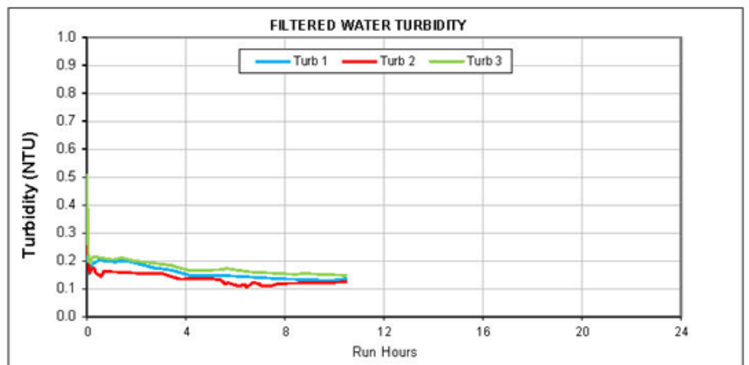
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.79	2.00	0.101
Filter Column 2	0.89	2.00	0.093
Filter Column 3	0.87	2.00	0.065

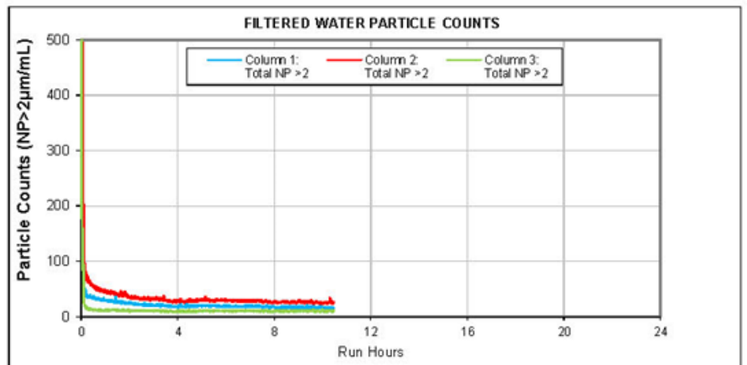
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	14	11.43	0
Filter Column 2	14	11.74	0
Filter Column 3	15	12.82	0

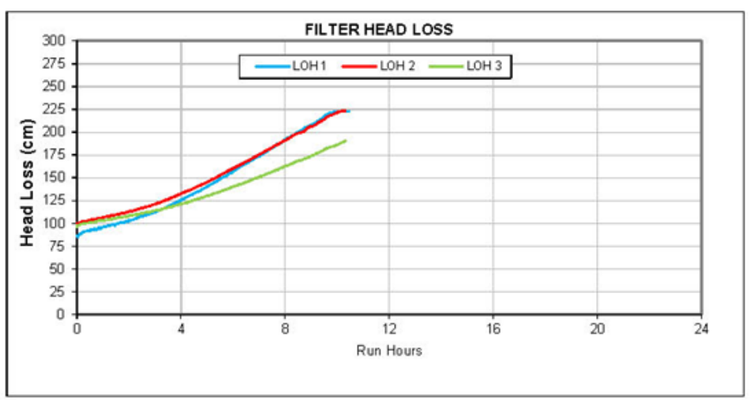
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

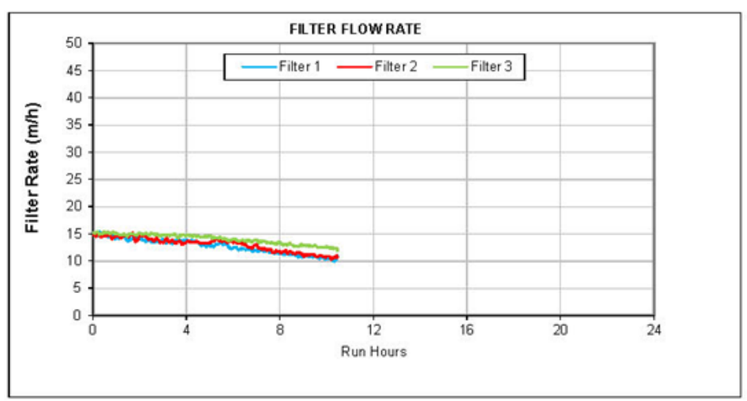












RUN SUMMARY

Run Started	15-Mar-16 18:02
Run Ended	16-Mar-16 4:30
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	0		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.072		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.83	0.83	0.83

ONLINE DATA SUMMARY

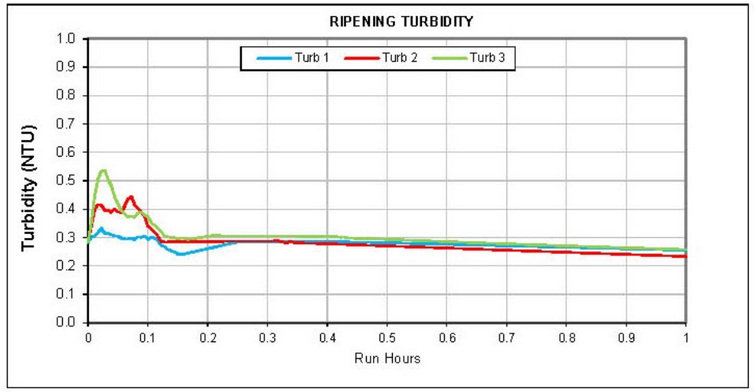
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.57	1.66	1.61
Column Influent	0.91	1.22	1.04
Filter Column 1 Effluent	0.13	0.71	0.16
Filter Column 2 Effluent	0.10	0.76	0.14
Filter Column 3 Effluent	0.15	0.86	0.18
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

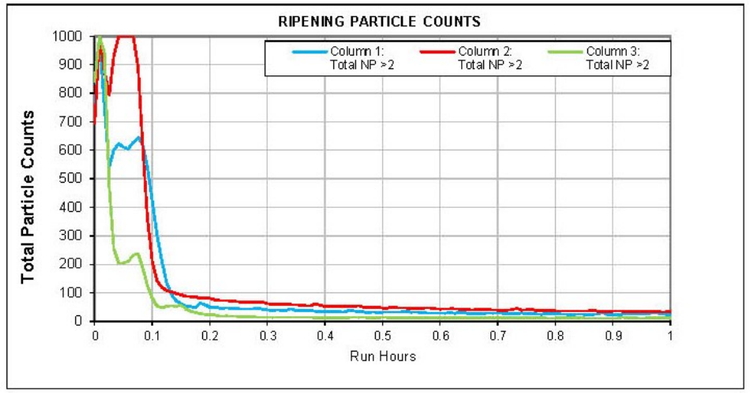
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	15	39	21
Filter Column 2 Effluent	24	47	30
Filter Column 3 Effluent	9	16	10

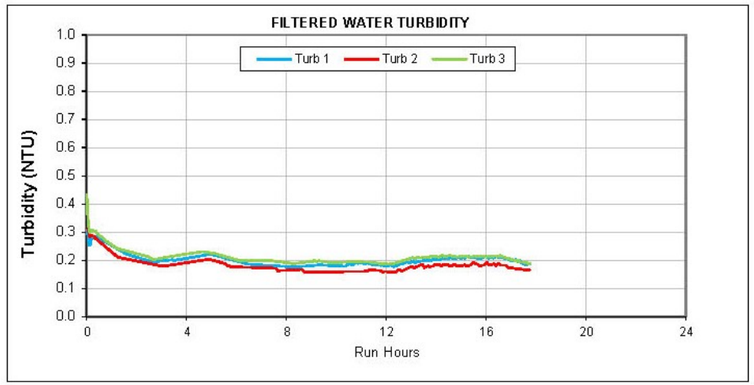
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.86	1.99	0.134
Filter Column 2	0.97	2.00	0.117
Filter Column 3	0.94	1.90	0.092

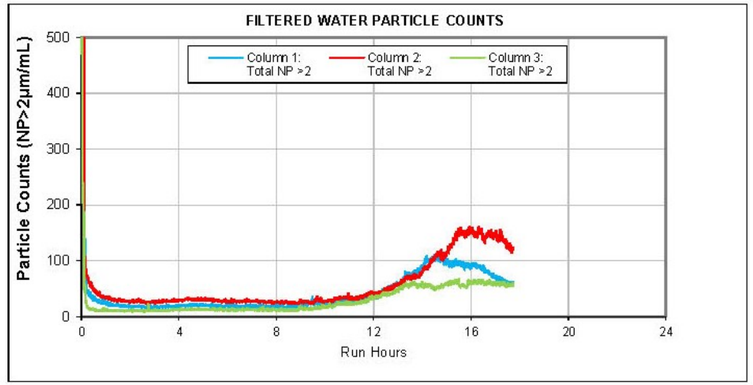
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	15	12.72	0
Filter Column 2	16	13.02	0
Filter Column 3	17	14.03	0

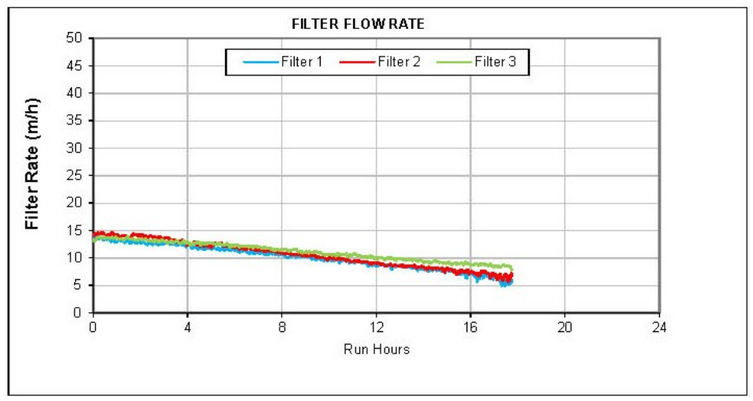
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	19-Mar-16 15:15
Run Ended	20-Mar-16 9:00
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	0		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.096		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.92	0.92	0.92

ONLINE DATA SUMMARY

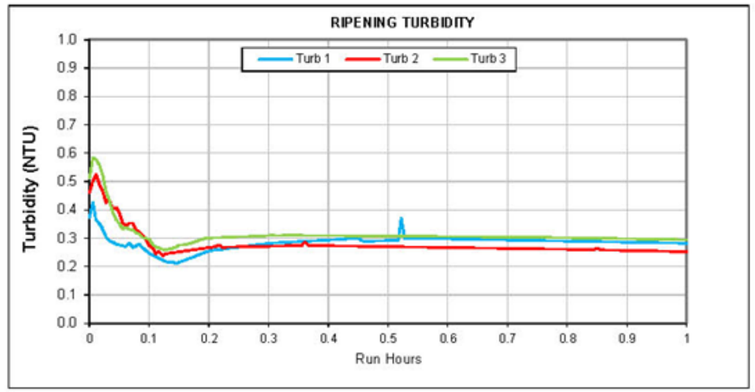
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.67	1.78	1.70
Column Influent	0.62	0.88	0.73
Filter Column 1 Effluent	0.17	0.33	0.20
Filter Column 2 Effluent	0.15	0.44	0.18
Filter Column 3 Effluent	0.19	0.54	0.21
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

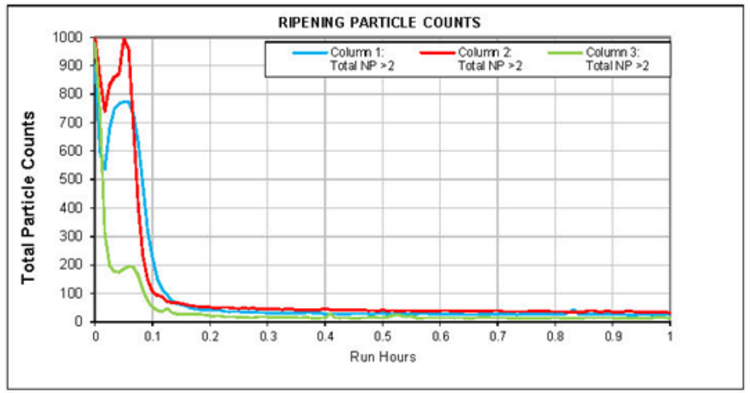
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	16	49	23
Filter Column 2 Effluent	24	50	30
Filter Column 3 Effluent	10	50	17

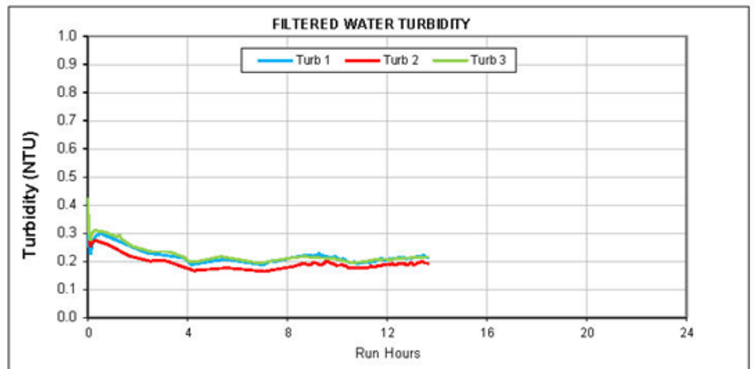
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.76	1.99	0.137
Filter Column 2	0.84	1.99	0.127
Filter Column 3	0.75	2.00	0.095

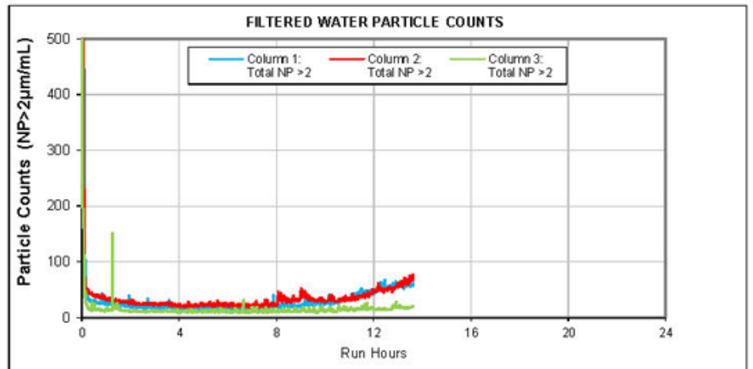
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	12	10.07	0
Filter Column 2	13	10.58	0
Filter Column 3	13	11.15	0

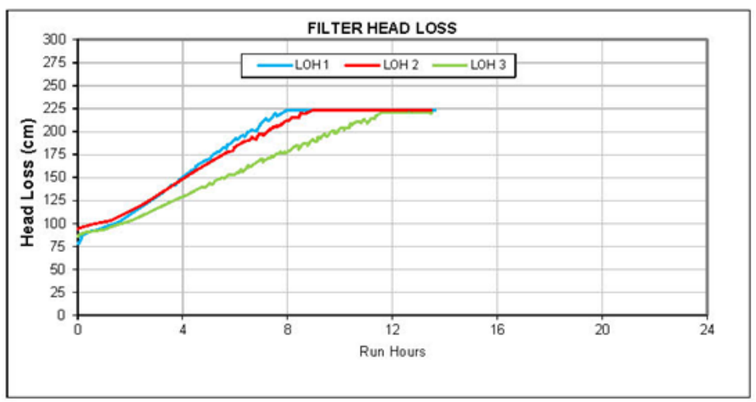
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

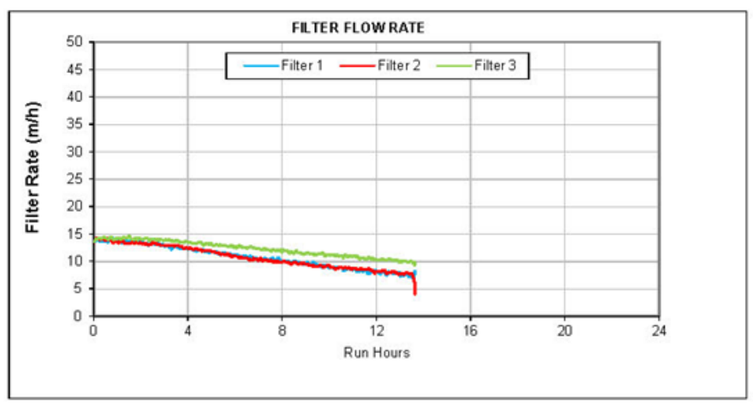












RUN SUMMARY

Run Started	20-Mar-16 18:31
Run Ended	21-Mar-16 8:10
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	0		mg/L
Polymer Type	Cationic LT 22S		
Polymer Dose	0.14		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.82	0.82	0.82

ONLINE DATA SUMMARY

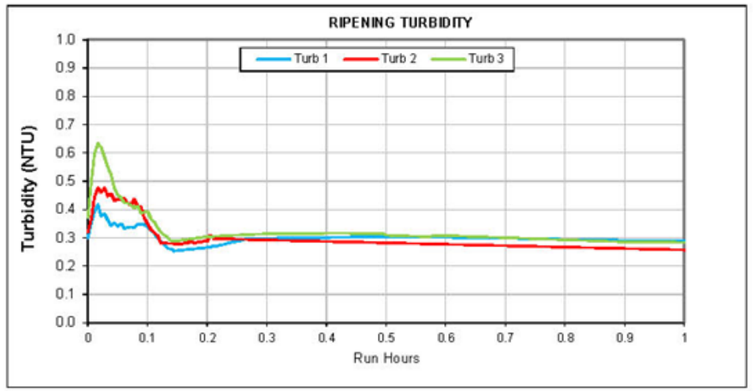
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.74	2.02	1.78
Column Influent	0.65	1.06	0.72
Filter Column 1 Effluent	0.19	0.43	0.22
Filter Column 2 Effluent	0.16	0.52	0.19
Filter Column 3 Effluent	0.19	0.58	0.22
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

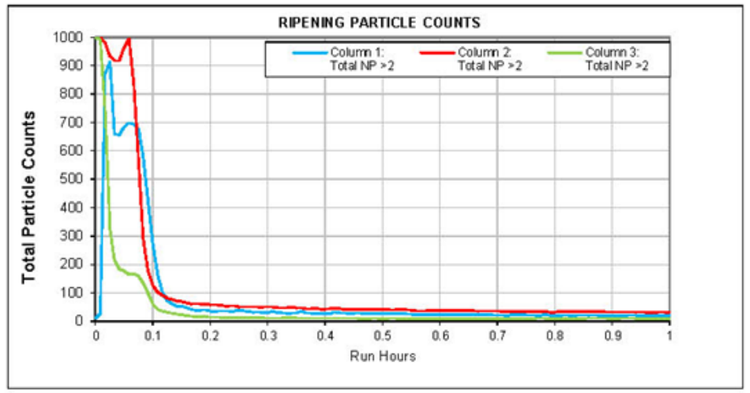
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	13	49	23
Filter Column 2 Effluent	19	51	29
Filter Column 3 Effluent	9	26	13

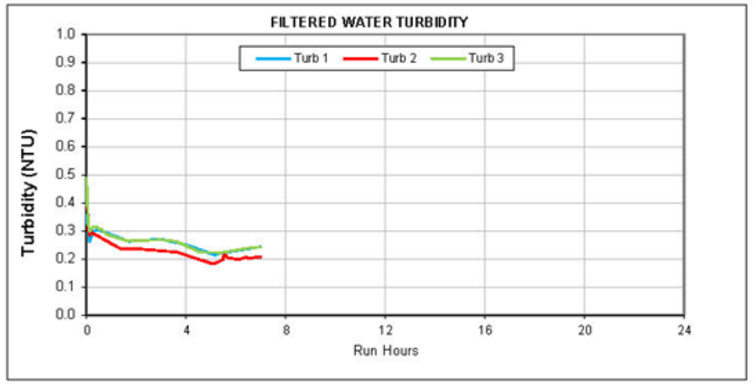
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.78	1.49	0.180
Filter Column 2	0.85	1.49	0.152
Filter Column 3	0.76	1.49	0.128

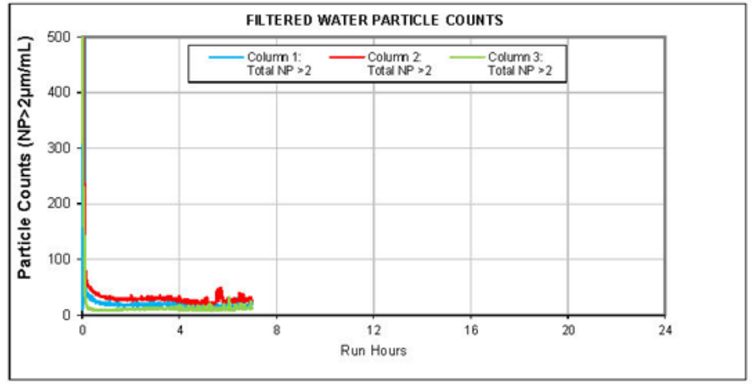
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	13	10.76	0
Filter Column 2	13	10.74	0
Filter Column 3	15	12.32	0

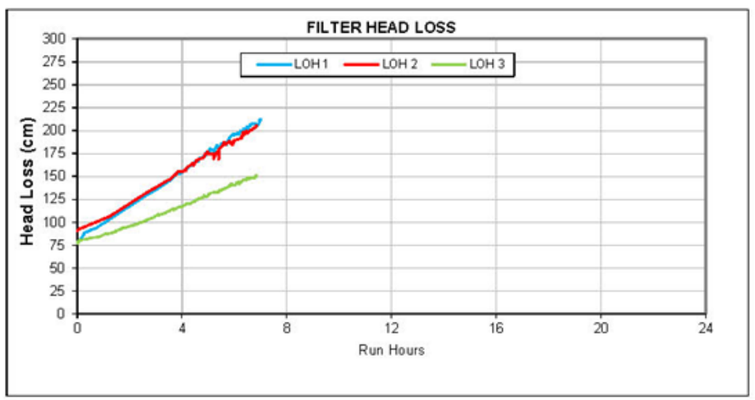
Media Specifications	**Column 1**	**Column 2**	**Column 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

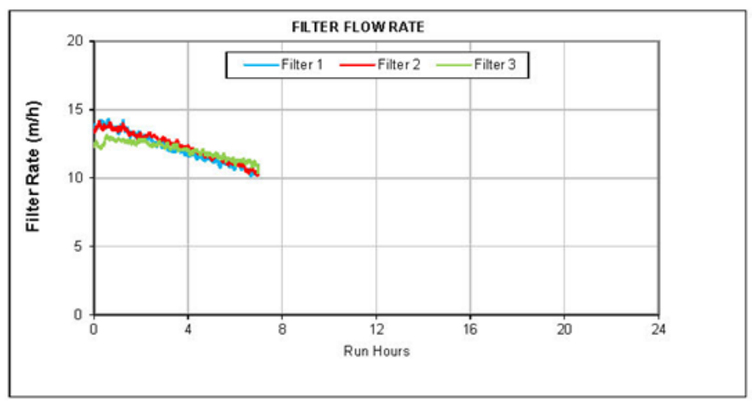












RUN SUMMARY

Run Started	20-Mar-16 10:52
Run Ended	20-Mar-16 17:52
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	0		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.22		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.82	0.82	0.82

ONLINE DATA SUMMARY

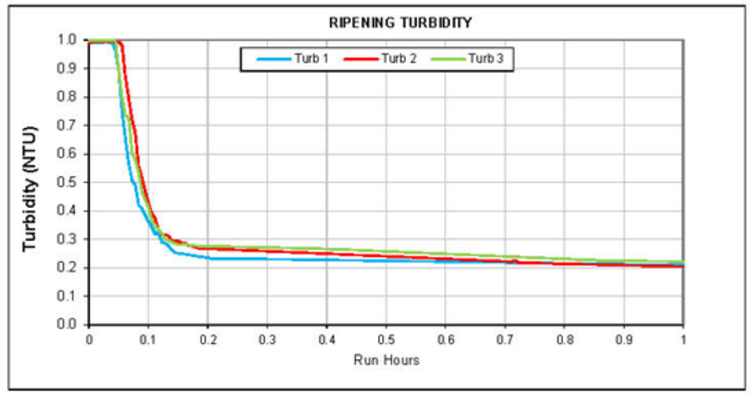
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.70	1.81	1.73
Column Influent	0.68	0.92	0.75
Filter Column 1 Effluent	0.21	0.42	0.26
Filter Column 2 Effluent	0.18	0.48	0.23
Filter Column 3 Effluent	0.22	0.63	0.26
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

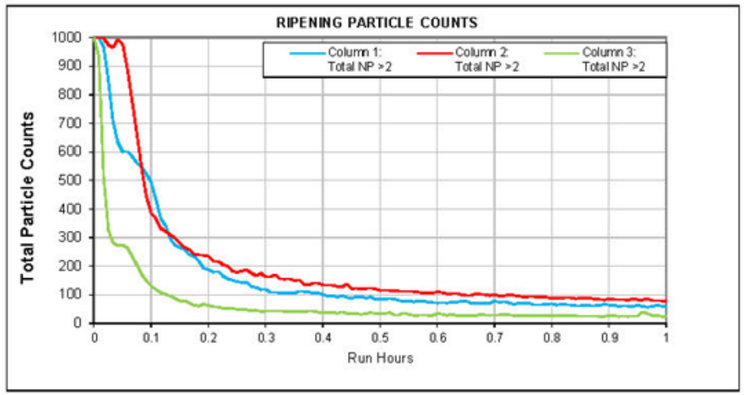
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	14	36	19
Filter Column 2 Effluent	20	45	28
Filter Column 3 Effluent	8	23	11

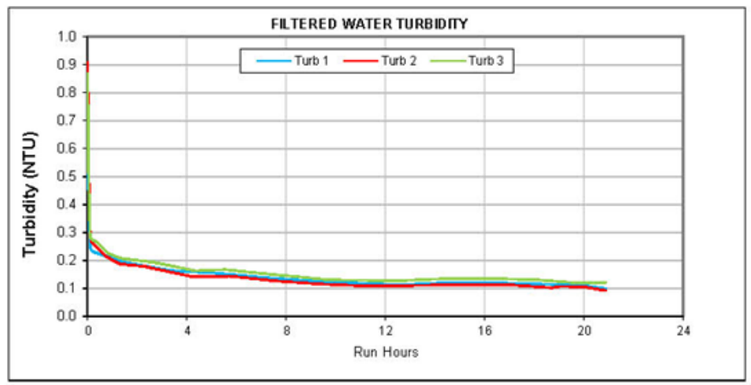
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.77	2.00	0.195
Filter Column 2	0.82	1.99	0.173
Filter Column 3	0.70	1.51	0.117

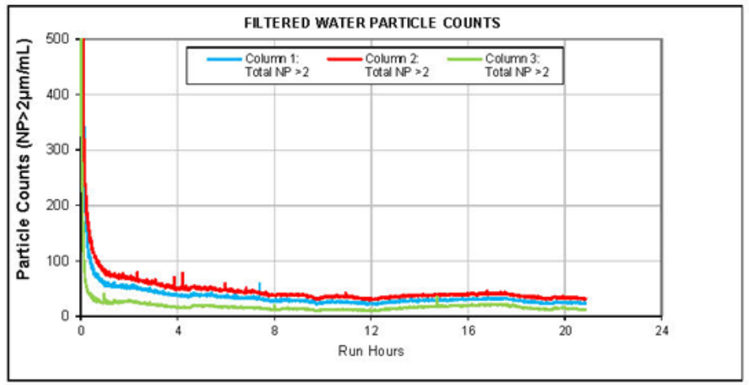
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	15	12.19	0
Filter Column 2	15	12.35	0
Filter Column 3	14	12.08	0

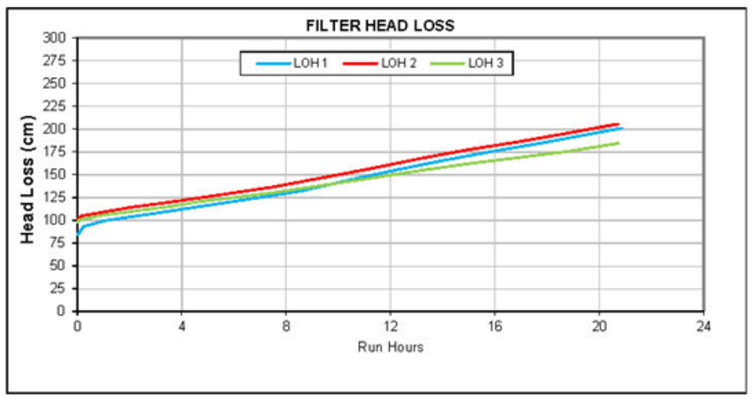
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

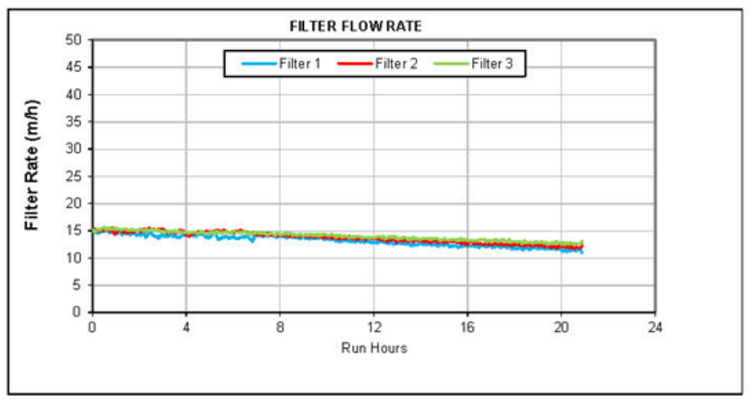












RUN SUMMARY

Run Started	05-Mar-16 14:37
Run Ended	06-Mar-16 11:30
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	1		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.78	0.78	0.78

ONLINE DATA SUMMARY

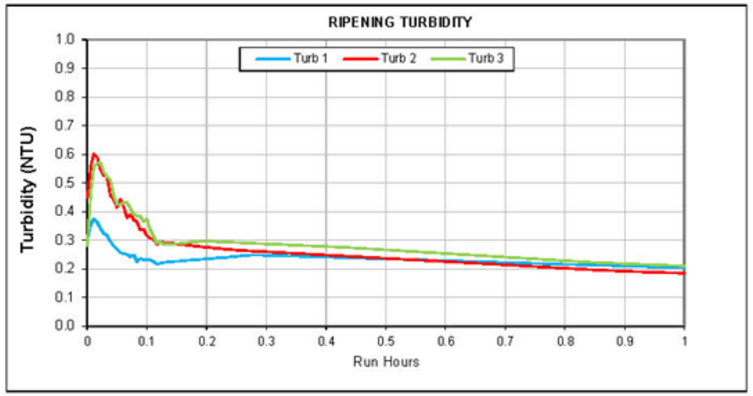
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.53	1.72	1.55
Column Influent	1.11	1.18	1.14
Filter Column 1 Effluent	0.10	0.99	0.14
Filter Column 2 Effluent	0.09	0.99	0.13
Filter Column 3 Effluent	0.12	1.00	0.15
Filter Column 1 Ripening Time (minutes)		1249.3	
Filter Column 2 Ripening Time (minutes)		1252.5	
Filter Column 3 Ripening Time (minutes)		DNR	

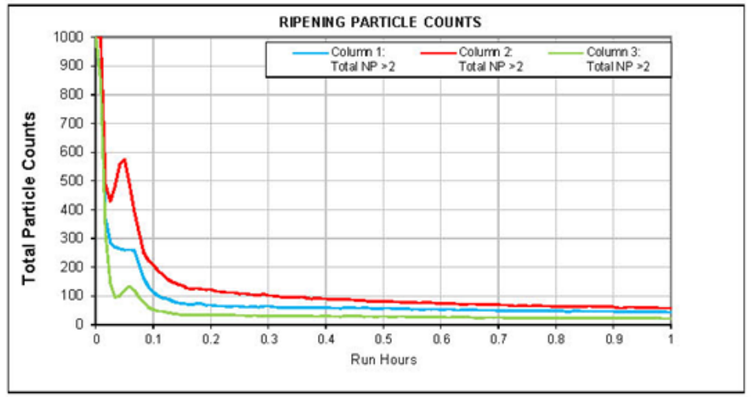
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	22	47	30
Filter Column 2 Effluent	31	53	39
Filter Column 3 Effluent	10	36	17

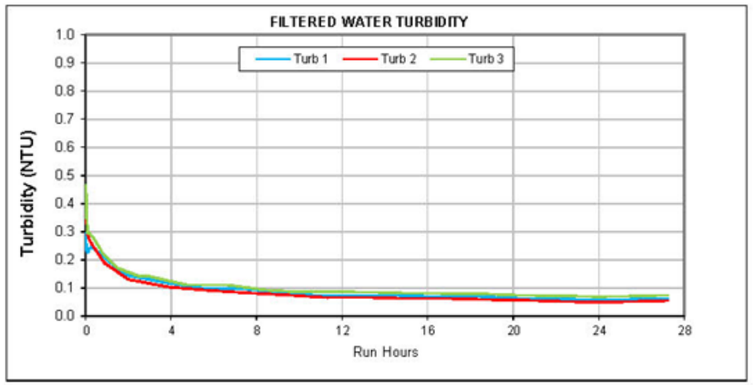
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.84	1.50	0.058
Filter Column 2	0.91	1.50	0.058
Filter Column 3	0.89	1.50	0.050

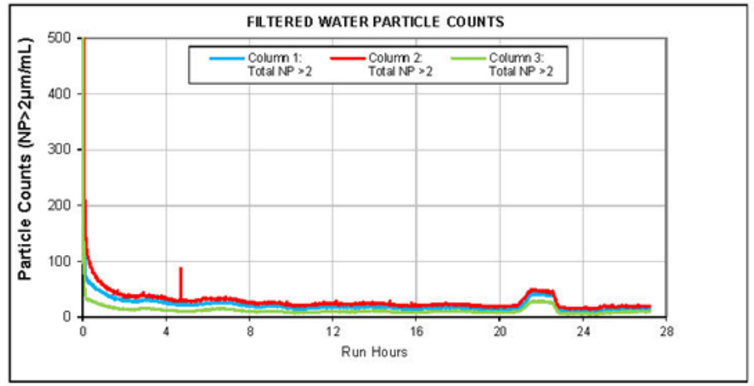
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	16	13.18	0
Filter Column 2	16	13.72	0
Filter Column 3	17	14.01	0

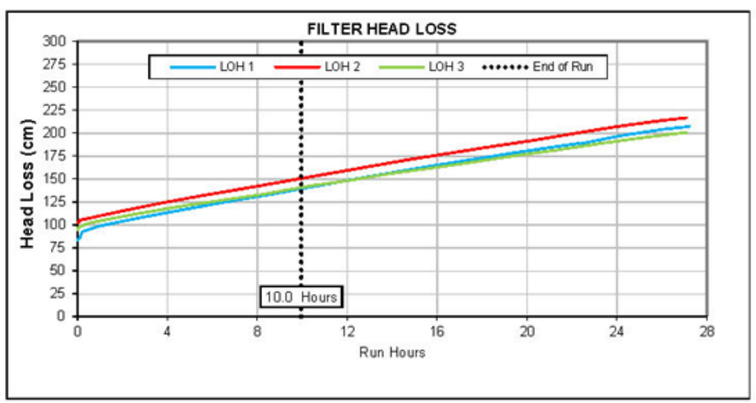
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

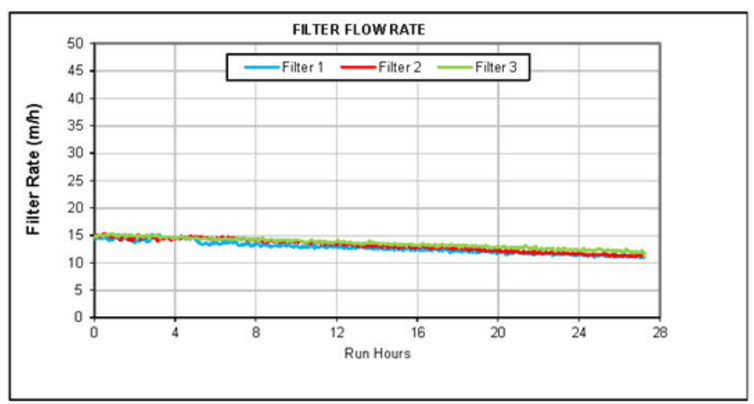












RUN SUMMARY

Run Started	06-Mar-16 12:40
Run Ended	07-Mar-16 15:55
Filter Column 1 Run Time (hrs)	6.91
Filter Column 2 Run Time (hrs)	5.51
Filter Column 3 Run Time (hrs)	4.88
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	2		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.78	0.78	0.78

ONLINE DATA SUMMARY

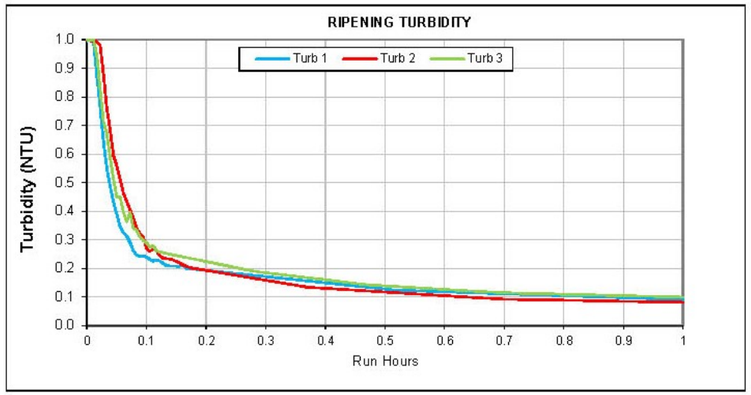
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	0.75	1.69	1.56
Column Influent	1.19	1.42	1.29
Filter Column 1 Effluent	0.06	0.10	0.07
Filter Column 2 Effluent	0.05	0.10	0.07
Filter Column 3 Effluent	0.07	0.10	0.08
Filter Column 1 Ripening Time (minutes)		327.3	
Filter Column 2 Ripening Time (minutes)		266.3	
Filter Column 3 Ripening Time (minutes)		463.0	

