Assessment of Filter Ripening at a Direct Filtration Plant, Halifax, NS

by

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DEDICATION

I dedicate this thesis to Matthew Malone for your everlasting support and patience throughout my entire academic experience.

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ABSTRACT

Filter-to-waste infrastructure is now commonly incorporated in recently constructed treatment plants and is required by many jurisdictions, including the Nova Scotia Standard for Surface Water Treatment. In the absence of filter-to-waste, operational backwash procedures, such as filter resting, decreased backwash duration, and extended terminal subfluidization wash (ETSW), have shown promise for decreasing ripening time and intensity. Halifax Water's J.D. Kline Water Supply Plant (JDKWSP) is not equipped with filter-to-waste. Due to the high cost associated with implementing this infrastructure an assessment of filter ripening was performed at this facility to determine if filter-to-waste was needed. The assessment consisted of four studies, including microbial monitoring during filter ripening, testing backwash procedural concepts and backwash water chemistry concepts, and an analysis of the current full-scale procedure.

A 12-month microbial monitoring program was established to examine pathogen breakthrough following filter start-up. Data was collected during filter ripening and tested for *Escherichia coli, Cryptosporidium parvum,* and *Giardia lamblia.* Zero detection of *E. coli* was observed in any sample. All *Cryptosporidium* and *Giardia* samples were not detected above a minimum detection limit of 50 counts/100 L.

Pilot-scale experiments observed the effects backwash procedure on filtered water quality. Turbidity, particle concentrations, and zeta potential were measured. Season was a statistically significant factor ($p<0.001$), with Winter trials resulting in the highest maximum turbidity during ripening, longest ripening time, maximum particle concentration, and achieved the lowest volume of produced filtered water. ETSW was found to be a significant factor ($p=0.004$) in shortening ripening time. Zeta potential fell out of range of the instrument method detection limit (MDL).

Bench-scale experiments were conducted to evaluate the effects of backwash water chemistry changes on filter ripening and filter run time. Turbidity, particle concentration, and zeta potential distributions during the filter run were measured. The interaction between pH and chlorine were found to have a statistically significant ($p=0.012$ and 0.010) influence on ripening time and maximum particles, with finished water conditions ($pH=7.2$, $[Cl_2]=1mg/L$) resulting in lower ripening time but higher particle passage during colder conditions. Zeta potential observations fell within the instrument MDL.

Microbial monitoring determined that filter-to-waste was not necessary to ensure a low risk of pathogen passage during ripening because the system already meets the desired objective. Bench-scale studies determined that wash water chemistry should not be changed. Pilot-studies determined that the current full-scale backwash procedure could be optimized, with respect to energy and water consumption. The full-scale analysis combined with pilot-scale experiments demonstrated potential cost savings that could result by reducing backwash duration. Monitoring of the full-scale backwash procedure assessed operator variance, energy consumption, and water consumption. Three procedural options were suggested offering potential annual cost savings ranging from $0 to $23,000, due to power and water consumptive savings.

LIST OF ABBREVIATIONS AND SYMBOLS USED

ALUM	Aluminum Sulphate
AWWA	American Water Works Association
oC	degrees Celsius
CWRS	Centre for Water Resource Studies
E. coli	Escherichia coli
ETSW	Extended Terminal Sub-fluidization Wash
FBWW	Waste Filter Backwash Water
ft	foot
h	hour
HPC	Heterotrophic Plate Count
JDKWSP	JD Kline Water Supply Plant
$KMnO_4$	Potassium Permanganate
KWH	kilowatt hours
L	liter
L/min	liters per minute
m	meter
m^2	square meter
MDL	Method Detection Limit
µm	micrometer
µg/L	micrograms per liter
mg/L	milligrams per liter
min	minute
mm	millimeter
µL	micro liter
ML/d	million liters per day
mV	millivolt
NSE	Nova Scotia Environment
NTU	nephelometric turbidity units
SD	Standard Deviation
UFBV	Unit Filter Bed Volume
USEPA	United States Environmental Protection Agency

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CHAPTER 1: INTRODUCTION

Filtration is a process used in water treatment where solids (flocculated material and other particles) are removed by physical and electrostatic means. The removal mechanisms are defined as transport, attachment, and detachment, where particles move through the filter media and attach by means of electrostatic forces. If the attachment bonds are not strong enough, or the pore size is not small enough for physical removal, some of the attached particles may detach. During effective filtration, most of these detached particles will reattach deeper in the filter (Huck et al., 2001).

Filtration is considered the polishing stage of water treatment where particles, some bacteria, and larger protozoa are captured in the filter media. This is the final stage of water treatment prior to disinfection. In direct filtration water treatment facilities there is no clarification stage meaning filtration is the only form of solids and microbe removal prior to disinfection (Droste, 1997). Filtration is a water treatment barrier that plays an important role in reducing the risk of pathogen transfer.

In multi-media granular filters, such as those made of sand and anthracite, solids penetrate through the filter to a certain depth. Throughout regular filter operation the pore space between the media becomes obstructed and the pressure head increases. At this point, the filters require cleaning. The process of cleaning the media of a filter is known as backwashing. Treated water is passed backwards through the filter during a backwash, often at a rate causing the filter media bed to fluidize, and sent through to waste collection, treatment, and disposal infrastructure. This process is performed until the media has been sufficiently cleaned (Droste, 1997). Following backwash a ripening phase occurs, where solids and bacteria that normally are captured pass through the media. The ripening phase makes the filtration barrier vulnerable to particle and pathogen passage into the distribution system. Filter ripening is described in detail in Section 1.1.

To reduce the risk of pathogen transfer, procedures have been developed to gain better control over filter ripening. Some procedures and infrastructure that can be employed include filter resting, slow start, extended terminal subfluidization wash (ETSW), shortening of backwash length and intensity, and filter-to-waste (Logsdon et al., 2002; Kawamura, 2000; Amburgey, 2005; Logsdon et al., 2005; Baird and Hillis, 1998; Cranston and Amirtharajah, 1987; Amburgey et al., 2004). Success in reducing the effects of ripening has also been shown by changing backwash water chemistry. These changes may include pH, chlorine, or the addition of polymer. Although it is a robust and wasteful procedure, filter-to-waste may be an important step of the multi barrier approach at reducing the risk of microbial passage. By directing the initial filtrate to the waste collection systems until turbidity reaches an acceptable level in the filtered water, filter-to-waste minimizes the risk of pathogen passage into the distribution system. In some cases where facilities are unable to meet turbidity goals and requirements during ripening, filter-to-waste becomes a necessary step. Filter-to-waste is not necessary to reduce microbial passage when turbidity goals are met (Soucie and Sheen, 2007).

1.1 Filter Ripening

Filter ripening is classified as a period of increased turbidity seen immediately following a backwash. For more than 30 years filter ripening has been studied as a result of its vulnerability to increased passage of microorganisms into the distribution system. Specifically, *Cryptosporidium* is of great concern due to its resistance to disinfection. For this reason, a great deal of research has been performed to develop methods to reduce the effects of ripening (Amirtharajah and Wetstein, 1980; Amirtharajah 1985; Baird and Hillis, 1998; Logsdon et al., 2002; Amburgey, 2005).

Filter ripening is caused by remnant particles remaining in the filter after a backwash and newly influent particles entering the filter. The ripening process can be broken down into five phases: lag, media disturbance and intra-media remnant, upper filtration remnant, influent mixing and particle stabilization, and filter media mixing and dispersed remnant particles (Amirtharajah and Wetstein, 1980; Amirtharajah, 1985), as shown in Figure 1.1.

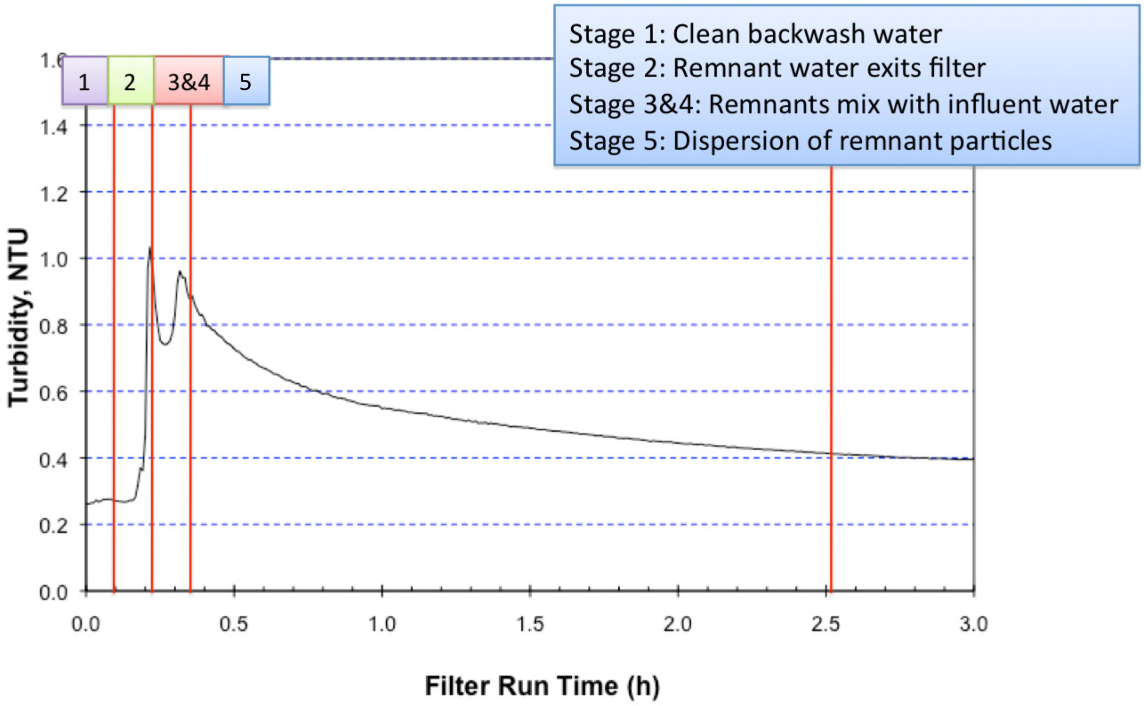

Figure 1.1 Graphical description of the stages of filter ripening (Amirtharajah and Wetstein, 1988; Amburgey, 2005)

The lag stage is a period of low turbidity seen at the beginning of ripening. This is due to clean backwash water remaining in the underdrains of the filter. As a result, this turbidity is equal to that of the water used for backwashing (Amirtharajah and Wetstein, 1980).

The media disturbance and intra-media remnant phase is the second stage of ripening and when the first increase in turbidity is seen. This is a result of particles that were dislodged from the media during backwash fluidization that were not removed. Remnant particles may also be present as a result of media collisions during settling (Amirtharajah and Wetstein, 1980).

The upper filtration remnant phase is due to remnant particles remaining above the filter media beginning to pass through the filter. These destabilized particles are able to pass back through the filter media as collector efficiency of the filter bed has not yet returned to adequate working order. This phase is often discussed in combination with stage four, the influent mixing and particle stabilization stage. This stage represents newly flocculated particles entering the filter and mixing with the remnant particles (Amirtharajah and Wetstein, 1980).

The filter media mixing and dispersed remnant particle stage is the final stage of ripening. This is when the remnant particles travelled through the filter and the filter media is beginning to establish collector efficiency. Filter media is able to capture newly flocculated influent particles and filtered water turbidity begins to decrease.

1.2 Turbidity monitoring

Drinking water treatment facilities are required to continuously monitor turbidity during filtration (Environment Act, 1995; Nova Scotia Environment, 2005). This includes the moment filters are turned online following a backwash until the end of the filter run. Inline turbidimeters allow for continuous observation of turbidity profiles during filter ripening and filtration cycles. From this data maximum turbidity during ripening, ripening time, and filter run times can be observed. Turbidity is often used as the primary parameter for assessing filter ripening.

Nova Scotia drinking water treatment standards require that facilities filter-to-waste until turbidity reaches 0.2 NTU. In fact, filtered water turbidity must be less than or equal to 0.2 NTU at least 95% of the time. Filtered water turbidity can never be greater than 1.0 NTU (Nova Scotia Environment, 2012). Due to the cost of construction, older facilities not equipped with filter-to-waste are interested in determining if the infrastructure is necessary. As part of this process both raw water and filtered water during ripening require microbial analysis. Current backwash processes should also require monitoring as they are somewhat undocumented at many facilities.

In a previous analysis of turbidity at JD Kline, some filters showed turbidity spikes greater than 0.2 NTU. It has been showed that *Giardia* may pass through a filter when turbidity is 0.2 NTU (Logsdon et al., 1981). Effective removal of pathogens may fluctuate over ripening phases of filter operation (Emelko et al., 2003). Reduced removal of *Cryptosporidium* has been shown to be lower during the ripening phase than in steady state operation (Emelko, 2003). For this reason, direct sampling and analysis for *Cryptosporidium*, *Giardia*, and *E. coli* should be performed as part of the assessment of filter ripening.

1.3 Particle monitoring

Particle monitoring is becoming recognized as an important procedure for optimizing water treatment plant performance (McTigue et al., 1998). Monitoring disinfection resistant protozoa, such as *Cryptosporidium* and *Giardia,* is both time consuming and costly. *Cryptosporidium* ranges between 3 to 6 µm in size (Huck et al., 2001) and *Giardia* ranges between 10 – 13 µm in size (Dai and Boll, 2006). Monitoring the effectiveness of a treatment process at removing particles greater than 2 µm can be done at a much lower cost. By ranking different types of treatments it is possible to show the relative effectiveness of each treatment by plotting particle concentration distributions. Both inline particle counters and micro flow imaging devices can provide particle size range concentrations. This can be accepted as an indirect method for monitoring microbial contaminants. It is a conservative approach to understanding filter efficiency at removing *Cryptosporidium* and *Giardia* (Huck et al., 2001).

McTigue et al. (1998) studied the relationships between particle concentrations and pathogens observed in a 100-plant survey. Although a direct relationship between particle concentration and *Cryptosporidium* or *Giardia* concentration was not found, particle concentrations that increase over long-term assessments have been related to increase risk of pathogen presence. Also, events with increased particle concentrations (spikes), such as during filter ripening, should be minimized. Pilot-studies showed that pathogens are more likely to pass during these events.

1.4 Surface Charge Monitoring

Due to ionization or bonding of other particles resulting from charge attraction, particles in a solution will have a particular surface charge. Zeta potential measures the net surface charge of particles in a solution. Particles, such as those found in raw water, are considered stable in nature and exhibit a highly negative or positive surface charge. The act of destabilizing these particles during water treatment comes primarily from the coagulation process. The addition of an inorganic metal, or coagulant, such as aluminum sulphate (alum), attracts highly charged particles causing the particles to agglomerate into larger units. As particles become destabilized, the zeta potential of solution approaches zero (Pernitsky et al., 2011).

The effectiveness of filtration is controlled by two mechanisms: physical removal and chemical removal. Physical removal is controlled by filtration rate and media characteristics. It is limited by the size and depth of the media. Chemical removal of particles is controlled by the electrostatic attraction of the destabilized particles to the filter media (Wang, 1998). By examination of charge differences between media and particles, zeta potential was found to be a useful tool for predicting filter activity (Stephan and Chase, 2001). Particles entering the filter must have a zeta potential close to 0 mV because sand anthracite filters have a negative charge. Inadequate coagulation, leaving a high negative charge, will cause the particles to repel and decrease filterability (Pernitsky et al., 2011).

The intensity of the backwashing process causes a change in the surface charge of the filter media. The act of fluidizing the filter media damages the optimized charge that was build up over the filter run. Optimization of media charge and build up of collector efficiency is a natural process known as conditioning. The conditioning of filter media begins immediately after a filter is put in service following a backwash and is complete after the filter ripening period. Zeta potential may be a useful measurement tool to describe filter performance and how the collector efficiency of the media increases during ripening.

1.5 Research Objectives

The overall goal of this thesis was to understand the effects of backwashing on filter ripening and understand risk of microbial passage through the filters during ripening. To meet this objective four sub-tasks were conducted. These sub-tasks are described as:

1. A 12-month full-scale microbial monitoring program
2. Pilot-scale experiments to observe effects of ETSW and decreased backwash duration
3. Bench-scale experiments to observe effects of polymer addition, pH, and chlorine
4. Full-scale backwash procedure monitoring

This thesis attempted to observe the statistical significance of backwash procedure and water chemistry at controlling increased turbidity, particle concentrations, and zeta potential during ripening periods. As part of this research, observations of the current full-scale backwashing procedure were made in an attempt to establish a baseline set of data and understand the magnitude of operator variance. The purpose of these experiments was to identify where optimization could be performed. Backwash procedural options were assessed to determine power and water consumption and the costs of each alternative.

CHAPTER 2: LITERATURE REVIEW

2.1 Removal of Microbial Pathogens

2.1.1 Public Health Concerns with Microorganisms

Pathogenic microbes, such as *Cryptosporidum*, *Escherichia coli (E. coli)*, and *Giardia* are sometimes found in surface water systems. They are found in waters that are in close contact with human or animal feces (LeChevallier et al., 1991; Logan et al., 2001; Kim et al., 2010; Graczyk and Fried, 2007). To ensure the health and safety of water consumers, barriers are needed to adequately block the passage of or inactivate harmful pathogens during the treatment process. Turbidity is used as an indirect method to estimate the presence of these microbiological parameters.

Cryptosporidium, although mostly found in unprotected source water, is a protozoan that can cause health problems within a human intestinal tract. It can cause an inconvenient infection in healthy adults but poses a larger risk to infants, the elderly, and people with compromised immune systems. In vulnerable individuals *Cryptosporidium* has been found to cause extreme sickness and death (Logan et al., 2001). A filtration step is required to adequately remove *Cryptosporidium* from water due to its resistance to chemical disinfection (Emelko, 2003).

The *E. coli* serotype O157:H7 is known to cause a severe gastrointestinal infection leading to bloody diarrhea, renal failure, and in some cases death. Children have been found to be most vulnerable to the illness. *E. coli* has been linked to almost 250 human deaths in the United States annually (Boyce et al., 1995).

Giardia is often found in surface waters that are inhabited by smaller animals, such as beavers or muskrats. *Giardia* is a protozoan parasite that causes severe gastrointestinal illnesses. Although *Giardia* is more susceptible to chemical disinfection than *Cryptosporidium,* filtration is the most effective way to ensure a 3-log reduction of both pathogens (Graczyk and Fried, 2007).

2.2 Seasonal Impact on Drinking Water Treatment

Seasonal can impact chemical and physical characteristics of surface water in Canada. The treatment of surface water for drinking water often requires operational adjustments to be made as seasonal temperatures change. Canadian surface waters can have temperature variations from $2^{o}C$ to $25^{o}C$ throughout the year. Chemical reaction rates are dependent on temperature and are usually reduced as temperature decreases, which can affect both the treatment and delivery of drinking water (Environment Canada, 1975).

Physical characteristics of water refer to temperature and density and viscosity. Colour and turbidity are also indirectly related to temperature due to temperature's effect on coagulation. Operations at a drinking water treatment facility will need to adjust to changing temperatures. Coagulation, sedimentation, and filtration are all affected by seasonal changes in surface water (Environment Canada, 1979). As temperature increases, the optimal pH for coagulation decreases (Maudling and Harris, 1968). The density, dynamic viscosity, and kinematic viscosities of water at $5^{o}C$ and $25^{o}C$ are shown in Table (Vennard and Street, 1975). The viscosity of water increases as temperature decreases, which slows the rate of sedimentation decreasing the removal of turbidity and colour. Due to the increase in viscosity during colder temperatures, filtration is also slowed down (Burnson, 1938). The ability of a filter to reduce turbidity is decreased, in part due to a weaker floc strength (AWWA, 1971). The filter media, if activated carbon, is also affected by temperature. Adsorptivity of this media has been found to increase as temperature decreases (Weber and Morris, 1964).

Table 2.1 Physical properties of water (Vennard and Street, 1975)

Physical Parameter	5°C	25°C
Density, ρ (kg/m^3)	1,000.0	997.0
Dynamic viscosity, μ (N-s/m^2)	1.518×10^{-3}	0.890×10^{-3}
Kinematic viscosity, ν (m^2/s)	1.519×10^{-6}	0.893×10^{-6}

Chemical characteristics of water that are related to water temperature are natural organic matter and the solubility product of calcium carbonate. Natural organic matter concentrations were found to increase in warmer temperatures, which led to an increase in disinfection by-product formation after chlorination (Stevens et. al, 1976). The solubility of calcium carbonate decreases with temperature. In water with low alkalinity, when temperatures increase, pH decreases, which increases the solubility of calcium carbonate. This can result in decreased scaling but increased corrosion (AWWA, 1971).

Physical, chemical, and operation effects of seasonal changes are summarized in Table 2.2.

Table 2.2 Summary of seasonal impacts on drinking water treatment

Parameters		Winter (cold)	Summer (warm)
Physical	Temperature	2^{o}C	25^{o}C
	Viscosity	Increase	Decrease
	Turbidity/Colour	Decrease	Increase
Chemical	Natural Organic Matter	Decrease	Increase
	Calcium Carbonate Solubility	Decrease	Increase
	pH	Decrease	Increase
Operational	Coagulation (Floc Strength)	Decrease	Increase
	Sedimentation Rate	Decrease	Increase
	Filtration Rate	Decrease	Increase

2.3 Techniques for Controlling Filter Ripening

Controlling filter ripening reduces the risk of microbial passage to the public. This is achieved by reducing the duration and intensity of turbidity spikes. The American Water Works Association conducted a survey with 44 drinking water utilities to understand the methods used to control filter ripening. The survey asked respondents to identify which controls were utilized and if the facility had been successfully keeping ripening turbidity below 0.3 NTU. The types of controls used by these utilities included filter-to-waste, filter resting, delayed filter startup, and addition of a coagulant or polymer. Most utilities reported using a combination of these methods and were successfully keeping ripening turbidity below 0.3 NTU (Logsdon et al., 2002). Filter resting and delayed filter startup are described in Sections 2.3.1 and 2.3.2, respectively.

Optimization of the backwash procedure can also play an important role in controlling filter ripening and reducing both energy and water consumption. Some examples of backwash procedures that may reduce the negative effects of ripening are turbidity control, altering backwash water chemistry, and using extended terminal subfluidization wash (ETSW) (Kawamura, 2000, Amburgey, 2005). Backwash optimization techniques are described in Sections 2.3.3 to 2.3.5.

2.3.1 Filter Resting

Filter resting, or delayed start, can be used to control ripening by keeping the filter out of service for a period of time immediately following a backwash. Newly flocculated or settled water enters the filter but before the filter is put back in service, the media is allowed to settle. It works in two ways. By allowing the filter media to settle completely the void spaces become smaller. Also, the remnant particles remaining above the filter can settle and the particles within to collect to the media. The advantage of this is that it requires no extra infrastructure and can be performed at any facility that has the capacity to keep a filter offline for a period of time. Some facilities using this technique reported no success in lowering ripening turbidity (Logsdon et al., 2002).

In a more recent review Logsdon et al. (2005) continued to support filter resting (delayed start) as a procedure able to reduce the initial turbidity spike seen during ripening. The suggested resting times are between 15 minutes and 48 hours but not longer. Resting filters for up to 48 hours can help reduce void spaces between media pores and aid in remnant particle attachment to media. However, holding filters out of service for longer periods may increase the risk of bacteria growth within the filter. The authors also described the results of a study comparing rapid gravity filters with no delay and delays of 46 minutes, 95 minutes, and 144 minutes. Turbidity results showed that all rested filters achieved a lower maximum turbidity during ripening and correspondingly, a faster ripening time. Both the 95- and 144-minute trials performed best at reducing the initial turbidity spike. The same study described how resting a filter for 144 minutes can reduce the number of particles greater than 2 μm passing through the filter during ripening.

Wierenga (1985), observed heterotrophic plate count (HPC) and coliform bacteria growth on washed filters kept offline for an extended period of time. Microbial growth was observed during summer with water temperatures in excess of 20^{o}C. Filters were kept offline for 40 and 64 hours. The highest bacteria growth was observed after 64 hours of resting. Some, but very little bacteria growth was observed after 40 hours of resting. This study was based upon a contamination within the distribution system leading to a boil order. Some washed filters were kept offline for an entire weekend, which is suspected to be the cause of increased microbial growth.

In a study of the effectiveness of filter resting, Baird and Hillis (1998) discuss pilot work that showed up to 65% reduction of particle passage during ripening. These results were tested at three full-scale facilities that were using filter resting. Effectiveness was measured using particle counts and assessing removal between 2 and 5 μm. Each of the facilities observed a significant increase in removal of particles in this size range.

Pizzi (2000) described filter resting as a method to optimize a facility's filter performance. He discussed a study that was performed in Ohio which compared the performance of two filters: one that was kept out of service for 4 hours after backwashing and another that was placed online immediately. The filter rested for 4 hours following the backwash showed a lower ripening turbidity and shorter run time. Specifically, filters rested for 4 hours had an average ripening time of 34 minutes. Filters not rested had an average ripening time of 60 minutes. Once the filter was backwashed and newly influent water allowed to fill the filter, resting the filter allowed for more time for electrostatic forces of the newly flocculated material to collect to the media.

Amburgey et al. (2004) performed pilot trials that tested the effectiveness of filter resting on reducing maximum turbidity and number of particles greater than 2 μm removed during ripening. Results showed that filter resting consistently achieved higher removals of both turbidity and particles in this size range than filters that were not rested. It was suggested that this was due to a longer time for particles to settle and reattach to each other or the filter media. The success of filter resting was also found to be dependent on the charge of the remnant particles remaining in the filter, which are significantly influenced by the backwash water chemistry.

2.3.2 Slow Start

Slow start is a method that requires a variable flow rate control valve. Water begins to be filtered at a low rate increasing to the full filtration rate over about 15 minutes. This allows the remnant particles a chance to settle and the void spaces between the filter media to become slightly smaller. Studies using only slow start show mixed results. Although gradually starting a filter after backwash usually increases removal of particles between 2 to 5 μm, the method might not solely be enough to keep filtrate within regulations. Slow start has shown most success with postponing ripening. This method is often paired with another control (Logsdon et al., 2002).

In a more recent review Logsdon et al. (2005) continued to support slow start as a method capable of reducing the effects of filter ripening. By gradually starting a filter the operation placed less stress on the remnant particles remaining in the filter. The authors also stated that a slow start might not be effective if the facility does not have a modern rate-control valve capable of being opened slowly and in multiple steps.

A study by Colton et al. (1996) found that a filter using slow start after a backwash was successful at removing particles in the 2 to 5 μm range during the ripening period. This research was conducted at a direct filtration facility using ferric III sulphate as a coagulant. Two scenarios were compared which included 30- and 60-minute durations to reach the full filtration rate. The effectiveness of each depended on the type of filtration media used. A 30-minute slow start was most effective for the larger sand filter media and visa versa for the 60-minute slow start. An overall 57% reduction of particles in the 2 to 5 μm size range was seen.

Baird and Hillis (1998) presented both pilot and full-scale observations of the effectiveness of both filter resting and slow start at reducing particle passage during ripening. Slow start was observed to significantly reduce the amount of particles in the 2 to 5 μm passing through the filters during ripening.

2.3.3 Turbidity Control

Turbidity control is a method where a filter is backwashed until the waste filter backwash water (FBWW) turbidity reaches between 10 and 15 NTU. In a survey conducted by the AWWA, utilities reported a large variation in this practice. Some utilities backwashed filters until the backwash turbidity reached less than 5 NTU, others backwashed until it was between 10 and 15 NTU, and others ceased backwashing before turbidity reached 15 NTU. There are advantages to each of these methods (Logsdon et al., 2002).

It is important to optimize the turbidity control of a backwash. Not only does the backwash process use a lot of energy and water, if a filter is over washed ripening time may increase. An under washed filter poses a risk of mudball formation and may decrease filter run time by causing a more rapid head loss. Optimizing this process can save money and decrease the ripening period (Logsdon et al., 2002).

Pizzi (2000) offered backwash considerations and suggest that filters should perform best when washing until turbidity reaches 4 to 5 NTU. This was found to ripen filters by maintaining some of the previous collector efficiency.

Kawamura (2000) described the entire filter cycle including advice on decreasing the negative effects of filter ripening by optimization of the backwash process. It is suggested that many water treatment facilities backwash filters excessively, making them too clean. That study suggested terminating the backwash when backwash water turbidity reaches between 10 to 15 NTU. Not only can backwash water turbidity control reduce ripening time and maximum turbidity seen during ripening, it will also reduce energy consumption. Kawamura (2000) also described possible problems associated with cleaning a filter to this range, or controlling the backwash turbidity. Some of the problems might include mudball formation and a shorter filter run time due to an increase rate of loss of head. These negative effects should not happen if the procedure is optimized for each facility by selecting the correct backwash rate.

In an evaluation of surface water treatment plant filter performance, Consonery et al. (1997) identified risks associated with starting filters that have not been backwashed. The authors stated that restarting unwashed filters increase the risk of protozoan passage during ripening. This principal can be applied to inadequately washed filters.

Amburgey et al. (2003) found that termination of a backwash at turbidity of 10 NTU would be ineffective at reducing the effects of ripening if followed by extended terminal subfluidization wash (described in section 2.3.4). This procedure is only effective at removing the steady state remnant particles and effectiveness was hindered by the presence of larger backwash particles.

2.3.4 Extended Terminal Subfluidization Wash

Extended terminal subfluidization wash (ETSW) is a backwashing process that removes remnant particles from the filter bed without further disrupting the media. Following a normal, optimized backwash procedure ETSW uses a backwash rate high enough to remove remnants from the filter column but not to fluidize the media. This helps reduce further removal of collector efficiency. The subfluidizing rate is usually used until one bed volume of water to passes through the filter. Using this procedure may reduce ripening time, backwash water and energy consumption, and decrease maximum turbidity during ripening (Amburgey et al., 2003; Amburgey, 2004; Amburgey and Amirtharajah, 2005, Amburgey and Brouckaert, 2005).

Amburgey et al. (2003) showed the effectiveness of ETSW at both pilot- and full-scale plants. The facility used direct biological filtration with dual media anthracite-sand filters. A cationic polymer was used as the main coagulant. Raw water was drawn from low turbidity surface water with turbidity typically ranging from 1 to 2 NTU. Backwash water consumption was reduced by 25 %. ETSW was successful at significantly reducing ripening time and maximum turbidity during ripening.

2.3.5 Backwash Water Chemistry

Changing the backwash water chemistry has been shown to be successful in reducing the effects of filter ripening. In particular, the addition of coagulant or cationic polymer injected directly into the backwash water has shown promise at reducing ripening time and maximum turbidity during ripening. This allows for increased adhesion of remnant particles to the media and also agglomeration of these particles, which allows for easier physical removal (Logsdon et al., 2002).

Problems with adding coagulant or polymer to backwash water might include unwanted floc formation in the clearwell and difficulties controlling the dosage during the short backwashing time and with respect to changing raw water conditions (Amburgey et al., 2003).

Cranston and Amirtharajah (1987) discuss the benefits of adding coagulant or polymer to backwash water. They performed experiments with the objective of reducing the negative effects of ripening while reducing the amount of water wasted during a filter-to-waste procedure. Using alum as the primary coagulant in backwash water showed to be successful at decreasing ripening time and maximum turbidity during ripening.

Pilot studies by Yapijakis (1982) demonstrated the impact of backwash water chemistry change to filter ripening. The author observed that the addition of polymer to backwash water significantly reduced the ripening time and maximum turbidity seen during ripening. Not only was this seen to improve ripening of a direct filtration process, it was also noted to increase solid settling speed in the backwash waste stream. In a cost analysis of this procedure, polymer could be added to the discharge end of the backwash pump to prevent needing backwash water mixing tanks.

The effects of backwash water chemistry were evaluated by Amburgey et al. (2004). One trial showed that chlorine had a negative effect on reducing filter ripening turbidity and ripening time. Other trials were inconclusive due to the effects of orthophosphate and polyphosphates (for corrosion control in the distribution system). The addition of these chemicals was unavoidable during the remaining trials. Further attempts to understand the effects of pH and chlorine were masked by these chemicals. The authors suggested that the 50/50 blend of orthophosphate and polyphosphate decreased the pH in the chlorine rich trial, lowering the negative zeta potential of the solution. Also, the same blend could have increased the pH of the chlorine deficient trial, increasing the negative zeta potential of the solution. As a result, the effects of chlorine in backwash water on filter ripening could not be seen during this trial.

2.4 Summary

Filter ripening is a period of increased turbidity that is observed following a backwash after filter startup. Due to this spike in turbidity, filter ripening is classified as a period of the filter cycle that is vulnerable to microbial passage. Although disinfection is capable of deactivating many microbes, some pathogens, such as *Cryptosporidium* and *Giardia* are resistant to disinfection. Filtration is an important barrier to prevent the passage of disinfection resistant pathogens.

Although filter-to-waste isolates filtered water during ripening from the system, the robustness of this procedure may not be required by all utilities. The previously discussed ripening control methods, or combinations of them, have shown to be successful in keeping ripening turbidity below required levels. The type of control method used depends on the facility, source water, treatment type, and the ability of the facility to keep filters offline for a period of time. Each method must be optimized for each site to prevent mudball formation, reduced filter run times, unwanted microbial growth on the filters, and to ensure they can adequately reduce ripening time and intensity. This thesis will analyze and discuss the effectiveness of each method with respect to turbidity and particle removal at the JDKWSP.

CHAPTER 3: MATERIALS AND METHODS

3.1 Full-scale Plant Overview

The JD Kline Water Supply Plant (JDKWSP) is a direct filtration plant that treats surface water from Pockwock Lake, which is located within a protected watershed in Halifax, Nova Scotia. This source water is characterized with having low alkalinity, low pH, and low turbidity. A schematic diagram of this facility is shown in Figure 3.1. It pumps water from the lake, which passes through a screen and enters a pre-oxidation stage of treatment. The oxidation stage is performed throughout three pre-mix tanks. The first tank uses lime to increase the pH to 10 and potassium permanganate to oxidize iron and manganese. The second tank provides mixing. Carbon dioxide is added to the third tank to decrease the pH to about 5.5 for optimal performance of the coagulant, aluminum sulphate (alum). It should be noted that during colder temperatures a coagulant aid (polymer) is added to the pre-mix stage. Chlorine is added during the pre-mix stages to maintain a residual of 0.05 mg/L at the end of treatment. This is to prevent bacteria growth on the filters. Water then passes through six hydraulic mixing cells where flocculation occurs. Once flocculated, the water passes through the filters. There are 8 filters in total, each are dual-media consisting of 2 ft of anthracite and 1 ft silica sand. A schematic of a JDKWSP filter is shown in Figure 3.2.

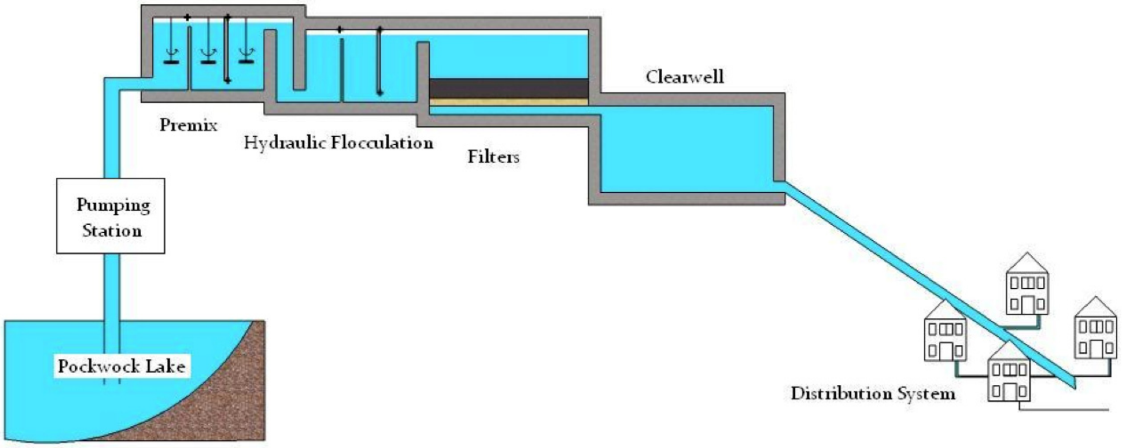

Figure 3.1 Schematic diagram of the JD Kline direct filtration water supply plant

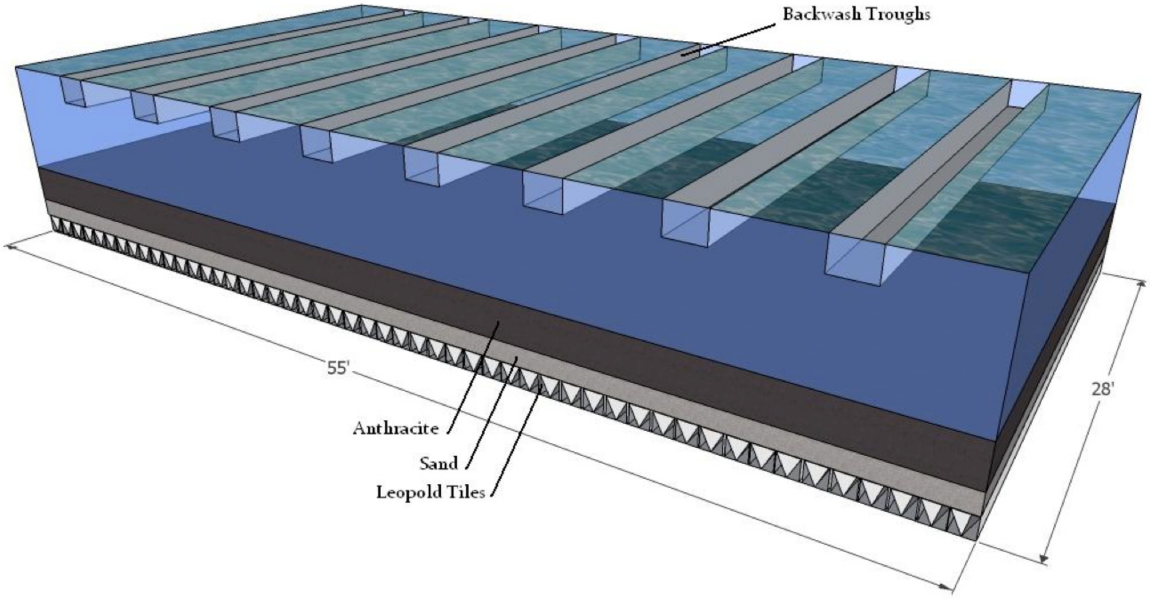

Figure 3.2 Schematic of the filters at the JD Kline water supply plant

3.2 Microbial Monitoring (Full-scale)

3.2.1 Sampling Schedule and Collection

As part of the project objectives a 12-month sampling campaign was followed to identify risk of microbial passage during filter ripening. The JDKWSP has eight filters in operation at full-scale. A sampling schedule was followed to ensure each filter was sampled equally. Each month three different filters were sampled for the 12-month duration, allowing seasonal observation.

An apparatus was machined to collect samples of filtered water during ripening for *Cryptosporidium*, *Giardia*, and *E. coli* testing. A schematic of this device is shown in Figure 4. The apparatus was designed allowing *E. coli* to be sampled every 10 minutes without disrupting the continuous sampling of *Cryptosporidium* and *Giardia*. The flow to the *Cryptosporidium* and *Giardia* sampling filter can be controlled, as per USEPA standard, to ensure that it remains at 2 L/min or less. Sampling ports were installed directly below each full-scale filter, as shown in Figure 3.3. Sample collection began 10 minutes after the filters had been put back online following a backwash and resting period.

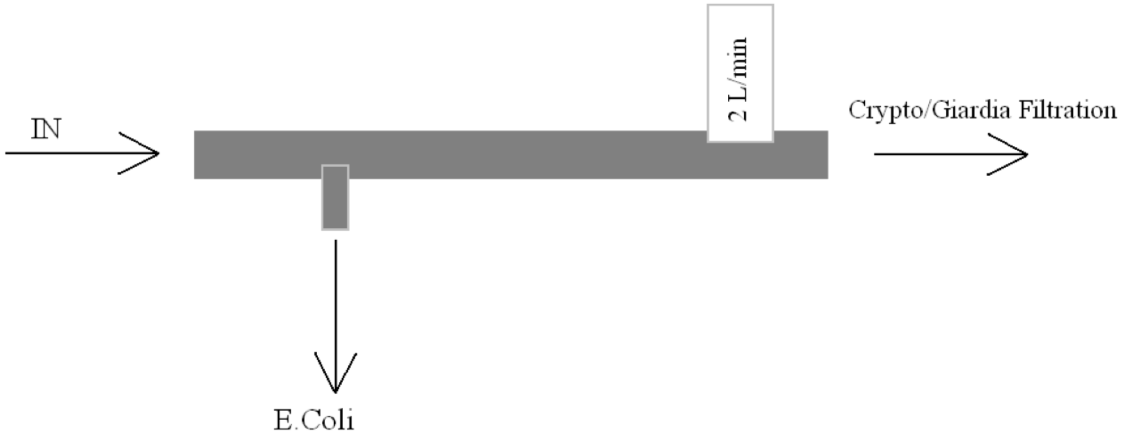

Figure 3.3 Schematic of microbial sampling apparatus

Three 100 mL samples were taken for *E. coli* at 10-, 20-, and 30-minutes and sampled in 100 mL sterilized sampling jars, as provided by the Capital Health Environmental Services Laboratory, Halifax, NS. Proper sampling procedures were followed, such as changing gloves for each sample and holding jar lid downwards, to ensure contamination did not occur. Samples were kept on ice until processed in the laboratory.

Cryptosporidium and *Giardia* sampling began immediately after the first *E. coli* sample had been collected. Water was passed through the EnviroChek® HV sampling capsule at 2 L/min for 1 hour, filtering approximately 120 L of water. The capsule was then removed from the sampling apparatus ensuring the cylinder remained full with sample water. Capsules were provided by Clancy Environmental Consultants, Inc. Samples were kept on ice until processed in the laboratory.

3.2.2 Microbial Analysis

Microbial analysis was performed by third party certified laboratories. *E. coli* was processed locally and *Cryptosporidium* and *Giardia* were sent to a laboratory in the north east United States.

3.2.2.1 Escherichia coli

Microbial analysis of *E. coli* was performed at the Environmental Services Laboratory for Environmental Chemistry and Water Bacteriology at the Queen Elizabeth II Health Sciences Center in Halifax, Nova Scotia. Analysis accounted for Most Probable Number (MPN) and Total Coliform counts. Results were presented as detects or non-detects. IDEXX Colilert 18 was used to determine if either E. coli or total coliforms were present in the samples.