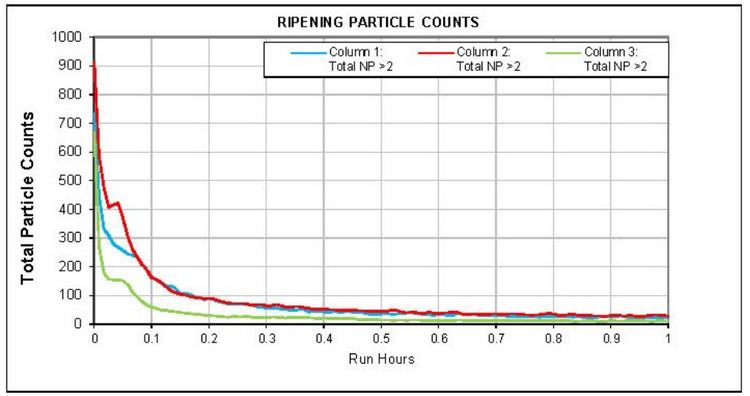
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	10	44	20
Filter Column 2 Effluent	15	48	26
Filter Column 3 Effluent	5	30	12

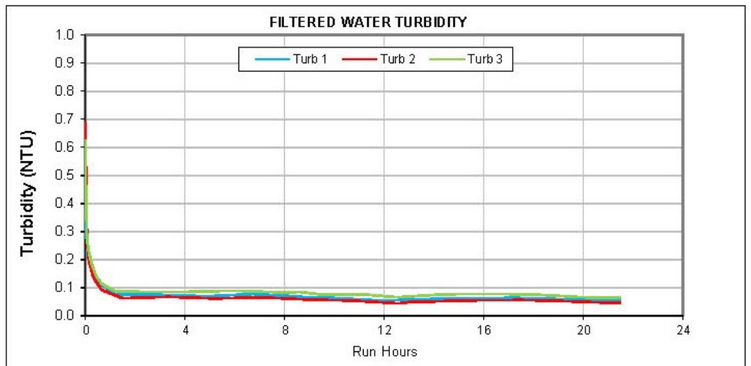
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.83	1.50	0.054
Filter Column 2	0.92	1.50	0.058
Filter Column 3	0.86	1.50	0.051

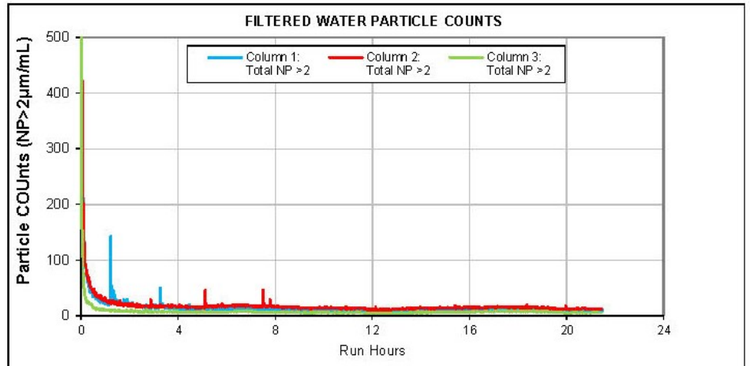
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.76	87
Filter Column 2	16	13.16	75
Filter Column 3	16	13.56	65

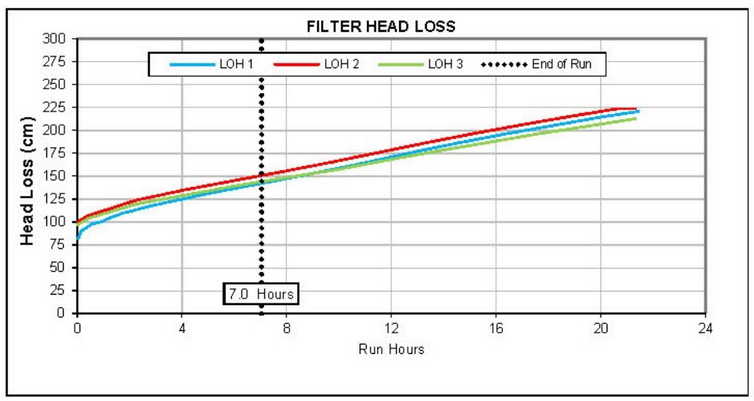
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

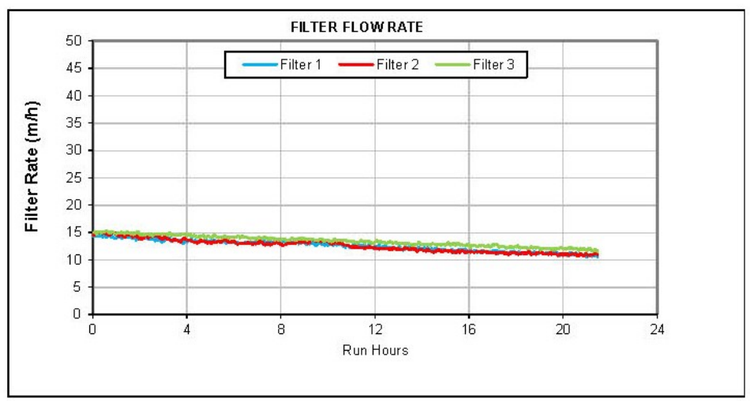












RUN SUMMARY

Run Started	12-Mar-16 12:41
Run Ended	13-Mar-16 11:10
Filter Column 1 Run Time (hrs)	7.58
Filter Column 2 Run Time (hrs)	6.40
Filter Column 3 Run Time (hrs)	7.47
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	2		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.048		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.12	1.12	1.12

ONLINE DATA SUMMARY

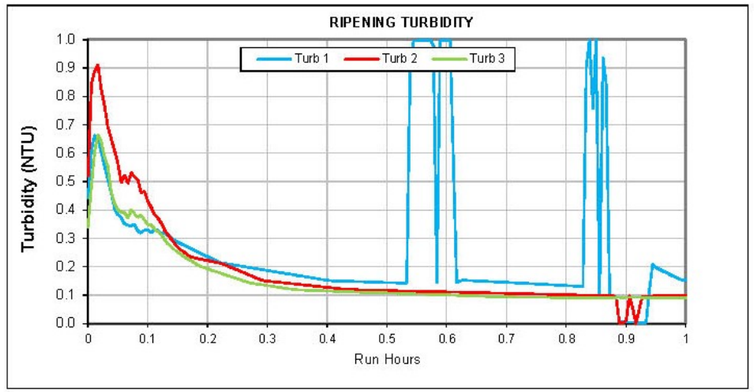
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.60	1.76	1.64
Column Influent	1.03	1.41	1.21
Filter Column 1 Effluent	0.05	0.10	0.07
Filter Column 2 Effluent	0.04	0.10	0.06
Filter Column 3 Effluent	0.06	0.10	0.08
Filter Column 1 Ripening Time (minutes)		51.7	
Filter Column 2 Ripening Time (minutes)		38.0	
Filter Column 3 Ripening Time (minutes)		59.3	

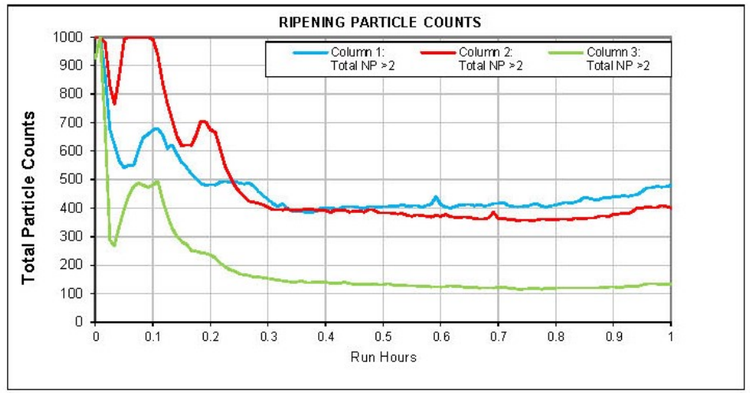
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	7	40	12
Filter Column 2 Effluent	10	37	16
Filter Column 3 Effluent	4	22	7

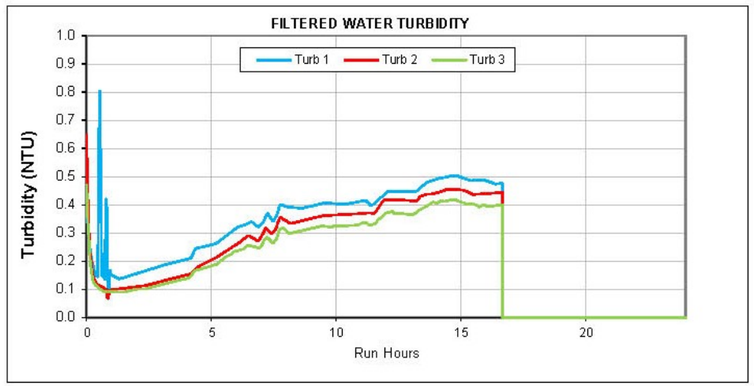
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.82	1.50	0.080
Filter Column 2	0.92	1.50	0.082
Filter Column 3	0.88	1.50	0.074

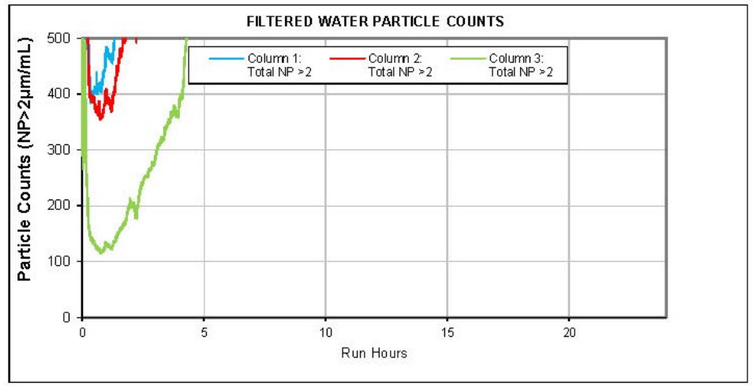
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.57	97
Filter Column 2	15	12.56	82
Filter Column 3	16	13.44	95

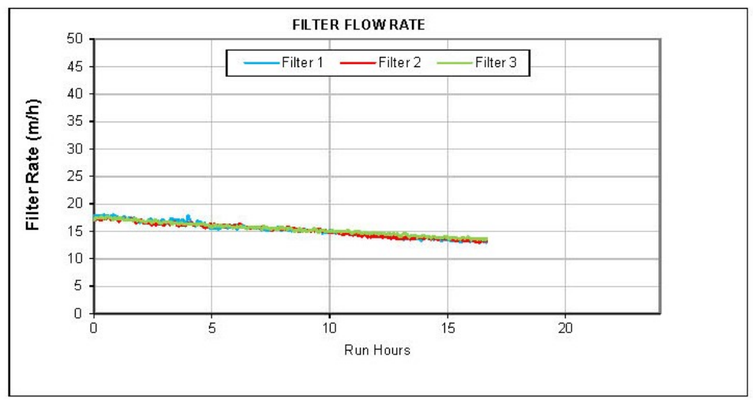
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	15-Dec-15 15:20
Run Ended	16-Dec-15 8:00
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.00		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.00	1.00	1.00

ONLINE DATA SUMMARY

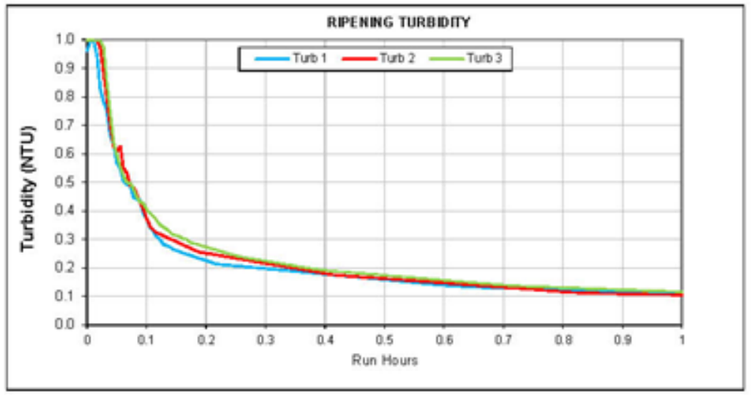
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.24	1.26	1.25
Column Influent	2.10	2.41	2.24
Filter Column 1 Effluent	0.00	0.12	0.03
Filter Column 2 Effluent	0.00	0.10	0.09
Filter Column 3 Effluent	0.09	0.10	0.09
Filter Column 1 Ripening Time (minutes)	DNR		
Filter Column 2 Ripening Time (minutes)	DNR		
Filter Column 3 Ripening Time (minutes)	DNR		

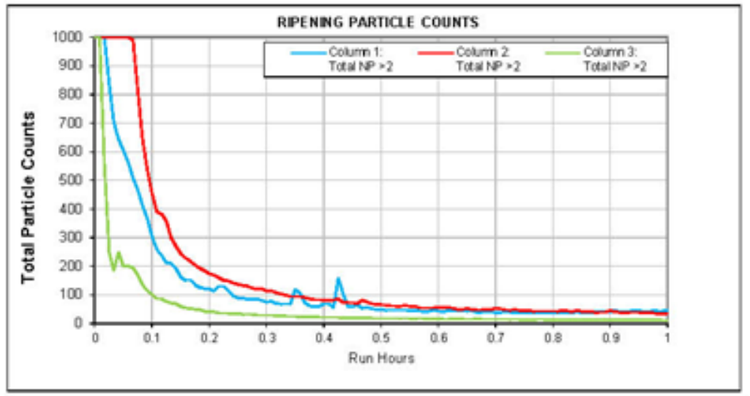
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1000	1000	1000
Filter Column 2 Effluent	1000	1000	1000
Filter Column 3 Effluent	999	999	999

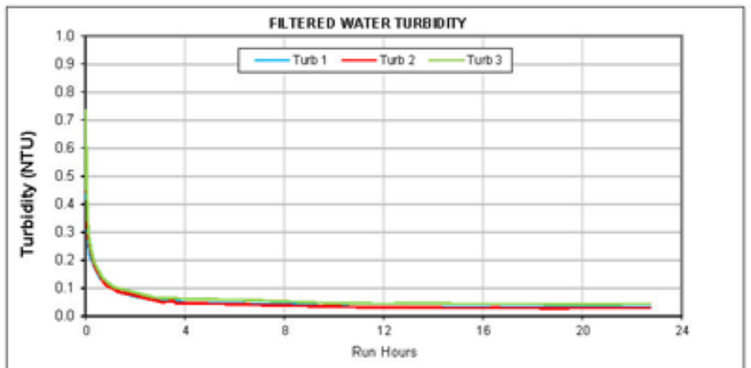
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.90	1.16	0.274
Filter Column 2	0.94	1.22	0.222
Filter Column 3	0.93	1.31	0.187

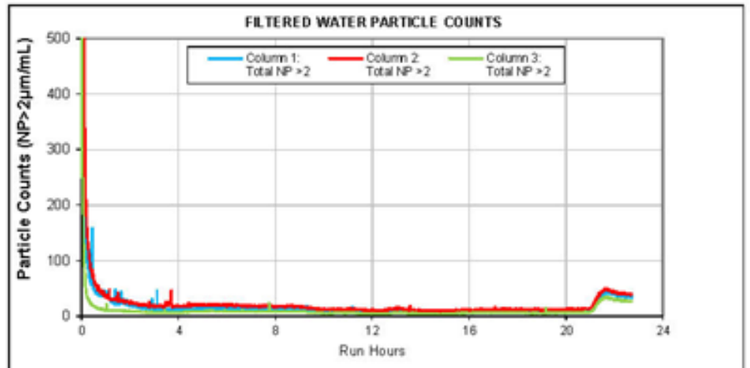
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	18	15.28	0
Filter Column 2	18	15.21	0
Filter Column 3	18	15.40	0

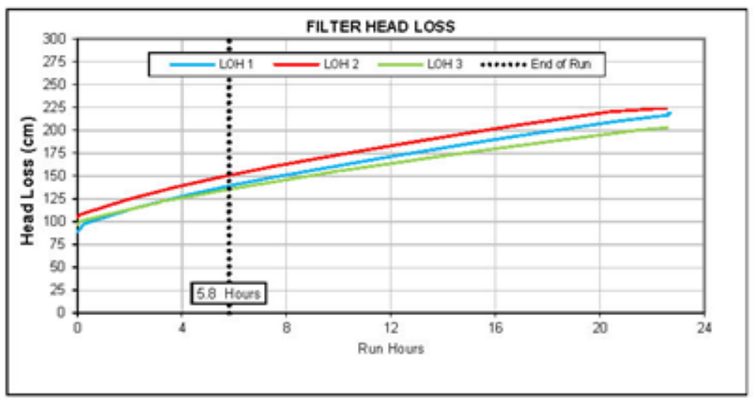
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

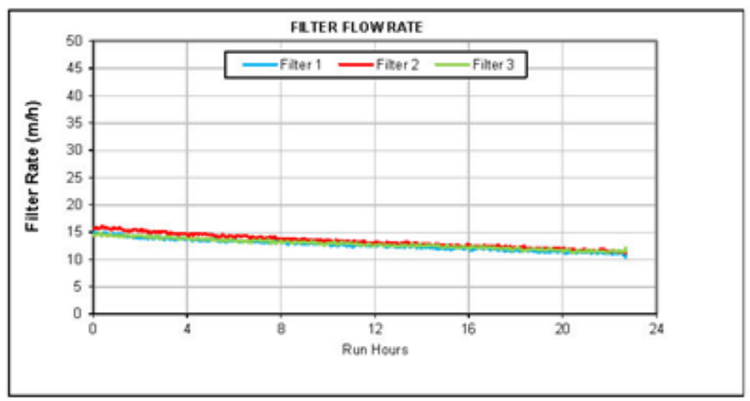












RUN SUMMARY

Run Started	16-Feb-16 12:17
Run Ended	17-Feb-16 11:00
Filter Column 1 Run Time (hrs)	6.61
Filter Column 2 Run Time (hrs)	4.71
Filter Column 3 Run Time (hrs)	7.64
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.44	1.44	1.44

ONLINE DATA SUMMARY

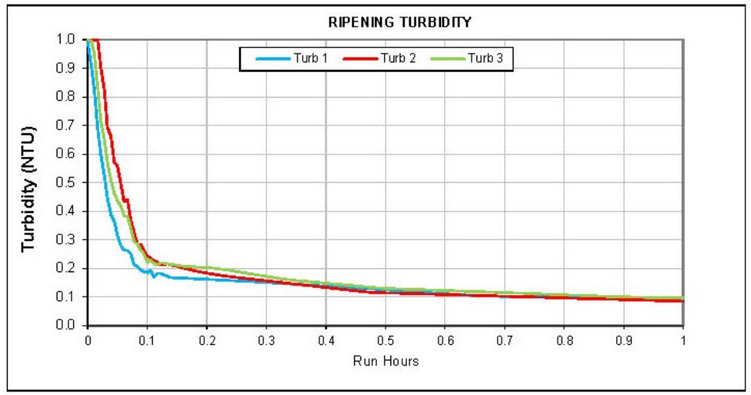
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.25	3.70	1.29
Column Influent	1.22	1.60	1.37
Filter Column 1 Effluent	0.03	0.10	0.04
Filter Column 2 Effluent	0.03	0.10	0.04
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		68.0	
Filter Column 2 Ripening Time (minutes)		65.7	
Filter Column 3 Ripening Time (minutes)		80.3	

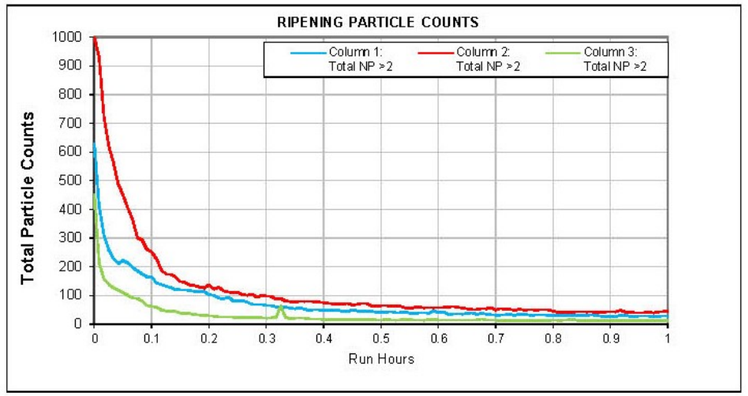
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	5	43	13
Filter Column 2 Effluent	9	47	17
Filter Column 3 Effluent	4	33	9

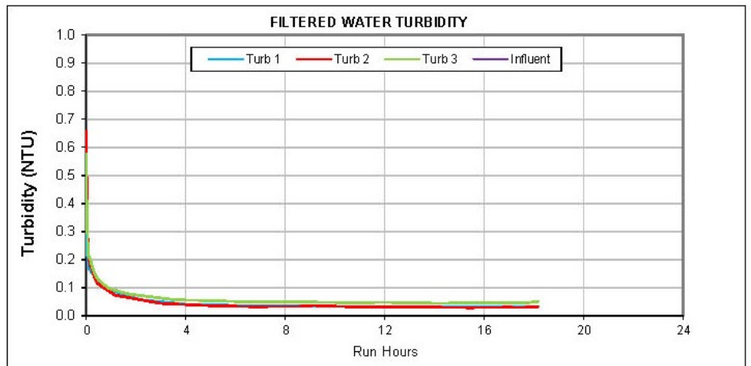
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.89	1.50	0.079
Filter Column 2	0.99	1.50	0.087
Filter Column 3	0.91	1.50	0.066

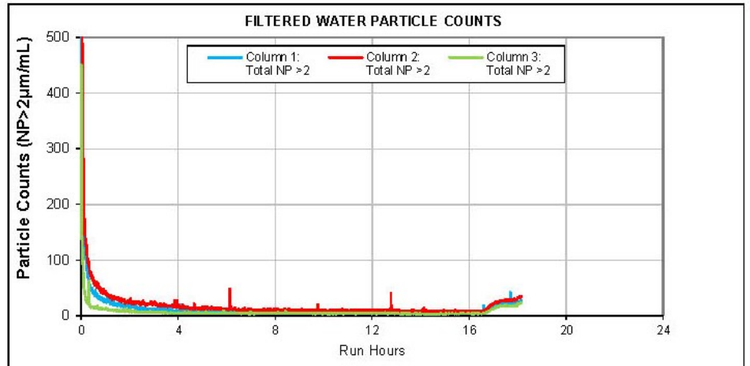
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	15	12.66	86
Filter Column 2	16	13.35	66
Filter Column 3	15	12.84	99

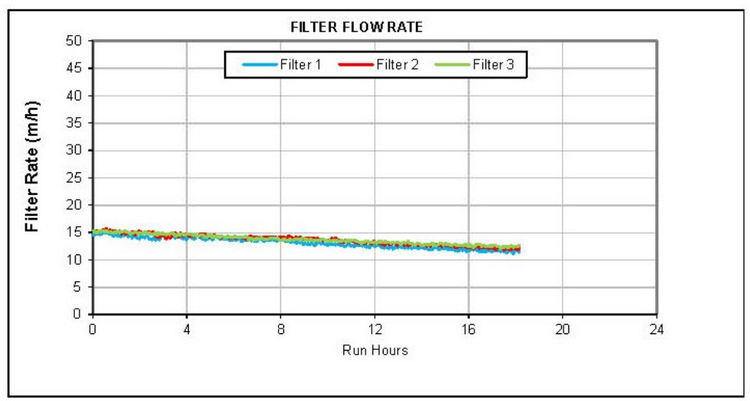
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	29-Feb-16 17:35
Run Ended	01-Mar-16 11:45
Filter Column 1 Run Time (hrs)	6.37
Filter Column 2 Run Time (hrs)	4.25
Filter Column 3 Run Time (hrs)	5.90
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.036		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.94	0.94	0.94
Filter Column 1 Ripening Time (minutes)	45.3		
Filter Column 2 Ripening Time (minutes)	44.3		
Filter Column 3 Ripening Time (minutes)	54.3		

ONLINE DATA SUMMARY

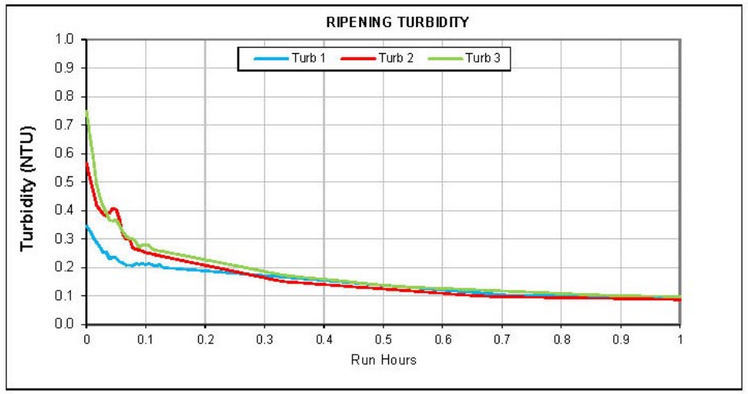
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.45	1.53	1.50
Column Influent	1.40	1.59	1.49
Filter Column 1 Effluent	0.03	0.10	0.04
Filter Column 2 Effluent	0.03	0.10	0.04
Filter Column 3 Effluent	0.04	0.10	0.05

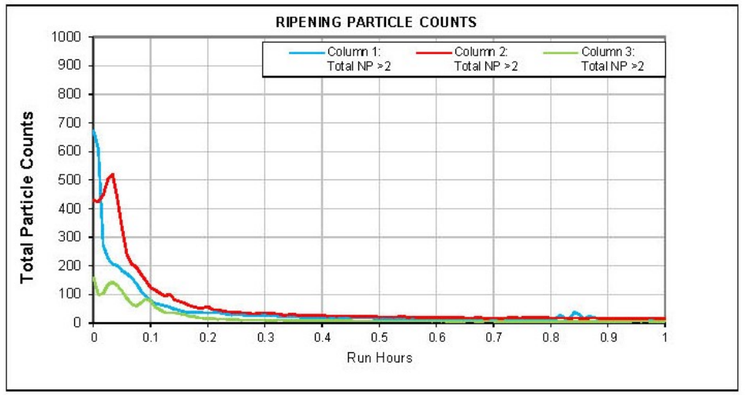
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	4	39	10
Filter Column 2 Effluent	7	42	14
Filter Column 3 Effluent	3	23	6

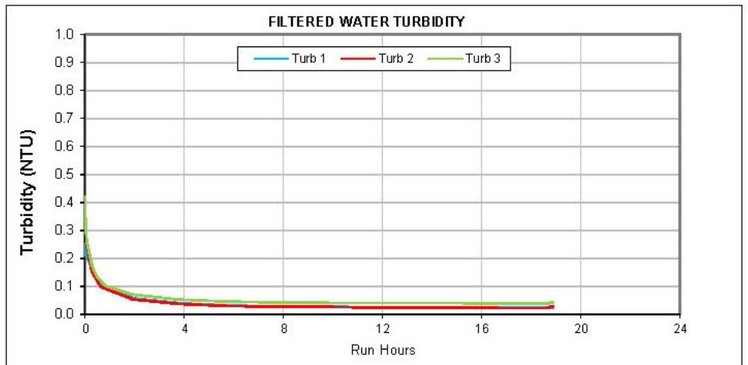
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.50	0.092
Filter Column 2	0.93	1.50	0.113
Filter Column 3	0.88	1.50	0.091

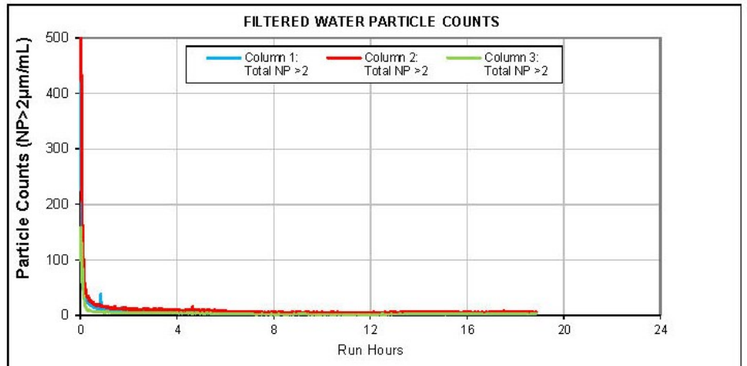
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.09	85
Filter Column 2	16	13.65	59
Filter Column 3	16	13.72	82

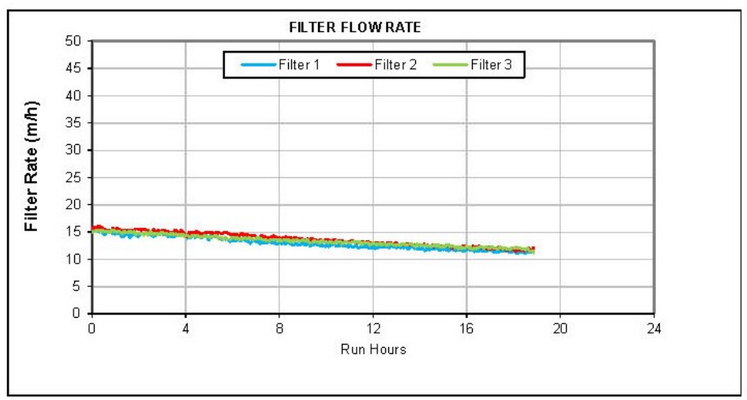
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	24-Feb-16 14:52
Run Ended	25-Feb-16 9:45
Filter Column 1 Run Time (hrs)	5.93
Filter Column 2 Run Time (hrs)	4.09
Filter Column 3 Run Time (hrs)	5.94
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.048		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.90	0.90	0.90

ONLINE DATA SUMMARY

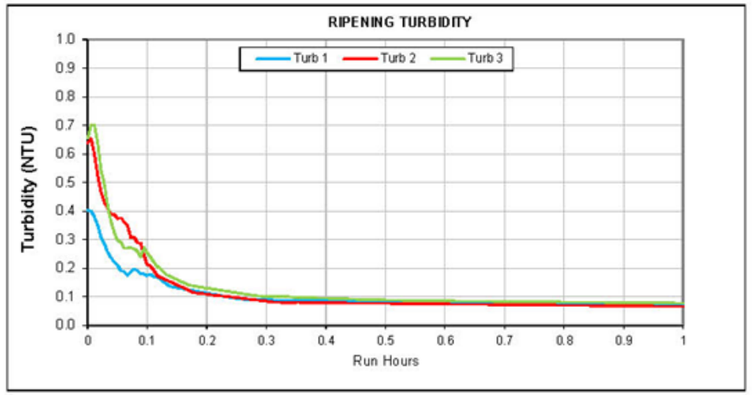
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.29	1.41	1.33
Column Influent	1.13	1.46	1.30
Filter Column 1 Effluent	0.02	0.10	0.03
Filter Column 2 Effluent	0.02	0.10	0.03
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		47.7	
Filter Column 2 Ripening Time (minutes)		39.7	
Filter Column 3 Ripening Time (minutes)		55.0	

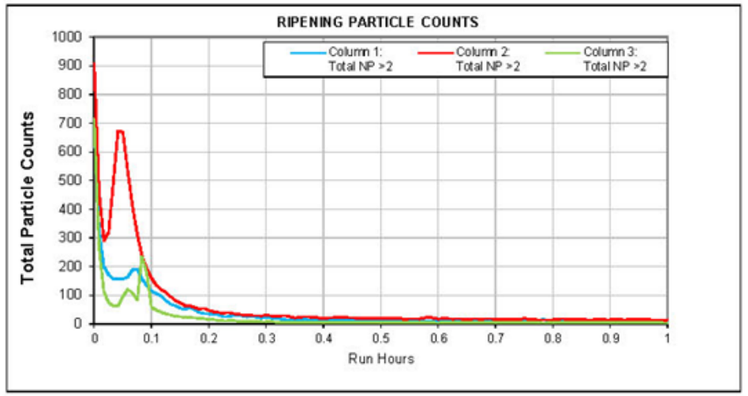
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	2	25	5
Filter Column 2 Effluent	4	26	7
Filter Column 3 Effluent	1	9	3

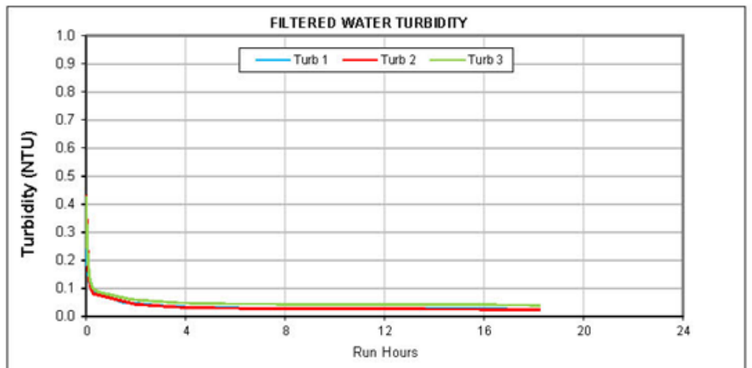
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.87	1.50	0.094
Filter Column 2	0.96	1.50	0.112
Filter Column 3	0.88	1.50	0.090

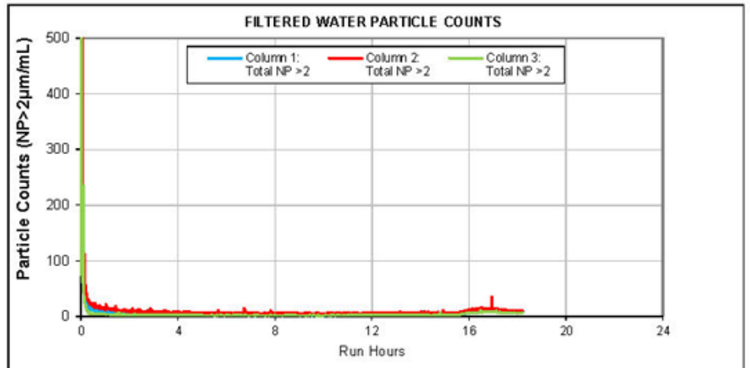
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.94	80
Filter Column 2	16	13.67	59
Filter Column 3	16	13.38	81

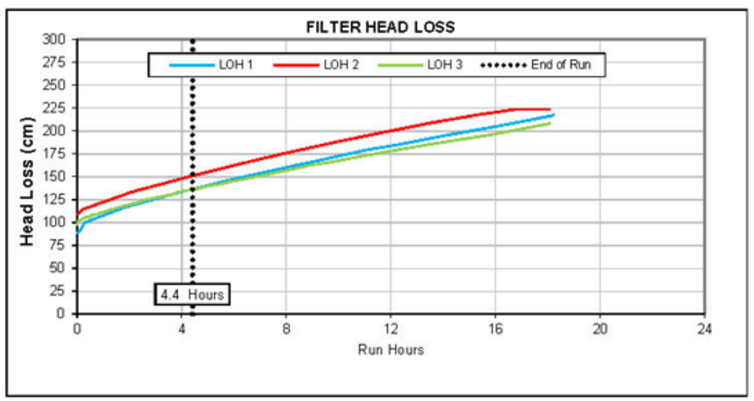
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

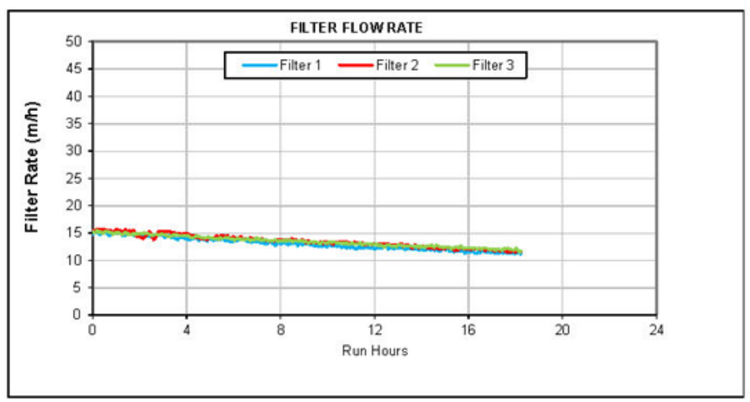












RUN SUMMARY

Run Started	23-Feb-16 17:21
Run Ended	24-Feb-16 11:35
Filter Column 1 Run Time (hrs)	6.14
Filter Column 2 Run Time (hrs)	4.17
Filter Column 3 Run Time (hrs)	6.62
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.072		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.90	0.90	0.90

ONLINE DATA SUMMARY

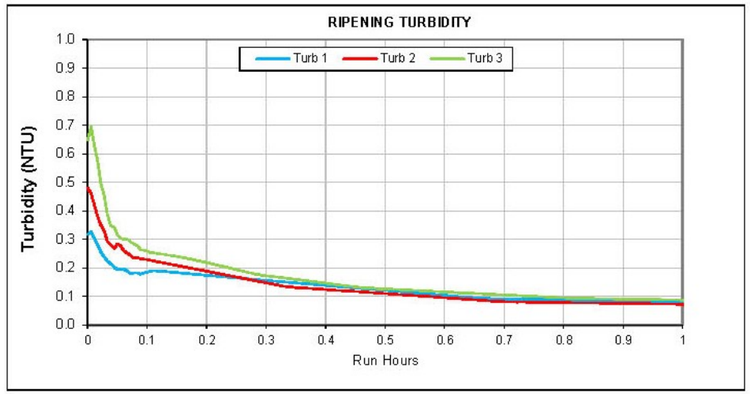
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.30	1.38	1.34
Column Influent	1.30	1.60	1.42
Filter Column 1 Effluent	0.02	0.10	0.03
Filter Column 2 Effluent	0.02	0.10	0.03
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		14.3	
Filter Column 2 Ripening Time (minutes)		14.3	
Filter Column 3 Ripening Time (minutes)		19.3	