This procedure is capable of detecting E. coli at 1 CFU/100 mL sample in the presence of 2 million (or less) Heterotrophic Plate Count (HPC) bacteria. It uses nutrients that, when consumed by E. coli and total coliforms, produces fluorescence. IDEXX Colilert 18 is able to detect bacteria within 18 hours (USEPA, 2008).

The sample was added to a vessel containing Colilert-18 nutrients. A reagent was added to the 100 mL sample and shaken until dissolved. Then, the sample was placed in a warm water solution for 20 minutes until the temperature reached between 32 and 38^{o}C. After incubating for 18 hours, the sample is placed next to a comparator (yellow in colour). If the sample is more yellow than the comparator it is placed under a 6 Watt 365 nm UV light. If the sample shows a brighter fluorescence than the comparator then E. coli is present. If not, only total coliforms can be confirmed (USEPA, 2008).

3.2.3.2 Cryptosporidium and Giardia

Microbial analysis of *Cryptosporidium* and *Giardia* are performed at the Consulting and Microbiological Laboratory Services department at Clancy Environmental Consultants, Inc. in Saint Albans, Vermont. The results were presented as detects or non-detects.

This procedure is based on USEPA Method 1623: *Cryptosporidium* and *Giardia* in water by filtration. Water was filtered through the EnviroChek® HV capsule, depositing oocysts, cysts, and other materials on the filter. For analysis, a solvent was washed through the filter then placed in a centrifuge to remove the excess water. *Cryptosporidium* oocysts and *Giardia* cysts were centrifuged and pelletized. Oocysts and cysts were then magnetized by attaching magnetized anti-*Cryptosporidium* and anti-*Giardia* antibodies. A magnet was then passed over the magnetized oocysts and cysts, which separated them from the inessential material. Oocysts and cysts were stained and counted under a differential interference contrast microscope (USEPA, 2005).

3.3 Backwash Procedure Monitoring (Full-scale)

3.3.1 Backwash Turbidity Profiling

Filter backwash procedures are performed at the JDKWSP after 80 hours of filter run time, the turbidity reaches 0.2 NTU, or the filter reaches a headloss of 2.15 m. The backwashing process is a somewhat undocumented process, with respect to turbidity of FBWW. A sample schedule was coordinated such that one filter could be sampled each week. It was found that a typical backwash has a duration of less than 8 minutes. Samples were collected in 200 mL plastic containers above the filter media at intervals of 1 minute for the first four minutes and 30 seconds for the remainder of the backwash. The samples were then analyzed on a Hach 2100N laboratory turbidimeter.

A unique backwash profile was created each time using turbidity, backwash water volume used, and energy consumed. The operator who performed the backwash was also recorded. The goal was to understand how clean a typical filter gets during a backwash and make suggestions on process optimization options. The process of backwashing a filter requires the operator to visually inspect the clarity of the water as it is being backwashed. The backwash pumps were shut off once a fixed point on the backwash trough becomes visible. This backwash procedure leaves some room for interpretation so operator variance was considered by observing trends in backwash duration.

3.3.2 Filter Ripening Profiling

Operators at the JDKWSP practice filter resting following a backwash, keeping the filter offline for a minimum of 1 hour. To understand the relationship between the full-scale backwash procedure and filter ripening, samples were taken of filter effluent water during the ripening period. Typically ripening time is less than 1 hour. The samples were taken for 1 hour at 5 minute intervals for the first 30 minutes and then at 10 minute intervals for remaining 30 minutes. Although many more backwashes were performed throughout the year, samples were taken on 23 days for particle analysis. These sampling periods were used for the assessment of the current full-scale process. Particle and zeta potential analysis were performed on these samples in the Center for Water Resource Studies (CWRS) laboratory at Dalhousie University. Particle analysis was performed on a Brightwell Micro-Flow Imager at high resolution. Zeta potential analysis was performed on a Melvern Zeta Sizer using the Smoluchowski method. Turbidity during ripening was measured with inline turbidimeters at the JDKWSP.

3.4 Pilot-scale Plant Overview

The pilot-scale plant at the JDKWSP uses a direct filtration process to simulate the full-scale system. It is made up of identical treatment trains, both of which treat water from Pockwock Lake. Each train first passes lake water through a screen. Next, the water enters a pre-oxidation stage of treatment. The oxidation stage is performed throughout three pre-mix tanks. The first tank uses lime to increase the pH to 10 and potassium permanganate to oxidize iron and manganese. The second tank provides mixing. Carbon dioxide is added to the third tank to decrease the pH to about 5.5 for optimal performance of the coagulant, aluminum sulphate (alum). It should be noted that unlike full-scale, during colder temperatures polymer is not used as a coagulant aid. Instead, the coagulant dose is increased. Chlorine is added during the pre-mix stages to maintain a residual of 0.05 mg/L at the end of treatment. This is to prevent bacteria growth on the filters. Once leaving the pre-mix stage water is passed through three 11 L tanks, which utilize mechanical mixing for flocculation. Flocculated water is passed to three cylindrical filters. Filters are capable of being operated in unison. Each filter contains 2 ft of anthracite and 1 ft of silica sand. A filtration rate of 2.36 L/min is used. Backwash procedures can be simulated and altered using backwash rates, durations, and filter resting. A schematic of the pilot-scale plant filters are shown in Figure 3.4.

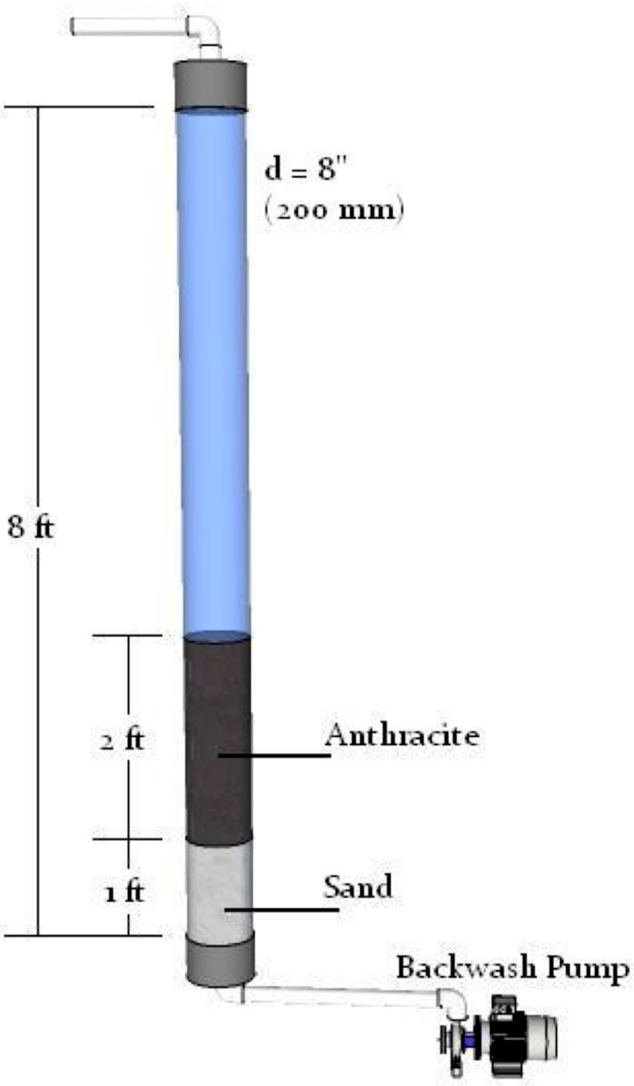

Figure 3.4 Schematic of a pilot-scale filter at the JD Kline water supply plant

3.5 Experimental Design (Pilot- and Bench-scale)

Experiments were planned using a factorial design. A summary of the experimental designs that are discussed in the following sections is presented in Table 3.1.

Table 3.1 Summary of experimental designs

Section	Experiment Scale	Concept Tested	Factors Studied	Response Parameters
3.4.1	Pilot-scale	Backwash Procedure	Temperature Turbidity Control ETSW	Primary: Turbidity Others: Particle Concentration Zeta Potential
3.4.2	Bench-scale	Backwash Water Chemistry	pH Chlorine Polymer	

3.5.1 Backwash Procedure Experiments (Pilot-scale)

Two backwash concepts were tested against full-scale conditions at pilot-scale. The full-scale conditions were simulated based on process and backwash turbidity. Simulated conditions consisted of backwashing the filter at 20 L/min for 240 seconds, 35 L/min for 80 seconds, and 20 L/min for 240 seconds followed by filter resting for 60 minutes. The stepwise backwash rates were chosen to simulate the ramping up and down of full-scale backwash pump. Also, these rates consistently gave a backwash turbidity of less than 5 NTU.

The theories being tested at pilot-scale were extend terminal subfluidization wash (ETSW) and turbidity control, or backwashing until turbidity is between 10 and 20 NTU. The experiment was set up using a mixed three-factor, two- and three-level factorial design including seasonal variance (temperature, two-level), backwash turbidity (two-level), and ETSW rate (three-level). ETSW trials did not employ filter resting. The high and low values for seasonal variance were summer and winter, respectively. Backwash turbidity high and low values were between 10 and 20 NTU and less than 5 NTU, respectively. ETSW rate high, mid, and low values were 9.5 L/min, 5.5 L/min, and 0 L/min, respectively. To achieve a backwash turbidity of between 10 and 20 NTU, filters were backwashed after breakthrough at 15 L/min for 240 seconds, 30 L/min for 80 seconds, and 15 L/min for 240 seconds. This condition was then rested for 60 minutes. The stepwise backwash rates were chosen to simulate the ramping up and down of the full-scale backwash pump. Four trials in winter and summer employed an ETSW rate following a backwash. Each ETSW condition involved using a subfluidizing rate for 600 seconds (10 minutes), which allowed one entire bed volume of water to be pushed through the filter.

Hach 1720E low range process inline turbidimeters provided data showing filter run time to break through, maximum turbidity during ripening, and ripening time. Break through was considered to be when turbidity surpassed 0.2 NTU. Hach inline particle counters were used to assess particle concentrations during ripening. Zeta potentials were measured during ripening by collecting grab samples and processing them on a Melvern Zeta Sizer.

3.5.2 Backwash Water Chemistry Experiments (Bench-scale)

The objective of this study was to observe the possible effects of backwash water chemistry changes on filter ripening. The concepts being tested at bench-scale consisted of polymer addition to backwash water, and pH and chlorine dose changes. Four factors were used to understand the effects on filter ripening. The experiment was set up using a four-factor, two-level factorial design and including seasonal variance (temperature), polymer addition, pH change, and chlorine dose change. The parameters being observed were maximum turbidity during ripening, ripening time, and bed volumes produced. This experiment was performed at the CWRS laboratory at Dalhousie University using plant produced flocculated water. The purpose of this experiment was to evaluate the addition of polymer to backwash water at this facility and the effectiveness of using clearwell water (pH = 5, chlorine dose = 0.05 mg/L) against finished water (pH = 7.2, chlorine dose = 1 mg/L).

The filters used were 25.4mm (1”) diameter glass columns (Fischer Scientific). The 50.8mm (2”) of anthracite and 25.4mm (1”) of silica sand were used to create dual-media filter columns. These ratios were consistent with those at full-scale and pilot-scale. A filtration rate of 43 mL/min was held constant for the entire filter run. The laboratory setup is shown in Figure 5. Samples were collected for the entire duration of the filter run at every 5 minutes for the first 30 minutes, every 10 minutes for the next 30 minutes, and then every 30 minutes until break through or the filtration rate approaches 0 mL/min. Turbidity for each sample was measured on a Hach 2100N laboratory turbidimeter. A particle analysis was performed on each sample using a Brightwell Micro-Flow Imager on high resolution. A photo of the bench scale setup is shown in Figure 3.5.

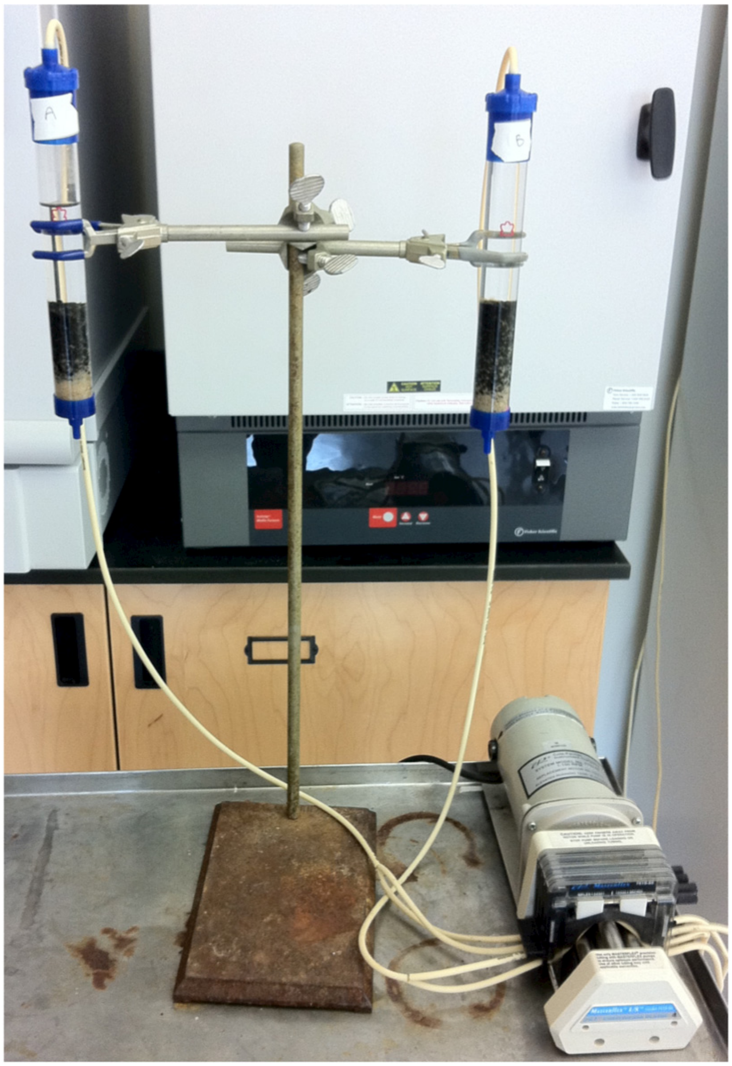

Figure 3.5 Bench-scale experimental setup

3.6 Statistical Analysis

3.6.1 Factorial Design

Factorial design analysis was used to design pilot-scale and bench-scale experiments. A factorial designed experiment is an efficient way of assessing if an independent variable causes a response and the significance of that response. It has the advantage of providing a large amount of information with the minimum amount of experiments. A design matrix is used to separate the responses of each factor by the high and low level values. The size of the design matrix is chosen based on the level and number of factors (Berthouex and Brown, 2002).

Experimental data for all factorial designs was analyzed using Minitab 16. This program determined which factors, or interactions of factors, had a statistically significant influence over each response. Significance is determined using the P-value. All of these experiments accept that if the P-value is less than 0.05, the factor, or interaction, is statistically significant. This means that there is a 95% chance, or higher, that the factor is actually playing a significant role in influencing the response.

3.6.2 Method Detection Limit

The method detection limit (MDL), or limit of detection, determines the variability that exists within a measurement method. It provides the minimum amount of a substance that an instrument can measure and report with 99% confidence (Berthouex and Brown, 2002). The MDL for the Melvern Zeta Sizer was calculated using the USEPA method, as described by Berthouex and Brown (2002). Results from this analysis were used to determine the instrumental measurement error.

Using filtered water from the JDKWSP, two sets of 10 replicates were processed in the Melvern Zeta Sizer. Combining two sets allowed for an improved (pooled) estimate with ν = 18 degrees of freedom.

The variance between each of the replicate measurements and pooled variance was calculated using equation 1 and 2. An F test can be used to determine if both sets can be pooled. The results can only be pooled if the ratio of the variances for both sets are less than $F_{v,v}$. Results are shown in Table 3.2.

Equation 1

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2$$

Equation 2

$$s_{pooled}^2 = \frac{s_{first\ set}^2 + s_{second\ set}^2}{2}$$

The MDL was then calculated using a t-distribution for 99% confidence and a standard deviation estimate α = 0.01 and ν = 18 degrees of freedom. Equation 3 was used to calculate the MDL. Results are shown in 3.2.

Equation 3

$$\mathrm{MDL} = \mathrm{s}\times t_{v,\alpha=0.01}$$

Table 3.2 Results from Melvern Zeta Sizer instrument method detection limit using JDKWSP filtered water

	Set 1	**Set 2**	**Pooled**
s^2	4.17	5.29	4.73
s	2.04	2.30	2.17
v	9	9	18
F	3.18		-
t	2.821		2.552
MDL	5.75 mV	6.49 mV	5.54 mV

3.6.3 Tukey's Method

Tukey's Method was used to assess the variability between each of the bench-scale filters. Tukey's Method is similar to performing multiple t-tests. Differences calculated between the means of each filter can be compared with a two-sided 95% confidence interval known as a "Studentized Range Statistic", $q_{k,v,\alpha/2}$. Using a pooled variance, s^2_{pool}, the confidence interval for the difference between y_i and y_{i+1} can be found. It is calculated using the following Equation 4 (Berthouex and Brown, 2002).

Equation 4

$$y_i - y_{i+1} \pm \frac{q_{k,v,\alpha/2}}{\sqrt{2}} s_{pool} \sqrt{\frac{1}{n} + \frac{1}{n}}$$

Tukey's Method was used to evaluate which filters are behaving the same and which are behaving differently, with respect to each response. Using the same backwash water for each test (control), it was determined if any filter was behaving differently. Ripening time and run time were the same for each filter (5 minutes and 180 minutes, respectively). Tukey's Method was used to determine if the filters behaved differently with respect to maximum turbidity during ripening. The results are displayed in Table 3.3.

Table 3.3 Tukey's Method results showing that when looking at maximum turbidity during ripening for each of the bench-scale filters

Filter j	Filter i (Average = ybar)							
	1 (0.094)	2 (0.3)	3 (0.101)	4 (0.072)	5 (0.085)	6 (0.105)	7 (0.087)	8 (0.093)
1	-	-	-	-	-	-	-	-
2	0.051	-	-	-	-	-	-	-
3	-0.115	-0.166	-	-	-	-	-	-
4	0.016	-0.035	0.131	-	-	-	-	-
5	0.023	-0.028	0.138	0.007	-	-	-	-
6	0.05	-0.001	0.165	0.034	0.027	-	-	-
7	0.002	-0.049	0.117	-0.014	-0.021	-0.048	-	-
8	0.049	-0.002	0.164	0.033	0.026	-0.001	0.047	-

Using Equation 5, the difference in the true means with 95% confidence was determined as:

Equation 5

$$-0.0233 \le y_i - y_{i+1} \le 0.0233$$

This shows that none of the filters are behaving differently when looking at maximum turbidity during ripening.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Microbial Monitoring (Full-scale)

During the ripening period, filtered water was collected and analyzed for the presence of *E. coli, Cryptosporidium,* and *Giardia.* Sampling was performed during the first hour after the filters were placed back online after a backwash. Each sampling period captured the highest turbidity spike during ripening which was considered to be the most vulnerable period for microbial passage.

Source water samples were collected by Halifax Water operators and analyzed for *E. coli, Cryptosporidium,* and *Giardia.* Data from this sampling program was used as a comparison with ripening data to assess the total risk of microbial passage through the filters and into the distribution system. These results are discussed in the following sections. Results are presented as detects and non-detects. pH and turbidity were monitored during all sampling periods pH varied slightly between 5.8 and 6.1 throughout the entire sampling campaign. Turbidity mostly remained below 0.1 NTU with the highest spike occurring on January 26, 2010 and reaching 0.11 NTU. Turbidity during sampled ripening events falls within an acceptable range of less than 0.2 NTU.

4.1.1 E. coli Monitoring

Microbial sampling of *E. coli* was conducted for both source water and filtered water. There were 108 total samples collected during filter ripening over a 12-month period. Three samples were collected from each filter and three filters were sampled each month.

Halifax Water operators at the JDKWSP sampled source water continuously for *E. coli*. For this analysis, 48 samples were taken bi-weekly over a 2-year period.

The results from each of these sampling periods show zero detections of *E. coli* for both filtered water during ripening and source water samples. These results are summarized in Table 4. Given the pristine source water quality, results indicate a low risk of *E. coli* presence in source water. Source water quality and results from filtered water during ripening indicate a low risk of microbial passage into the distribution system during the most vulnerable portion of the filtration cycle. The results of this study demonstrated that installing filter-to-waste infrastructure will pose no benefit to the facility in protecting public health.

4.1.2 Cryptosporidium Monitoring

Microbial sampling of *Cryptosporidium* was conducted for both source water and filtered water. There were 36 total samples collected during filter ripening over a 12-month period. One sample was collected (continuously for each ripening period) per filter and three filters were sampled each month. Halifax Water operators at the JDKWSP sampled source water for *Cryptosporidium.* For this analysis, 36 samples were analyzed.

The results from each of these sampling periods show zero detections of *Cryptosporidium* for both filtered water during ripening and source water samples. These results are summarized in Table 4.1. Given the pristine source water quality, results indicate a low risk of *Cryptosporidium* presence in source water. Source water quality and results from filtered water during ripening indicate a low risk of microbial passage into the distribution system during the most vulnerable portion of the filtration cycle. Installing filter-to-waste infrastructure will pose no benefit to the facility in protecting public health.