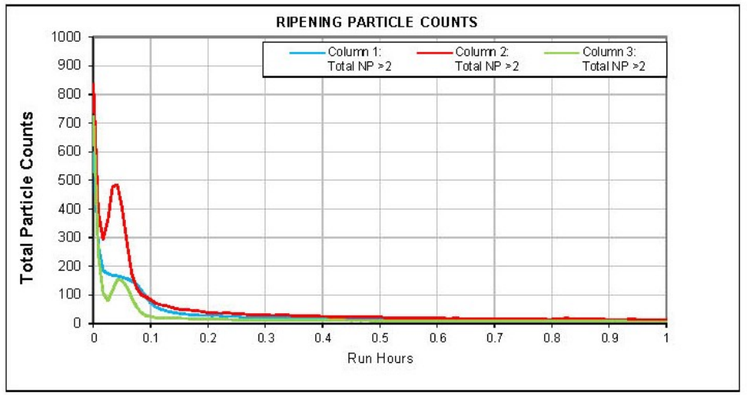
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	2	15	4
Filter Column 2 Effluent	5	24	8
Filter Column 3 Effluent	1	9	3

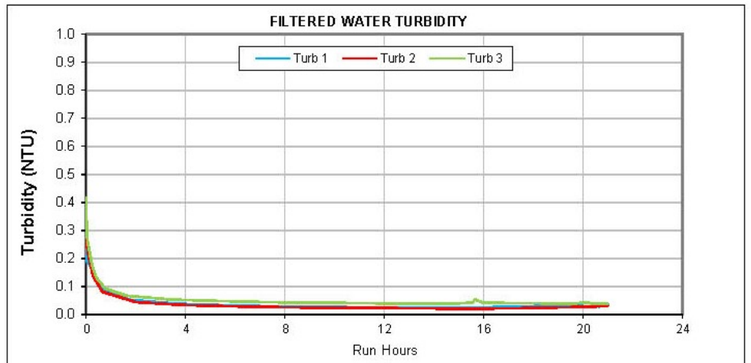
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.88	1.50	0.096
Filter Column 2	0.99	1.50	0.116
Filter Column 3	0.90	1.50	0.086

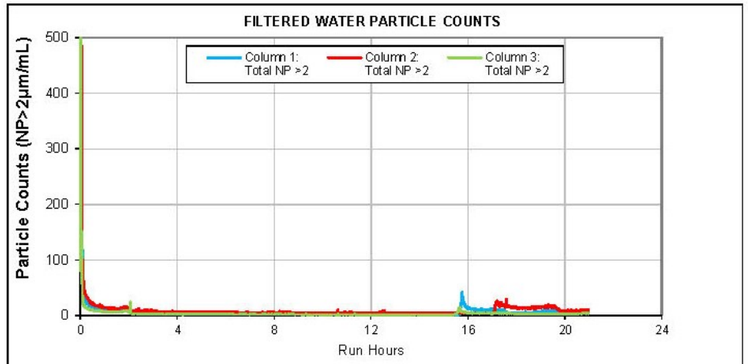
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.03	84
Filter Column 2	16	13.52	59
Filter Column 3	16	13.46	91

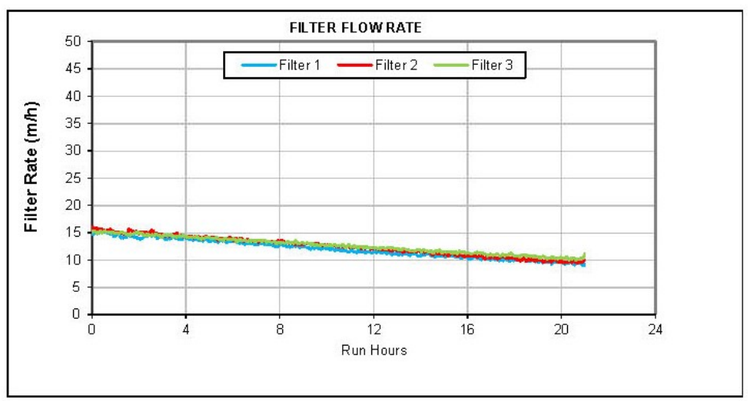
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	25-Feb-16 11:18
Run Ended	26-Feb-16 8:18
Filter Column 1 Run Time (hrs)	4.79
Filter Column 2 Run Time (hrs)	3.60
Filter Column 3 Run Time (hrs)	5.26
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.096		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.85	0.85	0.85

ONLINE DATA SUMMARY

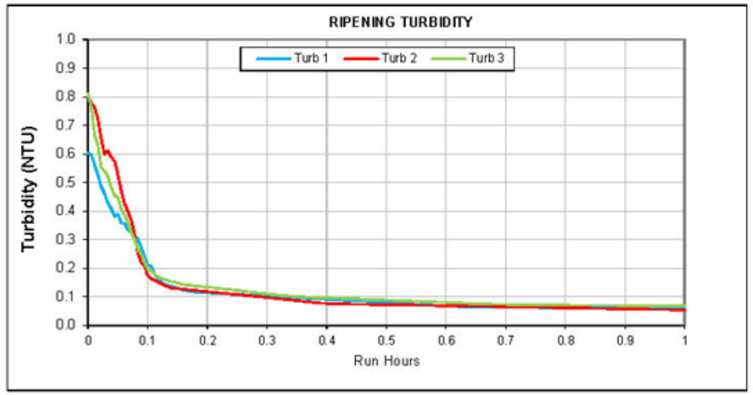
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.32	1.41	1.36
Column Influent	1.19	1.56	1.39
Filter Column 1 Effluent	0.02	0.10	0.03
Filter Column 2 Effluent	0.02	0.10	0.03
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		37.3	
Filter Column 2 Ripening Time (minutes)		34.3	
Filter Column 3 Ripening Time (minutes)		45.0	

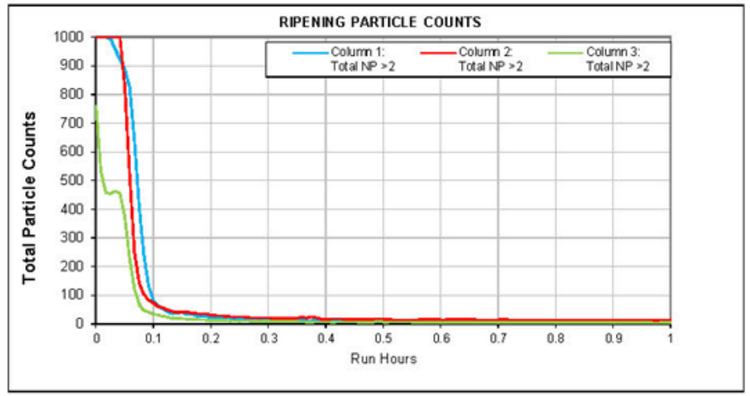
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1	25	5
Filter Column 2 Effluent	4	28	8
Filter Column 3 Effluent	1	13	3

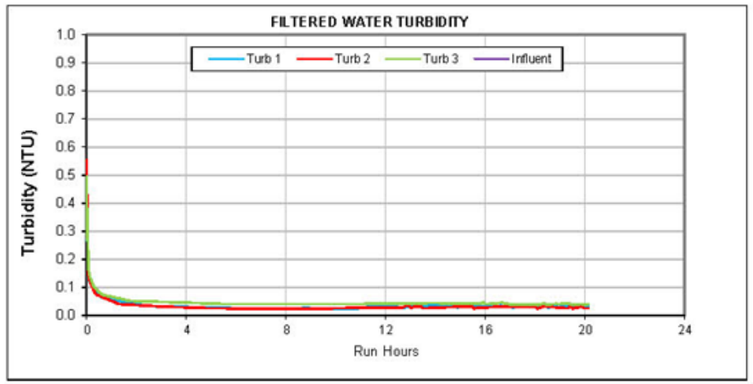
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.92	1.50	0.106
Filter Column 2	1.03	1.50	0.111
Filter Column 3	0.95	1.50	0.091

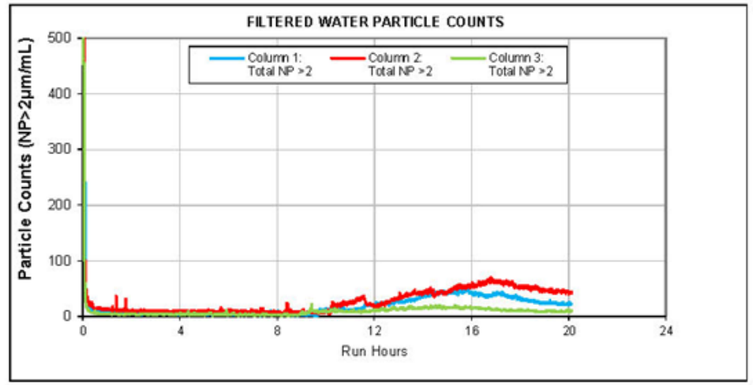
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	14	12.02	64
Filter Column 2	15	12.50	51
Filter Column 3	15	12.65	72

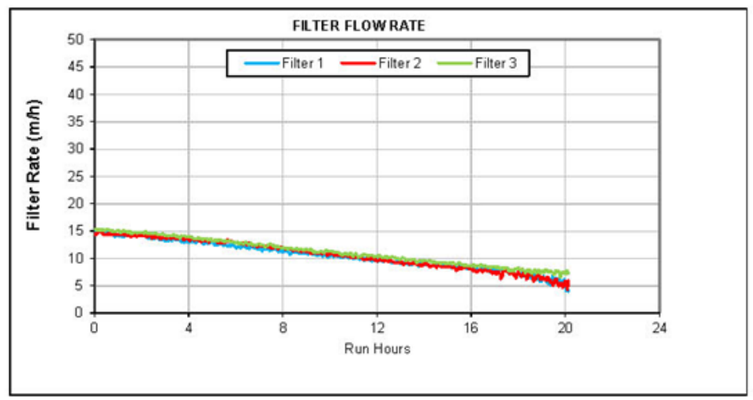
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	11-Feb-16 12:01
Run Ended	12-Feb-16 8:09
Filter Column 1 Run Time (hrs)	3.30
Filter Column 2 Run Time (hrs)	2.84
Filter Column 3 Run Time (hrs)	3.70
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.14		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.96	0.96	0.96

ONLINE DATA SUMMARY

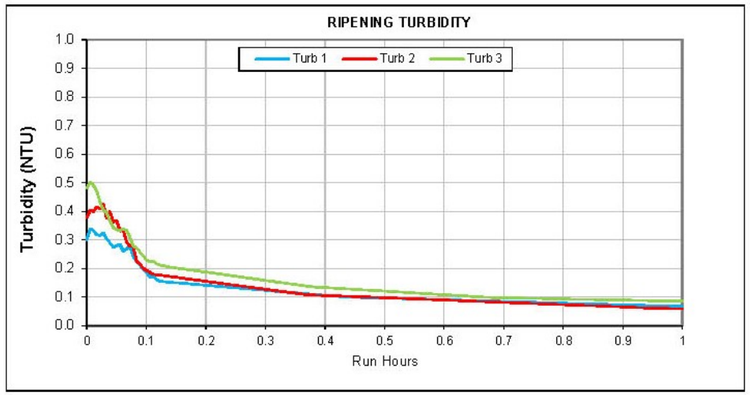
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.30	1.37	1.33
Column Influent	1.24	1.80	1.38
Filter Column 1 Effluent	0.02	0.10	0.03
Filter Column 2 Effluent	0.02	0.10	0.03
Filter Column 3 Effluent	0.04	0.10	0.04
Filter Column 1 Ripening Time (minutes)		19.3	
Filter Column 2 Ripening Time (minutes)		17.3	
Filter Column 3 Ripening Time (minutes)		21.7	

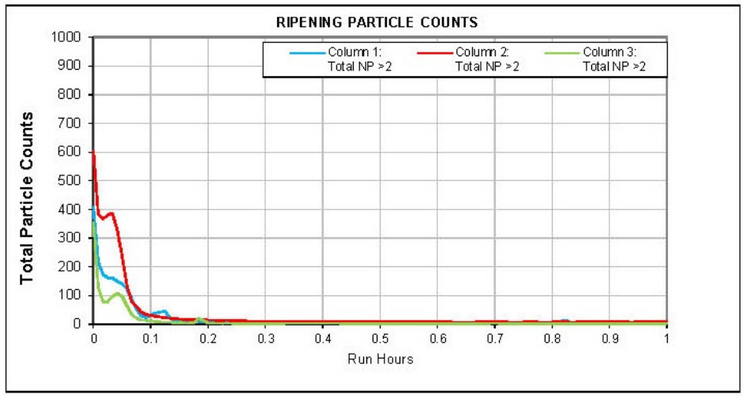
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1	45	17
Filter Column 2 Effluent	5	50	17
Filter Column 3 Effluent	1	18	8

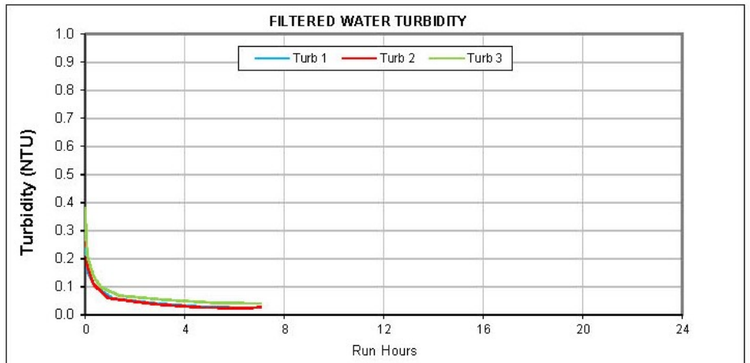
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.88	1.49	0.169
Filter Column 2	0.95	1.50	0.175
Filter Column 3	0.88	1.49	0.151

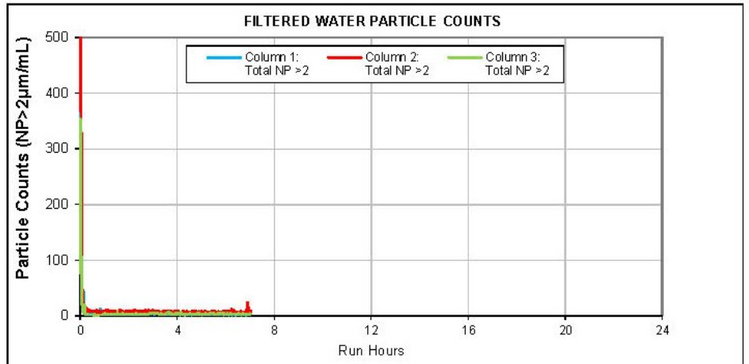
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	13	10.53	44
Filter Column 2	13	10.64	38
Filter Column 3	13	11.22	51

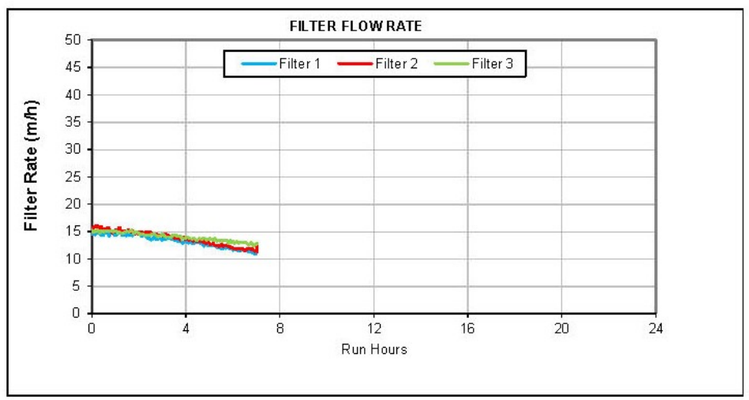
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	26-Feb-16 10:02
Run Ended	26-Feb-16 17:05
Filter Column 1 Run Time (hrs)	3.19
Filter Column 2 Run Time (hrs)	2.40
Filter Column 3 Run Time (hrs)	3.73
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	3		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.22		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.75	0.75	0.75

ONLINE DATA SUMMARY

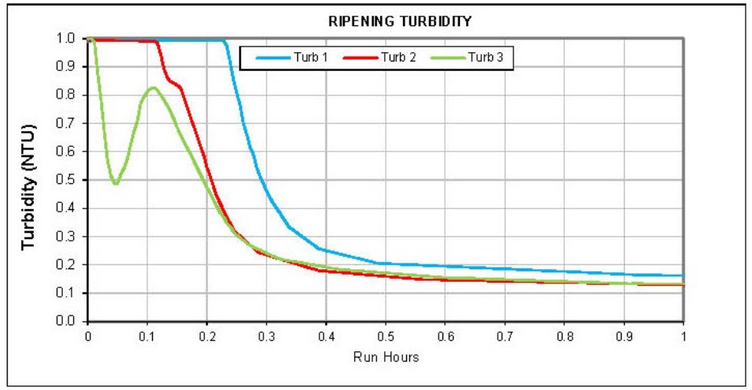
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.35	1.44	1.37
Column Influent	1.12	1.54	1.26
Filter Column 1 Effluent	0.03	0.10	0.04
Filter Column 2 Effluent	0.02	0.10	0.04
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		26.3	
Filter Column 2 Ripening Time (minutes)		28.3	
Filter Column 3 Ripening Time (minutes)		40.0	

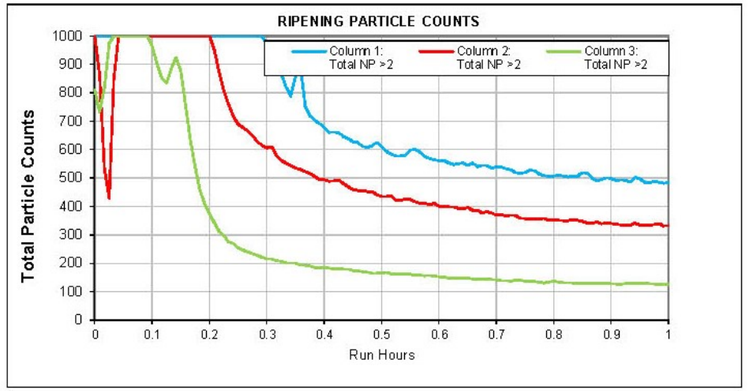
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1	12	3
Filter Column 2 Effluent	5	21	8
Filter Column 3 Effluent	1	7	3

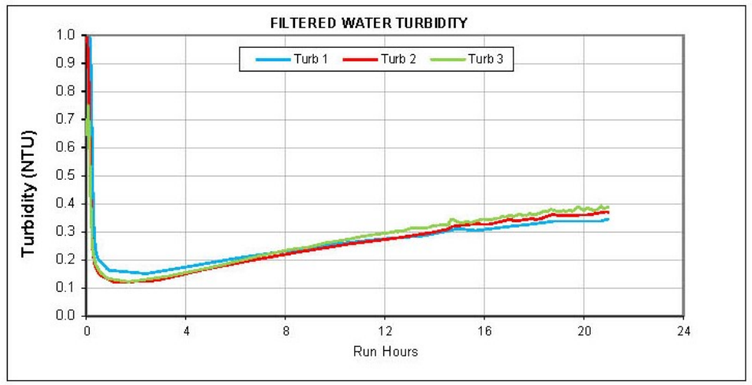
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.86	1.49	0.175
Filter Column 2	0.96	1.49	0.186
Filter Column 3	0.87	1.49	0.142

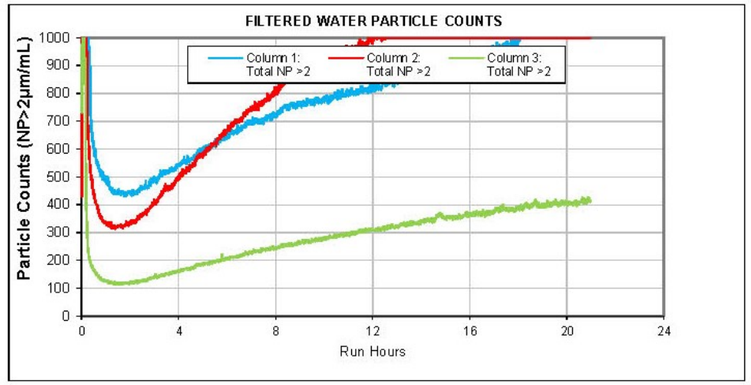
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.28	43
Filter Column 2	17	13.82	34
Filter Column 3	17	14.05	51

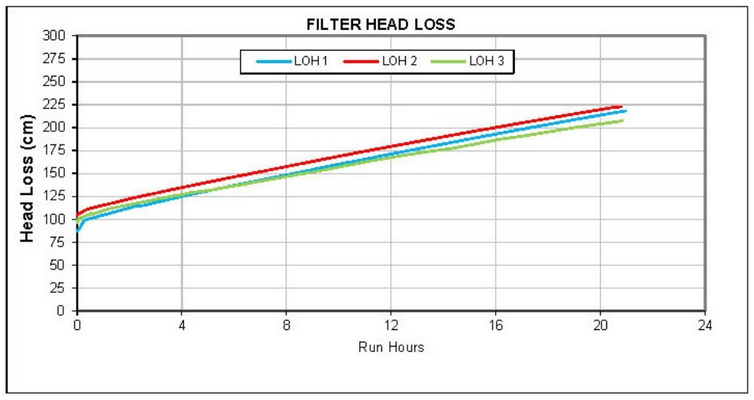
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

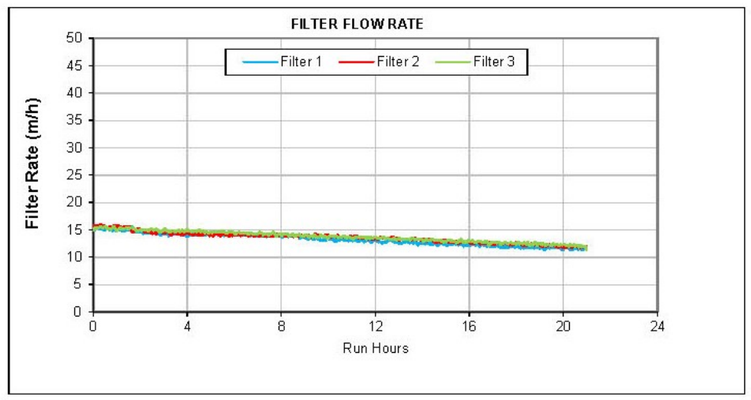












RUN SUMMARY

Run Started	09-Feb-16 12:01
Run Ended	10-Feb-16 9:00
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	6		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.00		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.98	0.98	0.98

ONLINE DATA SUMMARY

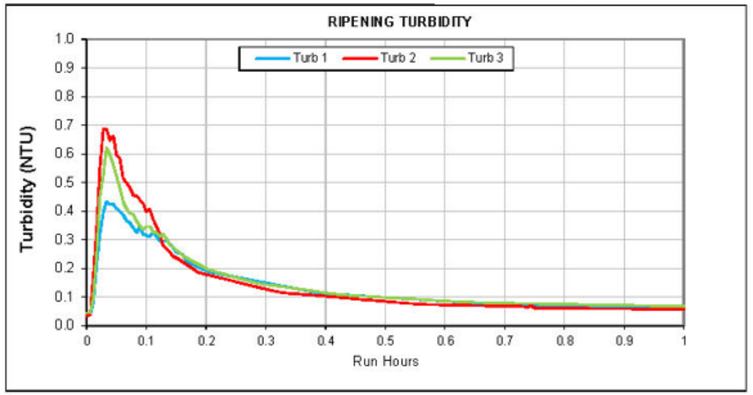
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.31	1.41	1.35
Column Influent	1.73	1.91	1.77
Filter Column 1 Effluent	0.15	0.99	0.26
Filter Column 2 Effluent	0.12	0.99	0.26
Filter Column 3 Effluent	0.12	1.00	0.27
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

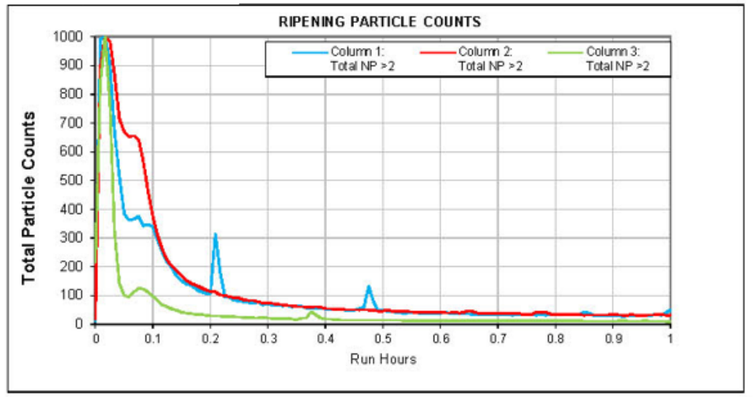
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1000	1000	1000
Filter Column 2 Effluent	1000	1000	1000
Filter Column 3 Effluent	415	415	415

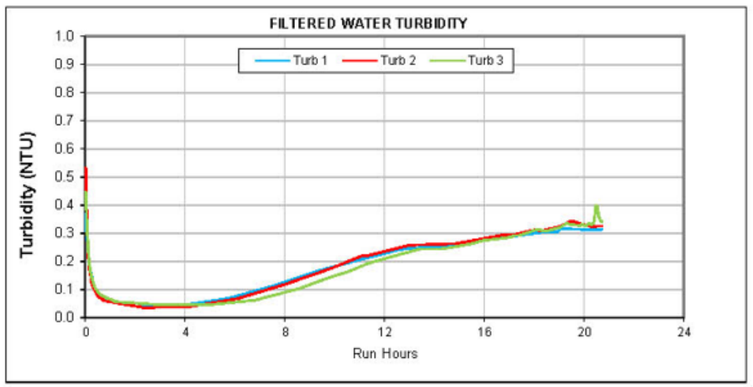
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.87	2.00	0.065
Filter Column 2	0.93	2.00	0.066
Filter Column 3	0.87	2.00	0.059

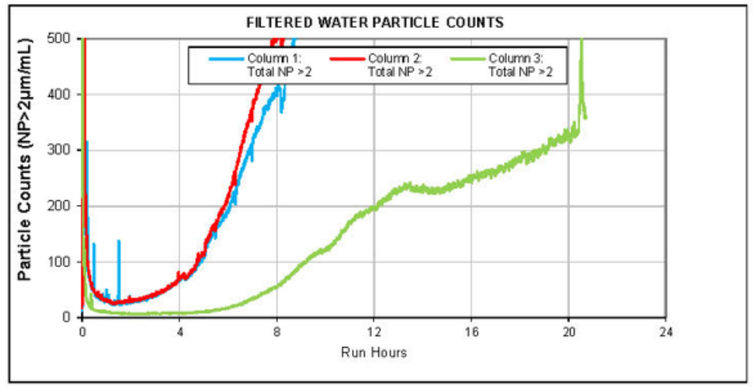
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.23	0
Filter Column 2	16	13.57	0
Filter Column 3	16	13.71	0

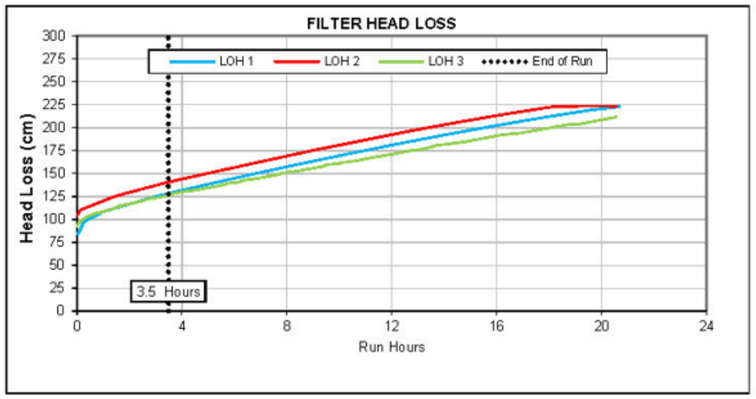
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

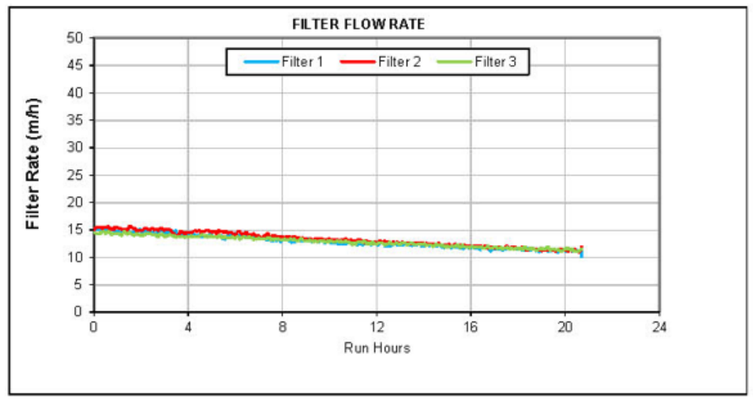












RUN SUMMARY

Run Started	17-Feb-16 14:17
Run Ended	18-Feb-16 11:00
Filter Column 1 Run Time (hrs)	2.99
Filter Column 2 Run Time (hrs)	3.06
Filter Column 3 Run Time (hrs)	7.32
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	6		mg/L
Polymer Type	Cationic		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.84	0.84	0.84

ONLINE DATA SUMMARY

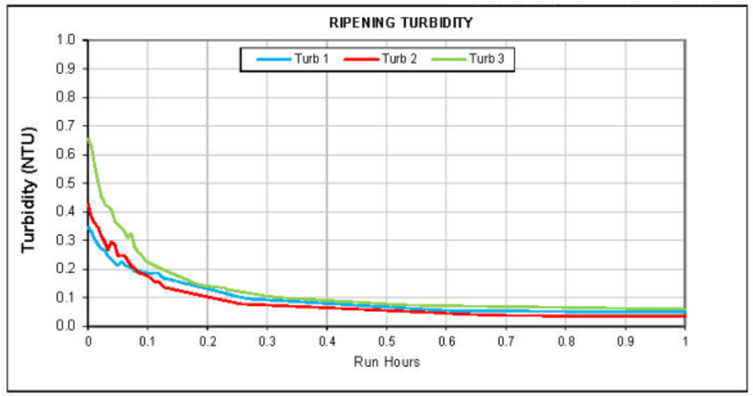
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.25	1.31	1.28
Column Influent	1.65	1.90	1.79
Filter Column 1 Effluent	0.04	0.10	0.06
Filter Column 2 Effluent	0.04	0.10	0.05
Filter Column 3 Effluent	0.05	0.10	0.06
Filter Column 1 Ripening Time (minutes)		29.3	
Filter Column 2 Ripening Time (minutes)		25.0	
Filter Column 3 Ripening Time (minutes)		29.3	

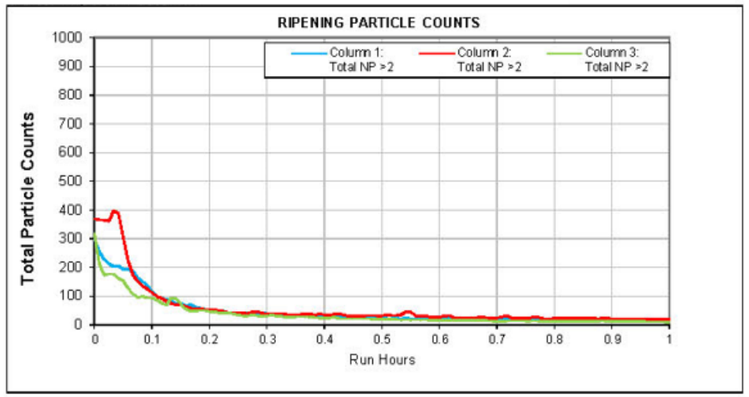
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	23	50	34
Filter Column 2 Effluent	25	50	35
Filter Column 3 Effluent	6	50	15

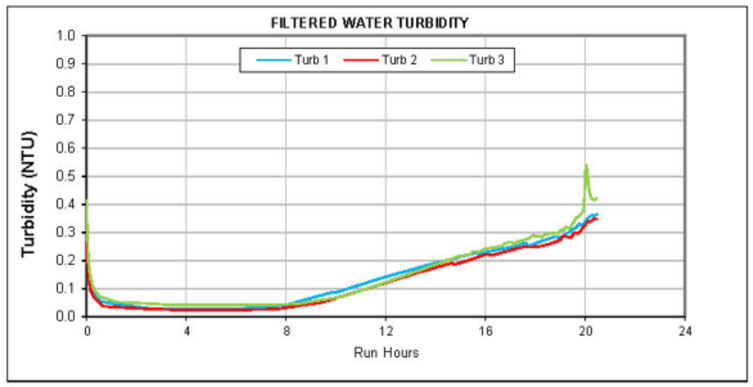
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.85	1.28	0.125
Filter Column 2	0.94	1.39	0.131
Filter Column 3	0.85	1.49	0.082

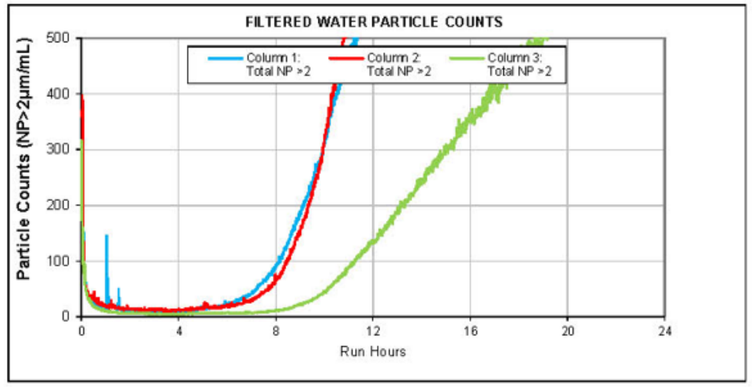
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.91	42
Filter Column 2	16	13.28	44
Filter Column 3	15	12.87	97

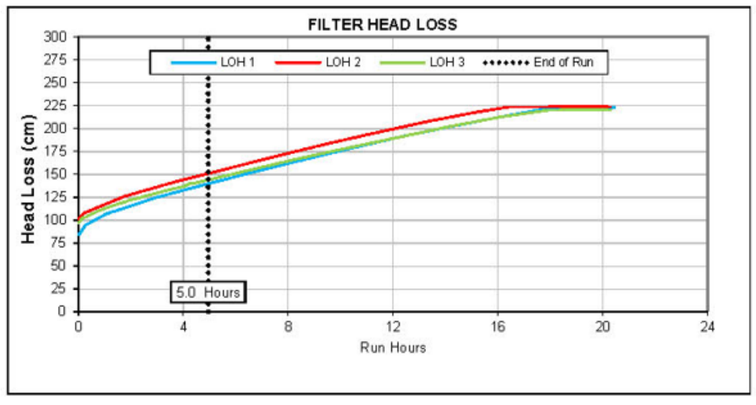
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 - 1.1
Anthracite Depth (inchs)	18	18	18

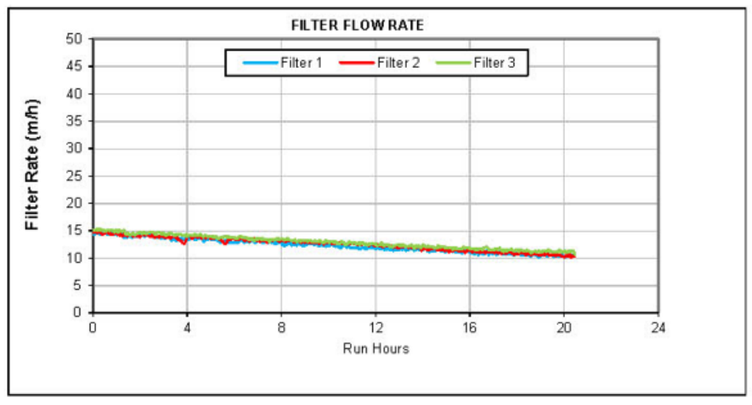












RUN SUMMARY

Run Started	11-Mar-16 14:32
Run Ended	12-Mar-16 11:00
Filter Column 1 Run Time (hrs)	6.06
Filter Column 2 Run Time (hrs)	4.74
Filter Column 3 Run Time (hrs)	5.63
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	6		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.048		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.25	1.25	1.25

ONLINE DATA SUMMARY

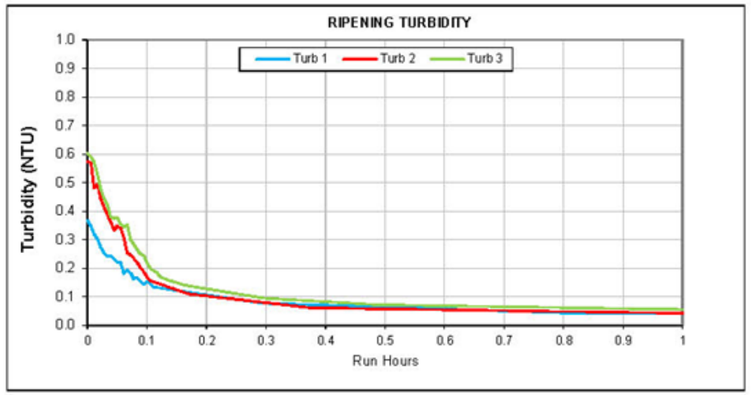
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.59	1.68	1.63
Column Influent	1.65	1.82	1.73
Filter Column 1 Effluent	0.03	0.10	0.04
Filter Column 2 Effluent	0.02	0.10	0.04
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		15.7	
Filter Column 2 Ripening Time (minutes)		12.3	
Filter Column 3 Ripening Time (minutes)		19.3	

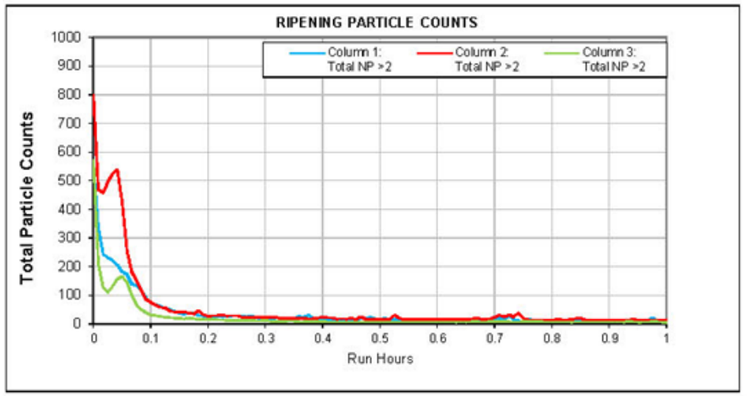
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	8	49	18
Filter Column 2 Effluent	10	48	19
Filter Column 3 Effluent	4	46	12

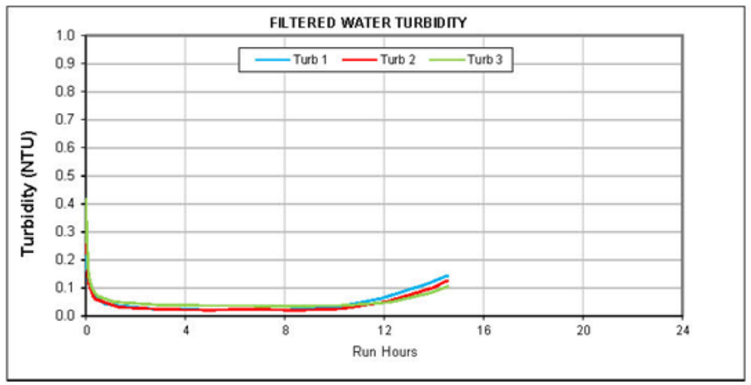
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.50	0.104
Filter Column 2	0.92	1.50	0.117
Filter Column 3	0.86	1.50	0.107

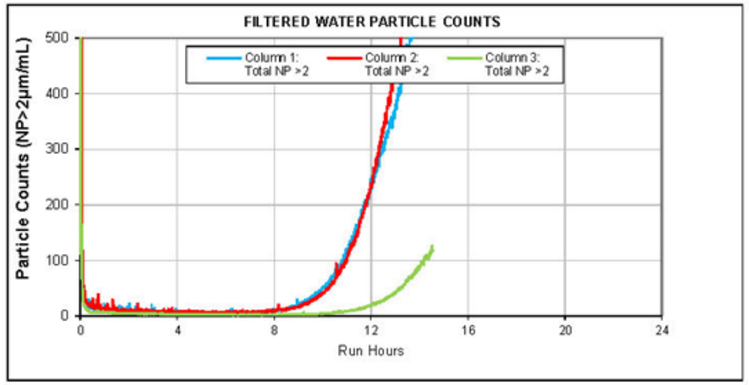
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.28	79
Filter Column 2	15	12.55	63
Filter Column 3	15	12.93	77

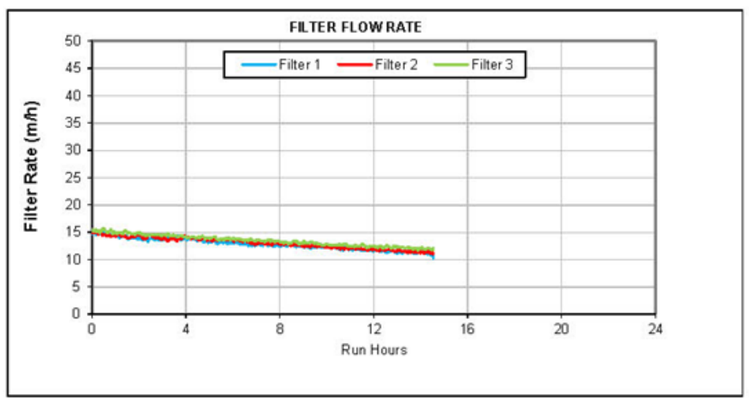
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	03-Mar-16 17:31
Run Ended	04-Mar-16 8:05
Filter Column 1 Run Time (hrs)	4.81
Filter Column 2 Run Time (hrs)	3.76
Filter Column 3 Run Time (hrs)	4.61
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	6		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.072		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.45	1.45	1.45

ONLINE DATA SUMMARY

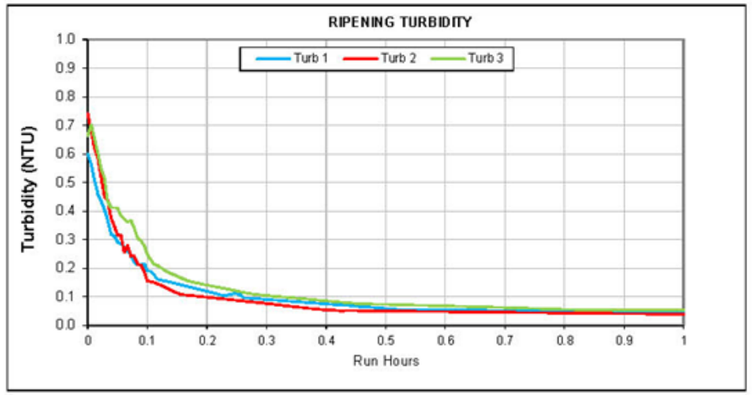
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.48	1.56	1.51
Column Influent	1.64	1.95	1.78
Filter Column 1 Effluent	0.02	0.10	0.04
Filter Column 2 Effluent	0.02	0.10	0.03
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		13.3	
Filter Column 2 Ripening Time (minutes)		12.7	
Filter Column 3 Ripening Time (minutes)		17.0	

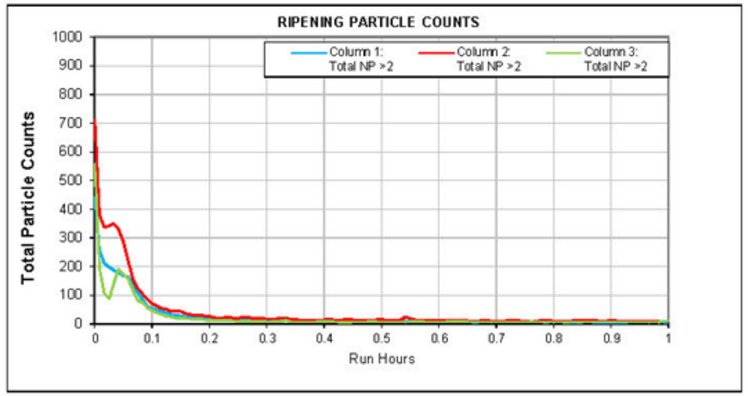
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	3	46	10
Filter Column 2 Effluent	6	47	12
Filter Column 3 Effluent	2	49	7

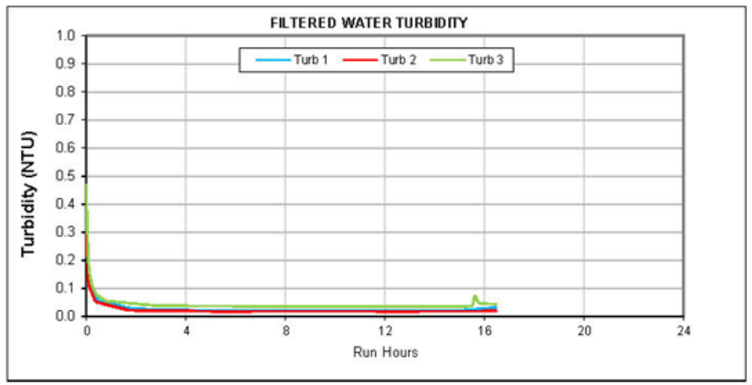
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.86	1.50	0.127
Filter Column 2	0.94	1.50	0.141
Filter Column 3	0.89	1.50	0.124

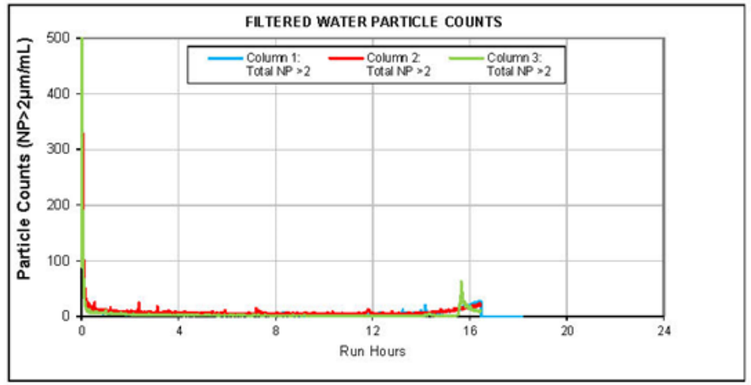
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	15	12.83	64
Filter Column 2	16	13.01	50
Filter Column 3	16	13.49	64

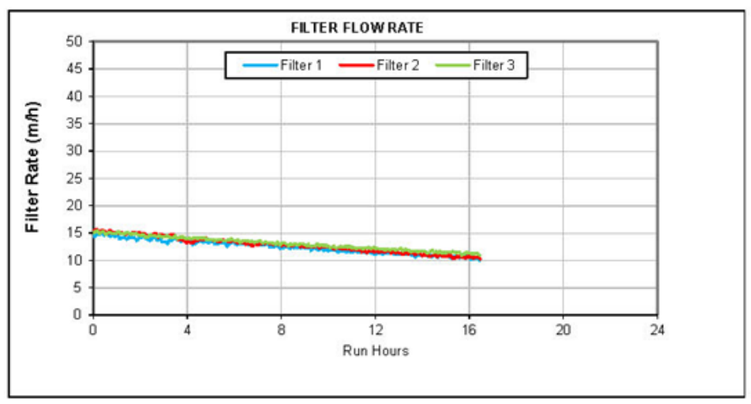
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	01-Mar-16 14:02
Run Ended	02-Mar-16 6:30
Filter Column 1 Run Time (hrs)	4.36
Filter Column 2 Run Time (hrs)	3.05
Filter Column 3 Run Time (hrs)	4.29
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	6		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.096		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.90	0.90	0.90

ONLINE DATA SUMMARY

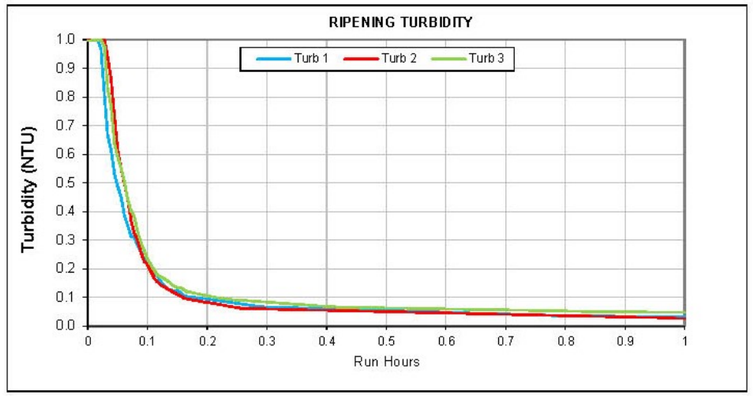
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.44	1.55	1.50
Column Influent	1.71	1.94	1.80
Filter Column 1 Effluent	0.02	0.10	0.02
Filter Column 2 Effluent	0.02	0.10	0.02
Filter Column 3 Effluent	0.03	0.10	0.04
Filter Column 1 Ripening Time (minutes)		15.7	
Filter Column 2 Ripening Time (minutes)		11.7	
Filter Column 3 Ripening Time (minutes)		19.7	

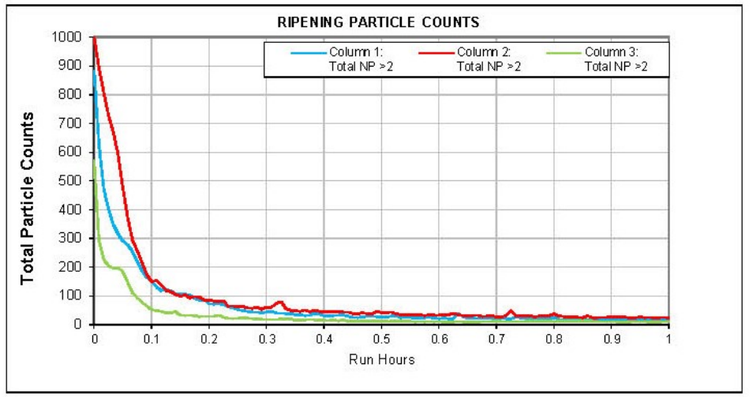
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1	25	4
Filter Column 2 Effluent	4	22	7
Filter Column 3 Effluent	1	25	3

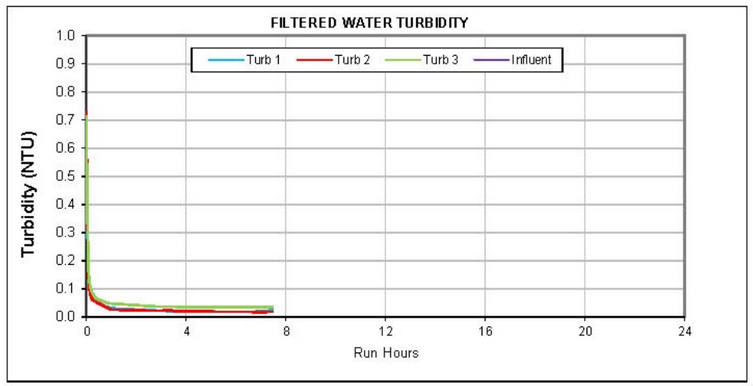
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.50	0.141
Filter Column 2	0.93	1.50	0.174
Filter Column 3	0.87	1.50	0.135

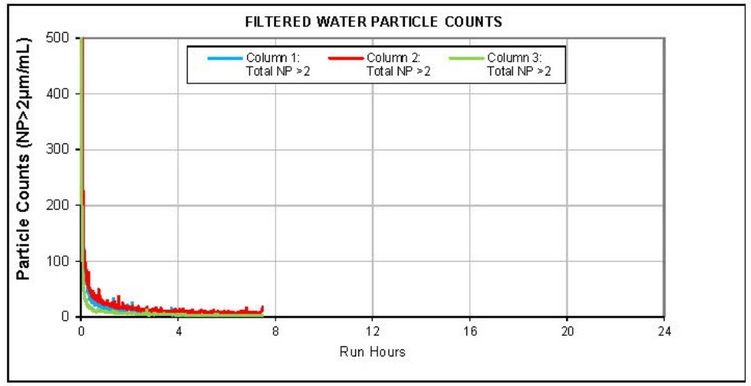
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.45	58
Filter Column 2	15	12.80	43
Filter Column 3	16	13.08	59

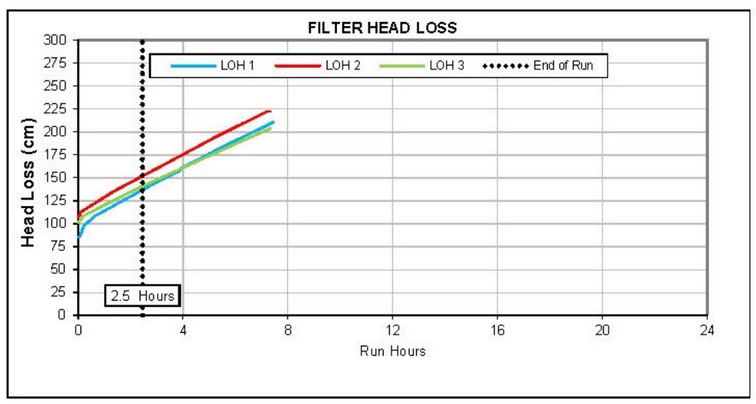
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

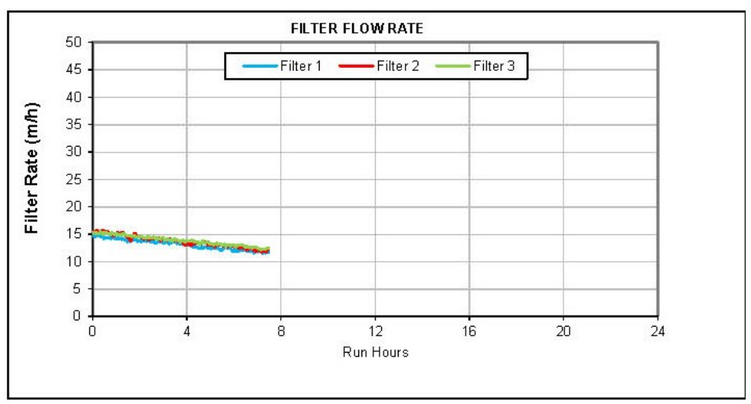












RUN SUMMARY

Run Started	03-Mar-16 9:04
Run Ended	03-Mar-16 16:33
Filter Column 1 Run Time (hrs)	3.13
Filter Column 2 Run Time (hrs)	2.29
Filter Column 3 Run Time (hrs)	3.05
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	6		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.22		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.45	1.45	1.45

ONLINE DATA SUMMARY

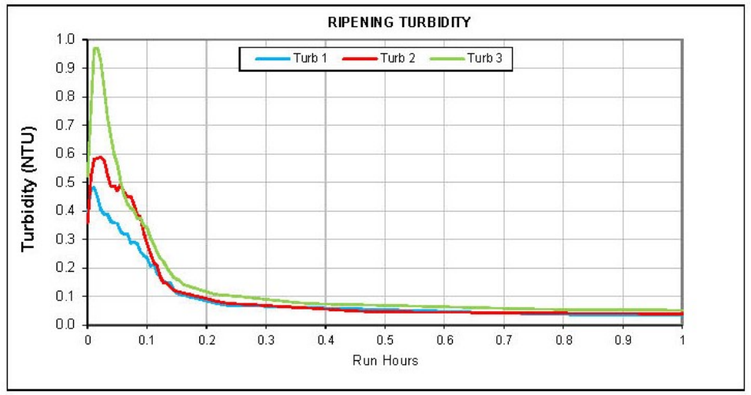
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.53	1.59	1.56
Column Influent	1.74	1.96	1.84
Filter Column 1 Effluent	0.02	0.10	0.03
Filter Column 2 Effluent	0.02	0.10	0.02
Filter Column 3 Effluent	0.03	0.10	0.04
Filter Column 1 Ripening Time (minutes)		11.0	
Filter Column 2 Ripening Time (minutes)		9.7	
Filter Column 3 Ripening Time (minutes)		13.0	

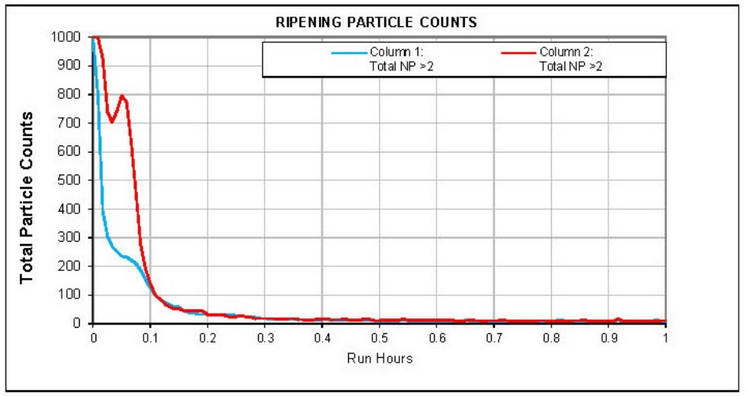
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	2	39	8
Filter Column 2 Effluent	6	43	13
Filter Column 3 Effluent	2	30	5

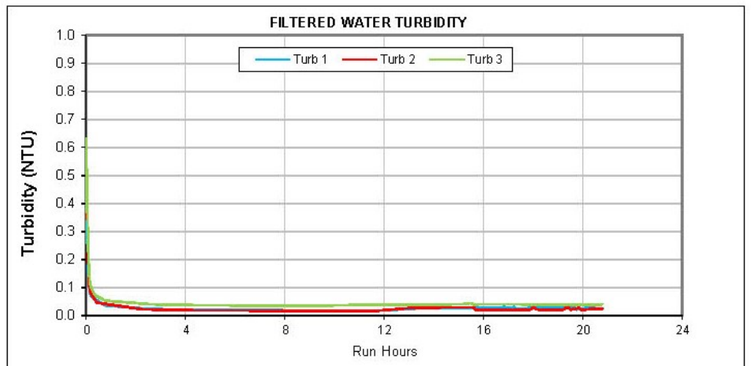
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.85	1.49	0.196
Filter Column 2	0.95	1.49	0.224
Filter Column 3	0.89	1.49	0.184

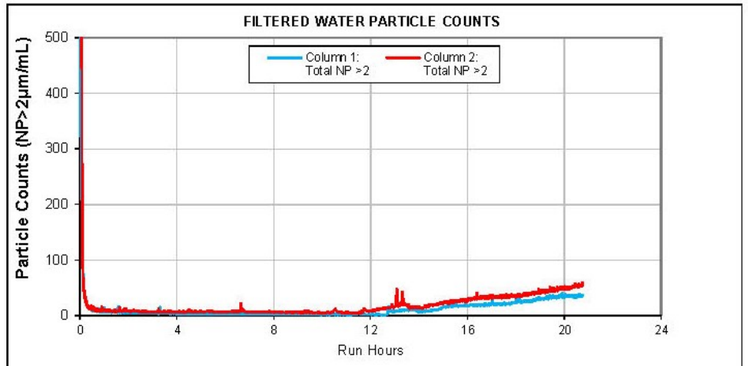
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.14	40
Filter Column 2	16	13.67	29
Filter Column 3	17	13.85	43

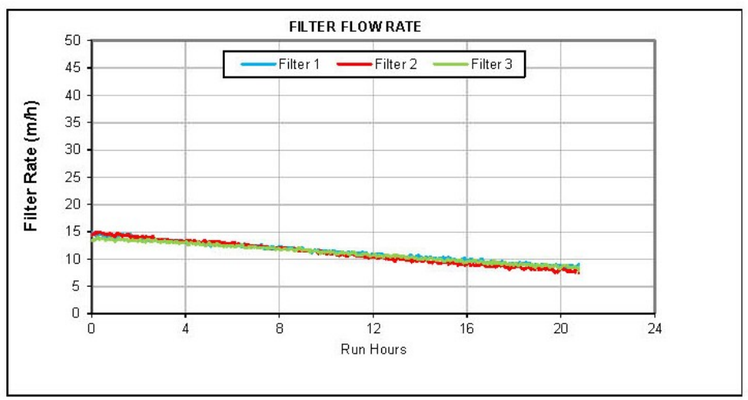
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	01-Feb-16 12:13
Run Ended	02-Feb-16 9:00
Filter Column 1 Run Time (hrs)	4.34
Filter Column 2 Run Time (hrs)	3.47
Filter Column 3 Run Time (hrs)	5.37
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	6		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.14		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.75	0.75	0.75

ONLINE DATA SUMMARY

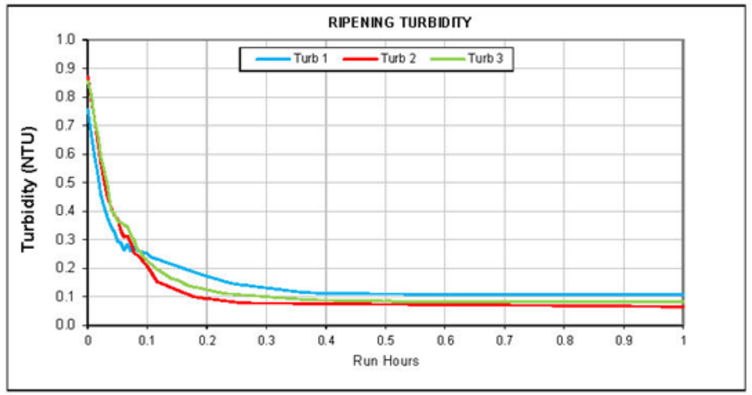
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.35	1.49	1.39
Column Influent	1.52	2.15	1.73
Filter Column 1 Effluent	0.02	0.10	0.02
Filter Column 2 Effluent	0.02	0.10	0.02
Filter Column 3 Effluent	0.04	0.10	0.04
Filter Column 1 Ripening Time (minutes)		10.3	
Filter Column 2 Ripening Time (minutes)		11.3	
Filter Column 3 Ripening Time (minutes)		15.3	

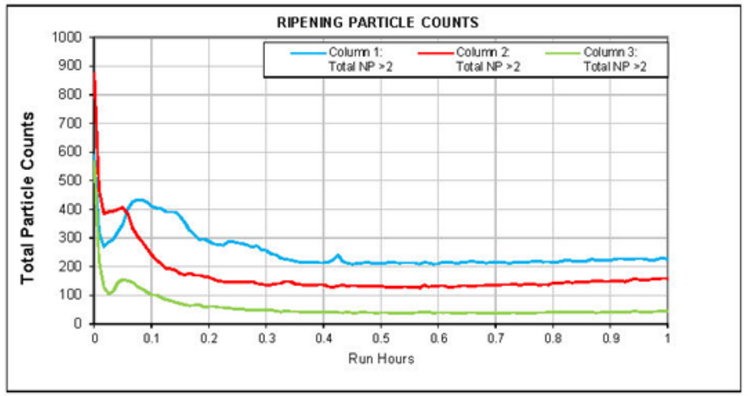
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1	36	10
Filter Column 2 Effluent	5	49	16
Filter Column 3 Effluent	Data Lost	Data Lost	Data Lost

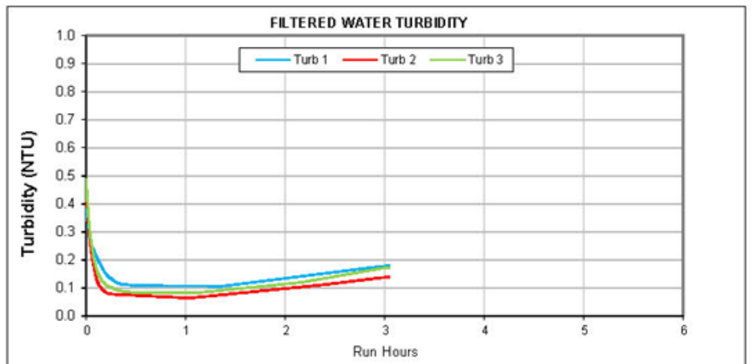
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.82	1.50	0.149
Filter Column 2	0.87	1.50	0.172
Filter Column 3	0.77	1.50	0.130

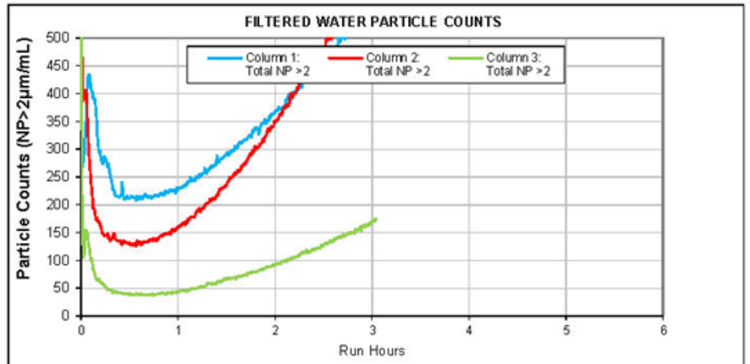
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	14	11.38	57
Filter Column 2	13	11.10	46
Filter Column 3	13	11.17	67

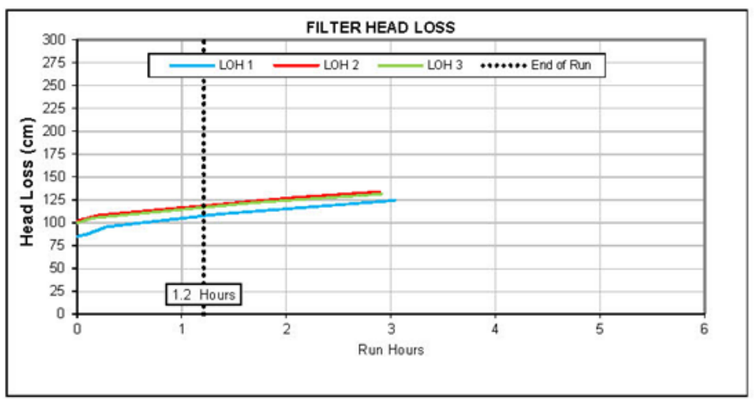
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

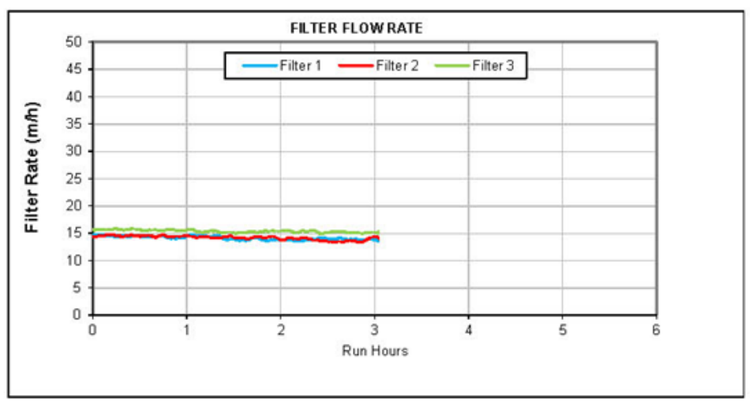












RUN SUMMARY

Run Started	10-Mar-16 13:57
Run Ended	10-Mar-16 17:00
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.91
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.80	0.80	0.80

ONLINE DATA SUMMARY

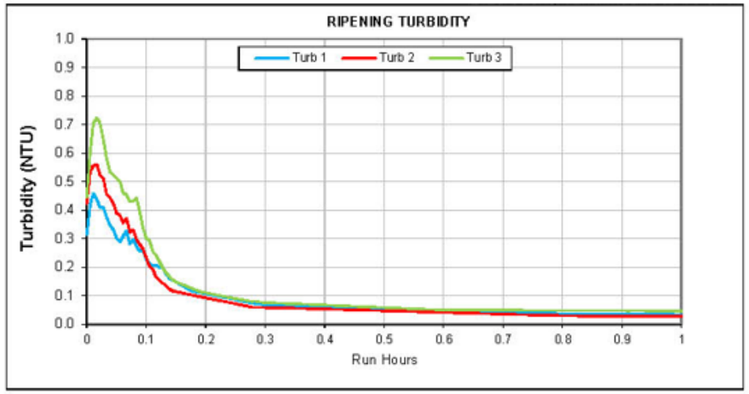
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.69	1.87	1.75
Column Influent	1.98	2.13	2.04
Filter Column 1 Effluent	0.11	0.18	0.12
Filter Column 2 Effluent	0.06	0.10	0.08
Filter Column 3 Effluent	0.08	0.10	0.09
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		18.0	

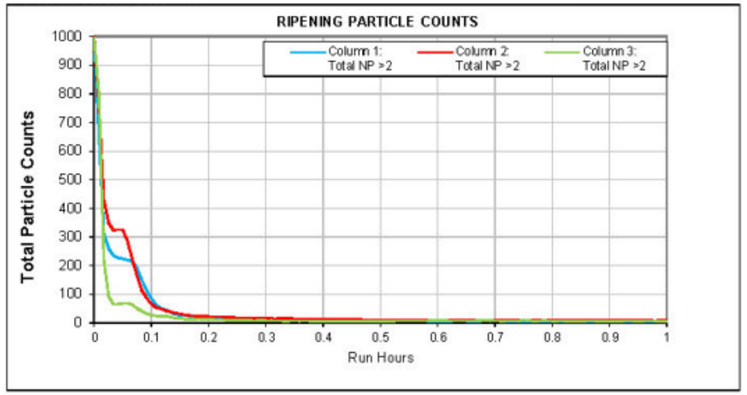
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	569	569	569
Filter Column 2 Effluent	662	662	662
Filter Column 3 Effluent	37	50	42

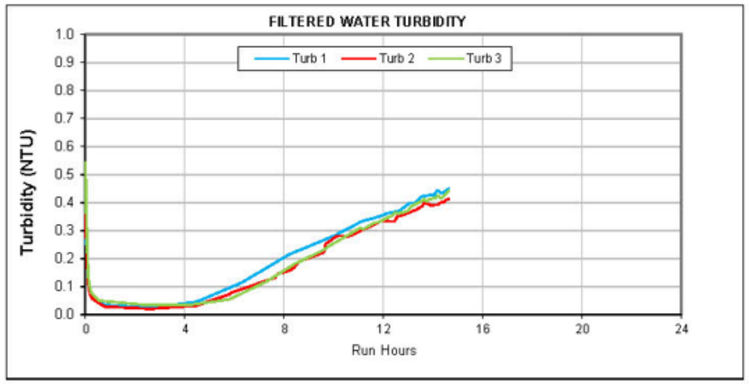
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.85	1.24	0.130
Filter Column 2	0.92	1.26	0.162
Filter Column 3	0.90	1.15	0.207

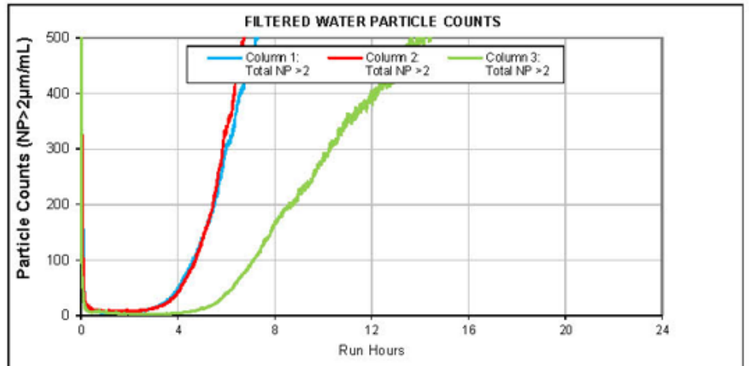
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	17	14.14	0
Filter Column 2	17	14.17	0
Filter Column 3	18	15.38	13

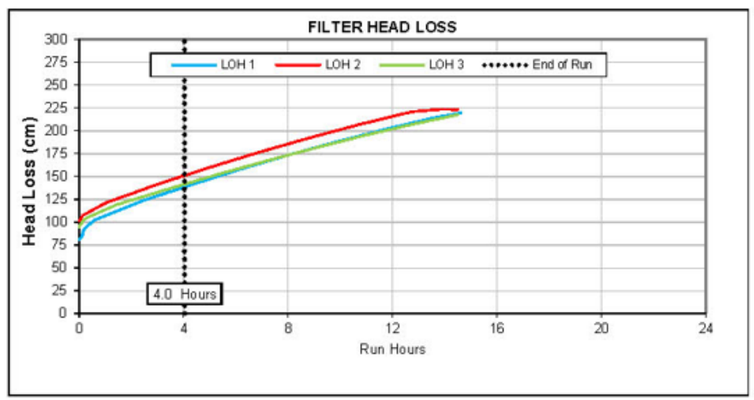
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

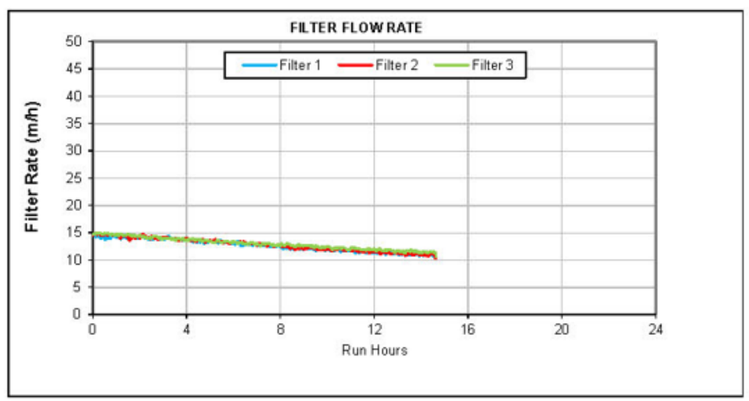












RUN SUMMARY

Run Started	07-Mar-16 17:21
Run Ended	08-Mar-16 8:00
Filter Column 1 Run Time (hrs)	3.82
Filter Column 2 Run Time (hrs)	3.87
Filter Column 3 Run Time (hrs)	4.91
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.048		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.21	1.21	1.21

ONLINE DATA SUMMARY

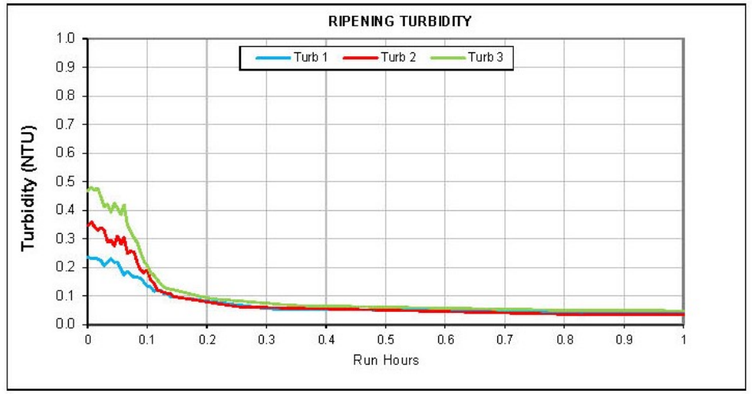
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	0.73	0.75	0.74
Column Influent	1.83	2.09	1.92
Filter Column 1 Effluent	0.02	0.10	0.05
Filter Column 2 Effluent	0.02	0.10	0.04
Filter Column 3 Effluent	0.03	0.10	0.05
Filter Column 1 Ripening Time (minutes)		13.0	
Filter Column 2 Ripening Time (minutes)		11.0	
Filter Column 3 Ripening Time (minutes)		13.7	