Table 4.1 Result summary from microbial sampling campaigns

	Number of Detects		
	E. coli	*Cryptosporidium*	*Giardia*
Source Water	0 (n=48)	0 (n=24)	0 (n=24)
Filtered Water	0 (n=108)	0 (n=36)	0 (n=36)

4.1.3 Giardia Monitoring

Microbial sampling of *Giardia* was conducted for both source water and filtered water. There were 36 total samples collected during filter ripening over a 12-month period. One sample was collected (continuously for each ripening period) per filter and three filters were sampled each month. Halifax Water operators at the JDKWSP sampled source water for *Giardia.* For this analysis, 36 samples were analyzed.

The results from each of these sampling periods show zero detections of *Giardia* for both filtered water during ripening and source water samples. These results are summarized in Table 4. Given the pristine source water quality, results indicate a low risk of *Giardia* presence in source water. Source water quality and results from filtered water during ripening indicate a low risk of microbial passage into the distribution system during the most vulnerable portion of the filtration cycle. Installing filter-to-waste infrastructure will pose no benefit to the facility in protecting public health.

4.2 Backwash Procedural Techniques (Pilot-scale)

The effects of backwash procedural changes were observed in pilot-scale trials. Treatment conditions were held constant for the trial period. Treatment chemicals were run the same as the full-scale conditions with lime increasing the pH to 10. Potassium permanganate ($KMnO_4$) was added to aid in the oxidation process. Coagulant (aluminum sulphate) dose was 10 mg/L, floc pH targeted to be 5.3, and flocculation mixing speeds at 60, 40, and 20 rpm. Chlorine was dosed such that a residual of 0.05 mg/L remained after filtration. Each filter consisted of 2 ft of anthracite and 1 ft of silica sand. The same filtration rate was used for each filter and held constant at 2.36 L/min. Previous work at the JDKWSP has shown that each of the pilot-scale filters were behaving the same, with respect to turbidity and other parameters. This was shown using paired t-tests (Knowles, et al., 2012).

Factorial Design

Once each filter was shown to behave identically to one another, settings on each pilot filter were changed to represent experimental backwash procedures. Although backwash settings varied between each of the three pilot filters, all other conditions and loadings on the filters were identical (i.e. premix, flocculation and coagulation, and filtration rates). Two factorial designed experiments were run throughout the winter and summer to gain an understanding of seasonal effects. One of the experiments considered the effects of cleaning a filter during a backwash (backwashed until turbidity reached between 10 and 20 NTU) and comparing it to current full-scale conditions (backwashed until turbidity reached less than 5 NTU). The other experiment was performed to observe the effects of extended terminal subfluidization wash (ETSW). ETSW rates were chosen at 9.5 L/min and 5.5 L/min. Since ETSW is intended to follow an optimized backwash, backwash turbidities of between 10 and 20 NTU and less than 5 NTU were incorporated in the experiment. Results from the factorial analysis are presented in each section.

4.2.1 Turbidity Analysis

Using turbidity as the assessment parameter, maximum turbidity during ripening, ripening time, and total filtered volume, or bed volumes (BVs), and turbidity were ranked with respect to each experimental condition. A filter is considered ripened once the turbidity drops below 0.2 NTU (Nova Scotia Environment, 2012). Industry best practice strives to keep filtered water turbidity below 0.1 NTU at all times. In conjunction with the 0.2 NTU treatment standard, this thesis also considered ripening time to be the length of time it takes for the turbidity to drop below 0.1 NTU after it is placed back in service following a backwash. A filter run is complete once turbidity reaches over 0.2 NTU (breakthrough), which governs the amount of water produced during that run. Unlike full-scale operation, pilot-scale filters were operated until after breakthrough as they, although in operation, were not supervised for 24 hours each day. Inline turbidimeters were used to record this information.

Turbidity profiles were created for each experimental condition. Representative plots, taken from each sample set, were used to relatively compare ripening periods for ETSW and filter resting conditions. These profiles were created for both winter and Summer trials and are shown in Figures 4.1 and 4.2.

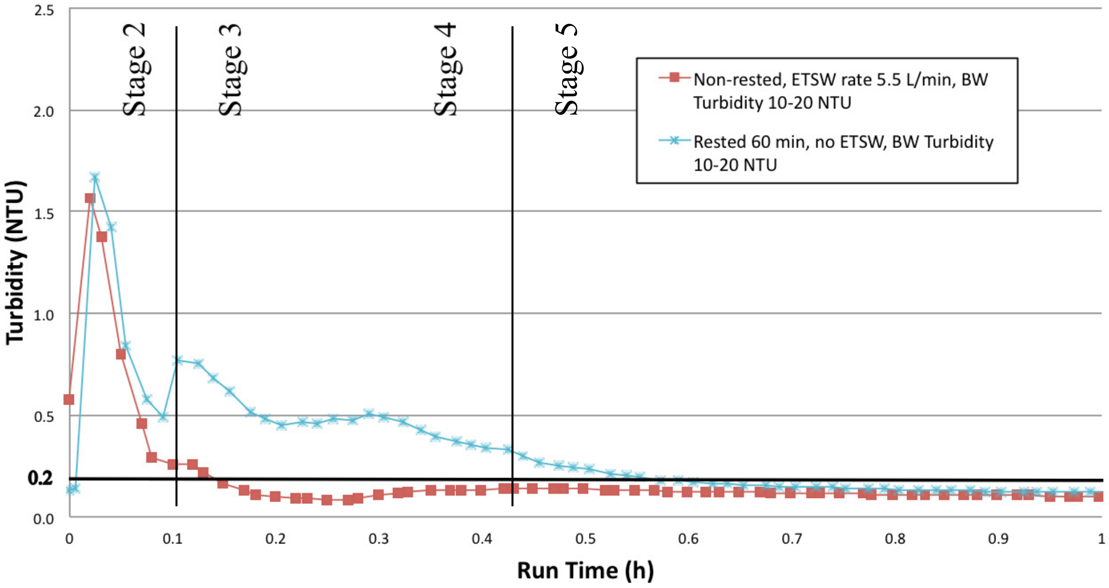

Figure 4.1 Winter pilot-scale turbidity profiles during ripening for an ETSW and a resting procedural condition

Ripening stages during Winter trials can be easily observed in Figure 7. Similar trends were seen in all ETSW trials (non-rested) and were also seen in both rested conditions. Due to these trends Figure 4.1 has been simplified, showing only one ETSW trial and one rested trial. Stage 1 of ripening occurred within the first few seconds of each filter run, independent of the backwashing condition. It should be noted that Stage 1 had a longer duration at full-scale but this is likely a reflection of pilot-plant operational differences due to the scale. Although maximum turbidity during Stage 2 varied for each condition, the duration was found to be within 0.1 hr (6 min), independent of the backwashing conditions. An obvious observation was with Stages 3, and 4 of ripening. Both conditions that used filter resting for 60 minutes and not employing ETSW showed increased durations of Stages 3 and 4. Although trends were similar, filter resting for 60 minutes after a backwash reaching turbidity of less than 5 NTU (simulated full-scale condition) had a lower turbidity at these stages than the rested condition with backwash reaching turbidity between 10 and 20 NTU. These stages were less apparent in turbidity profiles of conditions employing ETSW.

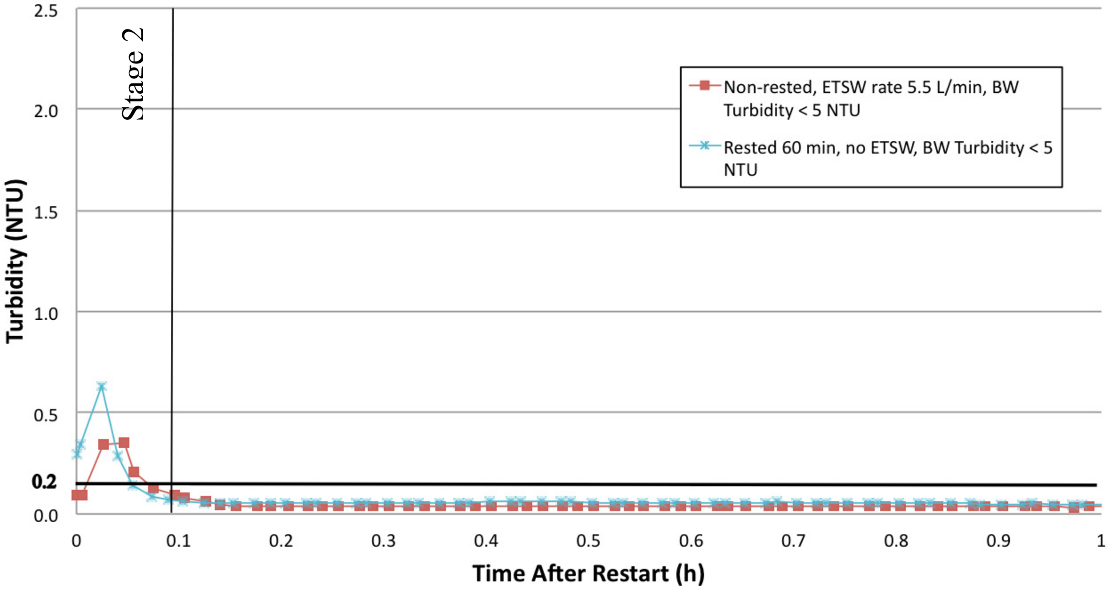

Figure 4.2 Summer pilot-scale turbidity profiles during ripening for an ETSW and a resting condition

Ripening stages during Summer trials can be observed in Figure 4.2. Similar trends were seen in all ETSW trials (non-rested) and were also seen in both rested conditions. Due to these trends Figure 7 has been simplified, showing only one ETSW trial and one rested trial. Stage 1 of ripening occurred within the first few seconds of each filter run, independent of the backwashing condition. Although maximum turbidity during Stage 2 varies for each condition tested, the duration appears to be within 0.07 hr (4.2 min), independent of the backwashing condition. Observation of Stages 3 and 4 are not apparent in the Summer trials. Comparing these observations to those seen in the Winter trials, the Summer trials observed a decreased turbidity and duration of these stages with every backwashing condition.

Maximum turbidity during ripening was taken as the highest value recorded after a filter was placed online following a backwash but before turbidity dropped below 0.1 NTU (industry best practice). The results for Winter and Summer trials are displayed in Table 4.2 and organized by backwash procedure.

Table 4.2 Maximum turbidity during ripening over winter and summer pilot-scale trials.

Description of Backwash Procedure	Winter	Summer
	Turbidity (NTU)	Turbidity (NTU)
ETSW Rate 9.5 L/min BW turbidity < 5 NTU	1.88 ± 0.14	1.11 ± 0.74
ETSW Rate 5.5 L/min BW turbidity < 5 NTU	1.29 ± 0.34	0.53 ± 0.17
ETSW Rate 5.5 L/min BW turbidity 10–20 NTU	1.57 ± 0.31	1.00 ± 0.79
ETSW Rate 9.5 L/min BW turbidity 10-20 NTU	1.72 ± 0.33	0.33 ± 0.15
Rested 60 min BW turbidity < 5 NTU	1.64 ± 0.36	0.68 ± 0.65
Rested 60 min BW turbidity 10-20 NTU	1.86 ± 0.21	0.88 ± 0.66

Maximum turbidity during ripening consistently occurred within stage 2 of filter ripening for each trial and during the Winter and Summer trials. Very little difference appears to exist in the maximum turbidity for each backwashing condition during Winter trials. ETSW with a rate of 5.5 L/min and backwash turbidity of less than 5 NTU appears to have the lowest average maximum turbidity during ripening, but might not be statistically significant. More variation existed between average maximum turbidities in the summer than winter, however, the overall intensity is much less. Two ETSW conditions have the lowest maximum turbidities. ETSW with a rate of 9.5 L/min and backwash turbidity of less than 5 NTU was found to have the lowest average maximum turbidity during ripening, but might not be statistically significant.

Data from the pilot-scale experiment were analyzed using Minitab 16. Replicate responses varied from n = 3 and 8 for the Winter trials and from n = 2 and 9 for Summer trials. This variance was due to unpreventable disruptions in ideal pilot operation. An analysis of variance was performed for maximum turbidity data using adjusted sum of squares for tests. The results of this analysis showed that season was a significant factor ($\alpha = 0.05$, P = 0.000). The interaction between ETSW rate and backwash turbidity was also found to be slightly significant ($\alpha = 0.05$, P = 0.044). All other factors and interactions were not found to be significant when looking at the effect of backwash procedure on maximum turbidity during ripening. P-values for insignificant factors ranged from P=0.484 to P=0.812.

The ripening times for Winter and Summer trials are displayed in Tables 4 and 5 and organized by backwash procedure. Both industry best practice (below 0.1 NTU) and the

Nova Scotia Treatment Standard for Municipal Public Drinking Water Systems (0.2 NTU) are considered for the assessment of ripening time. Ripening time was considered to be the time it took for each filter to drop below 0.1 NTU (Table 4.3) and 0.2 NTU (Table 4.4) once placed online following a backwash.

Table 4.3 Ripening times for winter and summer pilot-scale trials (Target turbidity = 0.1 NTU).

Description of Backwash Procedure	Winter	Summer
	Time (h)	Time (h)
ETSW Rate 9.5 L/min BW turbidity < 5 NTU	1.81 ± 0.77	0.13 ± 0.06
ETSW Rate 5.5 L/min BW turbidity < 5 NTU	1.40 ± 0.59	0.09 ± 0.00
ETSW Rate 5.5 L/min BW turbidity 10–20 NTU	1.12 ± 0.23	0.12 ± 0.05
ETSW Rate 9.5 L/min BW turbidity 10-20 NTU	1.85 ± 0.71	0.09 ± 0.02
Rested 60 min BW turbidity < 5 NTU	2.69 ± 1.49	0.96 ± 1.84
Rested 60 min BW turbidity 10-20 NTU	5.72 ± 4.51	0.37 ± 0.63

As seen in Table 4.3, ripening times throughout Winter trials appear to be influenced by backwash procedure. The condition that employed filter resting for 60 minutes and backwashed until turbidity reached between 10 and 20 NTU had the largest standard deviation and the largest average ripening time. Backwash procedures using ETSW rates all showed consistently lower ripening times than the other two conditions. The condition with ETSW rate of 5.5 L/min and backwash turbidity between 10 and 20 NTU has the lowest ripening time.

Table 4.4 Ripening times for winter and summer pilot-scale trials (Target turbidity = 0.2 NTU).

Description of Backwash Procedure	Winter	Summer
	Time (h)	Time (h)
ETSW Rate 9.5 L/min BW turbidity < 5 NTU	0.713 ± 0.5	0.061 ± 0.05
ETSW Rate 5.5 L/min BW turbidity < 5 NTU	0.118 ± 0.03	0.06 ± 0
ETSW Rate 5.5 L/min BW turbidity 10–20 NTU	0.113 ± 0.03	0.067 ± 0.06
ETSW Rate 9.5 L/min BW turbidity 10-20 NTU	0.335 ± 0.33	0.04 ± 0.03
Rested 60 min BW turbidity < 5 NTU	0.354 ± 0.36	0.036 ± 0.03
Rested 60 min BW turbidity 10-20 NTU	0.449 ± 0.41	0.037 ± 0.04

As seen in Table 4.4, ripening times throughout Winter trials appear to be influenced by backwash procedure. The condition that employed an ETSW rate of 9.5 L/min and backwashed until turbidity dropped below 5 NTU had the largest standard deviation and the largest average ripening time. In general, backwash procedures using ETSW rates were found to have consistently lower ripening times than the other conditions. The condition with ETSW rate of 5.5 L/min had the lowest in the set.

Data from the pilot-scale experiment was analyzed using Minitab 16. Replicate responses varied from n = 3 and 8 for the Winter trials and from n = 2 and 9 for Summer trials. Variance existed in sample numbers due to unpreventable disruptions in ideal pilot operation. An analysis of variance was performed for ripening time data using adjusted sum of squares for tests. The results of this analysis showed season to be a significant factor ($\alpha = 0.05$, $P = 0.000$). ETSW rate was also found to have a strong effect on ripening time ($\alpha = 0.05$, $P = 0.004$). The interaction between season and ETSW rate could be slightly significant ($\alpha = 0.05$, $P = 0.076$). All other factors and interactions were not found to be significant when looking at the effect of backwash procedure on maximum turbidity during ripening. P-values for insignificant factors ranged from P=0.133 to 0.462.

The average filtered volume, or bed volumes, are displayed in Table 4.5 and organized by backwash procedure. Although filters were operated until after break through occurred, duration of the filter run was considered until filtered water turbidity first reached 0.2 NTU.

Table 4.5 Filtered volumes (bed volumes) for winter and summer pilot-scale trials.

Description of Backwash Procedure	Winter	Summer
	Bed Volumes	Bed Volumes
ETSW Rate 9.5 L/min BW turbidity < 5 NTU	169.27 ± 13.39	339.96 ± 17.65
ETSW Rate 5.5 L/min BW turbidity < 5 NTU	167.84 ± 8.37	378.41 ± 17.26
ETSW	169.96 ± 21.42	353.39 ± 11.52

Rate 5.5 L/min BW turbidity 10–20 NTU		
ETSW Rate 9.5 L/min BW turbidity 10-20 NTU	172.42 ± 28.07	386.35 ± 8.54
Rested 60 min BW turbidity < 5 NTU	160.08 ± 7.57	350.20 ± 27.76
Rested 60 min BW turbidity 10-20 NTU	160.91 ± 7.76	355.09 ± 25.49

As seen in Table 4.5, bed volumes of filtered water during Winter trials appear to be slightly influenced by backwash procedure. Trials employing an ETSW rate, although having the highest standard deviation, show the highest average bed volumes produced. This graph shows trials using any ETSW rate can achieve an average increase of about 10 bed volumes over backwash procedures using filter resting for 60 minutes without an ETSW rate. The significance of these values cannot be comment on from this graph.

As seen in Table 6, bed volumes of filtered water during Summer trials were found to be much higher than in Winter trials. The average bed volumes increased by about a factor of 2, independent of backwash procedure. These trends are not observed to the same extreme at full-scale. Pilot-scale operations remain constant throughout the year, with respect to filter rate. Full-scale operations involve monitoring headloss and reducing the filter rate to increase the amount of time the filters are used. This process is referred to as placing the filters on local and increases the overall volume of water filtered during the winter months. The filtration rate is not reduced in the winter months and held constant at 2.36 L/min. The lowest average bed volumes produced was seen in the backwash procedure using an ETSW rate of 9.5 L/min and a backwash turbidity of less than 5 NTU. The backwash procedure using an ETSW rate of 5.5 and backwash turbidity between 10 and 20 NTU was equivalent to both procedures using filter resting. The other two procedures using ETSW were shown to produce 20 to 40 more average bed volumes than the rested conditions.

Data from the pilot-scale experiment was analyzed using Minitab 16. Replicate responses varied from n = 3 and 8 for the Winter trials and from n = 2 and 9 for Summer trials. Variance existed in sample numbers due to unpreventable disruptions in ideal pilot operation. An analysis of variance was performed for volume of water produced (bed volume) data using adjusted sum of squares for tests. The results of this analysis showed season to be a significant factor ($\alpha = 0.05$, $P = 0.000$). This result was expected from the results presented in Table 6. The two-way interaction between season and ETSW rate and backwash turbidity may be slightly significant ($\alpha = 0.05$, $P = 0.048$). The three-way interaction between each of the factors might also be slightly significant ($\alpha = 0.05$, $P = 0.061$). All other factors and interactions were not found to be significant when looking at the effect of backwash procedure on maximum turbidity during ripening. P-values for insignificant factors ranged from P=0.161 to 0.878.

4.2.2 Particle Analysis

Particle concentrations for pilot-scale observations were taken from inline particle counters and monitored continuously for the duration of each trial. Particle concentrations were based on particles greater than 2 μm in size and were reported as numbers/mL. Particle profiles during filter ripening were created and ranked with respect to each experimental condition. These profiles were created based on representative plots from each sample set. Profiles were created for both winter and Summer trials and are shown in Figures 4.3 and 4.4.