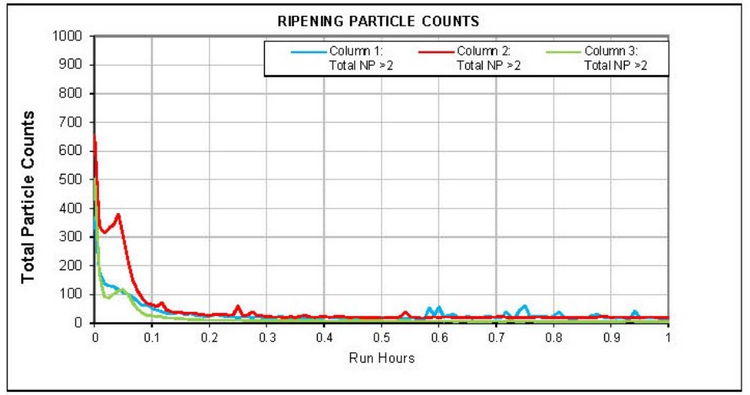
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	4	49	13
Filter Column 2 Effluent	7	47	15
Filter Column 3 Effluent	2	47	10

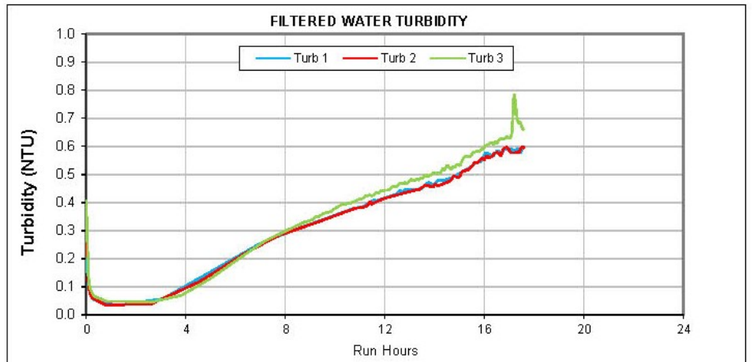
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.81	1.38	0.142
Filter Column 2	0.89	1.50	0.151
Filter Column 3	0.86	1.50	0.123

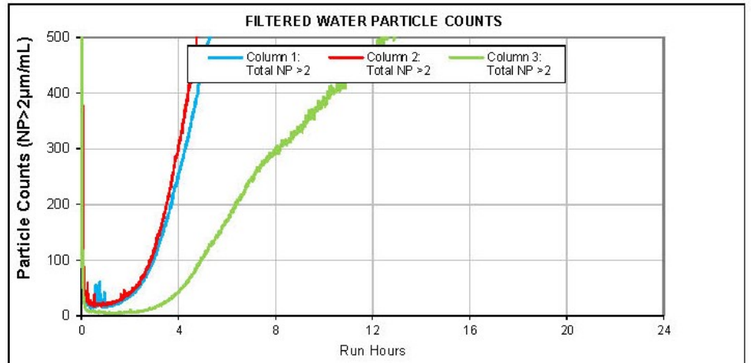
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	15	12.65	51
Filter Column 2	15	12.78	52
Filter Column 3	16	12.99	66

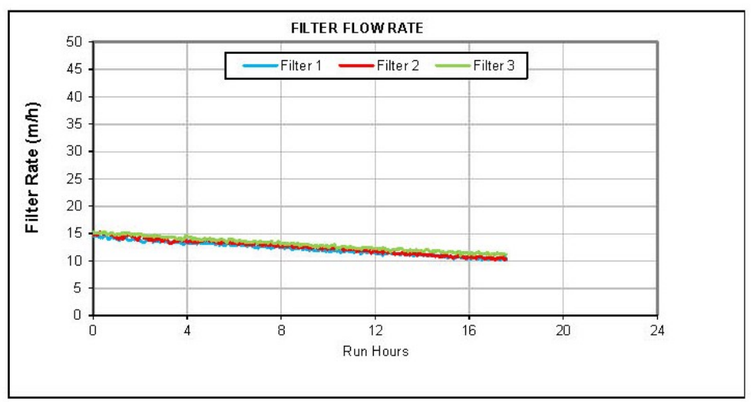
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	04-Mar-16 17:25
Run Ended	05-Mar-16 11:00
Filter Column 1 Run Time (hrs)	2.20
Filter Column 2 Run Time (hrs)	2.11
Filter Column 3 Run Time (hrs)	3.99
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.072		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.84	0.84	0.84

ONLINE DATA SUMMARY

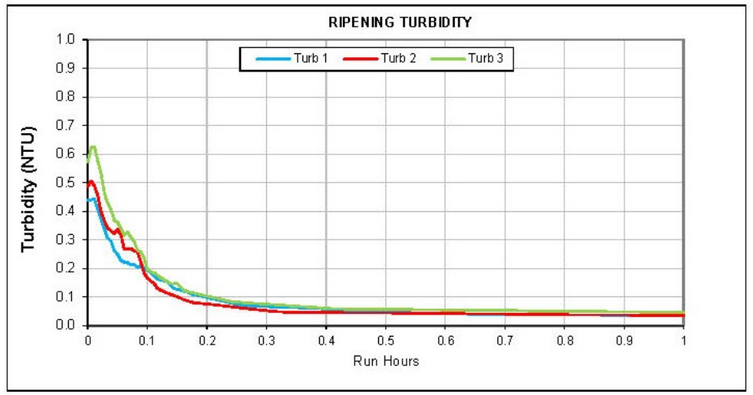
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.51	1.88	1.54
Column Influent	1.95	3.16	2.06
Filter Column 1 Effluent	0.03	0.10	0.05
Filter Column 2 Effluent	0.03	0.10	0.05
Filter Column 3 Effluent	0.05	0.10	0.06
Filter Column 1 Ripening Time (minutes)		8.3	
Filter Column 2 Ripening Time (minutes)		8.7	
Filter Column 3 Ripening Time (minutes)		11.3	

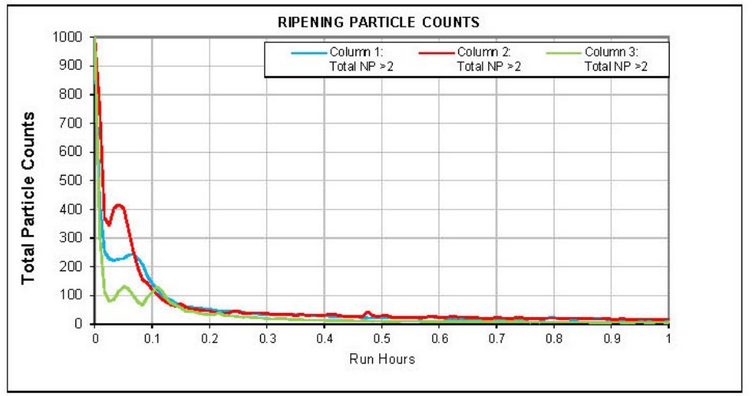
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	15	52	26
Filter Column 2 Effluent	18	51	28
Filter Column 3 Effluent	4	50	14

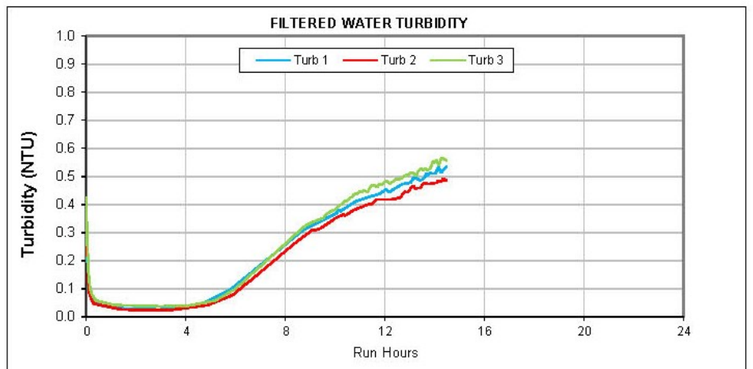
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.85	1.26	0.176
Filter Column 2	0.93	1.34	0.184
Filter Column 3	0.90	1.45	0.132

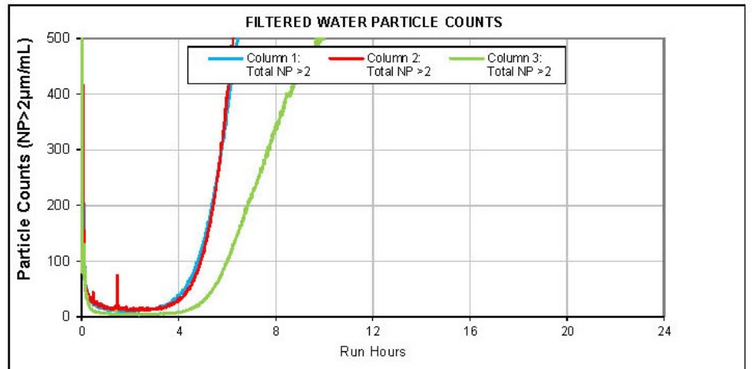
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	15	12.26	29
Filter Column 2	15	12.53	29
Filter Column 3	16	13.04	56

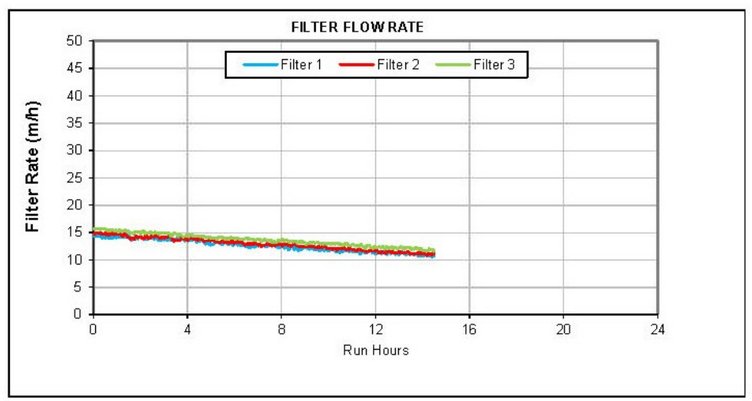
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	10-Mar-16 18:01
Run Ended	11-Mar-16 8:30
Filter Column 1 Run Time (hrs)	4.07
Filter Column 2 Run Time (hrs)	3.74
Filter Column 3 Run Time (hrs)	3.95
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.096		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.80	0.80	0.80

ONLINE DATA SUMMARY

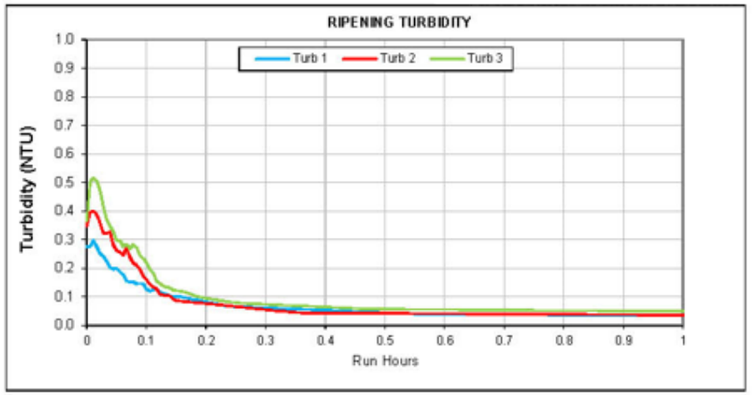
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.70	1.79	1.75
Column Influent	1.97	2.11	2.02
Filter Column 1 Effluent	0.03	0.10	0.04
Filter Column 2 Effluent	0.02	0.10	0.04
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		12.0	
Filter Column 2 Ripening Time (minutes)		9.3	
Filter Column 3 Ripening Time (minutes)		12.7	

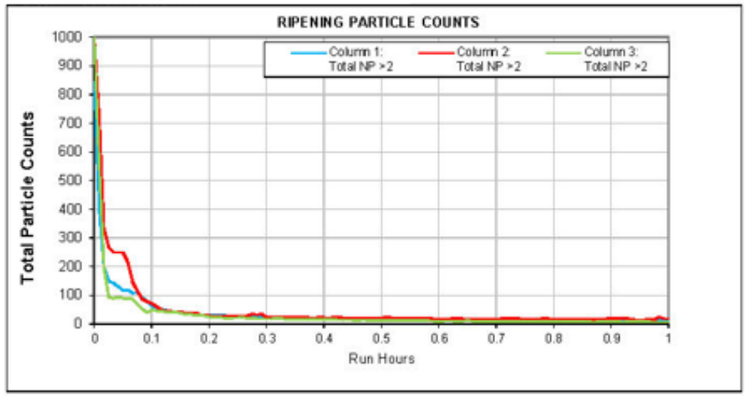
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	9	48	19
Filter Column 2 Effluent	12	51	20
Filter Column 3 Effluent	4	46	11

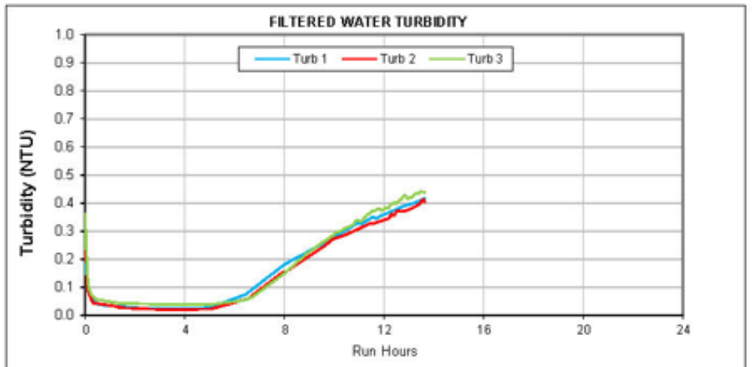
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.44	0.140
Filter Column 2	0.92	1.50	0.148
Filter Column 3	0.90	1.50	0.143

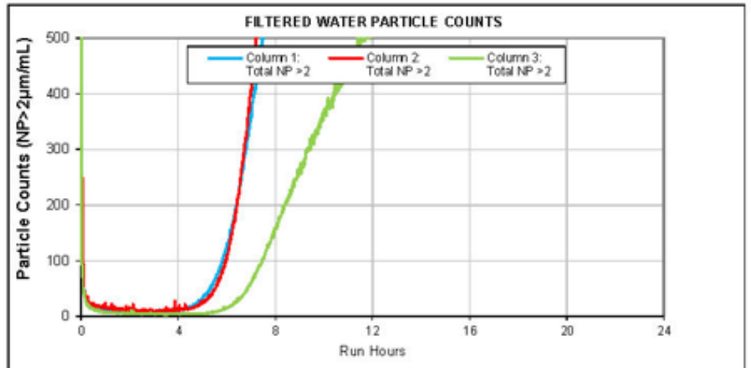
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.59	54
Filter Column 2	15	12.89	50
Filter Column 3	16	13.65	56

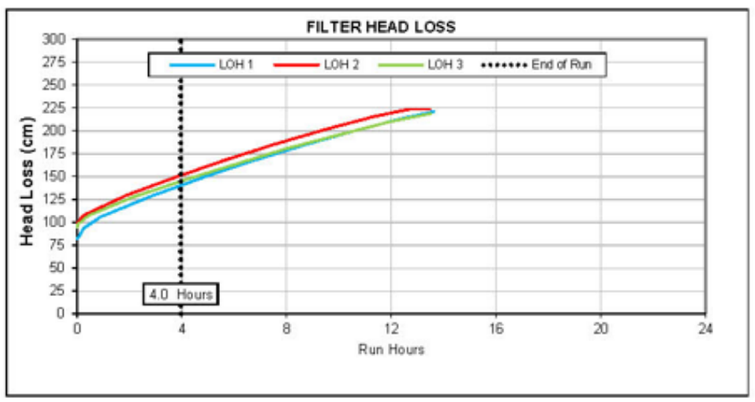
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

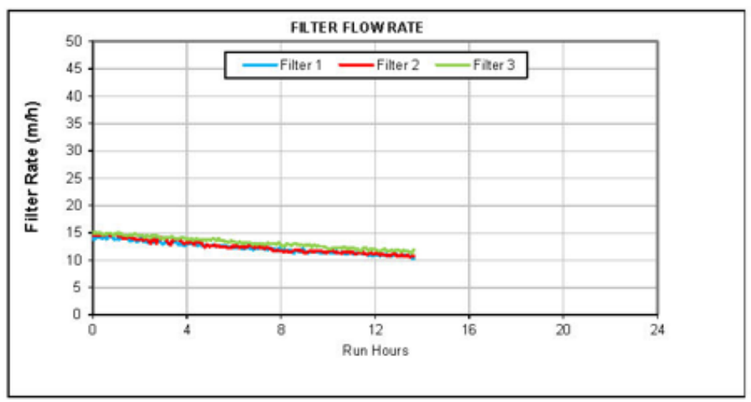












RUN SUMMARY

Run Started	14-Mar-16 18:21
Run Ended	15-Mar-16 8:00
Filter Column 1 Run Time (hrs)	4.72
Filter Column 2 Run Time (hrs)	3.81
Filter Column 3 Run Time (hrs)	4.44
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.11		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.86	0.86	0.86

ONLINE DATA SUMMARY

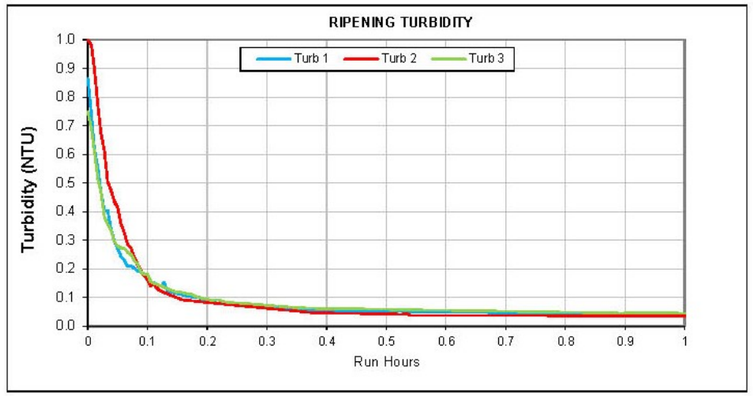
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.58	1.65	1.62
Column Influent	1.78	2.18	1.85
Filter Column 1 Effluent	0.02	0.10	0.04
Filter Column 2 Effluent	0.02	0.10	0.03
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		9.7	
Filter Column 2 Ripening Time (minutes)		8.7	
Filter Column 3 Ripening Time (minutes)		11.3	

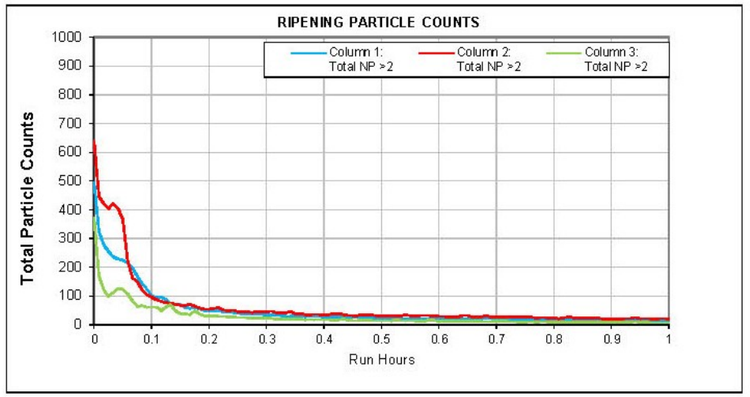
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	7	47	14
Filter Column 2 Effluent	8	48	16
Filter Column 3 Effluent	3	46	10

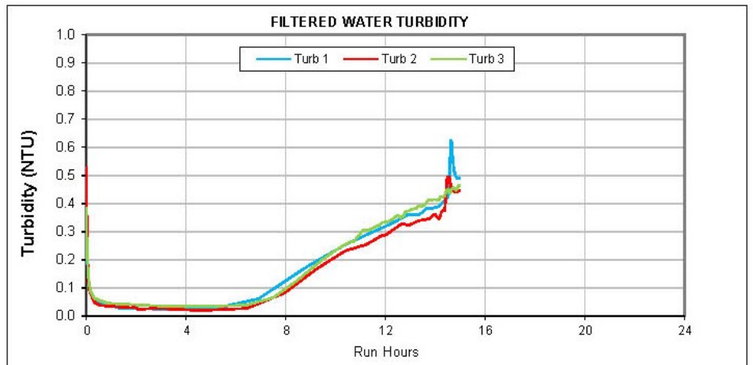
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.82	1.50	0.138
Filter Column 2	0.90	1.50	0.151
Filter Column 3	0.87	1.50	0.135

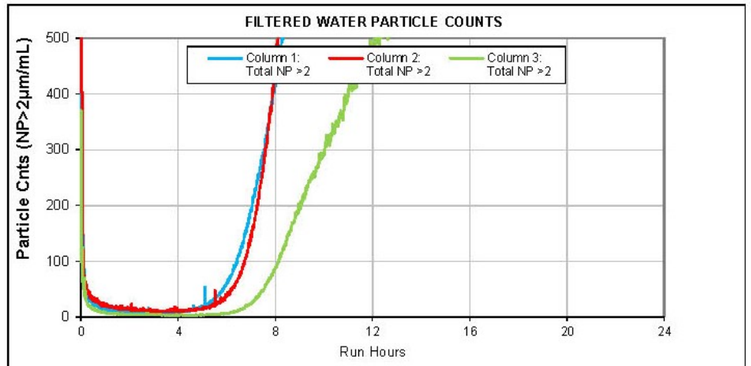
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.29	60
Filter Column 2	15	12.45	51
Filter Column 3	16	13.22	61

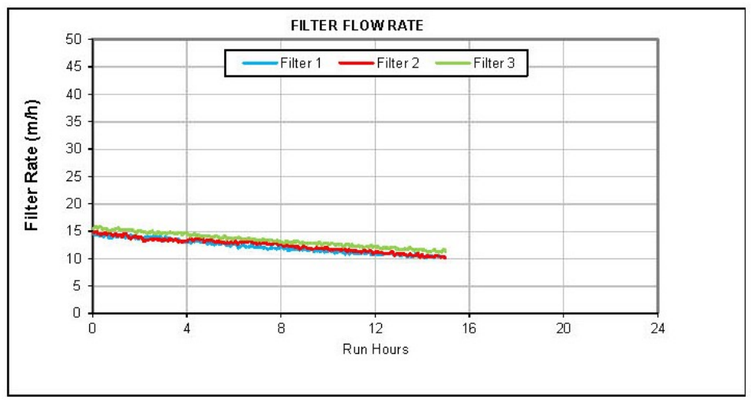
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	09-Mar-16 17:01
Run Ended	10-Mar-16 8:00
Filter Column 1 Run Time (hrs)	4.20
Filter Column 2 Run Time (hrs)	3.35
Filter Column 3 Run Time (hrs)	3.74
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.12		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.02	1.02	1.02

ONLINE DATA SUMMARY

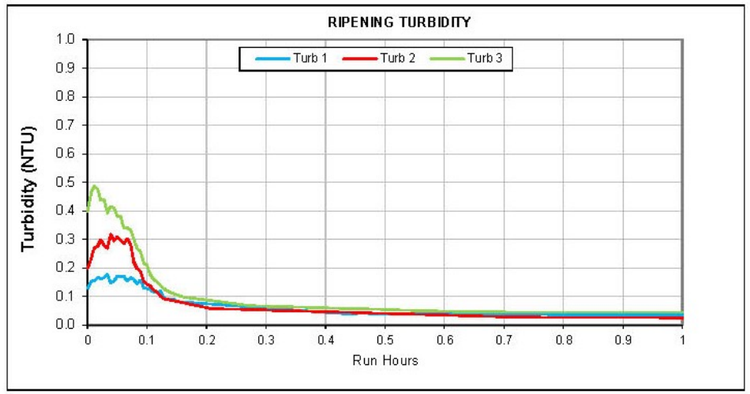
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.65	1.73	1.68
Column Influent	2.01	2.41	2.07
Filter Column 1 Effluent	0.02	0.10	0.04
Filter Column 2 Effluent	0.02	0.10	0.04
Filter Column 3 Effluent	0.03	0.10	0.04
Filter Column 1 Ripening Time (minutes)		11.3	
Filter Column 2 Ripening Time (minutes)		9.0	
Filter Column 3 Ripening Time (minutes)		11.3	

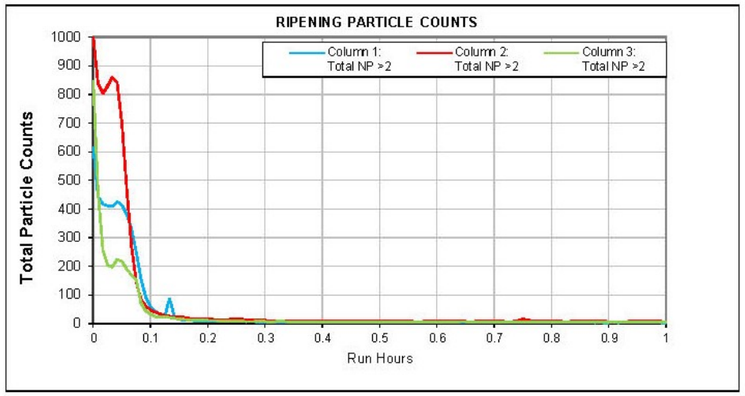
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	7	49	16
Filter Column 2 Effluent	10	47	18
Filter Column 3 Effluent	3	47	9

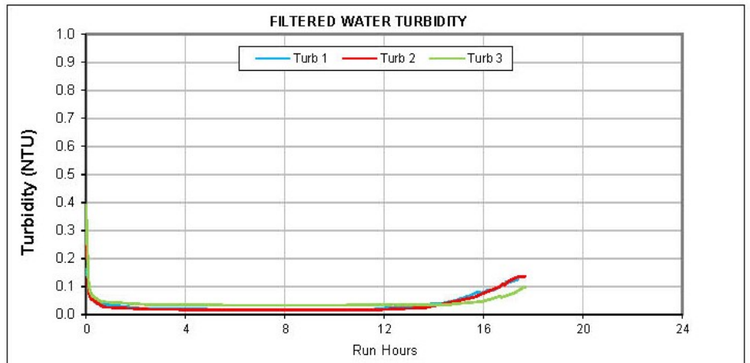
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.50	0.149
Filter Column 2	0.94	1.50	0.160
Filter Column 3	0.91	1.50	0.150

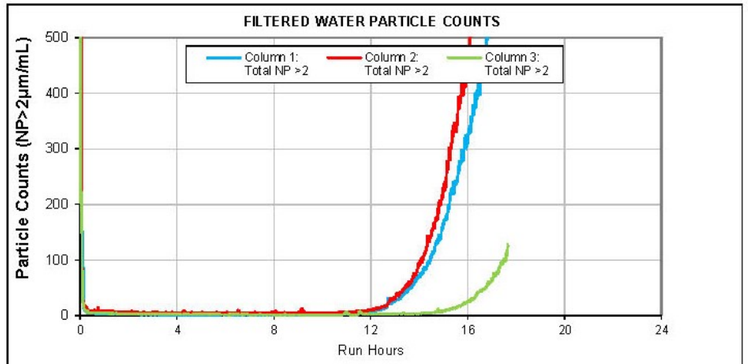
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.19	55
Filter Column 2	15	12.47	43
Filter Column 3	16	13.40	53

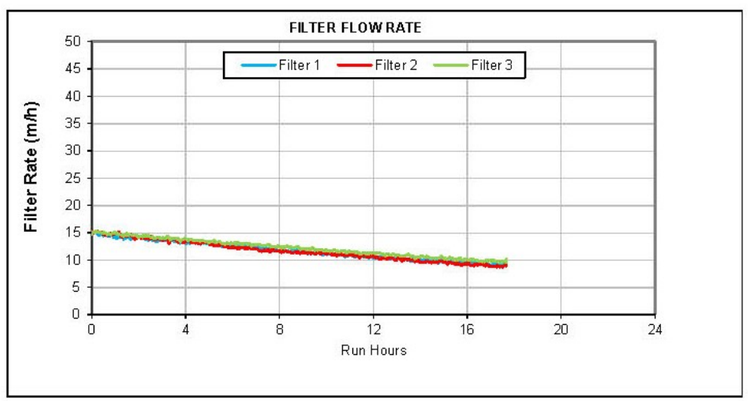
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	26-Feb-16 17:49
Run Ended	27-Feb-16 11:30
Filter Column 1 Run Time (hrs)	3.69
Filter Column 2 Run Time (hrs)	2.54
Filter Column 3 Run Time (hrs)	3.67
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.14		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.75	0.75	0.75

ONLINE DATA SUMMARY

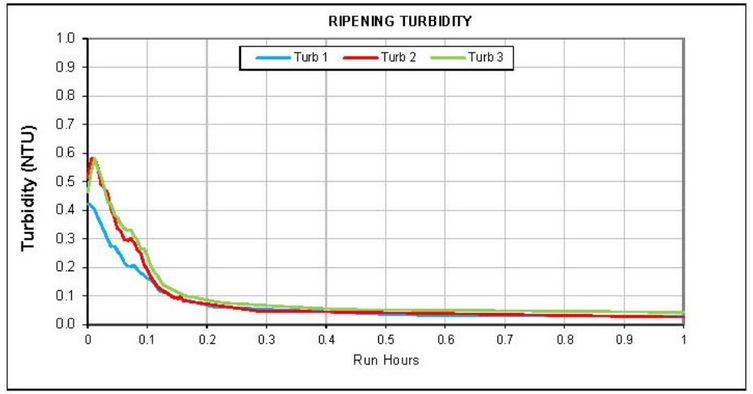
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.35	1.43	1.38
Column Influent	1.62	2.49	1.87
Filter Column 1 Effluent	0.02	0.10	0.03
Filter Column 2 Effluent	0.02	0.10	0.03
Filter Column 3 Effluent	0.03	0.10	0.04
Filter Column 1 Ripening Time (minutes)		7.7	
Filter Column 2 Ripening Time (minutes)		7.7	
Filter Column 3 Ripening Time (minutes)		9.7	

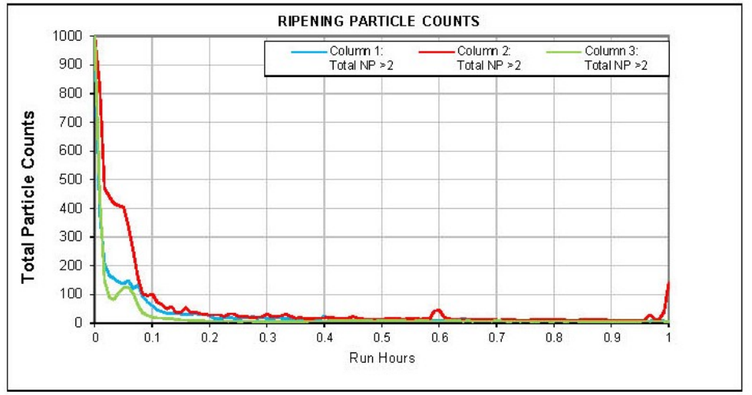
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1	47	5
Filter Column 2 Effluent	4	46	8
Filter Column 3 Effluent	1	46	5

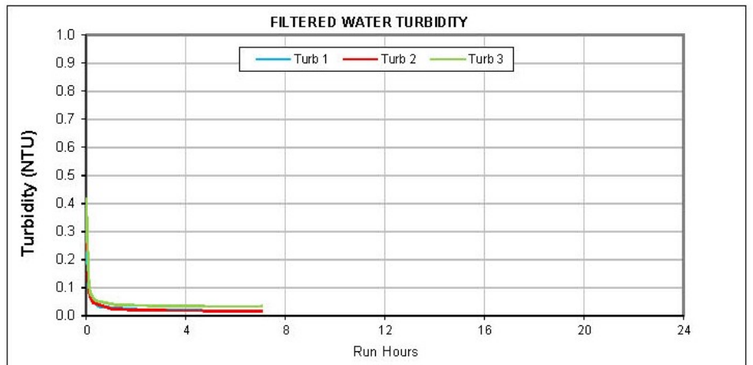
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.85	1.50	0.168
Filter Column 2	0.96	1.49	0.202
Filter Column 3	0.87	1.50	0.164

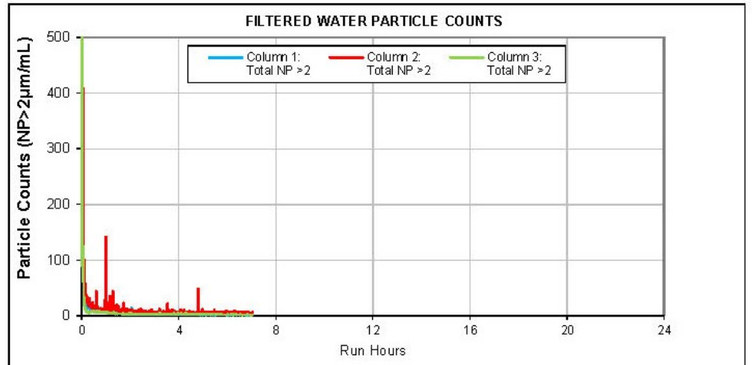
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	14	11.69	49
Filter Column 2	14	11.64	35
Filter Column 3	15	12.24	50

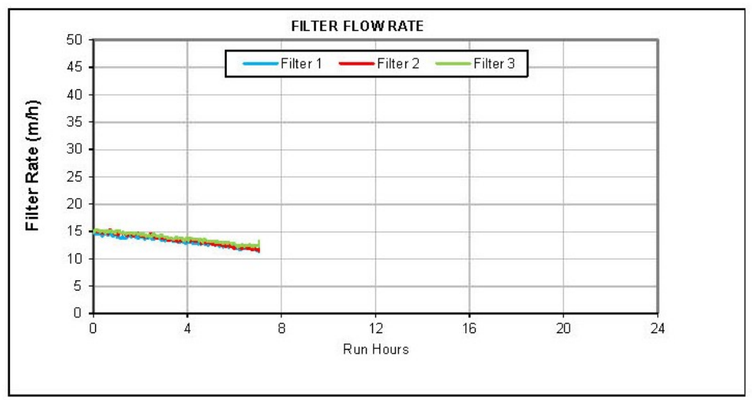
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	04-Mar-16 9:04
Run Ended	04-Mar-16 16:08
Filter Column 1 Run Time (hrs)	3.10
Filter Column 2 Run Time (hrs)	2.39
Filter Column 3 Run Time (hrs)	3.03
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	9		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.22		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.84	0.84	0.84

ONLINE DATA SUMMARY

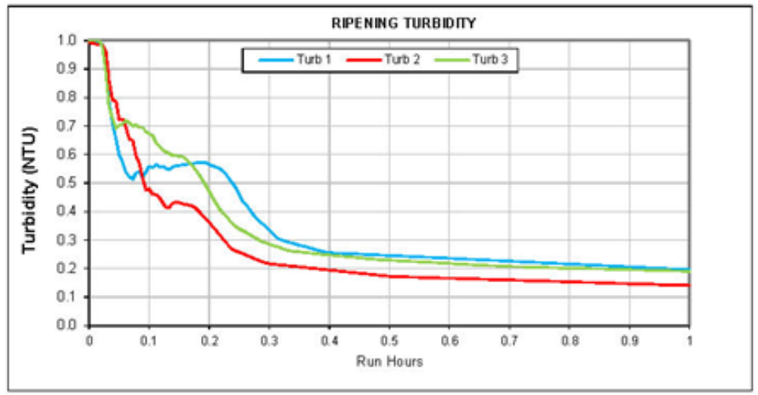
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.52	1.68	1.56
Column Influent	1.89	3.15	2.00
Filter Column 1 Effluent	0.02	0.10	0.02
Filter Column 2 Effluent	0.02	0.10	0.02
Filter Column 3 Effluent	0.03	0.10	0.04
Filter Column 1 Ripening Time (minutes)		8.3	
Filter Column 2 Ripening Time (minutes)		8.7	
Filter Column 3 Ripening Time (minutes)		10.0	

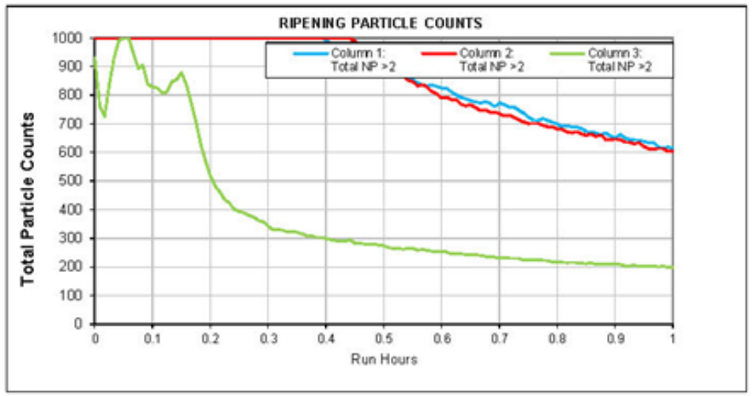
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1	30	4
Filter Column 2 Effluent	4	35	8
Filter Column 3 Effluent	1	10	3

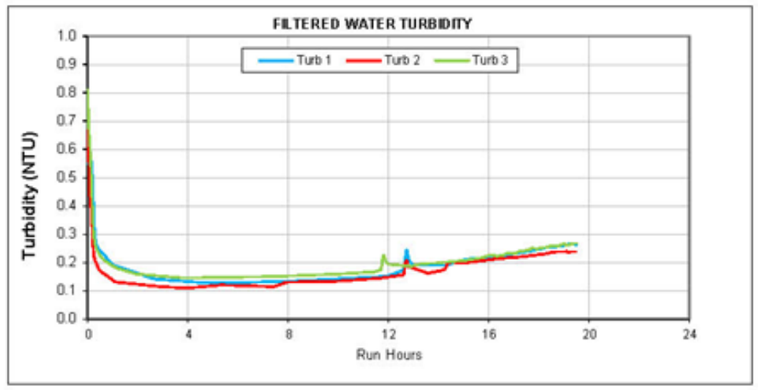
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.49	0.202
Filter Column 2	0.93	1.49	0.222
Filter Column 3	0.89	1.49	0.189

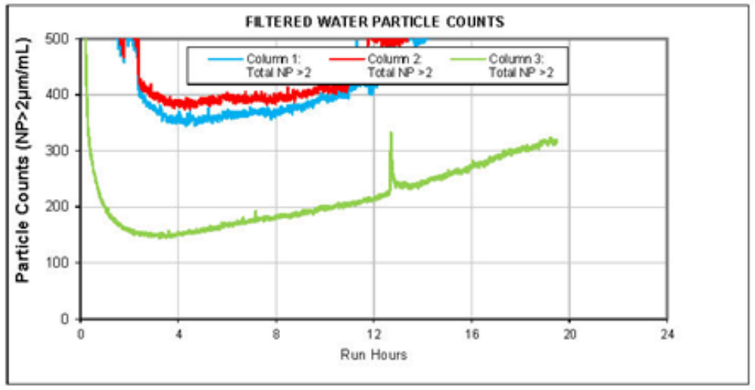
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.25	41
Filter Column 2	16	13.51	33
Filter Column 3	16	13.81	42

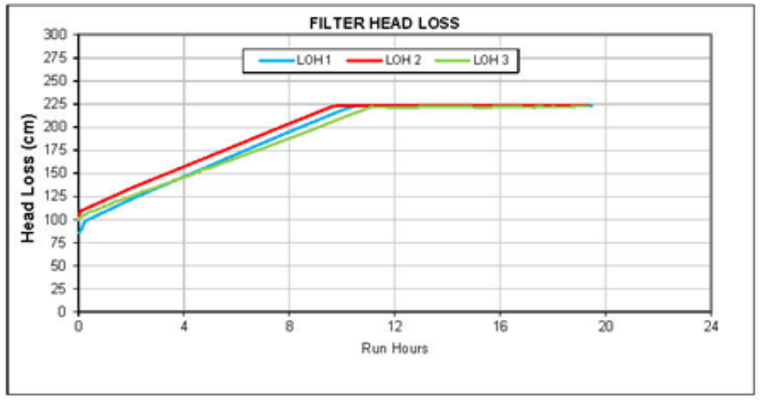
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

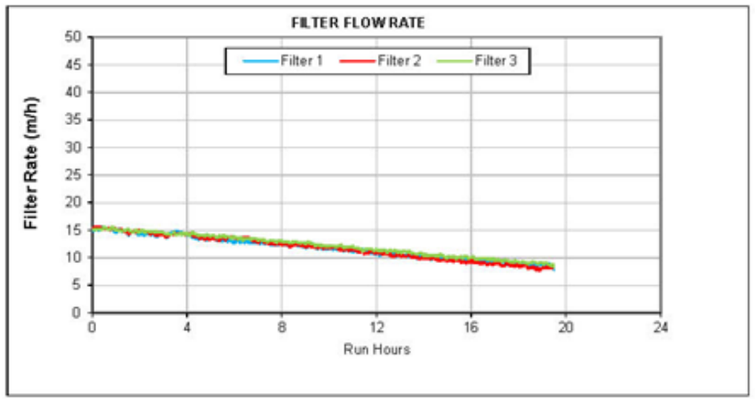












RUN SUMMARY

Run Started	08-Feb-16 12:40
Run Ended	09-Feb-16 8:10
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.00		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.00	1.00	1.00

ONLINE DATA SUMMARY

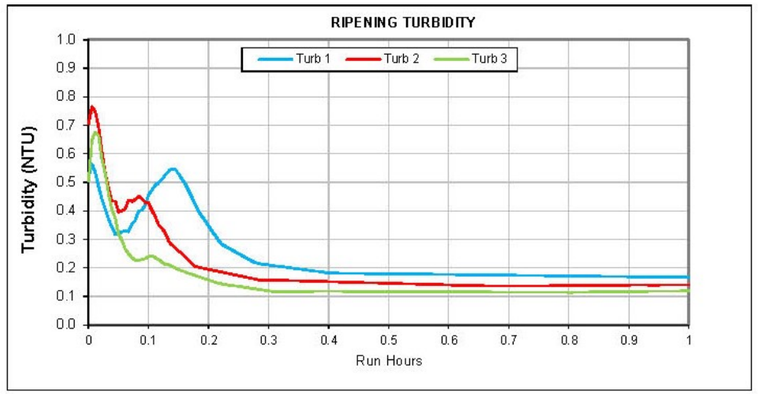
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.30	1.40	1.34
Column Influent	2.44	2.59	2.49
Filter Column 1 Effluent	0.13	0.99	0.18
Filter Column 2 Effluent	0.11	0.99	0.16
Filter Column 3 Effluent	0.14	1.00	0.19
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

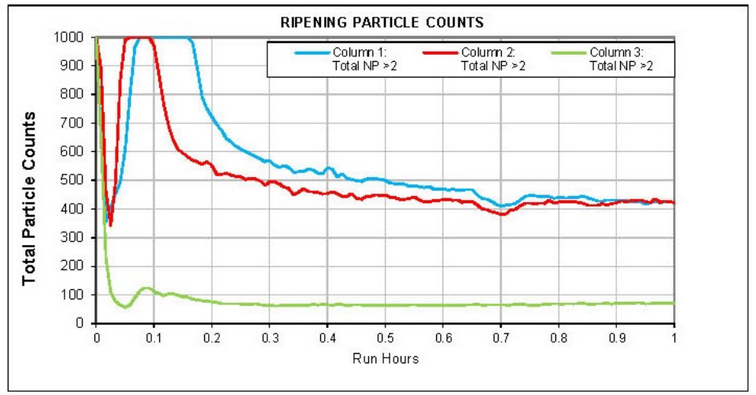
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	727	727	727
Filter Column 2 Effluent	786	786	786
Filter Column 3 Effluent	317	317	317

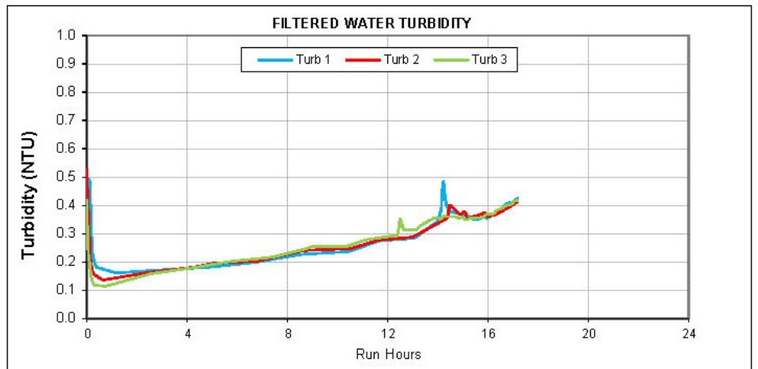
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.85	1.50	0.151
Filter Column 2	0.92	1.50	0.164
Filter Column 3	0.87	1.50	0.138

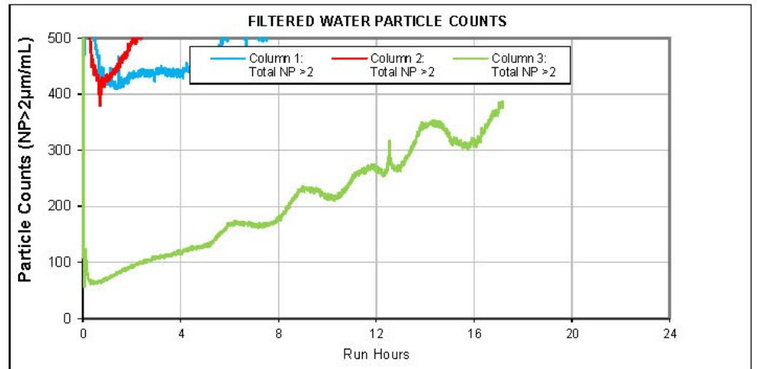
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	14	11.76	0
Filter Column 2	14	11.74	0
Filter Column 3	15	12.18	0

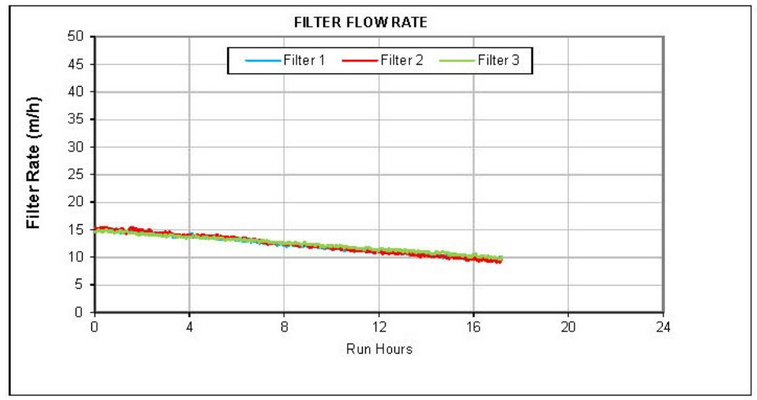
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	18-Feb-16 16:24
Run Ended	19-Feb-16 9:35
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.00	1.00	1.00

ONLINE DATA SUMMARY

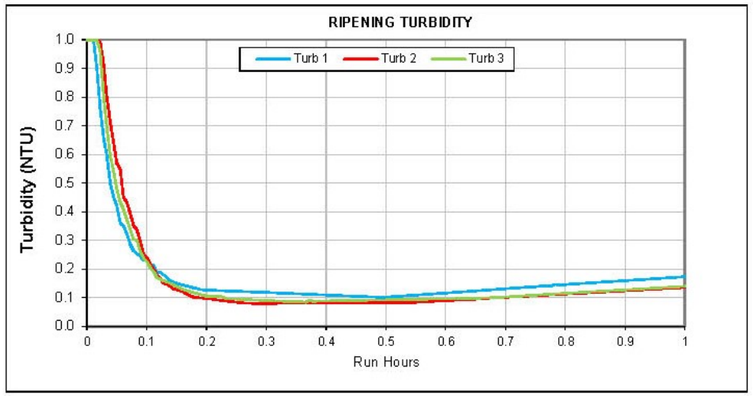
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.25	1.31	1.28
Column Influent	2.40	2.67	2.50
Filter Column 1 Effluent	0.16	0.56	0.25
Filter Column 2 Effluent	0.14	0.77	0.25
Filter Column 3 Effluent	0.11	0.68	0.25
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

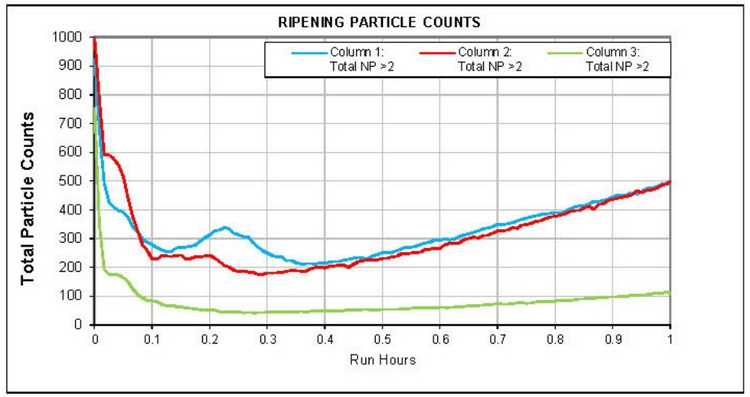
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1000	1000	1000
Filter Column 2 Effluent	1000	1000	1000
Filter Column 3 Effluent	375	375	375

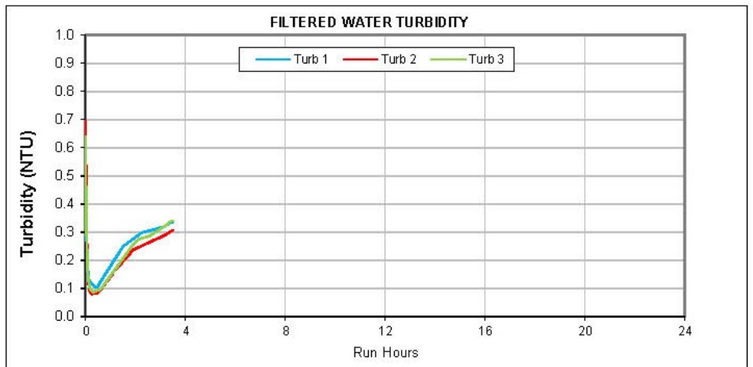
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.91	1.50	0.132
Filter Column 2	1.01	1.50	0.143
Filter Column 3	0.91	1.50	0.115

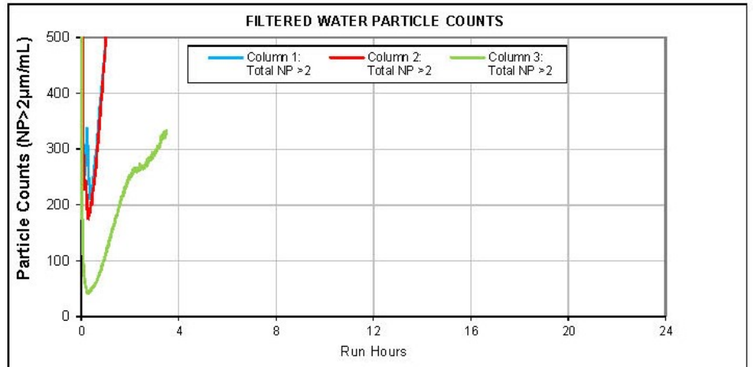
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.27	0
Filter Column 2	15	12.30	0
Filter Column 3	15	12.42	0

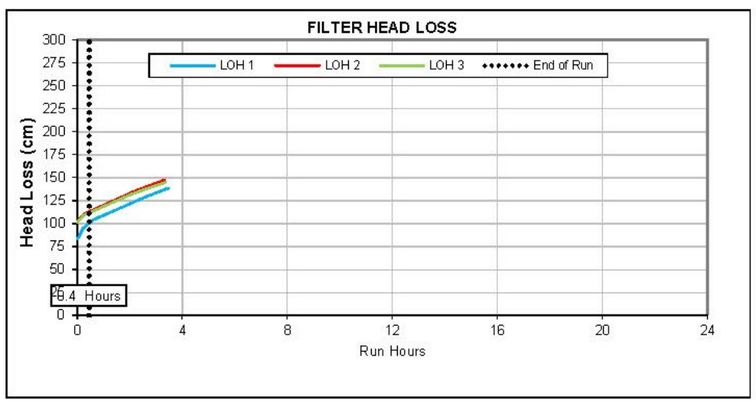
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

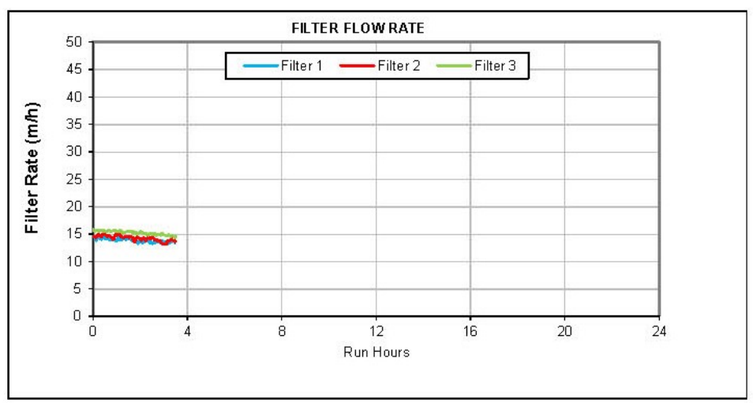












RUN SUMMARY

Run Started	10-Mar-16 9:28
Run Ended	10-Mar-16 12:58
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.21
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.048		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.80	0.80	0.80

ONLINE DATA SUMMARY

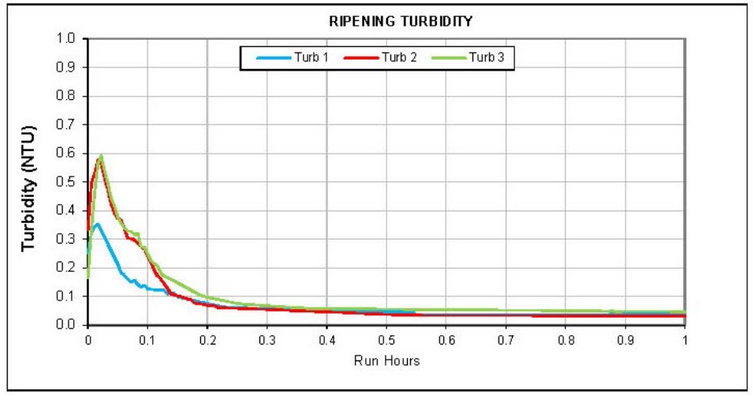
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.67	1.73	1.69
Column Influent	2.40	2.79	2.47
Filter Column 1 Effluent	0.10	0.13	0.11
Filter Column 2 Effluent	0.08	0.10	0.09
Filter Column 3 Effluent	0.08	0.10	0.09
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		14.0	

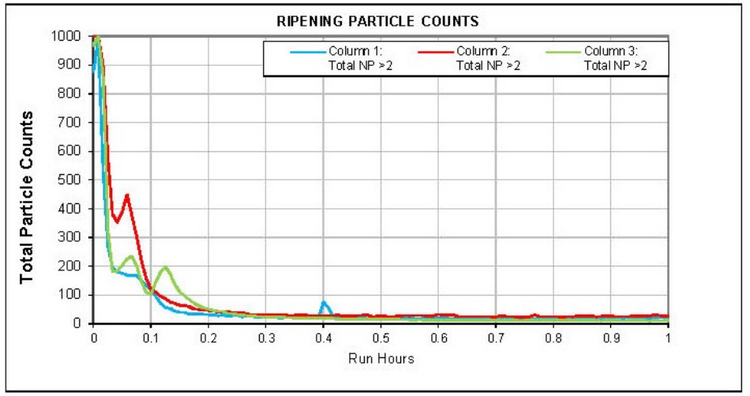
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	906	906	906
Filter Column 2 Effluent	1000	1000	1000
Filter Column 3 Effluent	42	51	45

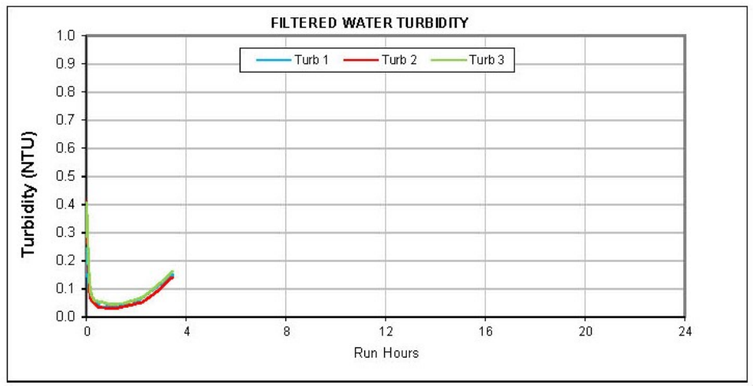
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.83	1.39	0.000
Filter Column 2	0.92	1.14	0.312
Filter Column 3	0.90	1.10	0.437

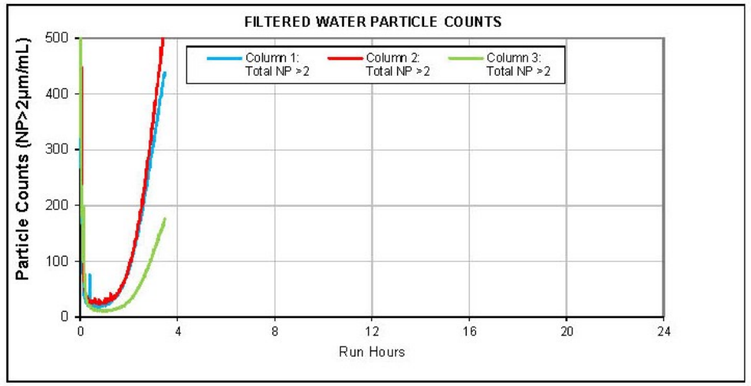
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	17	13.88	0
Filter Column 2	17	14.24	0
Filter Column 3	18	15.26	3

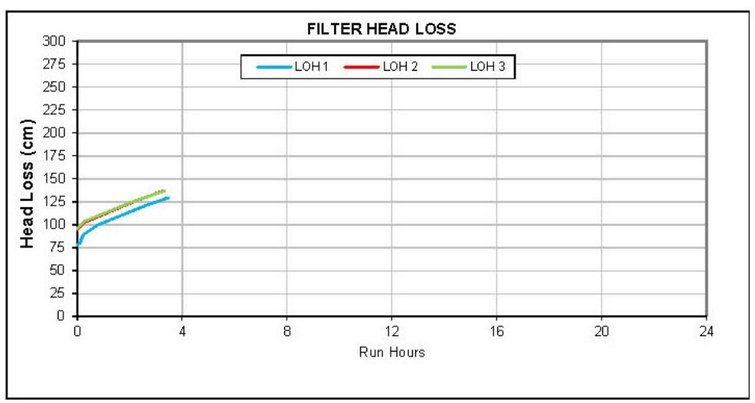
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

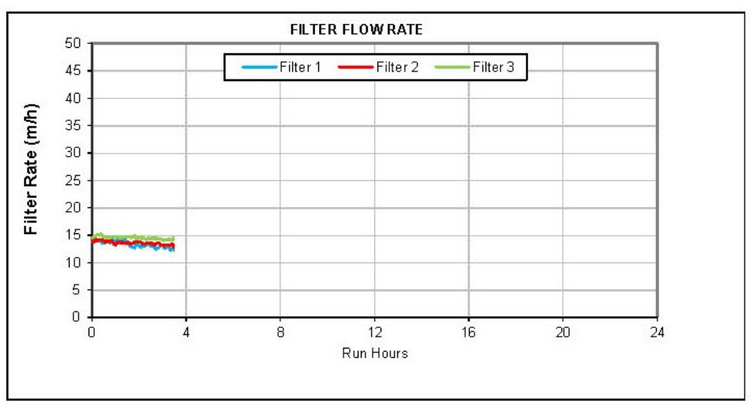












RUN SUMMARY

Run Started	17-Mar-16 12:06
Run Ended	17-Mar-16 15:35
Filter Column 1 Run Time (hrs)	1.53
Filter Column 2 Run Time (hrs)	1.47
Filter Column 3 Run Time (hrs)	2.17
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.072		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.83	0.83	0.83

ONLINE DATA SUMMARY

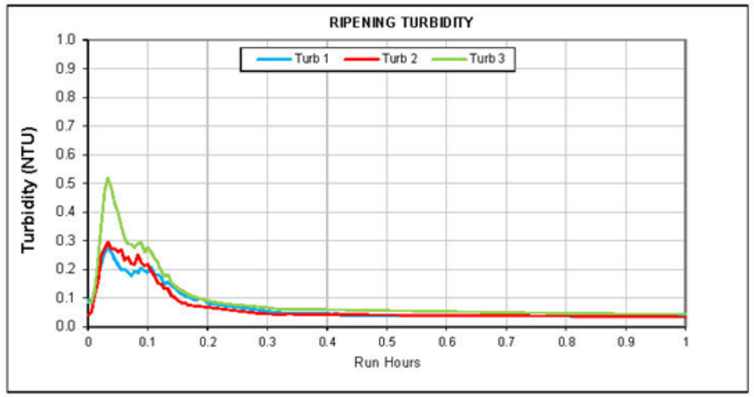
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.56	1.64	1.59
Column Influent	1.78	2.05	1.94
Filter Column 1 Effluent	0.04	0.10	0.05
Filter Column 2 Effluent	0.03	0.10	0.05
Filter Column 3 Effluent	0.05	0.10	0.06
Filter Column 1 Ripening Time (minutes)		9.0	
Filter Column 2 Ripening Time (minutes)		10.5	
Filter Column 3 Ripening Time (minutes)		12.5	

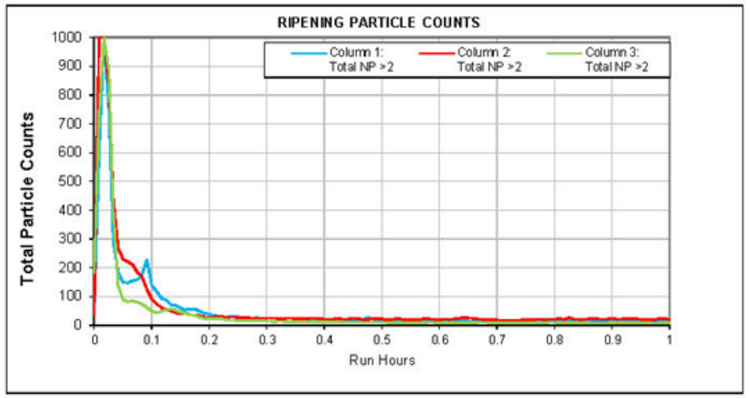
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	17	54	27
Filter Column 2 Effluent	24	49	31
Filter Column 3 Effluent	10	49	20

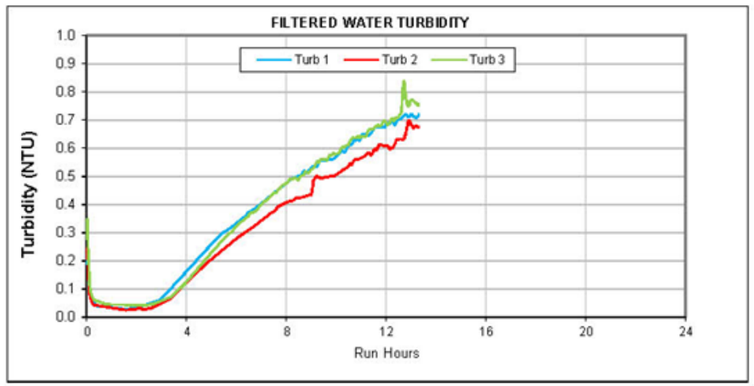
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.78	1.10	0.190
Filter Column 2	0.84	1.17	0.201
Filter Column 3	0.86	1.26	0.170

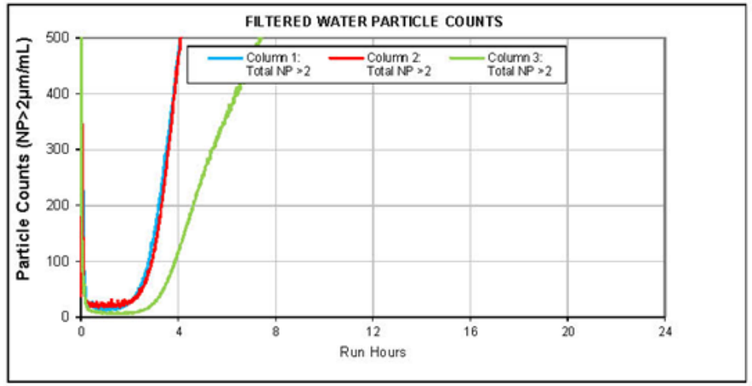
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.38	20
Filter Column 2	16	13.62	19
Filter Column 3	17	14.57	30

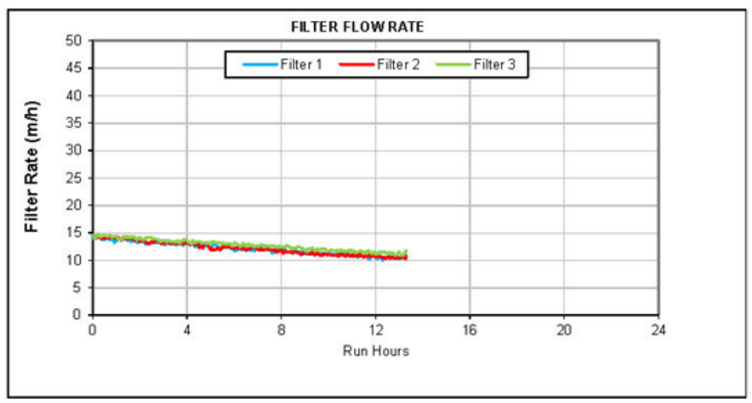
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	17-Mar-16 18:57
Run Ended	18-Mar-16 8:16
Filter Column 1 Run Time (hrs)	2.21
Filter Column 2 Run Time (hrs)	2.36
Filter Column 3 Run Time (hrs)	3.21
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.096		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.83	0.83	0.83

ONLINE DATA SUMMARY

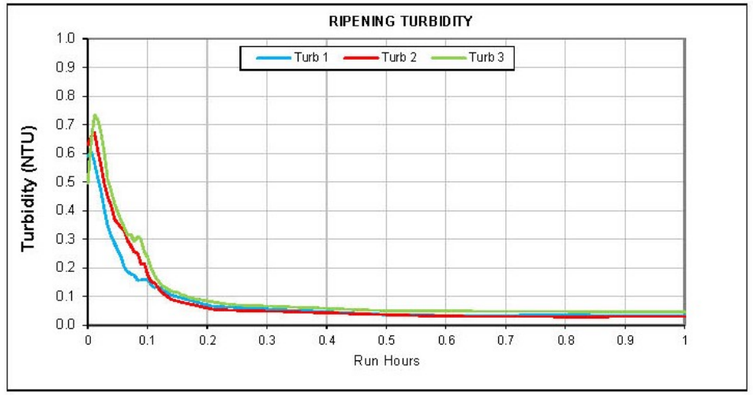
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.58	1.62	1.60
Column Influent	1.72	1.98	1.82
Filter Column 1 Effluent	0.03	0.10	0.05
Filter Column 2 Effluent	0.02	0.10	0.04
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		10.5	
Filter Column 2 Ripening Time (minutes)		9.0	
Filter Column 3 Ripening Time (minutes)		11.0	

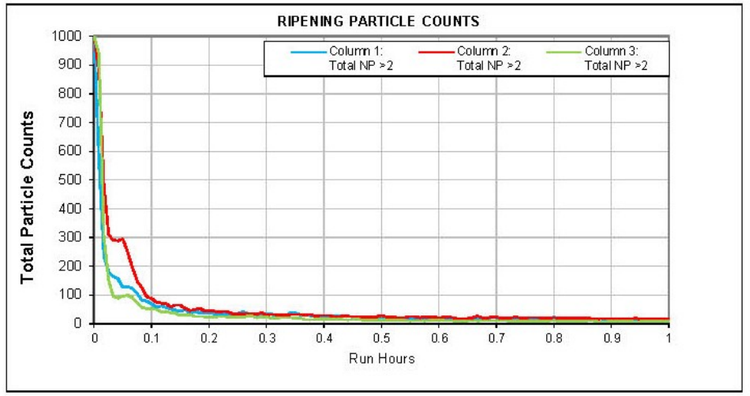
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	13	49	21
Filter Column 2 Effluent	18	50	26
Filter Column 3 Effluent	6	48	13

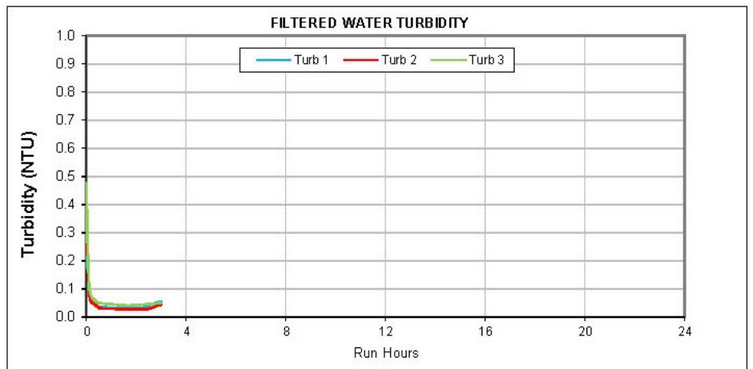
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.82	1.21	0.163
Filter Column 2	0.87	1.29	0.167
Filter Column 3	0.88	1.35	0.140

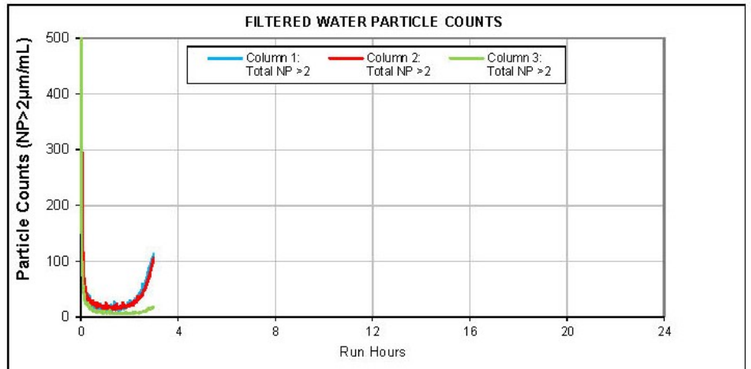
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	14	12.11	29
Filter Column 2	15	12.16	31
Filter Column 3	15	12.76	43

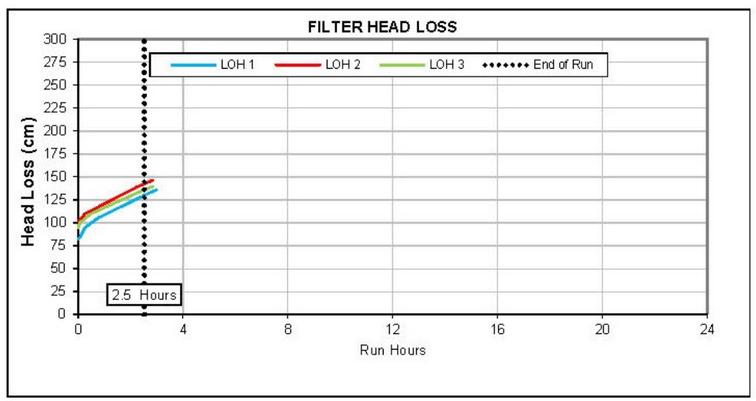
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 - 1.1
Anthracite Depth (inchs)	18	18	18

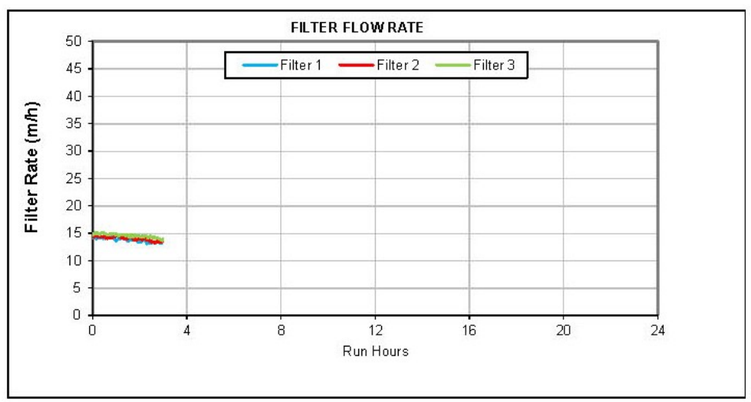












RUN SUMMARY

Run Started	14-Mar-16 14:24
Run Ended	14-Mar-16 17:24
Filter Column 1 Run Time (hrs)	2.37
Filter Column 2 Run Time (hrs)	2.44
Filter Column 3 Run Time (hrs)	2.83
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.12		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.86	0.86	0.86

ONLINE DATA SUMMARY

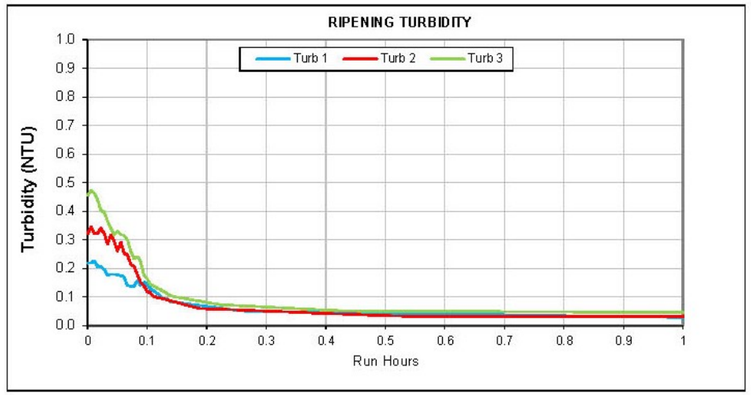
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.60	1.66	1.62
Column Influent	2.15	3.09	2.22
Filter Column 1 Effluent	0.03	0.10	0.04
Filter Column 2 Effluent	0.03	0.10	0.03
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		9.0	
Filter Column 2 Ripening Time (minutes)		11.5	
Filter Column 3 Ripening Time (minutes)		10.0	

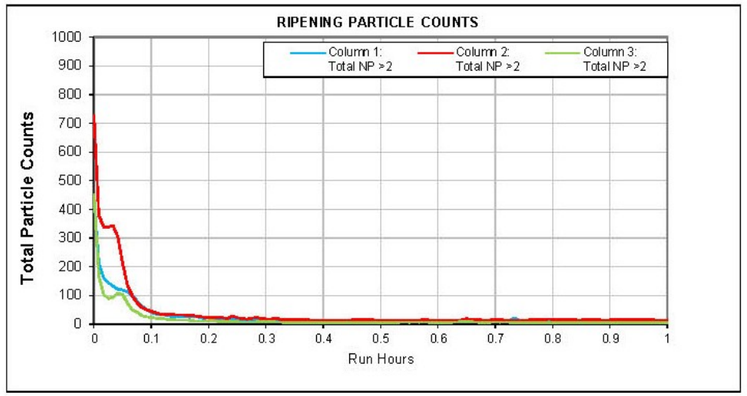
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	12	47	22
Filter Column 2 Effluent	14	48	23
Filter Column 3 Effluent	6	36	10