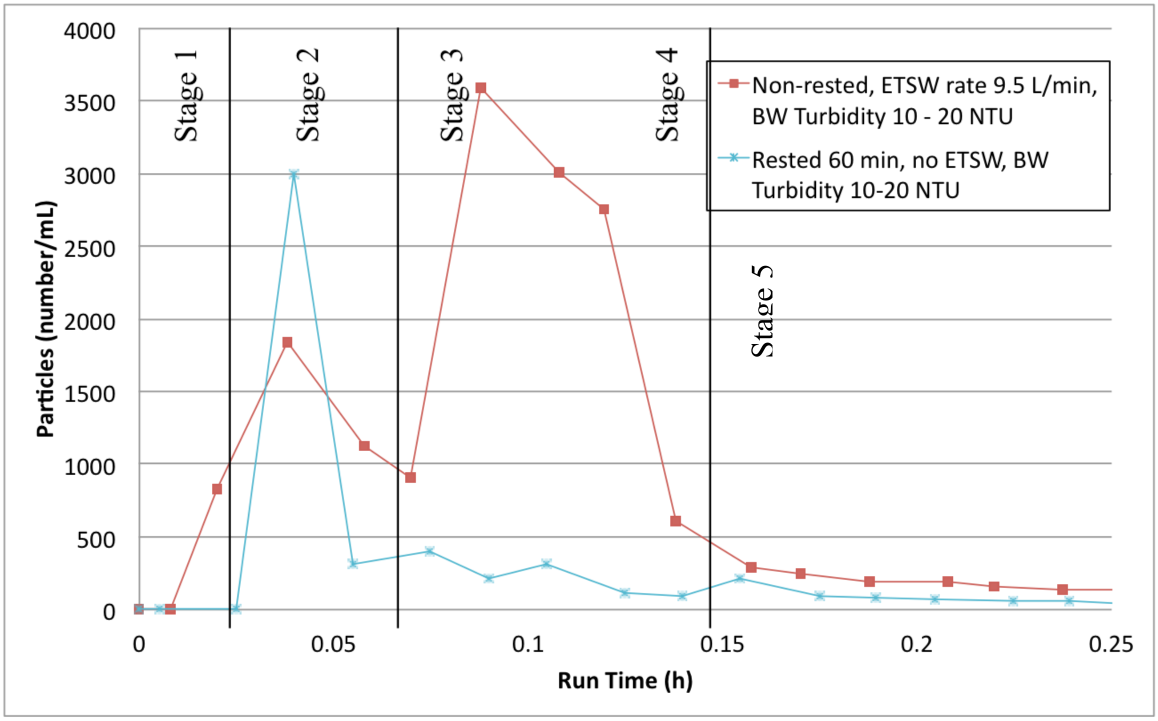

Figure 4.3 Winter pilot-scale particle profiles during ripening for an ETSW and resting procedural condition

Ripening stages can be clearly observed the particle concentrations in Figure 9. Similar trends were seen in all ETSW trials (non-rested) and were also seen in both rested conditions. Due to these trends Figure 4.3 has been simplified, showing only one ETSW trial and one rested trial. Stage 1 occurs within the first 0.025 hours (1.5 min) for each backwashing procedural condition. Stage 2 occurs within the first 0.075 hours (4.5 min) and stages 3 and 4 occur between 0.075 and 0.15 hours (4.5 and 9 minutes). The intensity of stages 3 and 4 are observed to be higher for the procedures using an ETSW rate following a backwash. These observations are not consistent with results found in literature and were not expected due to the trends seen in turbidity profiles.

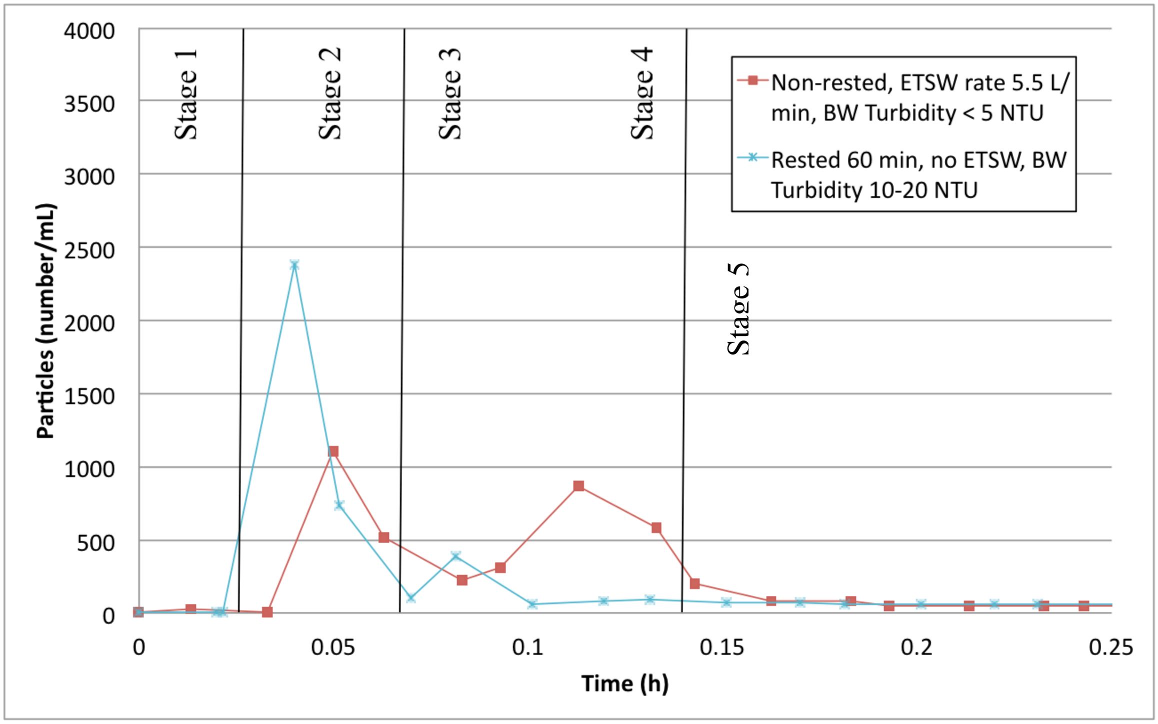

Figure 4.3 Summer pilot-scale particle profiles during ripening for and ETSW and a resting procedural condition

Ripening stages can be clearly observed the particle concentrations in Figure 4.4. Similar trends were seen in all ETSW trials (non-rested) and were also seen in both rested conditions. Due to these trends Figure 10 has been simplified, showing only one ETSW trial and one rested trial. Ripening times of 0.15 hr (9 min) or less are observed in Figure 16. Both conditions employing filter resting for 60 minutes with no ETSW rate appear to have a slightly shorter ripening time and a slightly higher maximum particle concentration during stage 2 but a decrease in particle concentration during stages 3 and 4. Statistical significance cannot be confirmed by these profiles.

The maximum particle concentrations of particles greater than 2 μm were observed during filter ripening. These maximum values are shown in Figures 4.5 and 4.6.

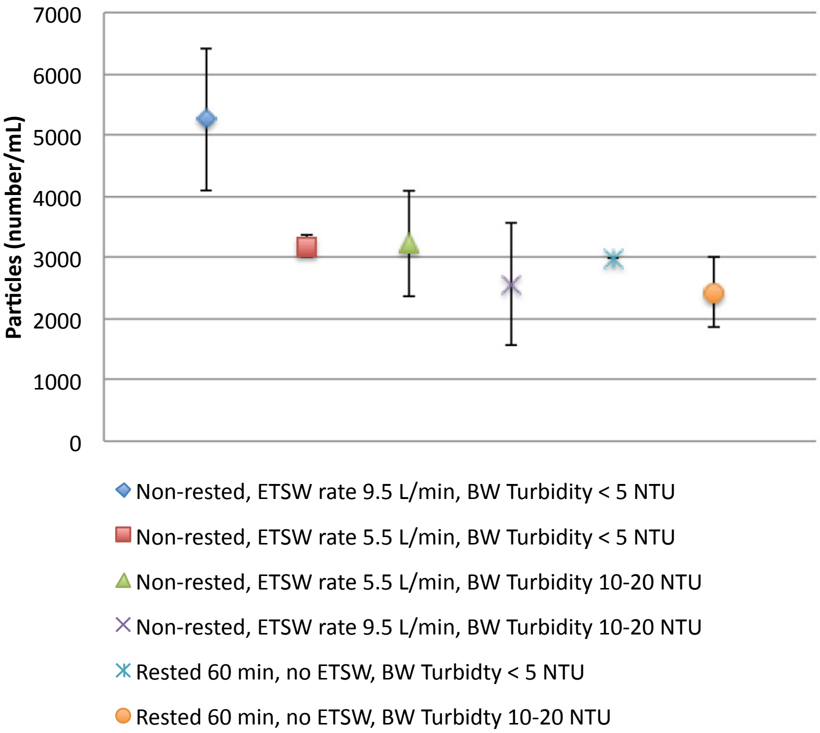

Figure 4.4 Maximum particle concentrations over Winter pilot-scale trials. Results from each ETSW and both resting conditions are displayed. Error bars indicate standard deviation.

As shown in Figure 4.5, the highest maximum particle concentrations during Winter trials were seen with the backwash procedure employing an ETSW rate of 9.5 L/min and a backwash turbidity of less than 5 NTU. Similar maximum particle concentration

intensities were observed with all other backwashing conditions. A high standard deviation exists for each backwashing condition.

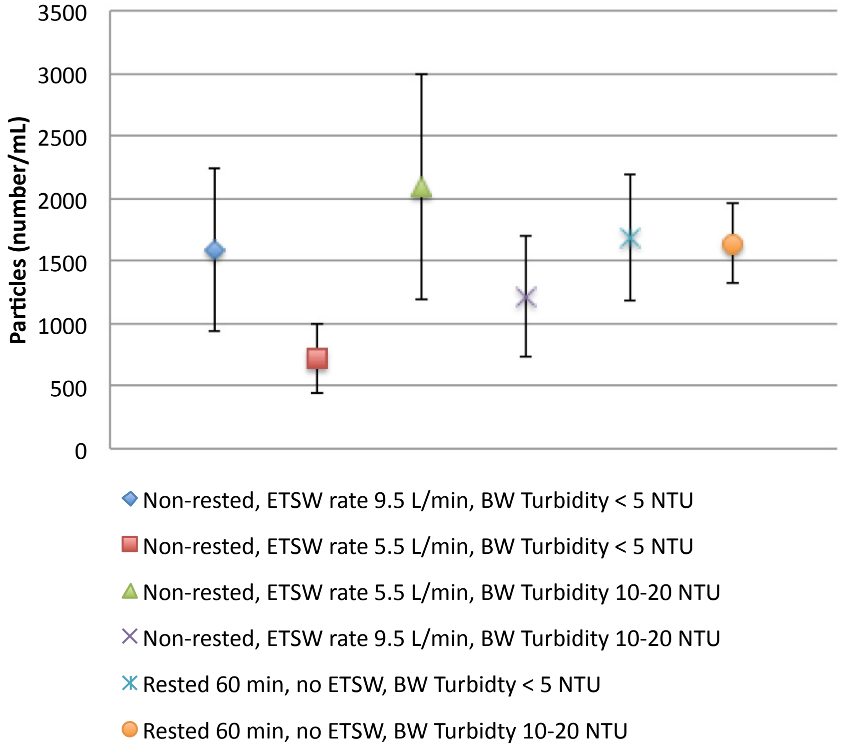

Figure 4.6 Maximum particle concentrations over summer pilot-scale trials. Results from each ETSW and both resting conditions are displayed. Error bars indicate standard deviation.

As shown in Figure 4.6, the highest maximum particle concentrations during Summer trials were seen with the backwash procedure employing an ETSW rate of 5.5 L/min and backwash turbidity between 10 and 20 NTU. Similar maximum particle concentration intensities were observed with all other backwashing conditions. A high standard deviation exists for each backwashing condition.

Data from the pilot-scale experiment was analyzed using Minitab 16. Replicate responses varied from n = 3 and 8 for the Winter trials and from n = 2 and 9 for Summer trials. Variance existed in sample numbers due to unpreventable disruptions in ideal pilot operation. An analysis of variance was performed for maximum particle concentrations during ripening using adjusted sum of squares for tests. The results of this analysis showed season to be a significant factor ($\alpha = 0.05$, $P = 0.000$). The two-way interaction between season and ETSW rate and backwash turbidity may be slightly significant ($\alpha = 0.05$, $P = 0.091$). All other factors and interactions were not found to be significant when looking at the effect of backwash procedure on maximum turbidity during ripening. P-values for insignificant factors ranged from $P=0.120$ to 0.699.

4.2.3 Zeta Potential Analysis

Pilot-scale samples for zeta potential observations were collected for a duration of 1 hour after filter start up. Measurements were performed on a Melvern Zeta Sizer, which had an instrument mean detection limit of 5.54 mV when using filtered water from the JDKWSP. Zeta potential profiles during filter ripening were created and ranked with respect to each experimental condition. These profiles were created based on representative plots from each sample set. Similar trends were seen in all ETSW trials (non-rested) and were also seen in both rested conditions. Due to these trends Figure 13 has been simplified, showing only one ETSW trial and one rested trial. Profiles were created for both winter and Summer trials and are shown in Figures 4.7 and 4.8.

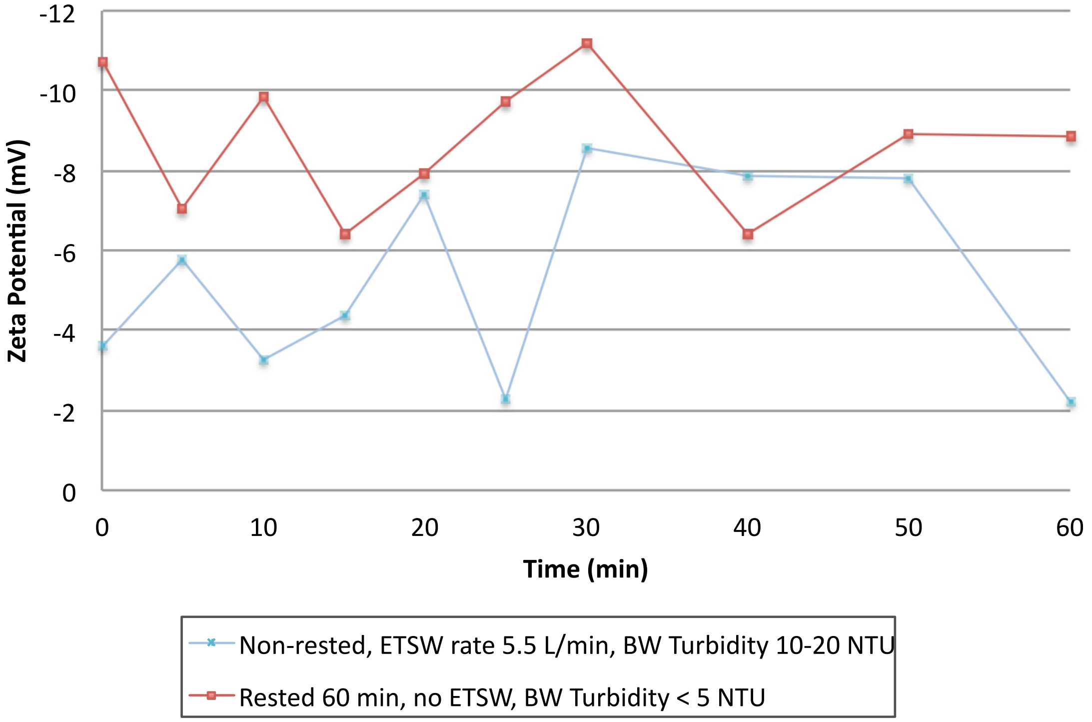

Figure 4.7 Representative zeta potential plots for pilot-scale experimental conditions (Winter trials)

As seen in Figure 4.7, the ETSW trial shown ranges from -2.2 mV to -8.7 mV and the rested trial shown ranges from -6.4 mV to -11.2 mV. ETSW appears to have a lower running negative charge than rested procedural conditions.

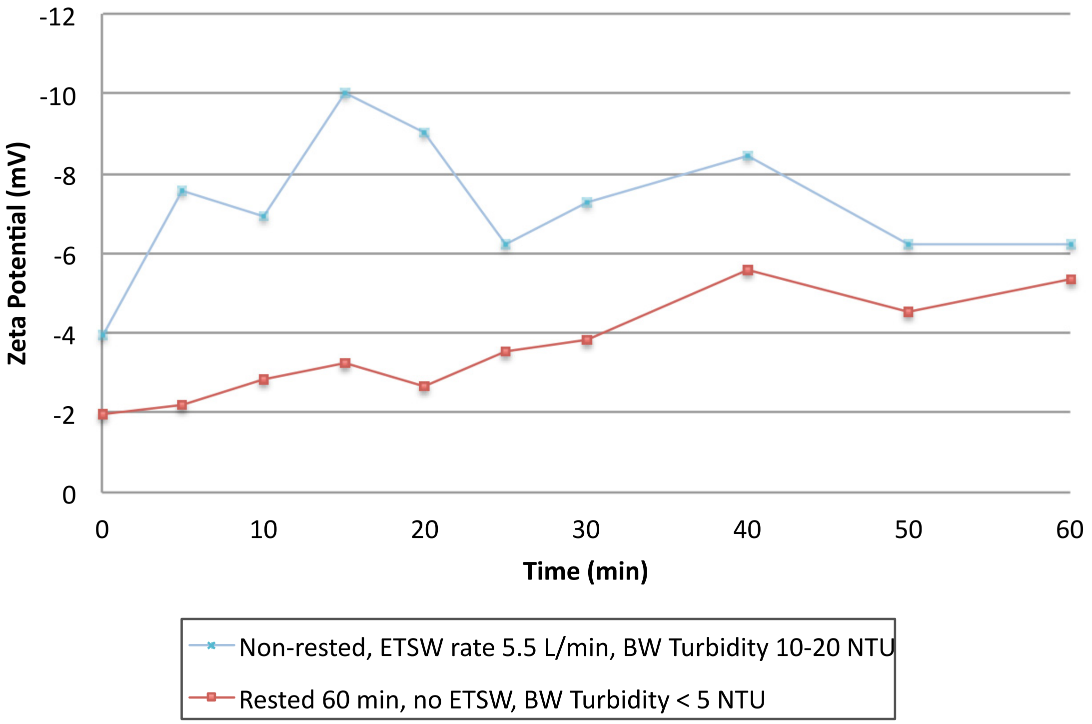

Figure 4.8 Representative zeta potential plots for pilot-scale experimental conditions (Summer trials)

As seen in Figure 4.8, the ETSW trial shown ranges from -4 mV to -10 mV and the rested trial shown ranges from -2 mV to -5.6 mV. ETSW appears to have a higher running negative charge than rested procedural conditions.

Although Figures 4.7 and 4.8 may appear to show trends, recall the instrument method detection limit (MDL) of 5.54 mV when using filtered water from the JDKWSP. Including all trials for both winter and summer, zeta potential results had ranges of 3 mV to ranges of 10 mV. Due to the variance in the results and the instrument MDL for filtered water at the JDKWSP, creating zeta profiles were not successful in describing collector efficiency for many of the sample values. This is due to the low particle concentration in filtered water. Sample intervals may have been too far apart to notice all trends existing during ripening.

4.3 Backwash Water Chemistry (Bench-scale)

The effects of backwash water chemistry changes were observed from bench-scale trials. Flocculated water was collected from the full-scale plant. All treatment up to filtration was performed at the JDKWSP. In the premix section of the JDKWSP, lime was used to increase the pH to 10. Potassium permanganate ($KMnO_4$) was added to aid in the oxidation process. Coagulant (aluminum sulphate) dose was 8 mg/L, floc pH targeted to be 5.3, and hydraulic mixing to flocculate the water. Chlorine was dosed such that a residual of 0.05 mg/L remained after filtration. The chlorine residual was read at 0 mg/L once the experiments were performed. Each of the 8 filters consisted of 2 in of anthracite and 1 in of silica sand. The same filtration rate was used for each filter and held constant at 43 mL/min. Filters were operated until spent and flow ceased, which was approximately 5 hours. The backwashing procedure did not monitor flow as it was performed with hand-operated syringes. Water volume used to backwash each filter was 720 mL. This volume of water was required for each filter to reach the same clarity. Clarity was decided based on visual inspection.

Tukey's Method

To ensure each of the bench-scale filters were statistically identical, flocculated water was run through each to monitor overall turbidity, maximum turbidity during ripening, ripening time, and run time. Run time and ripening time were found to be the same for each filter at 180 min and 5 min, respectively. Tukey's Method determined that each of the eight filters were behaving the same with respect to maximum turbidity.

Factorial Design

Once each filter was shown to behave identically to one another, each spent filter was backwashed with different backwash waters. Although backwash water chemistry varied between each of the eight filters, all other conditions and loadings on the filters were identical (i.e. premix, flocculation and coagulation, and filtration rates). Two factorial designed experiments were run throughout the winter and summer to gain an understanding of seasonal effects. The conditions observed were pH, chlorine dose, and polymer addition to the backwash water. The objective of this experiment was to understanding of the effects using finished water (pH of 7.2, chlorine dose of 1 mg/L). To do this, the current full-scale conditions of clearwell water (pH of 5, chlorine dose of 0.05 mg/L) were used in comparison. Also, polymer addition in backwash water was included as much literature discusses the capabilities to decrease the effects of ripening. The total factorial was a 4-factor, 2-level design. Results from the factorial analysis are presented in sections 4.3.1 and 4.3.2.

4.3.1 Turbidity Analysis

Assessing turbidity on small-scale filters requires judgment to identify what constitutes filter ripening and filter breakthrough. The bench scale filters, due to the small amount of filter media, were not able to achieve a filtered water turbidity of less than 0.1 NTU. As a result, ripening time was considered the time it took for filters to reach below 0.2 NTU and the filter run time was taken as the time before turbidity reached 0.5 NTU. Turbidity profiles for simulated clearwell and finished water with and without the addition of polymer are shown in Figures 4.9 and 4.10 for winter and Summer trials, respectively.

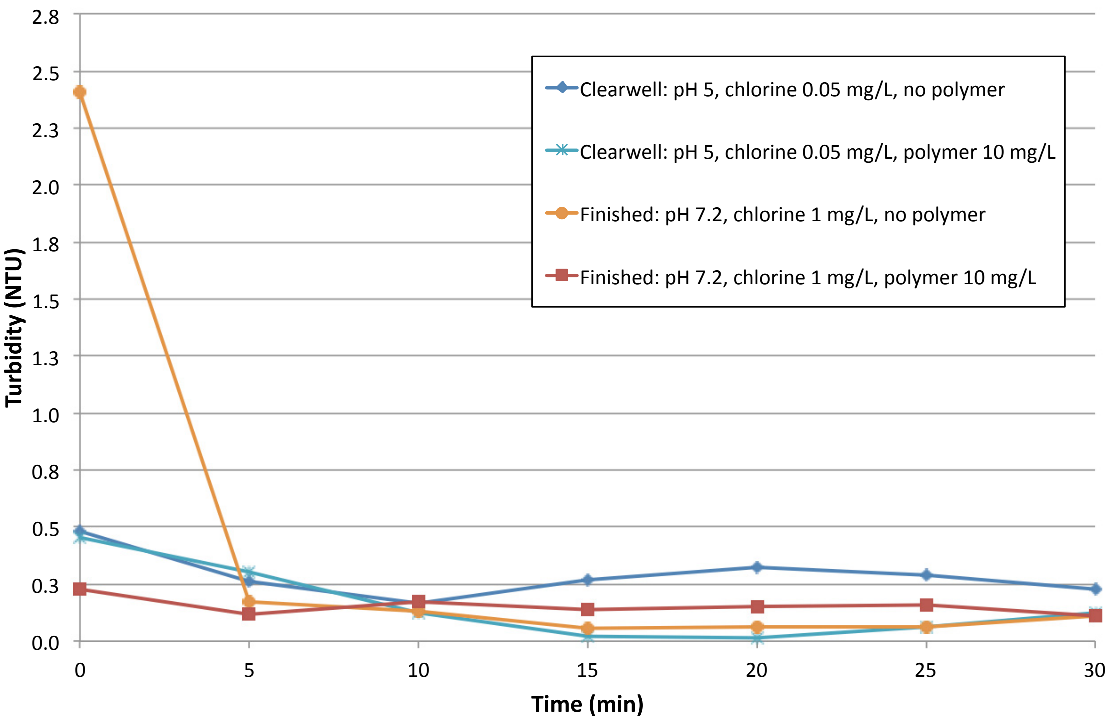

Figure 4.9 Winter bench-scale turbidity profiles for different backwash water chemistry conditions

Filter ripening can be observed in the representative plots, however, the specific stages of ripening were not apparent. Stage 1 of ripening was not observed due to the scale of the setup. The maximum turbidity during ripening and ripening time was found to vary for each condition. The condition using clearwell water with no polymer was found to have the longest ripening duration, however, this condition also produced the largest quantity of water throughout the filter run. Both clearwell conditions, with and without polymer, performed similarly in maximum turbidity duruing ripening but the clearwell condition with polymer was found to have a much shorter ripening time. Both clearwell and finished water conditions that used polymer were found to have short ripening time. Finished water with polymer produced a much lower volume of water than clearwell water with polymer (run time of 50 minutes and 120 minutes, respectively).

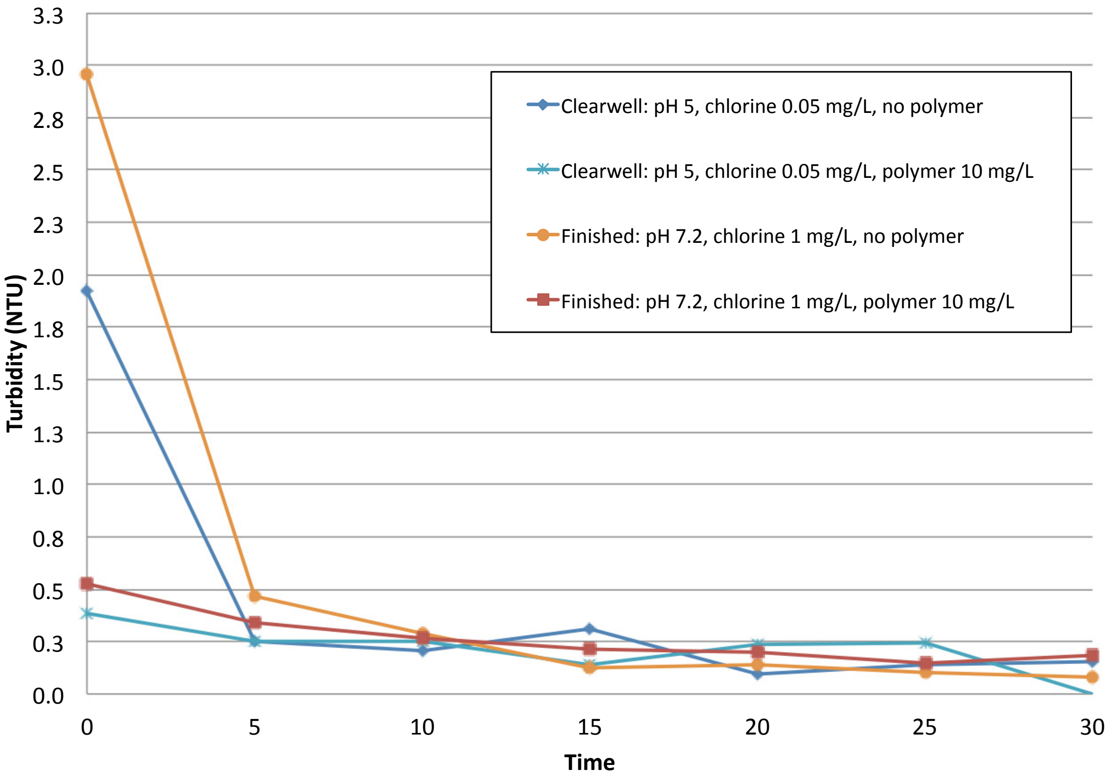

Figure 4.10 Summer bench-scale turbidity profiles for different backwash water chemistry conditions

Filter ripening can be easily observed in the representative plots, however as in the Winter trials, the specific stages of ripening during Summer trials are not apparent. Stage 1 of ripening occurs was not observed due to the scale of the setup. The maximum turbidity during ripening and ripening time were found to vary for each condition representation. The condition using clearwell water with no polymer has the longest ripening duration and each condition produced the same amount of water throughout the filter run (each with a run time of 150 minutes). Both clearwell and finished water conditions that used polymer were found to have the lowest maximum turbidity during ripening.

Maximum turbidity during ripening was taken as the highest value recorded after a filter was placed online following a backwash but before turbidity dropped below 0.25 NTU. Ripening was accepted at this value due to the performance limitations of each filter. The results for winter and Summer trials are displayed in Table 7 and organized by backwash procedure.

Table 4.6 Maximum turbidity during ripening over winter and summer bench-scale trials.

Description of Backwash Water Chemistry	Maximum Turbidity During Ripening (NTU)	
	Winter	Summer
Clearwell: pH 5 chlorine 0.05 mg/L no polymer	0.48	1.93
Clearwell w/ Polymer: pH 5 chlorine 0.05 mg/L polymer 10 mg/L	0.45	0.39
Finished: pH 7.2 chlorine 1 mg/L no polymer	2.24	2.96
Finished w/ Polymer: pH 7.2 chlorine 1 mg/L polymer 10 mg/L	0.23	0.52

As seen in Figures 4.9 and 4.10, maximum turbidity during ripening consistently occurred immediately after the filters were put back online after a backwash (at 0 minutes) for each trial and during the winter and summer. As shown in Table 4.6, very little difference appears to exist in the maximum turbidity for clearwell conditions and finished without polymer condition during the Winter trials. Finished water with polymer appears to have the lowest maximum turbidity during ripening and finished water without polymer appears to have the highest during Winter trials.

As seen in Table 4.6, very little difference appears to exist in the maximum turbidity for clearwell without polymer and finished without polymer conditions during Summer trials. Very little difference also was seen between clearwell with polymer and finished with polymer in the Summer trials. Both conditions with polymer were observed to have the highest maximum turbidity during ripening in summer.

Data from the bench-scale experiment was analyzed using Minitab 16. An analysis of variance was performed for maximum turbidity data using adjusted sum of squares for tests. The results of this analysis showed that no factors produced statistically significant responses. P-values for all factors ranged from $P=0.187$ to $P=0.914$, each of which are much greater than $\alpha = 0.05$.

Ripening time was taken as the time required for turbidity to drop below 0.25 NTU. Ripening was accepted at this value due to the performance of each filter. The results for winter and Summer trials are displayed in Table 4.7 and organized by backwash procedure.

Table 4.7 Ripening time over winter and summer bench-scale trials. Results from both clearwell and finished water, with and without polymer, are presented.

Description of Backwash Water Chemistry	Ripening Time (min)	
	Winter	Summer
Clearwell: pH 5 chlorine 0.05 mg/L no polymer	30	20
Clearwell w/ Polymer: pH 5 chlorine 0.05 mg/L polymer 10 mg/L	10	15
Finished: pH 7.2 chlorine 1 mg/L no polymer	5	15
Finished w/ Polymer: pH 7.2 chlorine 1 mg/L polymer 10 mg/L	0	20

As shown in Table 4.7, ripening time ranged between 0 and 30 minutes for each trial. Very little difference was found to exist in the ripening time for finished conditions and with and without polymer. Clearwell water without polymer was found to have the highest ripening time.

During Summer trials, very little difference was observed in ripening times for each condition. Ripening times ranged between 15 and 20 minutes for each trial and during the summer. Clearwell water without polymer and finished water with polymer were observed to have the highest ripening time.

Data from the bench-scale experiment was analyzed using Minitab 16. An analysis of variance was performed for ripening time data using adjusted sum of squares for tests. The results of this analysis showed that season and the combination of pH and chlorine produced statistically significant responses ($\alpha = 0.05$, $P_{season} = 0.012$ and $P_{pH\ x\ chlorine} = 0.012$). These results indicate that finished water without polymer should produce the shortest ripening time in both winter and summer. P-values for all statistically insignificant factors ranged from P=0.196 to P=0.787, each of which are much greater than $\alpha = 0.05$.

Run time was taken as the time in the filter run when the turbidity reached over 0.5 NTU. Run time was accepted at this value due to the performance of each filter. The results for winter and Summer trials are displayed in Table 4.8 and organized by backwash procedure.

Table 4.8 Run time over winter and summer bench-scale trials. Results from both clearwell and finished water, with and without polymer, are presented.

Description of Backwash Water Chemistry	Run Time (min)	
	Winter	Summer
Clearwell: pH 5 chlorine 0.05 mg/L no polymer	140	150
Clearwell w/ Polymer: pH 5 chlorine 0.05 mg/L polymer 10 mg/L	120	150
Finished: pH 7.2 chlorine 1 mg/L no polymer	70	150
Finished w/ Polymer: pH 7.2 chlorine 1 mg/L polymer 10 mg/L	50	150

As shown in Table 4.8, run time ranged between 50 and 140 minutes for each trial and during the winter. Finished water conditions, with and without polymer resulted in the shortest run times. Clearwell water with and without polymer were observed to have the longest run time. The use of polymer was found to decrease the run time. These relative observations cannot confirm if the results are statistically significant.

As shown in Table 4.8, each observed run time was 150 minutes during the summer experiments. No condition caused a change in this parameter.

Data from the bench-scale experiment was analyzed using Minitab 16. An analysis of variance was performed for ripening time data using adjusted sum of squares for tests. The results of this analysis showed that season was the only factor that produced a significantly significant response ($\alpha = 0.05$, $P_{season} = 0.011$). These results indicate that shorter run times can be expected during winter months. P-values for all statistically insignificant factors ranged from P=0.120 to P=0.922, each of which are much greater than $\alpha = 0.05$.

4.3.2 Particle Analysis

Bench-scale samples for particle concentration observations were collected for a duration of 1 hour after filter startup. Measurements were performed on a Brightwell Microflow Imager. Particle concentrations were based on particles greater than 2 μm in size and were reported as numbers/mL. Particle profiles during filter ripening were created and ranked with respect to each experimental condition. These profiles were created based on representative plots from each sample set. Profiles were created for both winter and Summer trials and are shown in Figure 4.11 and 4.12.

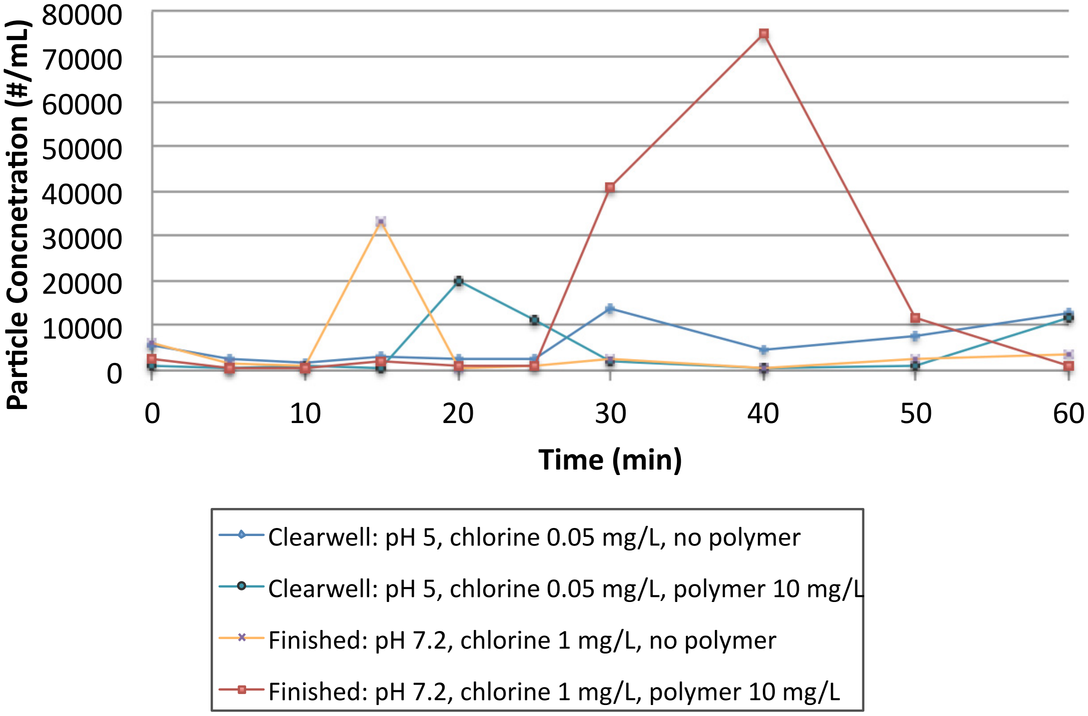

Figure 4.11 Particle profiles for winter bench-scale trials. Results from both clearwell and finished water, with and without polymer, are presented.

Maximum particle concentrations ranged between 4767 to over 75,000 particles/mL for each trial and during the winter. Finished water conditions, with and without polymer resulted in the highest maximum particle concentrations. Clearwell water with and without polymer were observed to have the lowest maximum particle concentrations, without polymer having the lowest. It should be noted that the highest particle concentrations do not correspond with ripening times, as ripening times were less than 20 minutes for each condition.

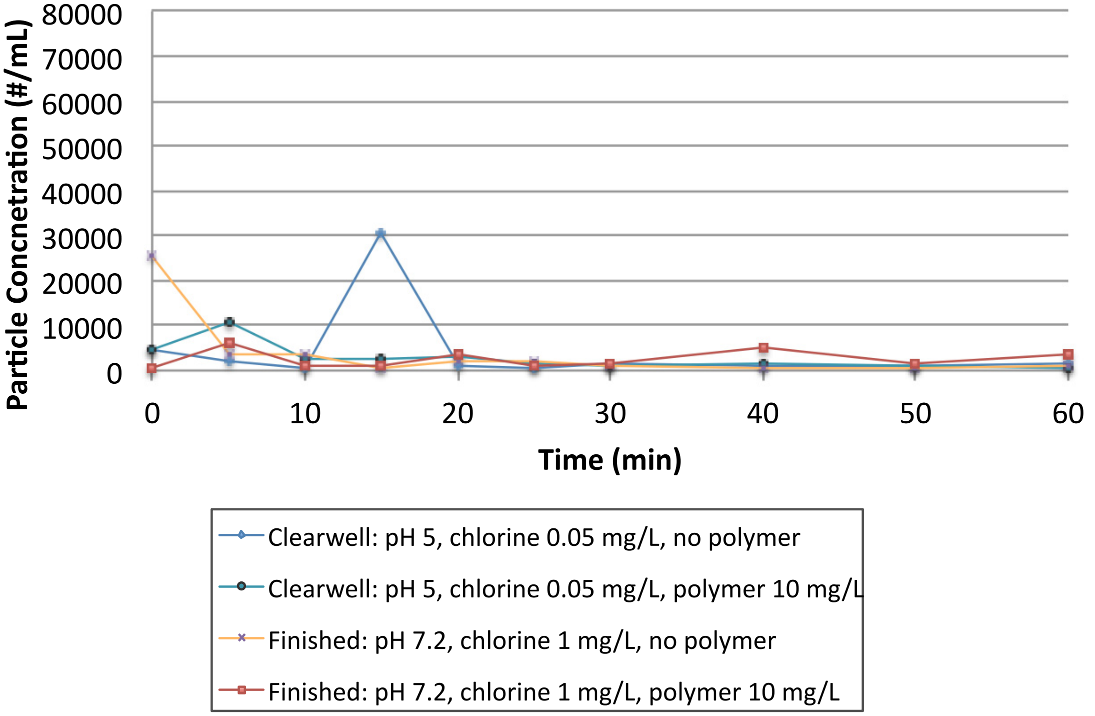

Figure 4.12 Particle profiles for summer bench-scale trials. Results from both clearwell and finished water, with and without polymer, are presented.

Maximum particle concentrations ranged between 4767 to over 75,000 particles/mL for each trial and during the summer. Clearwell water without polymer and finished water with polymer resulted in the highest maximum particle concentrations. It should be noted that particle concentrations during the Summer trials were much smaller than those seen during Winter trials.

Data from the bench-scale experiment was analyzed using Minitab 16. An analysis of variance was performed for maximum particle concentration data using adjusted sum of squares for tests. The results of this analysis showed that the interaction between pH and chlorine was the only factor that produced a significantly significant response ($\alpha = 0.05$, $P_{\text{pH x chlorine}} = 0.010$). These results indicate that clearwell water should produce the lowest maximum particle concnetraitons. P-values for all statistically insignificant factors ranged from P=0.196 to P=0.647, each of which are much greater than α = 0.05.

4.3.3 Zeta Potential Analysis

Bench-scale samples for zeta potential observations were collected for a duration of 1 hour after filter start up. Measurements were performed on a Melvern Zeta Sizer, which had an instrument mean detection limit of 5.54 mV when using filtered water from the JDKWSP. Zeta potential profiles during filter ripening were created and ranked with respect to each experimental condition. These profiles were created based on representative plots from each sample set. Profiles were created for both winter and Summer trials and are shown in Figures 4.13 and 4.14.

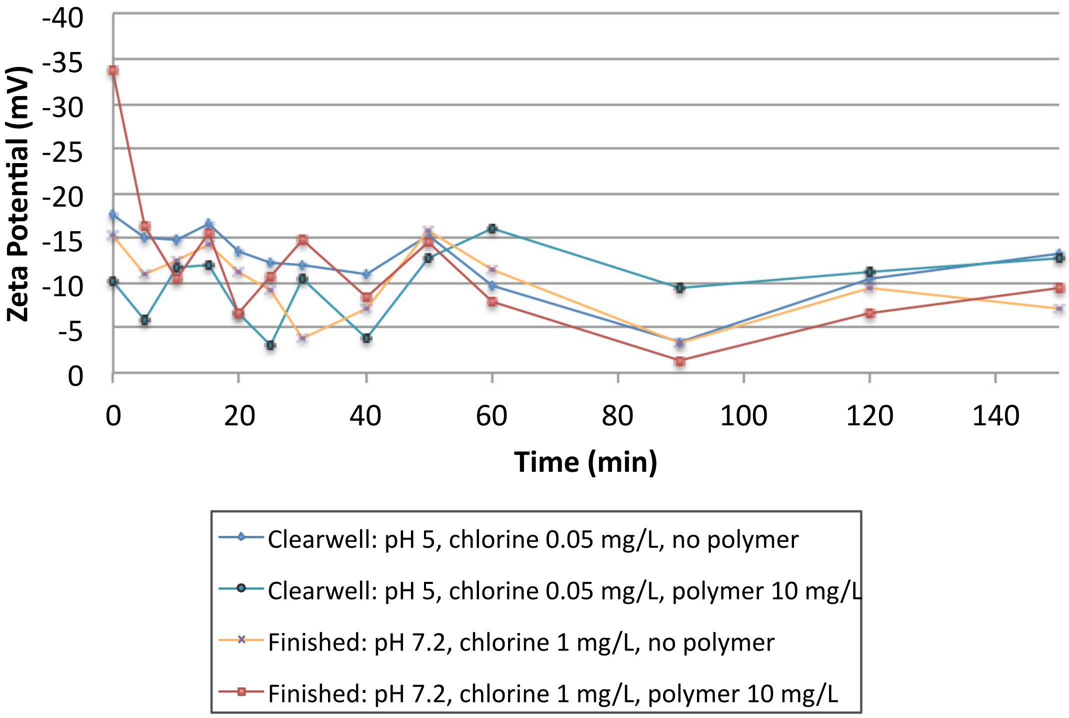

Figure 4.13 Zeta potential plots for bench-scale experimental conditions (Winter trials)

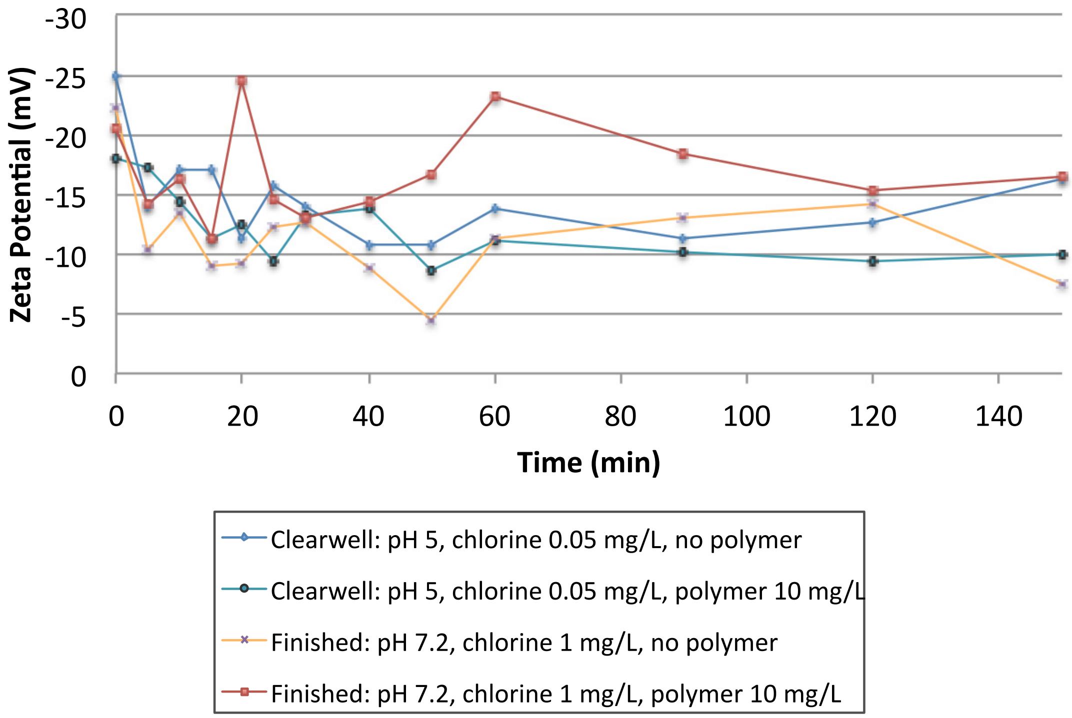

Figure 4.14 Zeta potential plots for bench-scale experimental conditions (Summer trials)

Recall the instrument method detection limit (MDL) of 5.54 mV when using filtered water from the JDKWSP. Including all trials for both winter and summer, as shown in Figures 4.13 and 4.14, zeta potential results had ranges of 5 mV to ranges of 12 mV. A slight decrease in zeta potential (becoming less negative) was observed for most trials. As the filter run continued, zeta potentials became slightly more negative. Also, both winter and Summer trials indicate that a backwash performed using finished water and polymer had a much more negative (-30 mV) start zeta potential and more sporadic throughout the duration of the filter run. Although this indicates that polymer addition does have an effect on filter ripening and the filter run, it is likely due to the lack of control over polymer conditioning of the media. It was difficult to control polymer conditioning manually in a bench-scale experiment. Given the erratic zeta potential readings, it might be concluded that polymer was over dosed for this experiment. Although most readings were above the instrument MDL, due to the low particle concentration in filtered water and the lack of control over the backwash, creating zeta profiles were not exceptionally successful in describing collector efficiency.