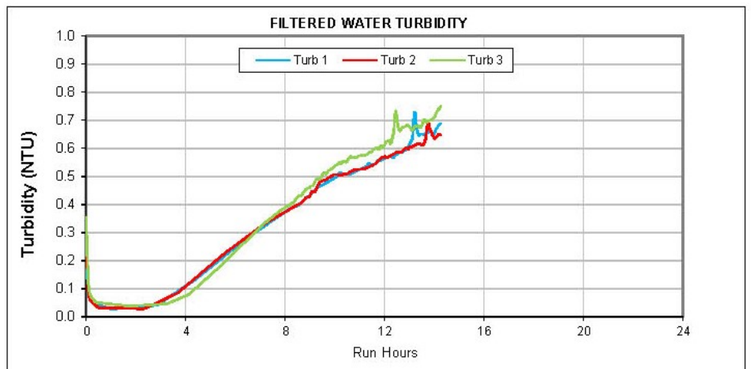
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.82	1.30	0.190
Filter Column 2	0.91	1.42	0.192
Filter Column 3	0.87	1.40	0.177

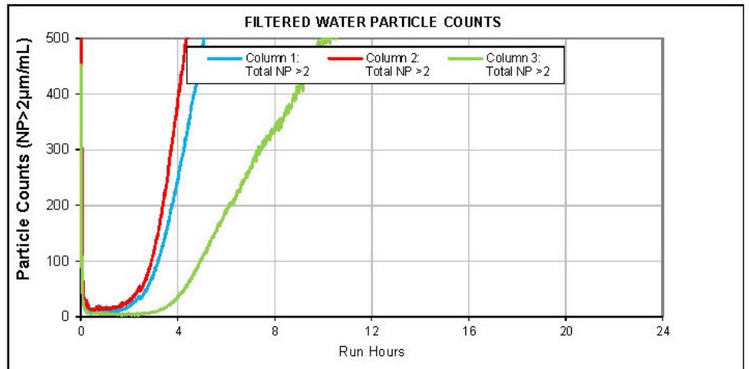
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.80	31
Filter Column 2	17	14.06	33
Filter Column 3	17	14.59	39

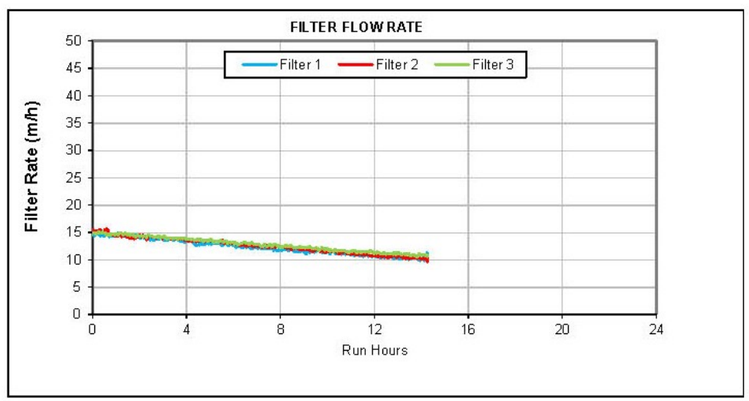
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	02-Mar-16 17:44
Run Ended	03-Mar-16 8:00
Filter Column 1 Run Time (hrs)	2.61
Filter Column 2 Run Time (hrs)	2.38
Filter Column 3 Run Time (hrs)	3.45
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.14		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.80	0.80	0.80

ONLINE DATA SUMMARY

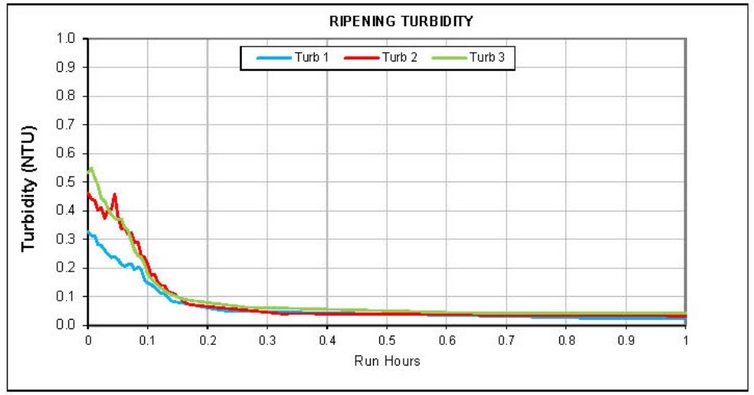
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.54	1.58	1.56
Column Influent	2.33	2.92	2.40
Filter Column 1 Effluent	0.03	0.10	0.05
Filter Column 2 Effluent	0.03	0.10	0.05
Filter Column 3 Effluent	0.04	0.10	0.05
Filter Column 1 Ripening Time (minutes)		7.7	
Filter Column 2 Ripening Time (minutes)		7.0	
Filter Column 3 Ripening Time (minutes)		9.0	

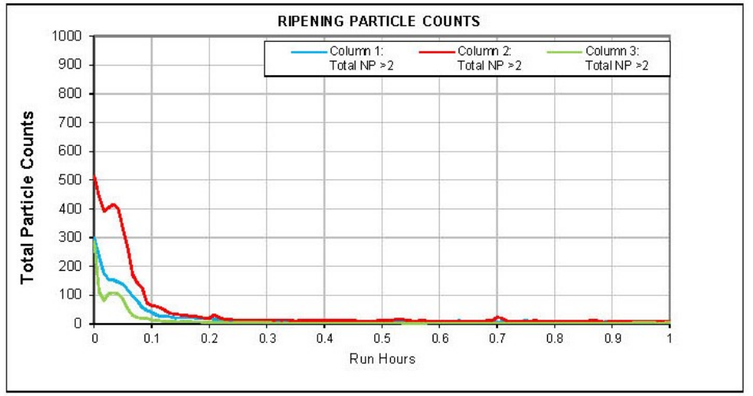
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	7	48	18
Filter Column 2 Effluent	12	53	23
Filter Column 3 Effluent	3	48	11

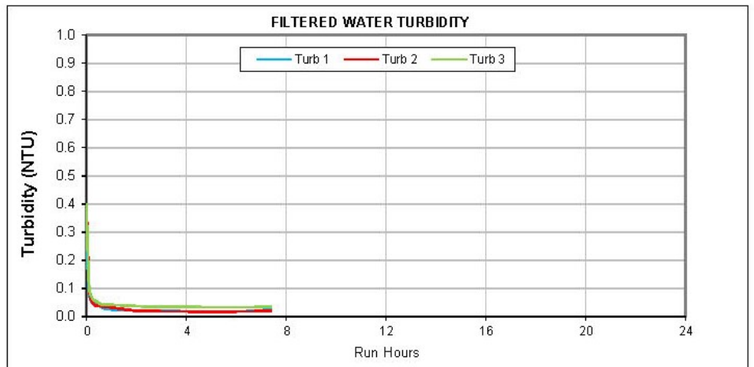
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.37	0.195
Filter Column 2	0.95	1.48	0.212
Filter Column 3	0.89	1.50	0.170

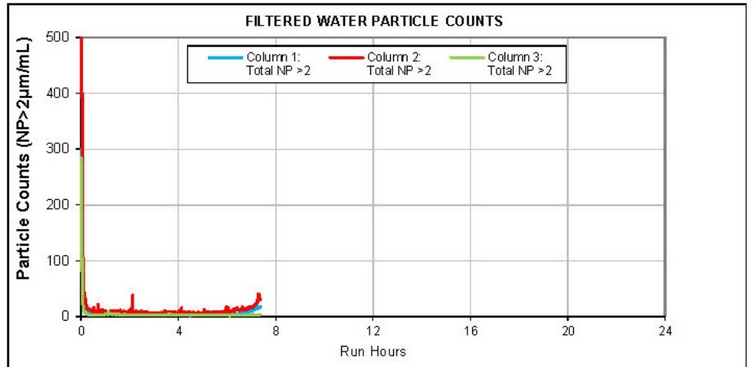
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.31	35
Filter Column 2	15	12.57	33
Filter Column 3	15	12.83	47

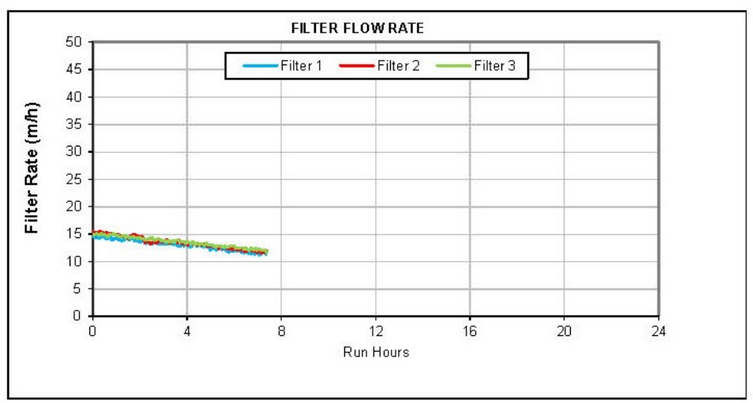
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	02-Mar-16 9:12
Run Ended	02-Mar-16 16:35
Filter Column 1 Run Time (hrs)	2.89
Filter Column 2 Run Time (hrs)	2.06
Filter Column 3 Run Time (hrs)	2.88
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	12		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.22		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.80	0.80	0.80

ONLINE DATA SUMMARY

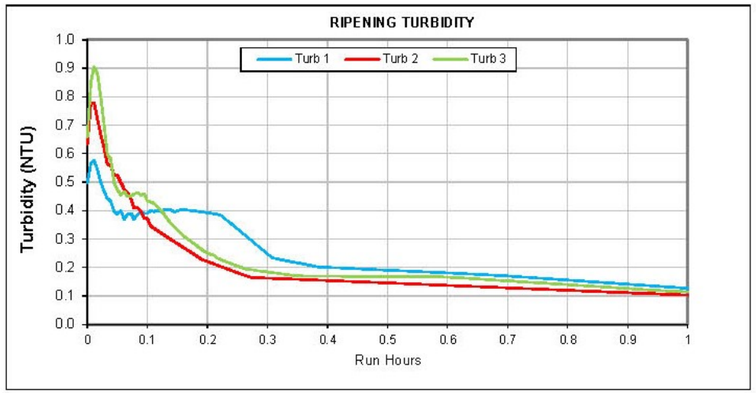
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.53	1.61	1.55
Column Influent	2.28	2.70	2.40
Filter Column 1 Effluent	0.02	0.10	0.02
Filter Column 2 Effluent	0.02	0.10	0.02
Filter Column 3 Effluent	0.03	0.10	0.04
Filter Column 1 Ripening Time (minutes)		8.0	
Filter Column 2 Ripening Time (minutes)		9.0	
Filter Column 3 Ripening Time (minutes)		9.0	

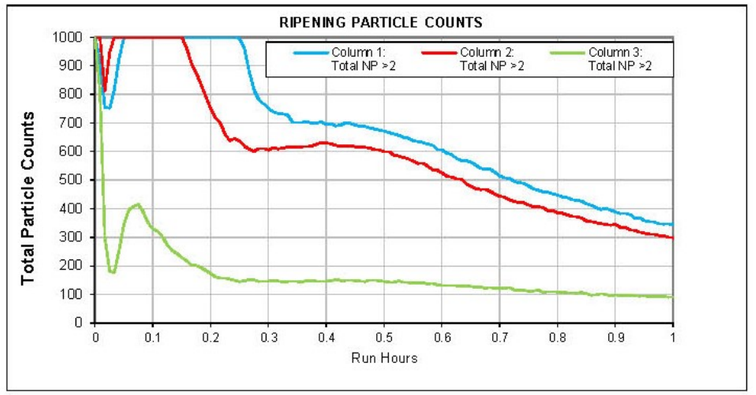
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	2	20	5
Filter Column 2 Effluent	6	36	10
Filter Column 3 Effluent	2	9	3

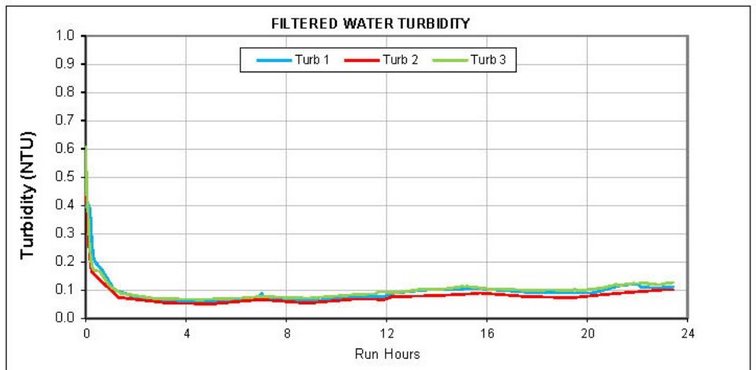
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.84	1.49	0.216
Filter Column 2	0.93	1.49	0.257
Filter Column 3	0.88	1.49	0.202

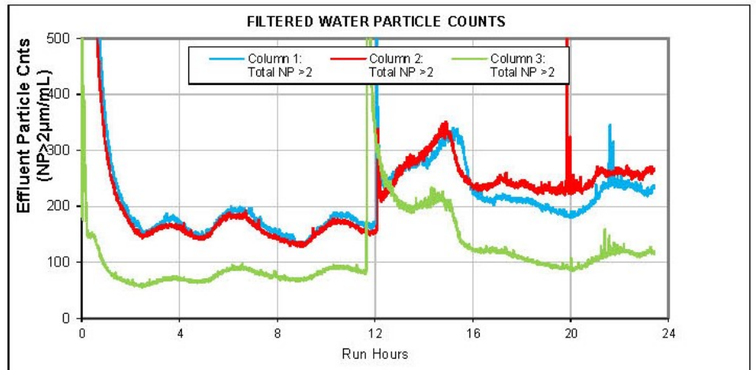
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	16	13.02	38
Filter Column 2	16	13.46	29
Filter Column 3	16	13.57	39

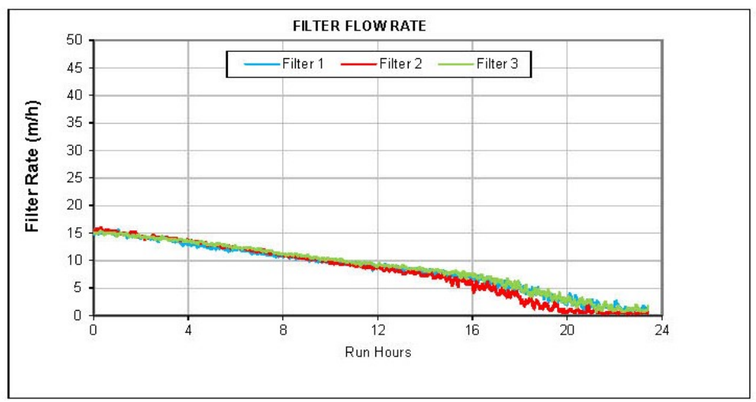
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	05-Feb-16 10:04
Run Ended	06-Feb-16 9:30
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.00		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.00	1.00	1.00

ONLINE DATA SUMMARY

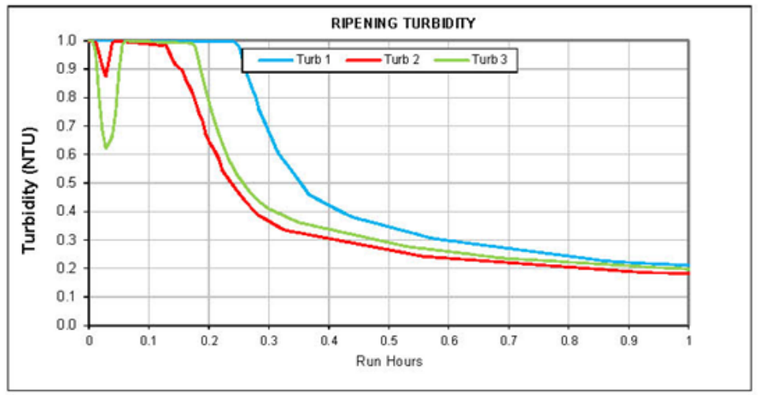
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.38	1.45	1.40
Column Influent	3.59	3.89	3.69
Filter Column 1 Effluent	0.06	0.10	0.07
Filter Column 2 Effluent	0.05	0.10	0.07
Filter Column 3 Effluent	0.07	0.10	0.08
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

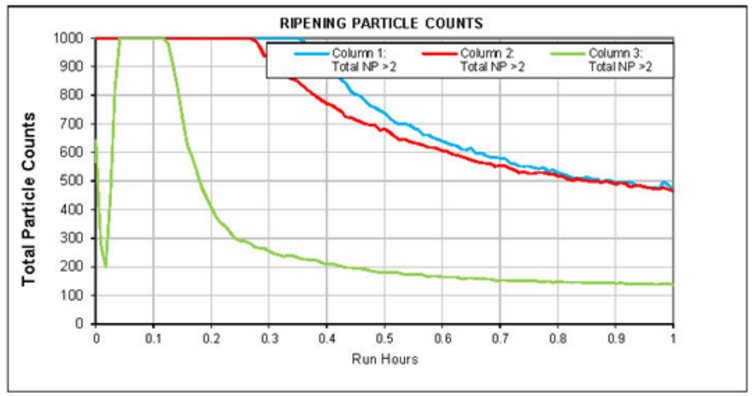
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	236	236	236
Filter Column 2 Effluent	268	268	268
Filter Column 3 Effluent	114	114	114

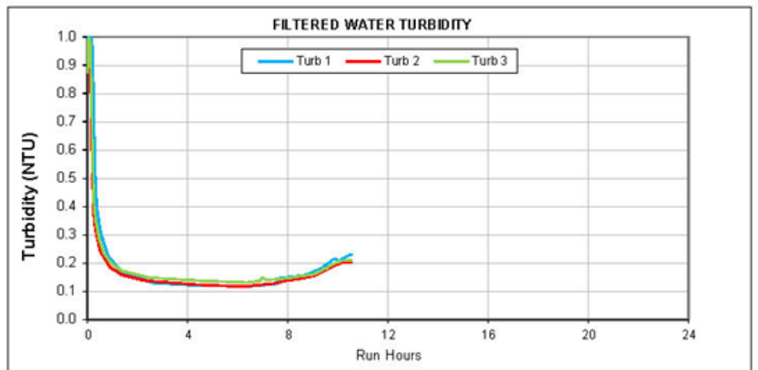
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.85	1.49	0.206
Filter Column 2	0.92	1.49	0.226
Filter Column 3	0.87	1.49	0.184

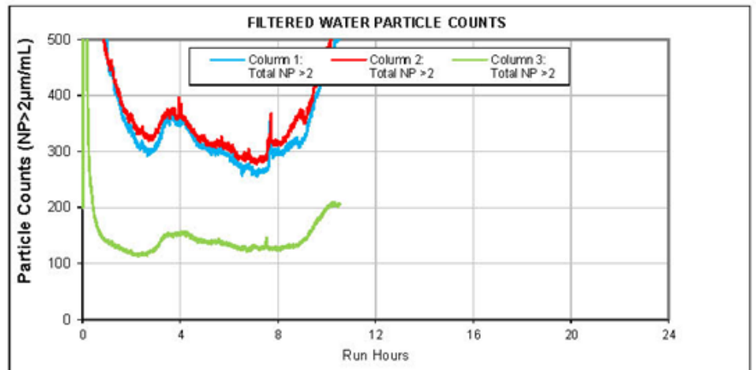
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	10	8.58	0
Filter Column 2	10	8.17	0
Filter Column 3	11	8.86	0

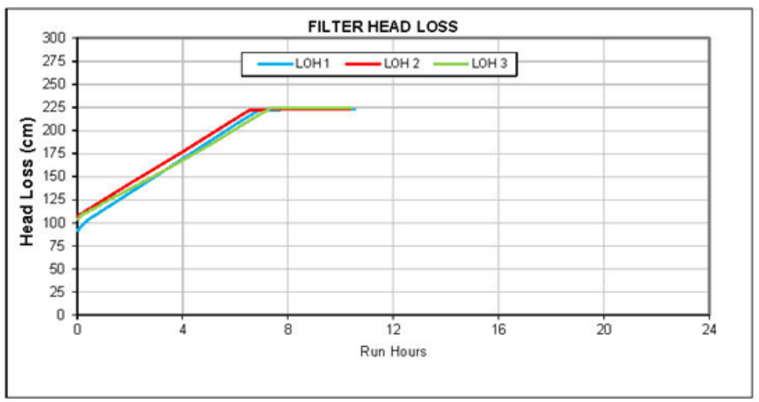
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

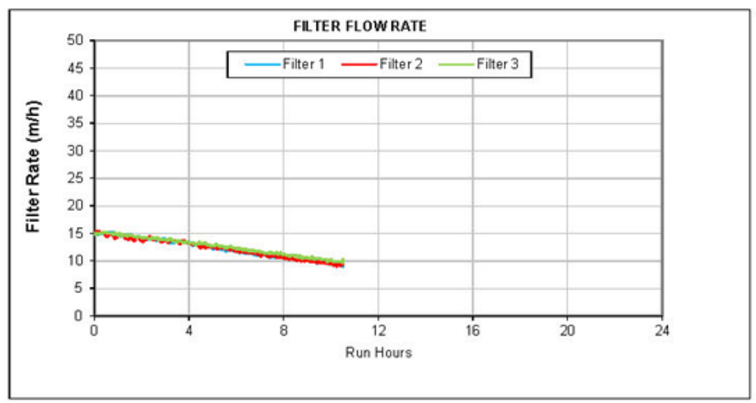












RUN SUMMARY

Run Started	21-Feb-16 12:28
Run Ended	21-Feb-16 23:00
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.024		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.85	0.85	0.85

ONLINE DATA SUMMARY

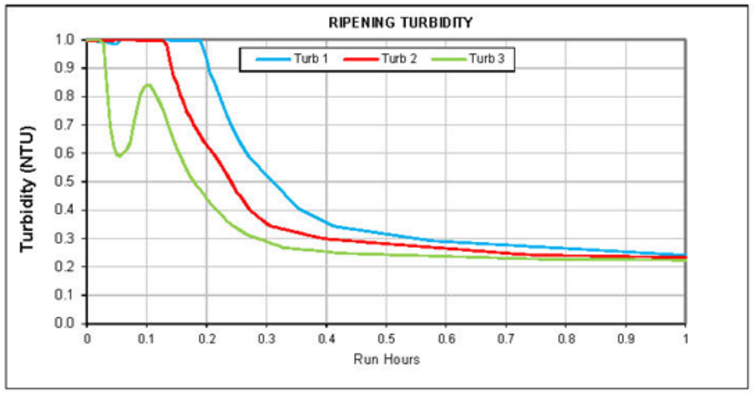
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.25	1.32	1.28
Column Influent	3.23	3.53	3.36
Filter Column 1 Effluent	0.12	1.00	0.18
Filter Column 2 Effluent	0.12	1.00	0.17
Filter Column 3 Effluent	0.13	1.00	0.18
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

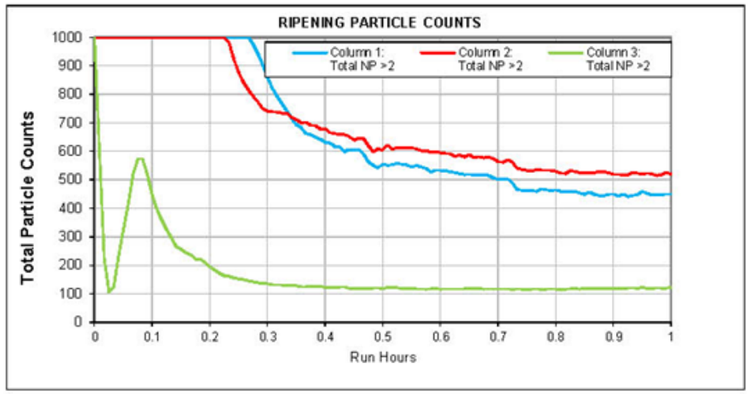
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	502	502	502
Filter Column 2 Effluent	524	524	524
Filter Column 3 Effluent	206	206	206

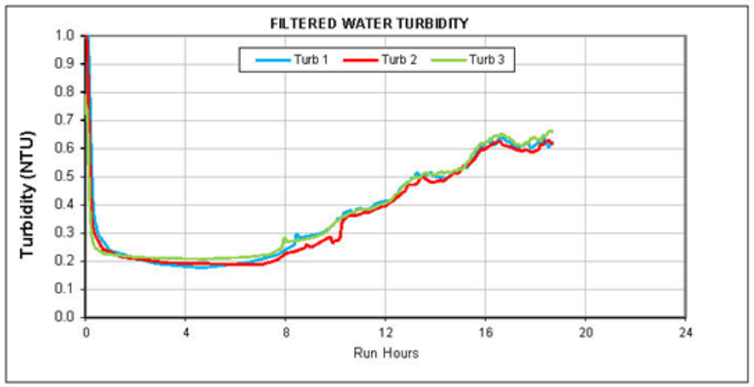
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.91	1.49	0.199
Filter Column 2	0.98	1.49	0.200
Filter Column 3	0.97	1.49	0.177

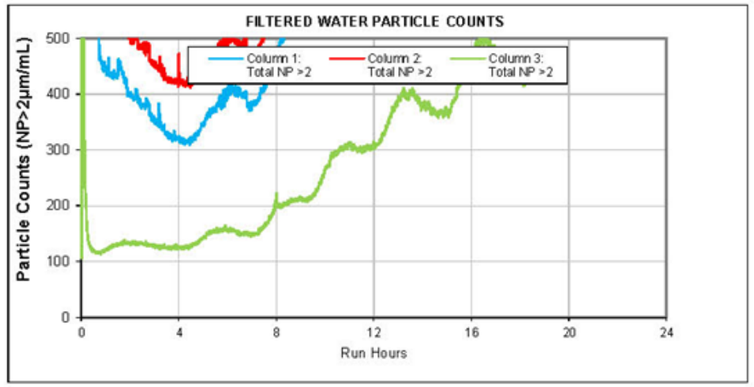
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	15	12.29	0
Filter Column 2	15	12.23	0
Filter Column 3	15	12.60	0

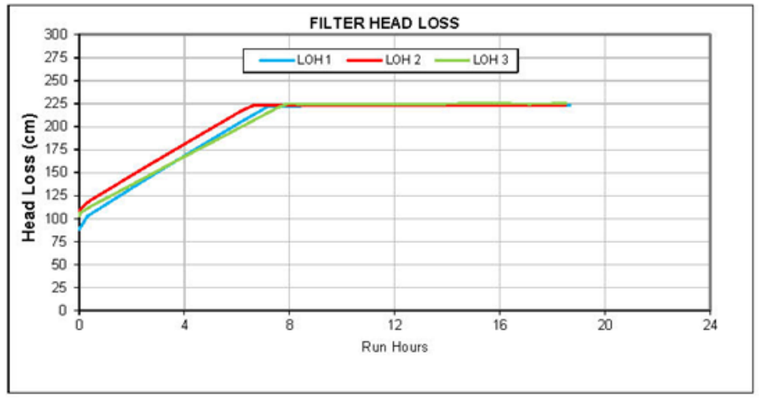
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

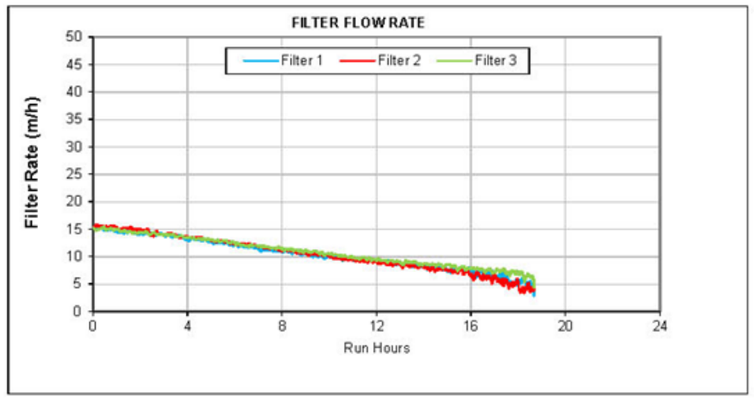












RUN SUMMARY

Run Started	22-Feb-16 13:39
Run Ended	23-Feb-16 8:20
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.048		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.95	0.95	0.95

ONLINE DATA SUMMARY

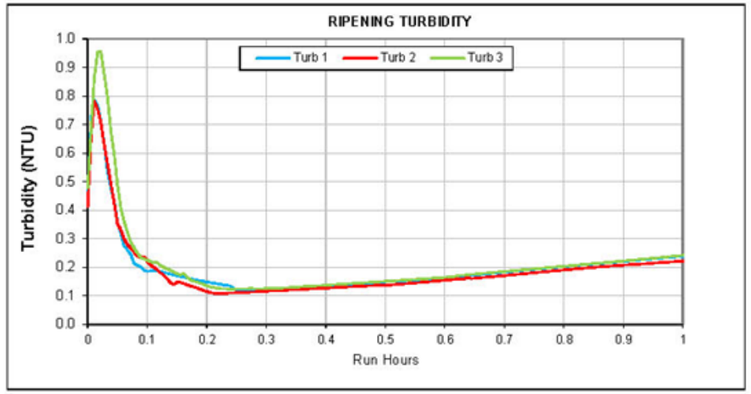
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.26	1.35	1.30
Column Influent	3.19	3.42	3.31
Filter Column 1 Effluent	0.18	1.00	0.37
Filter Column 2 Effluent	0.19	1.00	0.35
Filter Column 3 Effluent	0.21	1.00	0.37
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

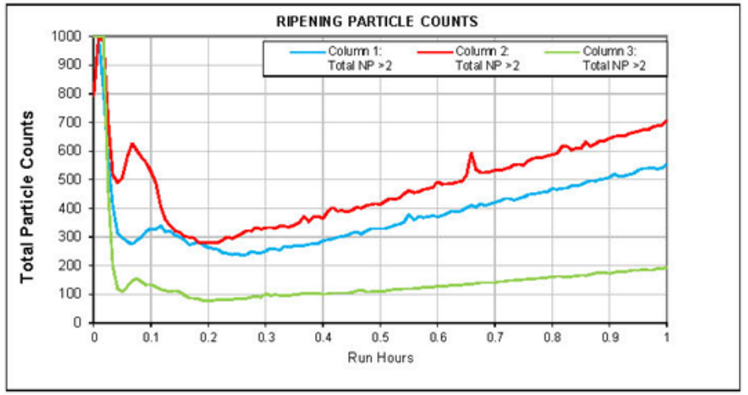
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	1000	1000	1000
Filter Column 2 Effluent	1000	1000	1000
Filter Column 3 Effluent	444	444	444

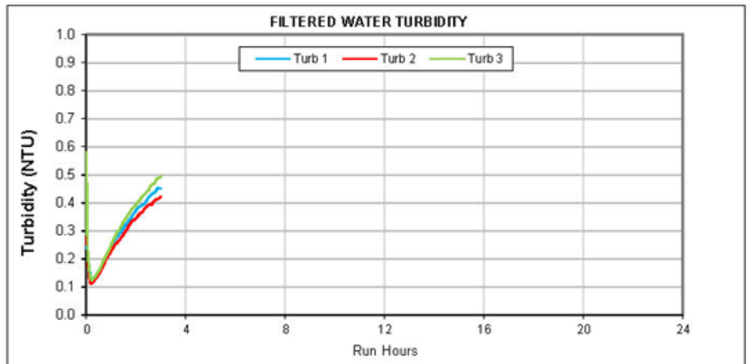
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.88	1.49	0.208
Filter Column 2	0.98	1.49	0.225
Filter Column 3	0.94	1.49	0.186

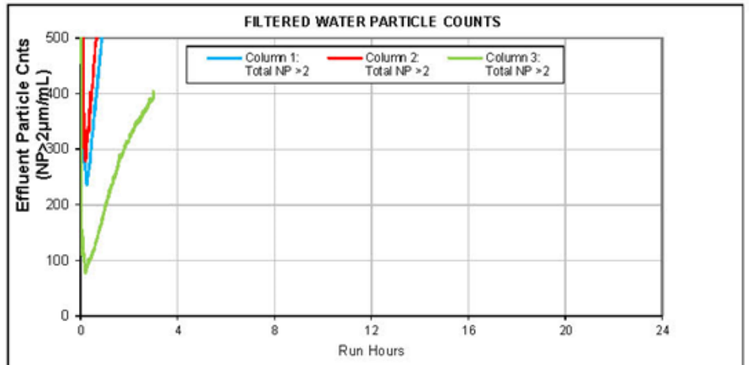
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	12	10.45	0
Filter Column 2	12	10.46	0
Filter Column 3	13	10.87	0

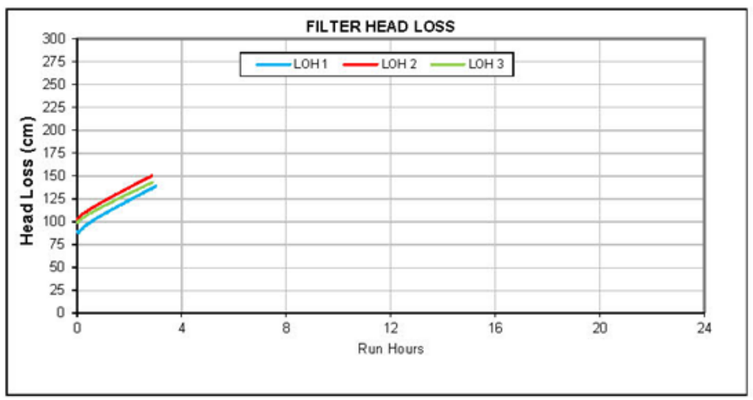
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

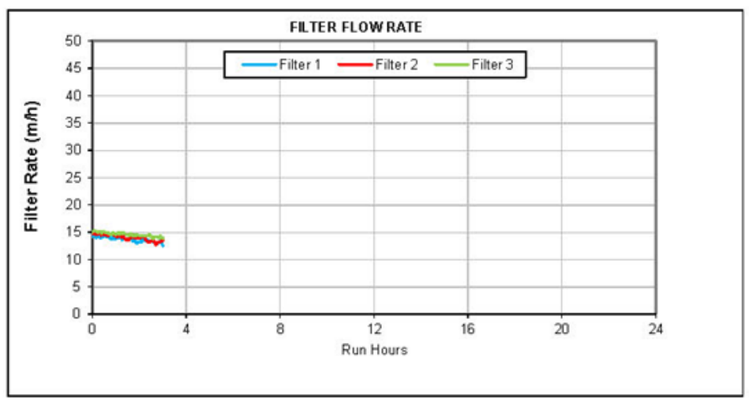












RUN SUMMARY

Run Started	15-Mar-16 14:03
Run Ended	15-Mar-16 17:04
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.072		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.83	0.83	0.83

ONLINE DATA SUMMARY

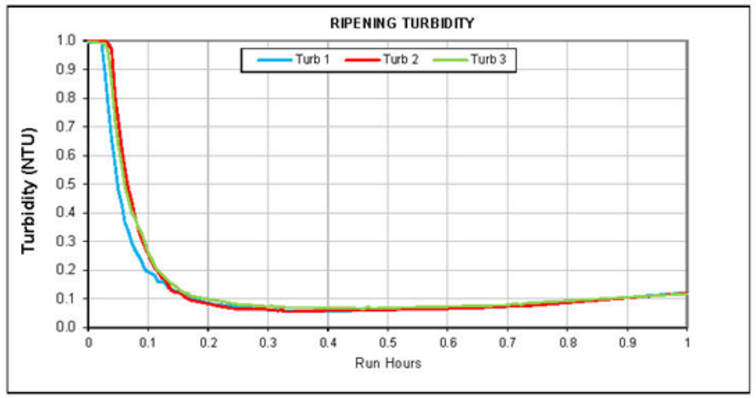
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.61	1.66	1.64
Column Influent	2.70	2.87	2.76
Filter Column 1 Effluent	0.12	0.79	0.30
Filter Column 2 Effluent	0.11	0.78	0.29
Filter Column 3 Effluent	0.12	0.96	0.33
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

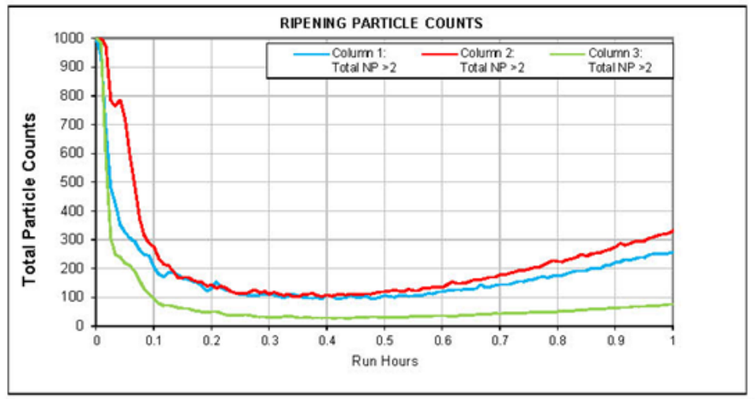
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	1000	1000	1000
Filter Column 2 Effluent	1000	1000	1000
Filter Column 3 Effluent	391	391	391