4.4 Current Backwash Procedure (Full-scale)

Using turbidity as the assessment parameter, maximum turbidity during ripening and ripening time were observed as part of the full-scale assessment. Ripening time is considered to be the length of time it takes for the turbidity to drop below 0.1 NTU after it is placed back in service following a backwash. A filter run is complete once turbidity reaches over 0.2 NTU (breakthrough), which governs the amount of water produced during that run. Full-scale filters were operated until breakthrough, they had been in service for 80 hours, or a headloss of 2.15 m was reached. Filters were monitored for 24 hours/day. Inline turbidimeters were used to record this information.

4.4.1 Turbidity Analysis

Turbidity profiles were created for both winter and summer. Representative plots, taken from each sample set, were used to relatively compare ripening periods for each season. These profiles are shown in Figure 4.15.

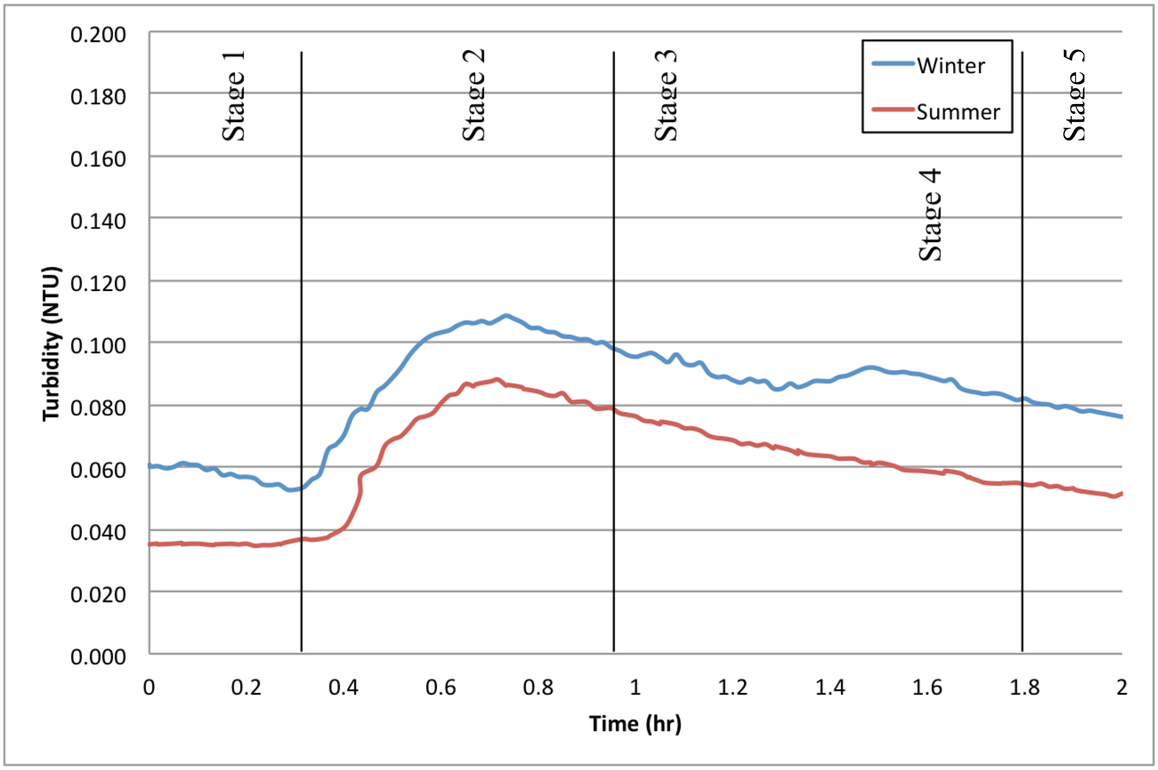

Figure 4.15 Winter and summer representative full-scale turbidity profiles during ripening

In keeping with filter ripening theory, ripening stages can be seen occurring on both the winter and summer plots. Stage 1, the period of low turbidity due to clean backwash water remaining below the filter drains, can be seen to occur between 0.3 and 0.4 hours on both plots. The maximum turbidity seen occurs at ripening stage 2. Stages 3 and 4 are easier to observe in the winter. Ripening theory states that these stages 2, 3, and 4 occur due to remnant particle reactions below the filter, in the media, and above the media. Ripening during the winter months has a greater impact on turbidity than summer months. Although turbidity exceedances do occur at full-scale, they are rare. Most filter ripening periods at the JDKWSP remain below 0.1 NTU, or fall below it within the first hour of ripening. Filter resting is used at the full-scale plant to reduce ripening time.

4.4.2 Particle Analysis

Particle concentrations for full-scale were taken on a Brightwell Micro-Flow Imager (MFI). Particle concentrations were based on particles greater than 2 μm in size and were reported as numbers/mL. Particle profiles during filter ripening were created and ranked with respect to season. These profiles were created based on representative plots from each sample set and are shown in Figure 4.16.

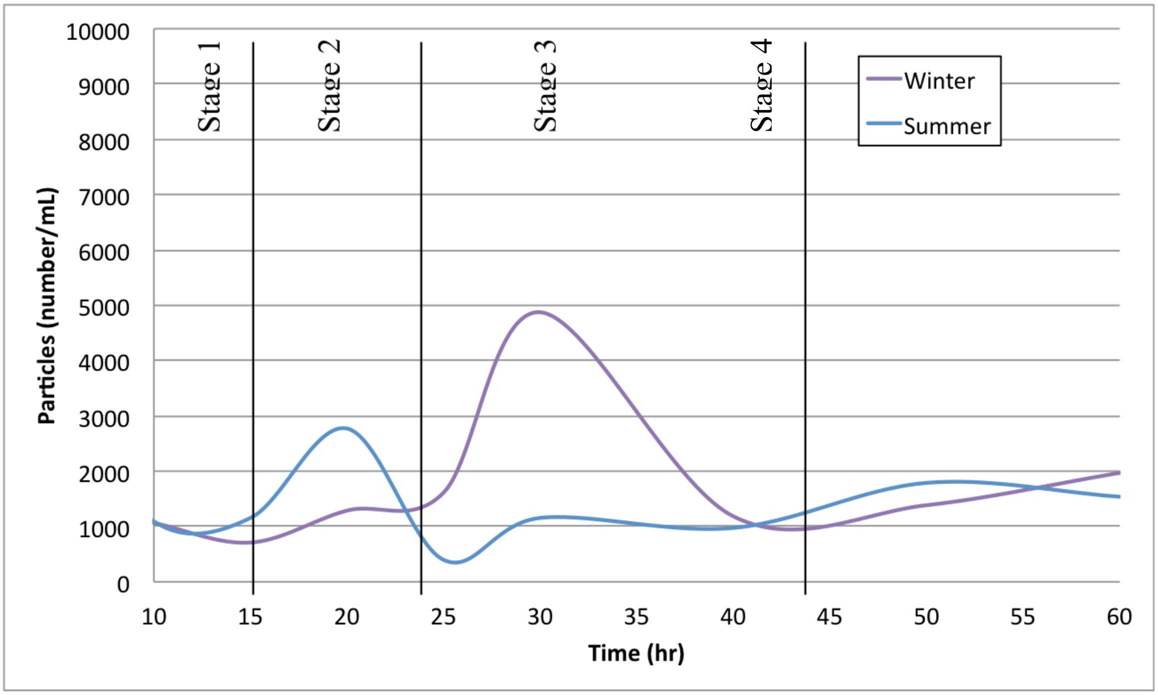

Figure 4.16 Winter and summer full-scale particle profiles during ripening

Ripening trends are observed in full-scale from MFI data representative plots. Plots show an increase in particle passage through the filter during ripening over the winter months. This is consistent with other observations made at the JDKWSP. Stage 1 of ripening is seen to occur in both representative samples around 15 minutes. Stages 2, 3, and 4 of ripening are apparent in both curves and appear within 45 minutes. Sampling frequency was a limitation of these observations. Due to the required length of time for processing, less frequent samples were taken. Inline particle counters are able to take readings continuously and during shorter time intervals.

4.4.3 Zeta Potential Analysis

Full-scale samples for zeta potential observations were collected for a duration of 1 hour after filter start up. Measurements were performed on a Melvern Zeta Sizer. Zeta potential profiles during filter ripening were created and ranked with respect to season. Zeta potential profiles for both winter and summer full-scale observations are shown in Figure 4.17.

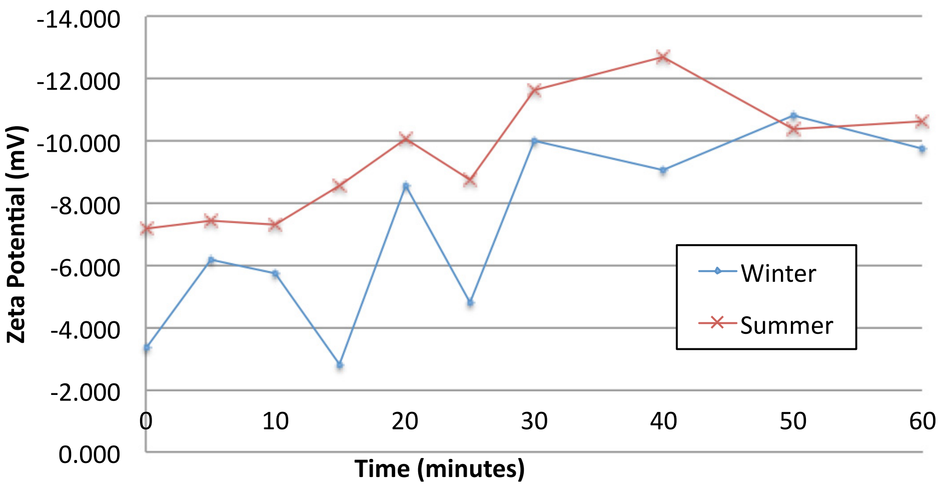

Figure 4.17 Representative full-scale zeta potential profiles for winter and summer observational trials

Recall the instrument method detection limit (MDL) of 5.54 mV when using filtered water from the JDKWSP. These representative plots are generalized from n=12 (winter) and n=10 (summer). Including all trials for both winter and summer, as shown in Figure

23, zeta potential results had ranges of 4 mV to ranges of 9 mV. Most sample measurements were above the instrument MDL. A trend can be observed in Figure 4.17 with zeta potential becoming more negative as the filter ripens. Sampling intervals may have been too far apart to notice all details during ripening. Due to low particle concentrations and sampling intervals, creating zeta profiles were slightly successful at describing collector efficiency during ripening.

4.5 Assessment of Energy and Water Consumption (Full-scale)

Full-scale profiles were created for thirteen backwash periods during the winter and ten backwash periods during the summer. Profiles were used to identify the turbidity that is reached during each backwash, or how “clean” the filters get during this process. Backwash water volume was then used to understand the relationship between the volumes required to achieve the respective backwash turbidities. The goal of this analysis was to discover if required backwash volume could be predicted depending on the previous filter loading. If so, visual inspection could be replaced with a calculated backwash time. Backwash rate was used to calculate the power consumed for each backwash. This data combined with water consumption was used to predict possible cost savings of an optimized backwash. To understand operator variance arising from the visual interpretation in the current backwash procedure the volume of backwash water used in excess of reaching 5 NTU was analyzed for each sampled backwash.

The twelve backwash operations observed during the winter months achieved a backwash turbidity of 0.607 NTU to 7.31 NTU. Backwash duration ranged between 7- to 9-

minutes and backwash volume ranged from 0.43 ML to 0.58 ML. The ten backwash operations observed during the summer months achieved a backwash turbidity of 1.36 NTU to 11 NTU. Backwash duration ranged between 7.5- and 9-minutes and backwash volume ranged from 0.49 ML to 0.59 ML.

Maximum duration (time) of a backwash did not correspond with maximum volume used. During each backwash, water was pumped at an increasing rate followed by a decreasing rate. The maximum flow rate reached and the duration of this rate was dependent on visual inspection and operation. When the fixed point on the backwash trough became visible the operator turned off the control to the pump, resulting in a decreasing flow rate. Variation existed between the rates of increasing and decreasing flow. This is likely due to small variations in filter media depth and type and condition of the underdrains, and ever changing environmental conditions. The underdrain tiles below the filter media allow for the flow of water in both directions without media loss. Originally, all tiles were ceramic Leopold®. Some cracks and damage formed in these tiles in some filters after years of use. Filters 5 and 6 showed significant damage resulting in replacement of these tiles in 2008 with plastic Leopold® tiles of the same dimensions.

To assess if a relationship exists between backwash volume used and the previous filter loading, each of these parameters were plotted in Figures 4.18 and 4.19.

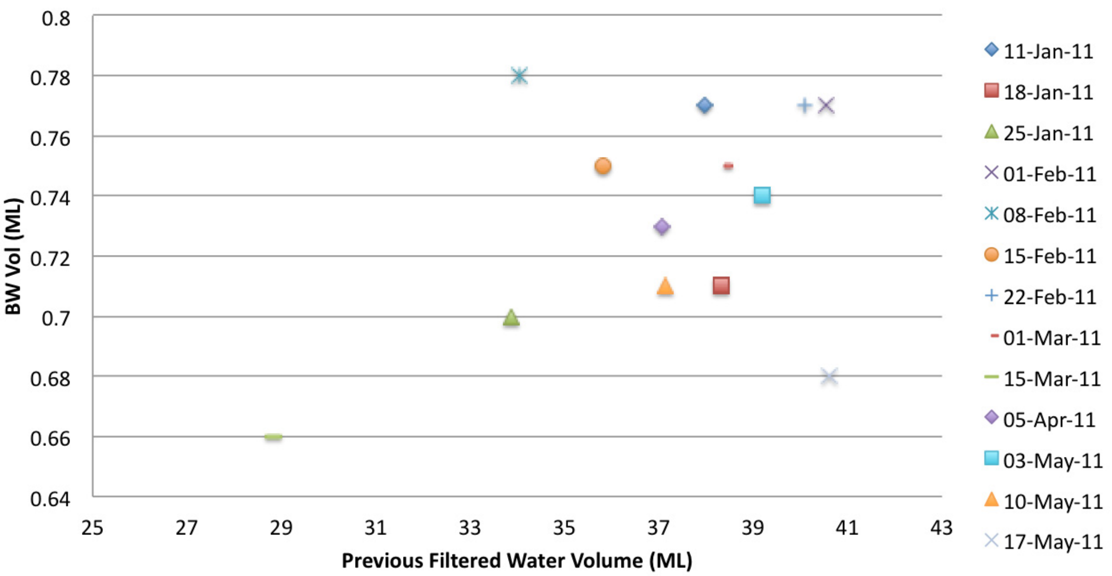

Figure 4.18 Backwash volume versus volume produced during previous filter run for 12 winter observations

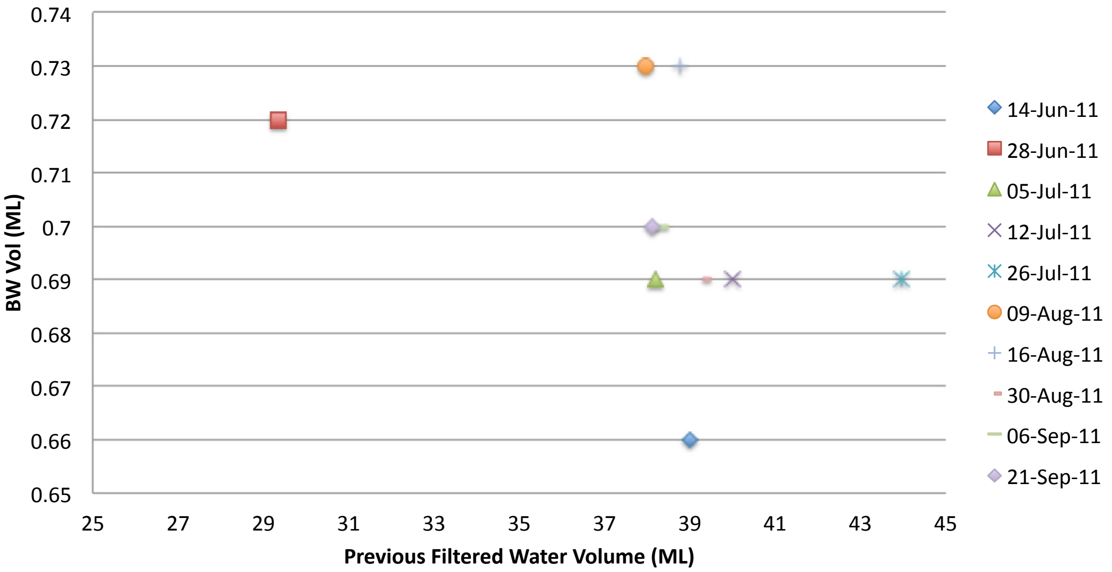

Figure 4.19 Backwash volume versus volume produced during previous filter run for 10 summer observations

A relationship between required backwash volume and previous filter loading could not be determined from this analysis. Many factors contribute to the required volume used for each backwash. Considering daily changes in raw water quality, chemical doses, and other constantly changing factors, a direct relationship was not found.

Although the pilot analysis in Section 4.2 showed that backwashing until turbidity reached between 10 and 20 NTU did not appear to perform as well as backwashing until turbidity reached less than 5 NTU, analysis showed that the differences in both methods were not statistically significant. As a result, backwashing until turbidity reaches between 10 to 20 NTU should sufficiently clean the filter during a backwash. Observations from full-scale backwash turbidity trials are presented in Table 4.9.

Table 4.9 Full-scale backwash turbidity profiling observations

Backwash Turbidity (NTU)	Number of Observations	
	Winter (n=12)	Summer (n=10)
10-20	0 (0%)	1 (10%)
5-10	2 (17%)	1 (10%)
Less than 5	10 (83%)	8 (80%)

Although variation existed between backwash duration after 5 NTU was reached, all observed backwash procedures in winter and summer fell below 20 NTU after a backwash duration of 7 minutes. Results of this analysis are displayed in Table 4.10.

Table 4.10 Results of full-scale backwash duration analysis

Backwash Duration (min)	Unit Filter Bed Volumes (UFBV)*	Number of Observations (turbidity reaching below 20 NTU)	
		Winter (n=12)	Summer (n=10)
7	3.97 SD: 0.29 Var: 0.08	12 (100%)	10 (100%)
6.5	3.85 SD: 0.29 Var: 0.08	11 (92%)	9 (90%)
6	3.69 SD: 0.36 Var: 0.13	10 (83%)	6 (60%)
5	3.11 SD: 0.48 Var: 0.23	8 (67%)	6 (60%)
4	2.78	1 (8%)	0 (0%)
3	-	0 (0%)	0 (0%)

* One UFBV at the JDKWSP is equal to 0.131 ML

To demonstrate the cost savings that could result from optimizing the backwash procedure at the JDKWSP, three alternatives were reviewed. These options are described in the list below.

1. Do nothing

   This option does not suggest any procedural changes. There will be no cost savings from reduced power or water consumption. The cost of this option was calculated from total cost of power consumed per kilowatt-hour (KWH) and the indirect cost of water consumed. The cost of water is calculated based on the revenue that could be generated from the water consumed.

2. Standardize operation time

   This option suggests backwashing each filter until 100% of the backwash water reaches between 10 to 20 NTU. As shown in table 10, 100% of the full-scale backwash observations reached between 10 and 20 NTU after a volume of 3.97 UFBV has passed through the filter (7-minutes of backwash at the JDKWSP). This is a conservative approach as some of the filters would be reaching a turbidity of less than 5 NTU at this time, however, turbidimeters would not need to be installed. The cost of power and water consumption were calculated as in option 1.

3. Install turbidimeters

   This option suggests backwashing each filter until that filter reaches between 10 to 20 NTU. The backwash time required to achieve this level of cleanliness varies for each backwash. Installation of turbidimeters above each filter to monitor backwash turbidity is required for this option. Here, operators would monitor the backwash turbidity ensuring that excess time was not used to complete each backwash. This would reduce power and water consumption for each backwash. This option offers the most cost savings of the three. The cost of power and water consumption were calculated as in option 1.

Option 1

The average time, power consumption, and water consumption during the winter and summer months were observed values and are shown in Table 4.11. The cost calculations were performed as shown in equation 1. The JDKWSP performs approximately 70 backwash procedures per month, which was used to calculate the annual cost.

Table 4.11 Cost calculations for the current backwash procedure

	Winter Observations	**Summer Observations**
Backwash Duration	Mean = 8.3 min SD = 29	Mean = 8.2 min SD = 27
Backwash Volume (UFBV)	Mean = 4.04 SD = 0.33	Mean = 4.06 SD = 0.29
Power Consumed	Mean = \$0.1155/backwash SD = 0.01	Mean = \$0.1158/backwash SD = 0.01
Water Consumed	Mean = 0.5296 ML SD = 0.04	Mean = 0.5312 ML SD = 0.04

The cost of power consumption was calculated using equation 1.

Equation 5

$$P = \frac{q\rho g h}{3.6\times10^{6}}$$

Where,

P = power (KW)
q = flow (m^3/hr)

ρ = density (kg/m^3)
g = gravity (9.81 m/s^2)
h = differential head (m)

The average cost of power consumption was calculated using the rate of $0.08/KWH. The cost of power consumption required to perform a backwash with the current procedure were found to be $0.1155/backwash (SD = 0.0094) for winter and $0.1158/backwash (SD = 0.0083) for summer.

The indirect cost of water consumption was considered to be the value of lost revenue from domestic customers. A direct cost of water could be calculated using the cost to produce the water, which would consider the cost of salaries, maintenance fees, capital costs, and operation costs divided by the total volume of water produced yearly. This information is confidential and will not be discussed in this analysis. The indirect costs were calculated using the domestic rate of \$0.509/m^3 ($2.3136/1000 imperial gallons). The indirect costs of water consumption required to perform a backwash with the current procedure were found to be $269.56/backwash (SD = 21.9) for winter and $270.36/backwash (SD = 19.3) for summer.

Considering there are approximately 70 backwash procedures performed at the JDKWSP each month, the total annual cost was calculated to be $226,865 ($100 for power and $226,765 for water). This estimate does not consider the cost required to produce the water.

<u>Option 2</u>

The variation existing between each backwash performed by the operators can be controlled by stopping each backwash after a volume of 3.97 UFBV has passed through the filter (7-minutes of backwash at the JDKWSP). Pilot studies demonstrated that backwashing until turbidity reaches between 10 and 20 NTU would not result in a statistically significant difference in maximum turbidity seeing during ripening, ripening time, or volume produced during the filter run. Employing this procedural change (shortening the backwash duration) would result in water, energy, and cost savings. Although some would reach a turbidity of less than 10 NTU, full-scale observations showed that 100% of the filters were cleaned appropriately during the backwash procedure. This operational change can be done without the installation of turbidimeters.

The average time, power consumption, and water consumption to ensure 100% of the backwash procedures reached between 10 and 20 NTU (without a turbidimeter) during the winter and summer months are shown in Table 4.12. The cost calculations were performed as shown in equation 1.

Table 4.12 Cost calculations for option 2

	Winter Observations	**Summer Observations**
Backwash Duration	7 minutes	7 minutes
Backwash Volume (UFBV)	3.95 SD = 0.04	4.01 SD = 0.04
Power Consumed	Mean = \$0.1127/backwash	Mean = \$0.1146/backwash

	SD = 0.01	SD = 0.01
Water Consumed	Mean = 0.5170 ML SD = 0.04	Mean = 0.5256 ML SD = 0.04

The average cost of power consumption was calculated using the rate of \$0.08/KWH. The cost of power consumption required to perform a backwash with the current procedure were found to be \$0.1127/backwash (SD = 0.0088) for winter and \$0.1146/backwash (SD = 0.0078) for summer.

As in option 1, the indirect cost of water consumption was considered to be the value of lost revenue from domestic customers. A direct cost of water, which would consider the expenses divided by the total volume of water produced annually, is not considered because the information is confidential. The indirect costs were calculated using the domestic rate of \$0.509/m^3 (\$2.3136/1000 imperial gallons). The indirect costs of water consumption required to perform a backwash with the current procedure were found to be \$263.16/backwash (SD = 20.5) for winter and \$267.55/backwash (SD = 18.2) for summer.

Considering there are approximately 70 backwash procedures performed at the JDKWSP each month, the total annual cost was calculated to be \$222,995 (\$95 for power and \$222,900 for water). This estimate does not consider the cost required to produce the water.

To calculate the cost *savings* resulting from employing option 2 were calculated by subtracting the values from option 1 and 2. Employing option 2 would result in a cost saving of $3869/year ($5 from power and $3865 from water).

Option 3

Optimization and variation control for backwash procedures at the JDKWSP can be achieved by installing turbidimters. Pilot studies demonstrated that backwashing until turbidity reaches between 10 and 20 NTU would not result in a statistically significant difference in maximum turbidity seeing during ripening, ripening time, or volume produced during the filter run. Adding turbidimeters to each filter above the media would result in optimized backwash durations. In turn, this would result in water, energy, and cost savings. Every backwash would reach a turbidity between 10 to 20 NTU.

The average time, power consumption, and water consumption required to adequately clean a filter during a backwash (by using turbiditmeters) are shown in Table 4.13. The cost calculations were performed as shown in equation 1.

Table 4.13 Cost calculations for option 3

	Winter Observations	**Summer Observations**
Backwash Duration	Variable (between 4 and 7 minutes)	Variable (between 5 and 7 minutes)
Backwash Volume (UFBV)	2.13 to 4.23	3.04 to 4.42

Power Consumed	Mean = $0.1008/backwash SD = 0.0128	Mean = $0.1084/backwash SD = 0.0099
Water Consumed	Mean = 0.4623 ML SD = 0.059	Mean = 0.4973 ML SD = 0.045

The average cost of power consumption was calculated using the rate of $0.08/KWH. The cost of power consumption required to perform a backwash with the current procedure were found to be $0.1008/backwash (SD = 0.0128) for winter and $0.1084/backwash (SD = 0.0099) for summer.

As in options 1 and 2, the indirect cost of water consumption was considered to be the value of lost revenue from domestic customers. A direct cost of water, which would consider the expenses divided by the total volume of water produced annually, is not considered because the information is confidential. The indirect costs were calculated using the domestic rate of $0.509/m^3 ($2.3136/1000 imperial gallons). The indirect costs of water consumption required to perform a backwash with the current procedure were found to be $235.34/backwash (SD = 29.9) for winter and $253.15/backwash (SD = 23.1) for summer.

Considering there are approximately 70 backwash procedures performed at the JDKWSP each month, the total annual cost was calculated to be $205,255 ($90 for power and $205,165 for water). This estimate does not consider the cost required to produce the water.

To calculate the cost *savings* resulting from employing option 3 were calculated by subtracting the values from option 1 and 3. Employing option 3 would result in a cost saving of $21,610/year ($10 from power and $21,600 from water).

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Microbial Monitoring

The lack of filter-to-waste infrastructure at the JDKWSP raised concerns over the passage of pathogens during vulnerable stages, like filter ripening. Because of the disinfection-resistant nature of *Cryptosporidium* and *Giardia,* they were of particular concern. *E. coli* was monitored as an indication of possible fecal contamination. Both source water and filtered water during ripening were sampled for a 12-month duration, with the exception of source water *E. coli* sampling which was performed bi-weekly for 48 months. A total of 108 *E. coli* samples were collected from November 2009 to October 2010. A total of 36 *Giardia* and 36 *Cryptosporidium* samples were collected. Sample processing was performed by third-party laboratories.

Important findings of this work show zero detections of *E. coli, Giardia,* or *Cryptosporidium* in any of the results. The pristine quality of source water in a protected water shed and lack of pathogen presence indicate the JDKWSP is at low risk of pathogen contamination. The current 2.5-log reduction credit for *Cryptosporidium* and *Giardia* is adequate treatment for water of this quality. Zero detection of *E. coli* also indicates no fecal contamination.

5.1.2 Backwash Procedure Concepts

Backwash procedural methods were tested at the pilot-scale plant at the JDKWSP. The objective of this study was to observe each procedural effect on controlling filter ripening. The response parameters measured were maximum turbidity during ripening, ripening time, bed volumes, and particle concentrations. Turbidity data taken from inline turbidimeters and particle counters proved useful in this analysis. The necessary detail seen by analyzing continuous samples enabled a close look at details during the short period of filter ripening. All treatment conditions upstream from filtration were set to mimic current full-scale plant processes.

Results showed that season held the largest significance over each of the factors. Slight trends could be seen from averaged maximum turbidity, ripening times, bed volumes, and maximum particle concentrations, but they also had large standard deviation from the mean. Factorial analysis showed the interaction between ETSW rate and backwash turbidity had a significant influence over maximum turbidity during ripening. ETSW rate independently had a significant influence over ripening time. Backwashing until turbidity reached between 10 to 20 NTU did not show a statistically significant increase the negative effects of filter ripening.

5.1.3 Backwash Water Chemistry Concept

Backwash water chemistries were tested at bench-scale. The objective of this study was to observe each procedural effect on controlling filter ripening. The response parameters measured were maximum turbidity during ripening, ripening time, bed volumes, and particle concentrations. Turbidity and particle data were read manually in the laboratory and proved useful in this analysis, however, the detail seen by analyzing continuous samples enabled a close look at details during the short period of filter ripening was not caputred.

Results showed that season and the interaction of pH and chlorine held the largest significance over factors. Factorial analysis showed that finished water conditions (pH=7.2, $[Cl_2]$=1.0 mg/L) reduced ripening time during colder temperatures but clearwell conditions performed best when considering particle passage.

5.1.4 Energy and Water Consumption

Turbidity was monitored during full-scale backwash procedures at the JDKWSP to gain an understanding of backwash duration, volume of wash-water used, and power consumed. Turbidity was measured using a laboratory turbidimeter and flow data was taken from Halifax Water's online monitoring system. This data was used to identify the energy and water consumed for a current backwash procedure. This information, combined with pilot-scale results, was useful for establishing options for reducing cost.

5.2 Recommendations

5.2.1 Microbial Monitoring

Given that concentrations of 0 were observed for *E. coli, Cryptosporidium,* and *Giardia,* the addition of filter-to-waste infrastructure would not benefit this facility. The addition of the robust infrastructure will not reduce the risk of microbial passage during ripening since the current risk is already very low.

5.2.2 Backwash Procedure Concepts

Although ETSW was found to decrease ripening time, the current procedure at full-scale is meeting regulations. ETSW, as a backwash procedure, holds a minimal benefit to the JDKWSP so installation of the necessary equipment is not justified. This option could be reviewed again if a degradation of water quality in the future was observed.
Backwashing until turbidity reaches between 10 to 20 NTU should be explored for the potential cost savings associated with the reduced water and power consumption.

5.2.3 Backwash Water Chemistry Concepts

Although finished water was observed to decrease ripening time during colder temperatures, clearwell water performed best with respect to particle passage. As a result, it is recommended to keep the current practice of using clearwell water for backwash at the JDKWSP.

5.2.4 Energy and Water Consumption

Although there will be a capital cost associated with installation of inline turbidimeters to monitor backwash turbidity, this option (option 3) is recommended due to the potential cost savings. Since the JDKWSP is currently within regulations, option 1 (do nothing) is adequate for producing high quality water quality but continue to consume water and energy in excess.

REFERENCES

Amburgey, J.E.; Amirtharajah, A.; Brouckaert, B.M.; and Spivey, N.C. (2003) An Enhanced Backwashing Technique for Improved Filter Ripening. Journal AWWA 95(12) 81-94.

Amburgey, J.E.; Amirtharajah, A.; Brouckaert, B.M.; and Spivey, N.C. (2004) Effect of Washwater Chemistry and Delayed Start on Filter Ripening. Journal AWWA 96 (1), 97–110.

Amburgey, J.E. (2005) Optimization of the Extended Terminal Subfluidization Wash (ETSW) Filter Backwashing Procedure. Water Research 39, 314-330.

Amburgey, J.E. and Amirtharajah, A. (2005) Strategic Filter Backwashing Tchniques and Resulting Particle Passage. J. Environ. Eng. 131(4), 535-547.

Amburgey, J.E. and Brouckaert, B.M. (2005) Practical and Theoretical Guidelines for Implementing the Extended Terminal Subfluidization Wash (ETSW) Backwashing Procedure. Journal of Water Supply 54(5), 329-337.

American Water Works Association (1971) Water Quality and Treatment, 3rd edition. McGraw-Hill, Toronto.

Amirtharajah, A. and Wetstein, D.P. (1980) Initial Degradation of Effluent Quality During Filtration. Journal AWWA 72(9), 518-524.

Amirtharajah, A. (1985) The Interface Between Filtration and Backwashing. Water Research 19(5), 581-588.

Baird, G. and Hillis, P. (1998) Full Scale Evaulation of Filter Start-up Strategies to Reduce Particle Passage Into Drinking Water Supply. *Proceedings of the AWWA Water Quality Technology Conference.* Denver, CO.

Berthouex, P.M. and Brown, L.C. (2002) Statistics for Environmental Engineers, Second edition. Lewis Publishers.

Boyce, T.G.; Swerdlow, D.L.; and Griffin, P.M. (1995) Escherichia Coli O157:H7 and the Hemolytic-Uremic Syndrome. The New England Journal of Medicine 333(6), 364-368.

Burnson, B. (1938) Seasonal Temperature Variations in Relation to Water Treatment. Journal AWWA 30 (793).

Colton, J.F.; Hillis, P.; and Fitzpatrick, C.S.B. (1996) Filter Backwash and Start-up Strategies for Enhanced Particulate Removal. Water Research 30(10), 2502-2507.

Consonery, P.J.; Greenfield, D.N.; and Lee, J.J. (1997) Pennsylvania's Filtration Evaluation Program. Optimizing Treatment Processes, Journal AWWA. August 1997, 67-77.

Cranston, K.O. and Amirtharajah, A. (1987) Improving the initial Effluent Quality of a Dual-Media Filter by Coagulants in Backwash. Journal AWWA 79(12), 50-63.

Dai, X. and Boll, J. (2006) Settling Velocity of Cryptosporidium Parvum and Giardia Lamblia. Water Research 40(6), 1321-1325.

Droste, Ronald L. (1997) Theory and Practice of Water and Wastewater Treatment. J. Wiley, NY.

Emelko, M.B.; Huck, P.M.; and Douglas, I.P. (2003) Cryptosporidium and Microsphere Removal During Late In-cycle Filtration. Journal AWWA 95(5), 173-182.

Emelko, Monica B. (2003) Removal of Viable and Inactivated Cryptosporidium by Dual- and Tri-media Filtration. Water Research 37(12), 2998-2008.

Environment Act. 1994-95. c.1, s.1. Found at: nslegislature.ca/legc/statutes/envromnt.htm

Environment Canada (1975) Water Quality Data for Surface Water for Alberta. Found at: http://environment.alberta.ca/01256.html

Graczyk, T.K. and Fried, B. (2007) Human Waterborne Trematode and Protozan Infections. Advances in Parasitology 64, 111-160.

Huck, P.M.; Coffey, B.M.; Emelko, M.B.; Maurizio, D.D.; Slawson, R.M.; Anderson, W.B.; Van Den Oever, J.; Douglas, I.P.; and O'melia, C.R. (2001) Effects of Filter Operation on Cryptosporidium Removal. Journal AWWA 94(6), 97-111.

Kawamura, Susumu (2000) Integrated Design and Operation of Water Treatment Facilities: 2nd Edition. John Wiley & Sons, Inc. New Jersey.

Kim, H.N.; Walker, S.L.; and Bradford, S.A. (2010) Macromolecule Mediated Transport and Retention of Escherichia coli O157:H7 in Saturated Porous Media. Water Research 44(4), 1082-1093.

Knowles, A.D.; MacKay, J.; and Gagnon, G.A. (2012) Pairing a Pilot-Plant to a Direct Filtration Water Treatment Plant. Canadian Journal of Civil Engineering 39(6), 689-700.

LeChevallier, M.W.; Norton, W.D.; and Lee, R.G. (1991) Giardia and Cryptosporidium spp. in Filtered Drinking Water Supplies. Applied and Environmental Microbiology 57(9), 2617-2621.

LeChevallier, M.W.; Norton, W.D.; and Lee, R.G. (1991) Occurrence of Giardia and Cryptosporidium spp. in Surface Water Supplies. Applied and Environmental Microbiology 57(9), 2610-2616.

Logan, A.J.; Stevik, T.K.; Siegrist, R.L.; and Ronn, R.M. (2001) Transport and Fate of Cryptosporidium Parvum Oocysts in Intermittent Sand Filters. Water Resources 35(18), 4359-4369.

Logsdon G.S. Hess, A.F., Chipps, M.J., Rachwal, A.J., 2002. Filter Maintenance and Operations Guidance Manual. AwwaRF, Denver, CO.

Logsdon, G.S., A.F. F. Hess, M.J. Chipps, and J. Gavre. 2005. After backwash: controlling the initial turbidity spike. *Opflow*, October 2005.

Logsdon, G.S.; Symons, J.M.; Hoye, R.L.; and Arozarena, M.M. (1981) Alternative Filtration Methods for Removal of Giardia Cysts and Cysts Models. Journal AWWA 27(2), 111.

Maudling, J.S. and Harris, R.H. (1968) Effect of Ionic Environment and Temperature on the Coagulation of Color-Causing Organic Compounds with Ferric Sulfate. Journal AWWA 60 (460).

McTigue, Nancy E. (1998) National Assessment of Particle Removal by Filtration. AWWA Research Foundation and American Water Works Association. USA.

Nova Scotia Environment. (2005) Guidelines for Monitoring Public Drinking Water Supplies. December 12, 2005. Found at: www.gov.ns.ca/nse/water/docs/Guidelines_for_Monitoring_Public_Drinking_Water_Supplies.pdf

Nova Scotia Environment (2012) Nova Scotia Treatment Standards for Municipal Drinking Water Systems. March 12, 2012.

Pernitsky, David J.; Cantwell, Raymond E.; Murphy, Ella; Paradis, Natalie; Boutlier, Jaimie; and Bache, Geoffe (2011) Use Zeta Potential to Improve Direct Filtration Operation. AWWA Op-flow. February, 2011 20-23.

Pizzi, Nick (2000) Optimizing Your Plant's Filter Performance. AWWA Op-flow, June 2000. 26(6), 37-38.

Soucie, W.J. and Sheen, B.J. (2007) Filter-to-Waste Optimization. Journal AWWA 99(5), 148-157.

Stephan, E.A. and Chase, G.G. (2001) A Preliminary Examination of Zeta Potential and Deep Bed Filtration Activity. Separation and Purification Technology 21(3), 219-226.

Stevens, A.A., Slocum, C.J., Seeger, D.R., and Robeck, G.G. (1976) Chlorination of Organics in Drinking Water. Journal AWWA, 68 (615).

USEPA. (2008) Approved Methods for the LT2 Enhanced Surface Water Treatment Rule – National Primary Drinking Water Regulations. Revised June, 2008. Found at: www.epa.gov/ogwdw/methods/pdfs/methods/methods_lt2.pdf

USEPA. (2005) Method 1623: Cryptosporidium and Giardia in Water by Filtration/IMS/FA. December 2005.

Vennard, J.K. and Street, R.L. (1975) Elementary Fluid Mechanics, 5th edition. John Wiley and Sons, Inc.

Weber, W.J. and Morris, J.C. (1964) Equilibria and Capacities for Adsoption on Carbon. J. Sanit. Eng. Div. Proc. Am. Soc. Civ. Eng., 90 (5A3), 79.

Wierenga, John T. (1985) Recovery of Coliforms in the Presence of a Free Chlorine Residual. Journal AWWA 77(11), 83-88.

Wang, Zhishi (1998) Effects of Zeta Potentials of Suspended Particles on Deep Bed Filtration for Water and Wastewater Treatment. *Proceedings from Canadian Society for Civil Enginering, Annual Conference: 5th Environmental Speciality Conference.* 2, 31-42.

Yapijakis, Constantine (1982) Direct Filtration: Polymer in Backwash Serves Dual Purpose. Journal AWWA 74(8), 426-428.