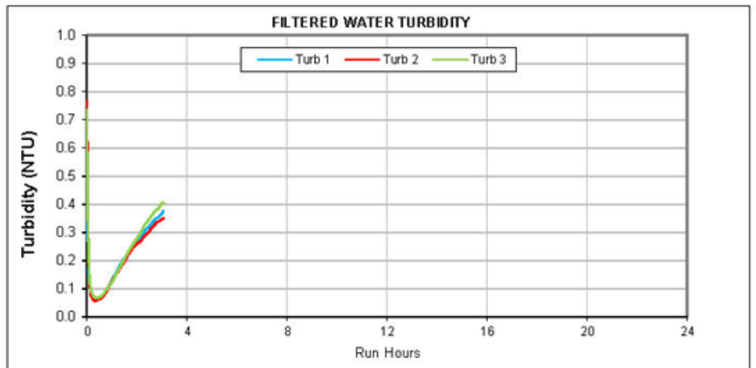
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.89	1.39	0.164
Filter Column 2	1.00	1.50	0.166
Filter Column 3	0.96	1.43	0.155

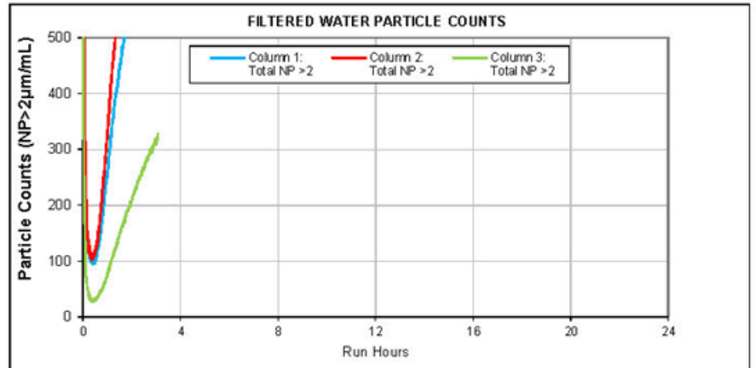
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	16	13.69	0
Filter Column 2	17	14.03	0
Filter Column 3	17	14.59	0

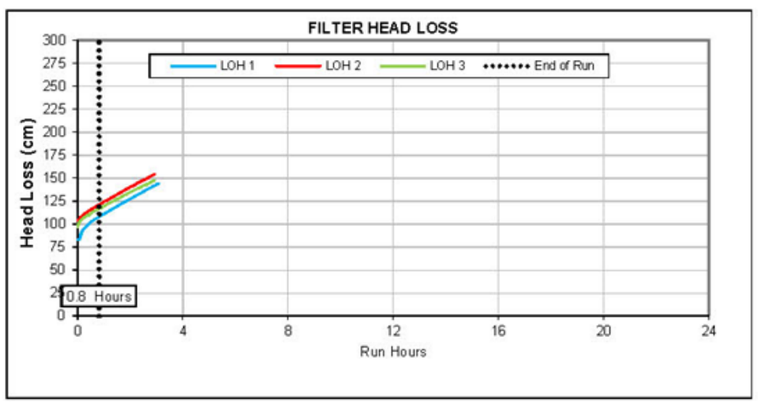
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

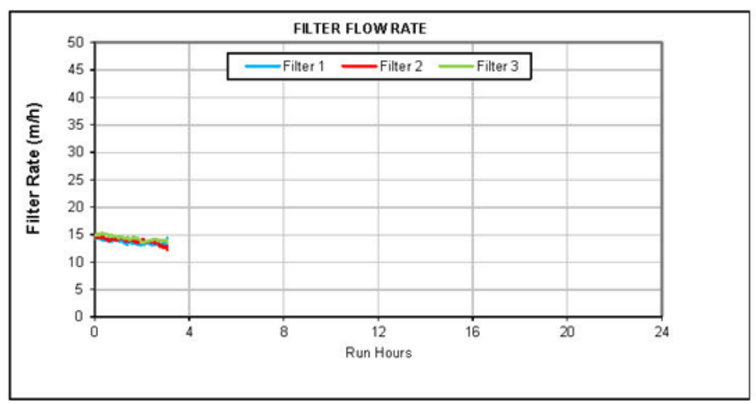












RUN SUMMARY

Run Started	15-Mar-16 9:53
Run Ended	15-Mar-16 12:58
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.59
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.096		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.83	0.83	0.83

ONLINE DATA SUMMARY

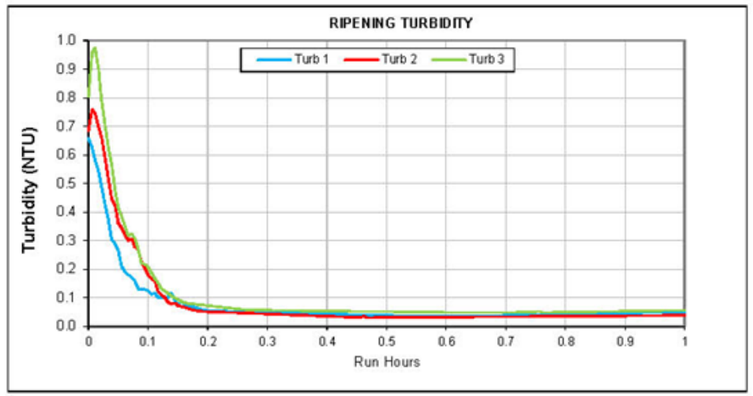
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.60	1.64	1.62
Column Influent	2.69	3.24	2.77
Filter Column 1 Effluent	0.06	0.10	0.07
Filter Column 2 Effluent	0.06	0.10	0.07
Filter Column 3 Effluent	0.07	0.10	0.08
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		13.0	

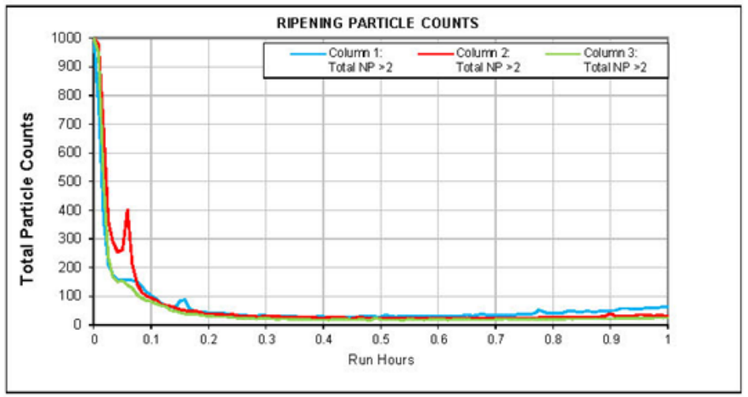
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	832	832	832
Filter Column 2 Effluent	1000	1000	1000
Filter Column 3 Effluent	27	50	36

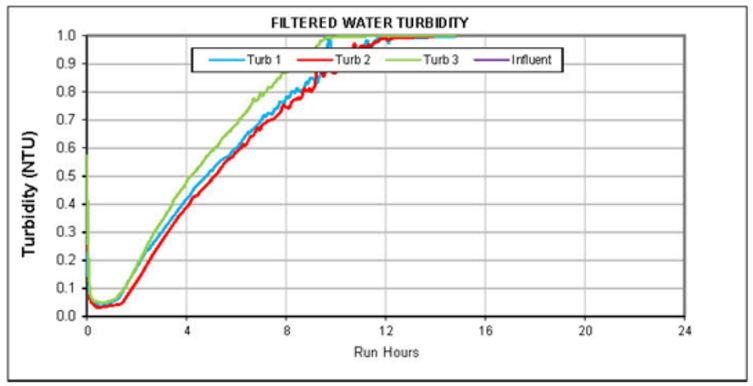
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.83	1.09	0.298
Filter Column 2	0.90	1.20	0.333
Filter Column 3	0.87	1.15	0.336

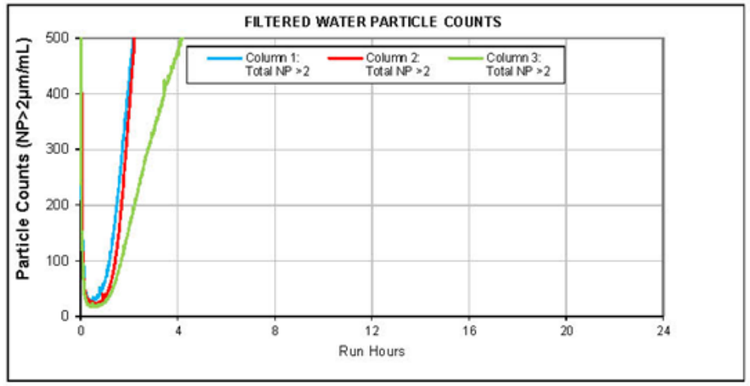
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	16	13.65	0
Filter Column 2	17	13.93	0
Filter Column 3	17	14.38	8

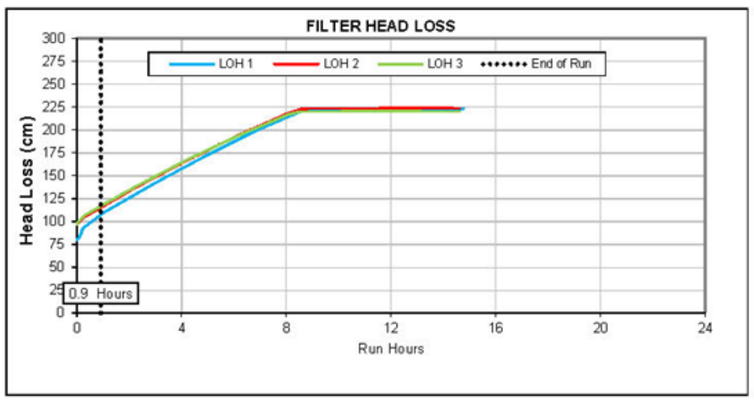
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18

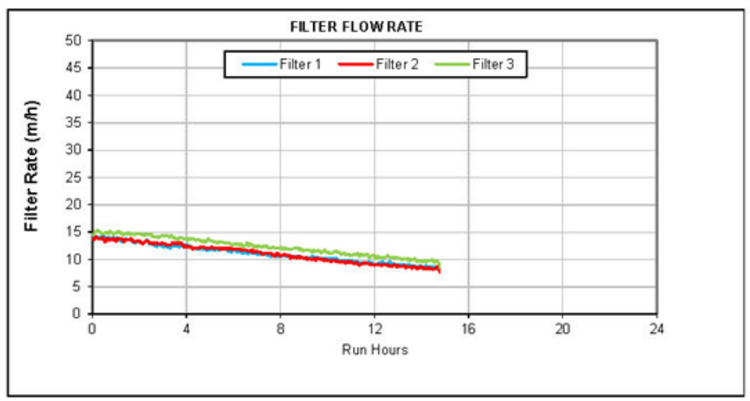












RUN SUMMARY

Run Started	21-Mar-16 17:28
Run Ended	22-Mar-16 8:15
Filter Column 1 Run Time (hrs)	0.73
Filter Column 2 Run Time (hrs)	1.01
Filter Column 3 Run Time (hrs)	1.21
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.14		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.74	0.74	0.74

ONLINE DATA SUMMARY

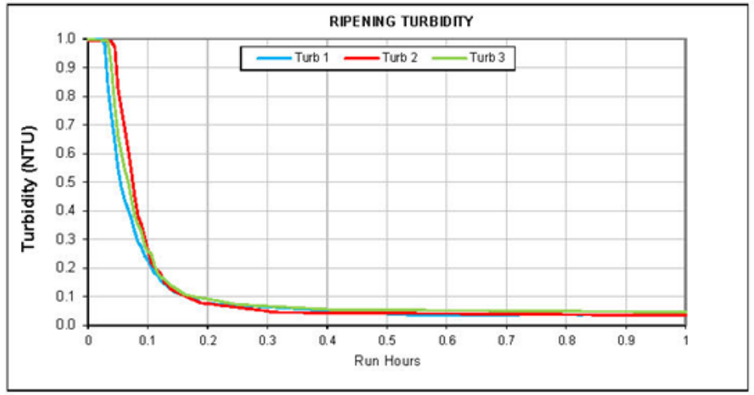
Turbidity	**Min (NTU)**	**Max (NTU)**	**Avg (NTU)**
Raw Water	1.83	1.90	1.86
Column Influent	2.60	2.70	2.63
Filter Column 1 Effluent	0.03	0.10	0.05
Filter Column 2 Effluent	0.03	0.10	0.05
Filter Column 3 Effluent	0.05	0.10	0.06
Filter Column 1 Ripening Time (minutes)		10.5	
Filter Column 2 Ripening Time (minutes)		9.5	
Filter Column 3 Ripening Time (minutes)		8.7	

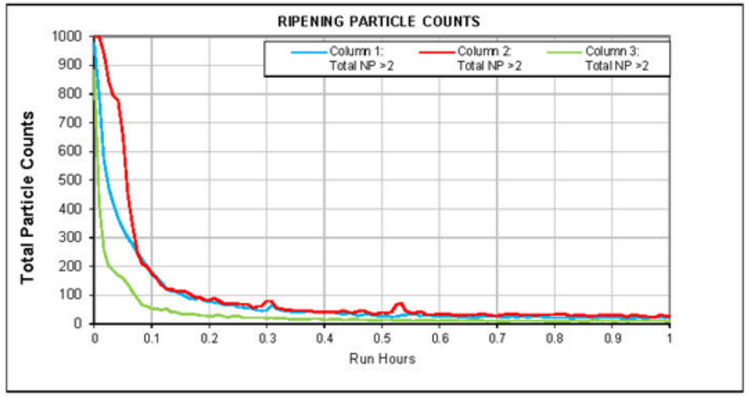
Particle Counts	**1 %ile (cts/mL)**	**99 %ile (cts/mL)**	**Avg (cts/mL)**
Filter Column 1 Effluent	27	51	35
Filter Column 2 Effluent	22	48	30
Filter Column 3 Effluent	17	50	26

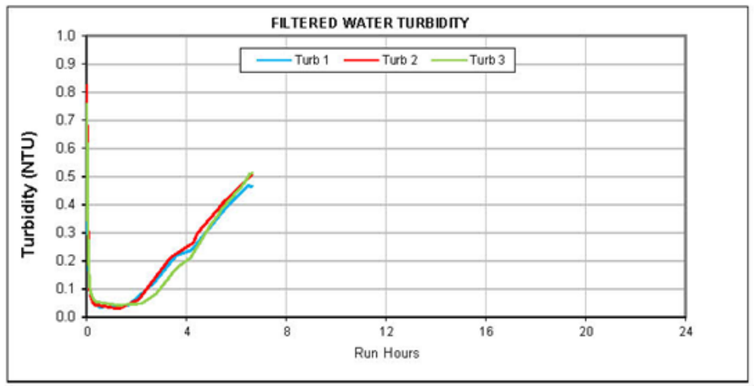
Head Loss	**Min (m)**	**Max (m)**	**Rate (m/hr)**
Filter Column 1	0.80	1.07	0.301
Filter Column 2	0.85	1.17	0.270
Filter Column 3	0.87	1.22	0.258

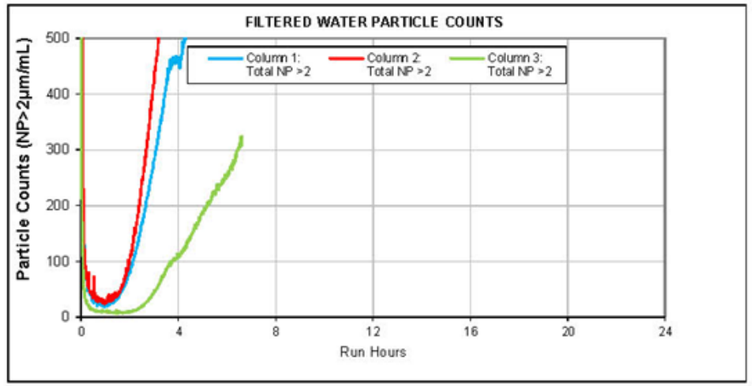
Flows	**Avg (mL/s)**	**Avg (m/hr)**	**UFRV (m^3/m^2)**
Filter Column 1	13	11.07	10
Filter Column 2	13	11.06	13
Filter Column 3	15	12.37	17

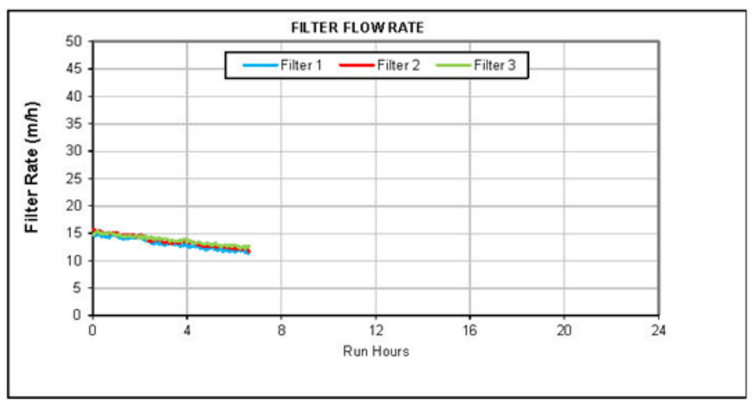
Media Specifications	**Filter 1**	**Filter 2**	**Filter 3**
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inchs)	18	18	18











RUN SUMMARY

Run Started	29-Feb-16 9:22
Run Ended	29-Feb-16 16:00
Filter Column 1 Run Time (hrs)	1.41
Filter Column 2 Run Time (hrs)	1.31
Filter Column 3 Run Time (hrs)	2.61
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.22		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	0.94	0.94	0.94

ONLINE DATA SUMMARY

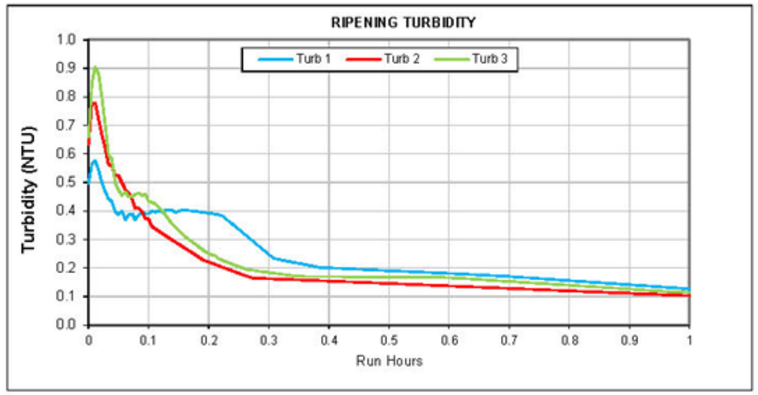
Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.50	1.53	1.51
Column Influent	3.25	3.68	3.31
Filter Column 1 Effluent	0.04	0.10	0.05
Filter Column 2 Effluent	0.03	0.10	0.05
Filter Column 3 Effluent	0.04	0.10	0.06
Filter Column 1 Ripening Time (minutes)		19.5	
Filter Column 2 Ripening Time (minutes)		20.0	
Filter Column 3 Ripening Time (minutes)		10.7	

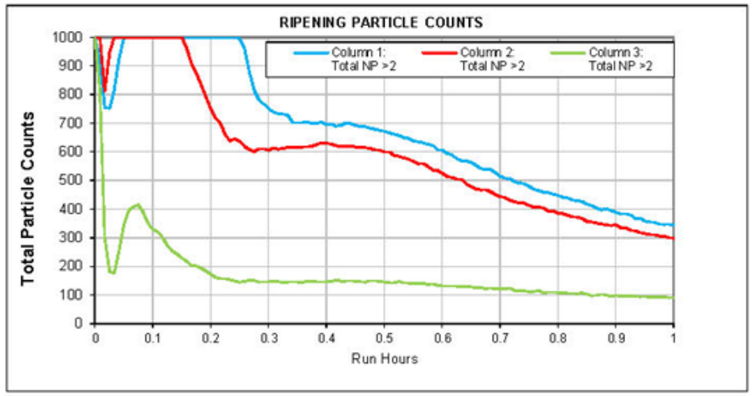
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	19	50	29
Filter Column 2 Effluent	24	58	36
Filter Column 3 Effluent	7	50	16

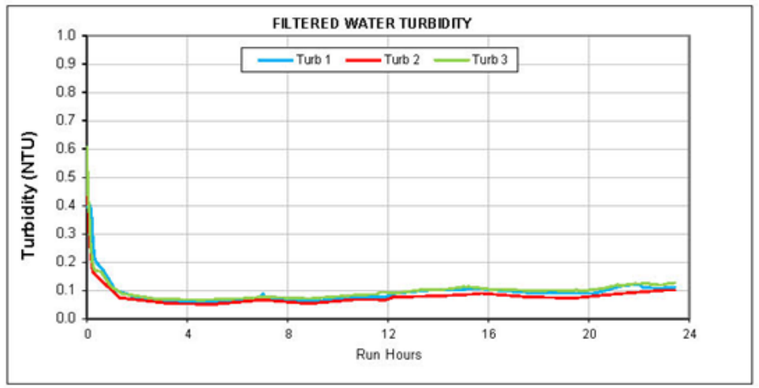
Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.84	1.31	0.268
Filter Column 2	0.95	1.43	0.292
Filter Column 3	0.90	1.49	0.215

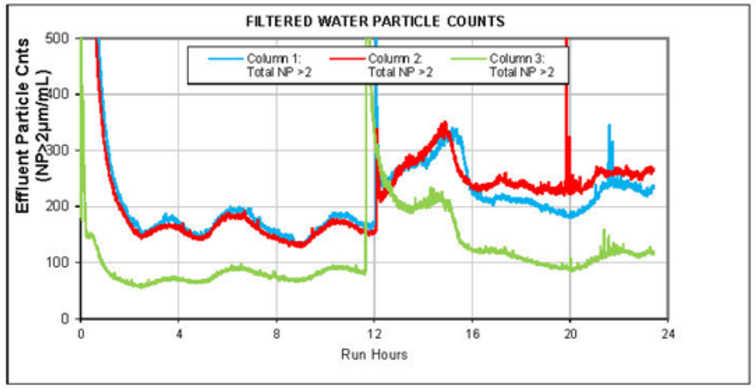
Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	16	13.15	19
Filter Column 2	16	13.64	19
Filter Column 3	16	13.79	36

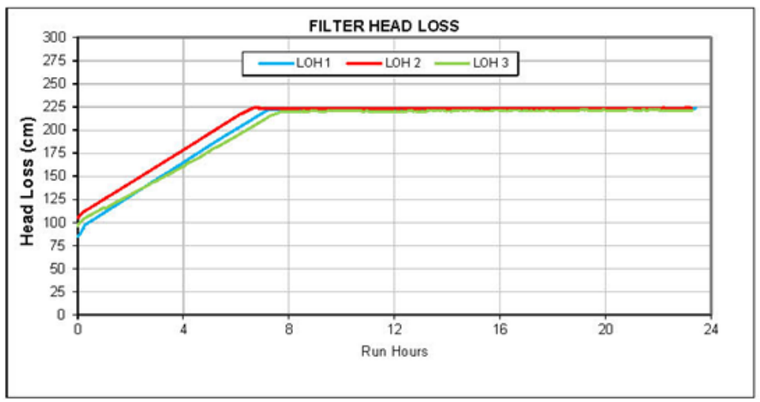
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inchs)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 - 1.1
Anthracite Depth (inchs)	18	18	18

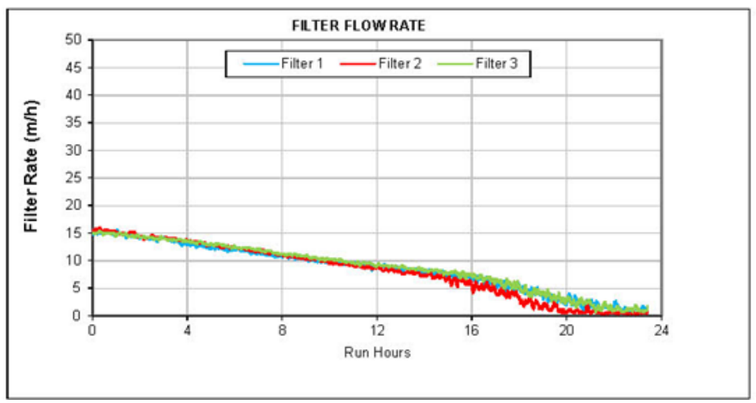












RUN SUMMARY

Run Started	05-Feb-16 10:04
Run Ended	06-Feb-16 9:30
Filter Column 1 Run Time (hrs)	0.00
Filter Column 2 Run Time (hrs)	0.00
Filter Column 3 Run Time (hrs)	0.00
Feed Water Source	Glenmore, North Flow EQ Tank
Objective	Direct filtration

Chemical Dosing			
Coagulant Type	Alum		
Coagulant Dose	18		mg/L
Polymer Type	Cationic LT22S		
Polymer Dose	0.00		mg/L
Pre-Chlorine Dose	N/A		mg/L
Filter	1	2	3
Free Chlorine Residual (mg/L)	1.00	1.00	1.00

ONLINE DATA SUMMARY

Turbidity	Min (NTU)	Max (NTU)	Avg (NTU)
Raw Water	1.38	1.45	1.40
Column Influent	3.59	3.89	3.69
Filter Column 1 Effluent	0.06	0.10	0.07
Filter Column 2 Effluent	0.05	0.10	0.07
Filter Column 3 Effluent	0.07	0.10	0.08
Filter Column 1 Ripening Time (minutes)		DNR	
Filter Column 2 Ripening Time (minutes)		DNR	
Filter Column 3 Ripening Time (minutes)		DNR	

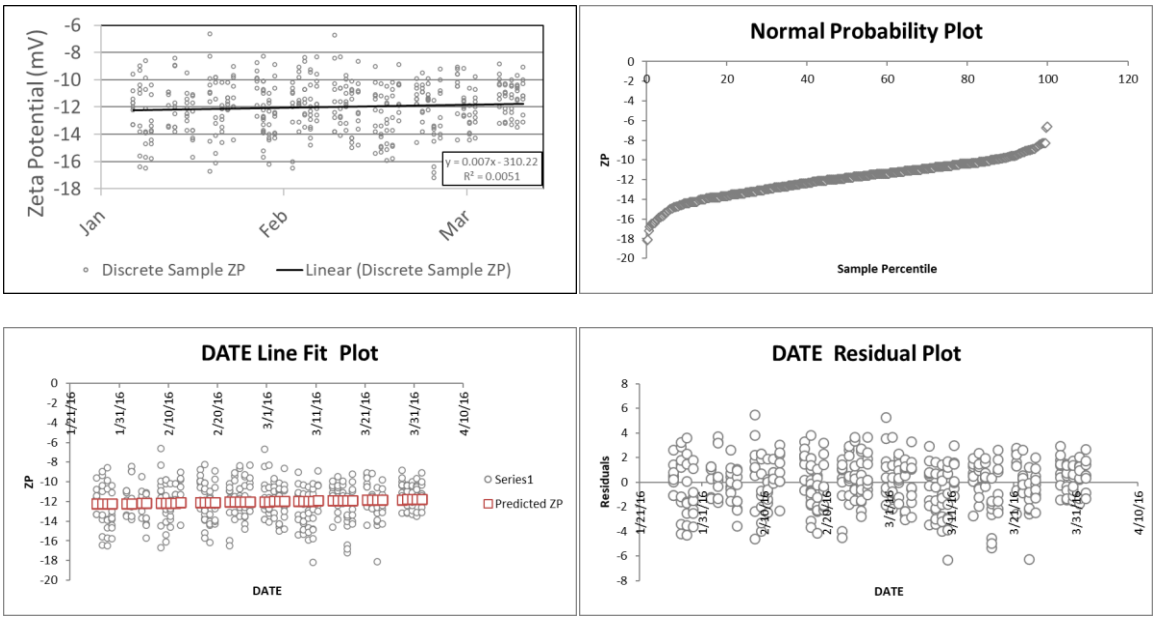
Particle Counts	1 %ile (cts/mL)	99 %ile (cts/mL)	Avg (cts/mL)
Filter Column 1 Effluent	236	236	236
Filter Column 2 Effluent	268	268	268
Filter Column 3 Effluent	114	114	114

Head Loss	Min (m)	Max (m)	Rate (m/hr)
Filter Column 1	0.85	1.49	0.206
Filter Column 2	0.92	1.49	0.226
Filter Column 3	0.87	1.49	0.184

Flows	Avg (mL/s)	Avg (m/hr)	UFRV (m^3/m^2)
Filter Column 1	10	8.58	0
Filter Column 2	10	8.17	0
Filter Column 3	11	8.86	0

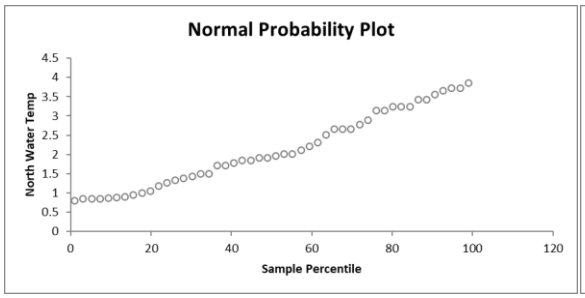
Media Specifications	Filter 1	Filter 2	Filter 3
Sand Size (mm)	0.45 - 0.50	0.45 - 0.50	0.45 - 0.50
Sand Depth (inches)	12	12	12
Anthracite Size (mm)	1.0 - 1.1	1.0 - 1.1	1.0 -1.1
Anthracite Depth (inches)	18	18	18

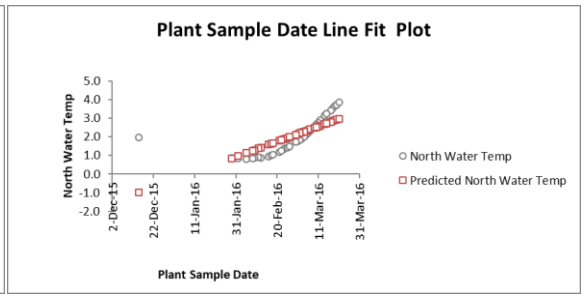
Appendix C : Direct In-line Filtration Pilot - Source Water Summary Statistics

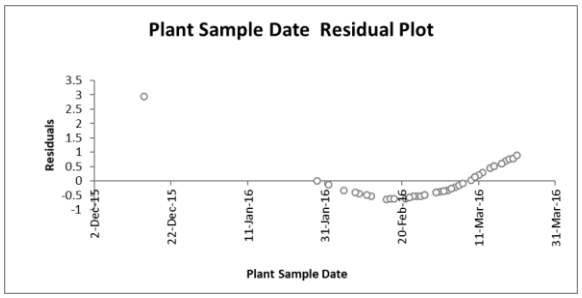


SUMMARY OUTPUT	ALPHA = 0.05							
Regression Statistics								
Multiple R	0.071413941							
R Square	0.005099951							
Adjusted R Square	0.0027141							
Standard Error	1.89904933							
Observations	419							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	7.708947675	7.708947675	2.137581122	0.144481548			
Residual	417	1503.863946	3.606388359					
Total	418	1511.572894						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-310.221224	203.9834235	-1.52081585	0.129063926	-711.1851466	90.74269931	-711.1851466	90.74269931
DATE	0.007029025	0.00480766	1.462046894	0.144481548	-0.002421245	0.016479294	-0.002421245	0.016479294

Figure C.1 Direct In-line filtration pilot. Source water zeta potential statistics showing that the slope of the daily average zeta potential values is not significantly different from zero at 5% confidence.

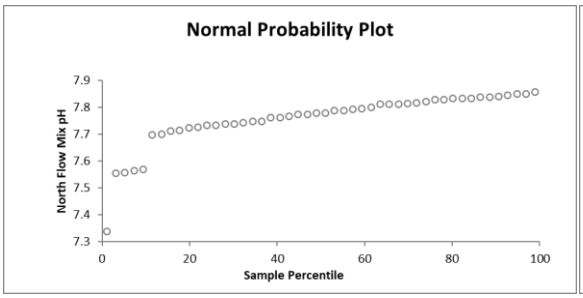


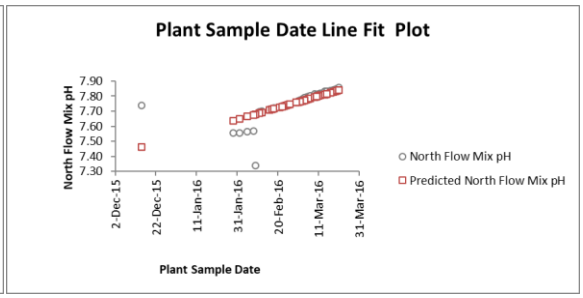


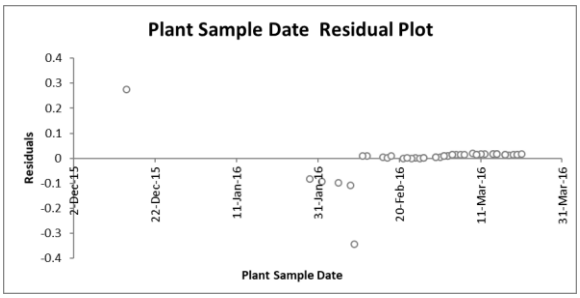


SUMMARY OUTPUT	ALPHA = 0.05							
Regression Statistics								
Multiple R	0.74670218							
R Square	0.557564145							
Adjusted R Square	0.547945974							
Standard Error	0.647783651							
Observations	48							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	24.32553055	24.32553	57.96987	1.1033E-09			
Residual	46	19.30268831	0.419624					
Total	47	43.62821886						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1731.020882	227.6308399	-7.60451	1.14E-09	-2189.217997	-1272.823766	-2189.217997	-1272.823766
Plant Sample Date	0.040847933	0.00536499	7.613795	1.1E-09	0.030048768	0.051647098	0.030048768	0.051647098

Figure C.2 Direct In-line filtration pilot. Source water temperature statistics showing the slope of the daily average temperate at 5% confidence.

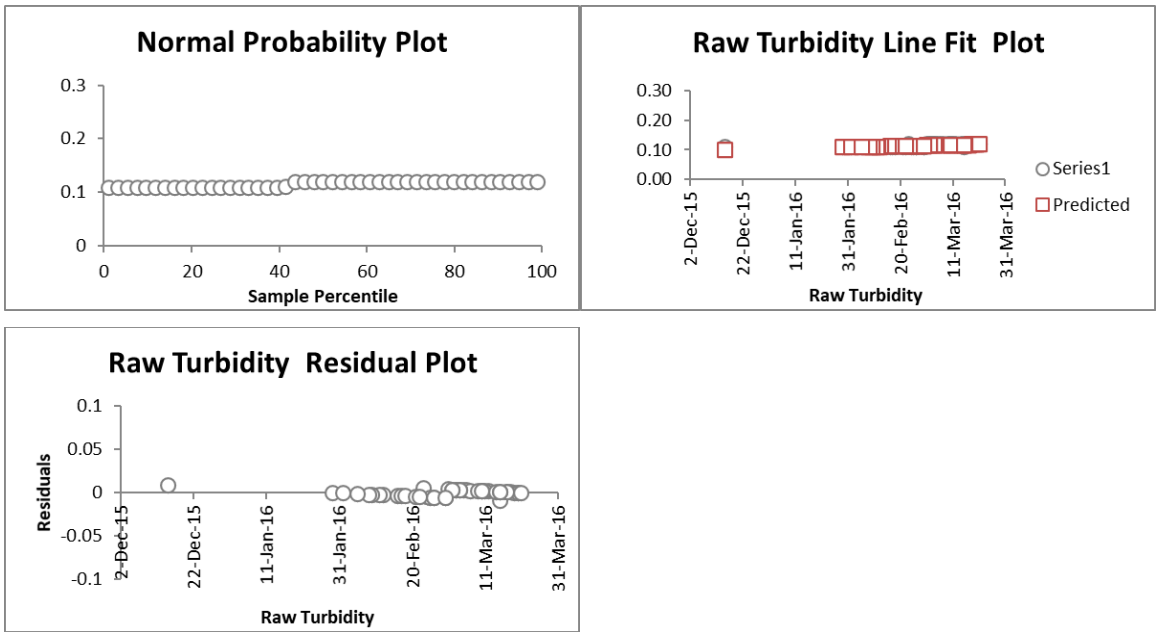






SUMMARY OUTPUT	ALPHA = 0.05							
Regression Statistics								
Multiple R	0.692634379							
R Square	0.479742383							
Adjusted R Square	0.468432435							
Standard Error	0.071659741							
Observations	48							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0.217820094	0.21782009	42.4177348	4.91349E-08			
Residual	46	0.23621545	0.00513512					
Total	47	0.454035543						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-156.2450503	25.18119588	-6.2048304	1.4269E-07	-206.9321687	-105.557932	-206.9321687	-105.557932
Plant Sample Date	0.003865342	0.000593491	6.5128899	4.9135E-08	0.002670706	0.005059977	0.002670706	0.005059977

Figure C.3 Direct In-line filtration pilot. Source water pH statistics showing the slope of the daily average pH at 5% confidence.



SUMMARY OUTPUT	ALPHA = 0.05							
Regression Statistics								
Multiple R	0.687430911							
R Square	0.472561258							
Adjusted R Square	0.460840397							
Standard Error	0.003661709							
Observations	47							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0.000540588	0.000540588	40.31796	9.43577E-08			
Residual	45	0.000603365	1.34081E-05					
Total	46	0.001143953						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-8.111603425	1.295719861	-6.260306465	1.28E-07	-10.72131719	-5.501889661	-10.72131719	-5.501889661
Plant Sample Date	0.00019391	3.05388E-05	6.349642885	9.44E-08	0.000132402	0.000255419	0.000132402	0.000255419

Figure C.4 Direct In-line filtration pilot. Source water turbidity statistics showing the slope of the daily average turbidity at 5% confidence.