OPERATIONAL CHALLENGES OF A DIRECT FILTRATION WATER TREATMENT PLANT IN LIGHT OF LAKE RECOVERY

by

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DEDICATION

I dedicate this thesis to my family for the everlasting support and patience throughout my entire academic experience.

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Abstract

There are many direct filtration plants across North America and around the world that continue to provide safe drinking water. One of the biggest challenge they have faced in recent times is changing water quality due to Lake Recovery. As lakes recover from years of acid deposition, they are responding both chemically and biologically. Although the effects of Lake Recovery in terms of changing water quality have been studied well (increased DOC and biology), their impacts on a water supply plant are not well understood. This thesis discusses the challenges that a water supply plant in Halifax, Nova Scotia is facing in light of Lake Recovery and how the utility has been able to overcome these challenges reactively as they come. Additionally, this thesis provides some short and long term opportunities for the plant to make it more robust and resilient to face the ongoing and upcoming Lake Recovery challenges.

Abbreviations and Symbols used

ACH	Aluminum Chlorohydrate
Alum	Aluminum Sulphate
AOPs	Advanced Oxidation Processes
ATP	Adenosine triphosphate
°C	Degrees Celsius
CFD	Computational fluid dynamics
CDWQG	The Guidelines for Canadian Drinking Water Quality
CLRTAP	Convention on Long-range Transboundary Air Pollution
CO_2 / CO2	Carbon Dioxide
d60	60% of the particles are finer than this size
d10	10% of the particles are finer than this size
DAF	Dissolved Air Floatation
DBP	Disinfection By-Products
DI	Deionized Water
DOC	Dissolved Organic Carbon
EBCT	Empty Bed Contact Time
ETSW	Extended Terminal Subfluidization Wash
FEEM	Fluorescence Excitation Emission Matrix
FRT	Filter Run Time
FSP	Full Scale Plant
ft/s	Feet per second
g	Gram
G-value	Velocity gradient
GAC	Granular Activated Carbon
HAA	Haloacetic acids
HAAFP	Haloacetic acid formation potential
HRM	Halifax Regional Municipality
JDKWSP	JD Kline Water Supply Plant
KMnO4	Potassium Permanganate
L	Liters
L/d	Liters per day
l/min	Liters per minute
LMWSP	Lake Major Water Supply Plant
MAC	Maximum Allowable Concentration
m	meters
m^3/m^2	Cubic meters per square meter
m/h	Meter per hour
mL	Milli-liter

ML	Million liters
MIB	Methyl-Isoborneol
μm	Micro-meter
μg/l	Microgram per liter
mg/l	Milligram per liter
mg/m^3	Milligram per cubic meter
mm	millimeter
ml/day	Milliliter per day
MLD	Million liters per day
MW	Molecular weight
mv	millivolt
NaOH	Sodium Hydroxide
ng	Nanogram
ng/cm^3	Nanogram per cubic meter
ng/l	Nanogram per liter
nm	nanograms
NOM	Natural Organic Matter
NO_X	Nitrous Oxides
NTU	nephelometric turbidity units
O3	Ozone
PAC	Powdered Activated Carbon
PID	proportional–integral–derivative
PLC	Programmable logic controller
ppb	Parts per billion
psi	Pounds per square inch
SO_2	Sulphur dioxide
TCU	true colour units
THMs	Trihalomethanes
THMFP	Trihalomethanes formation potential
T&O	Taste and odour
TOC	Total Organic Carbon
UFRV	Unit Filter Run Volume
USEPA	United States Environmental Protection Agency
VFDs	Variable Frequency Drives
WSP	Water Supply Plant
WTP	Water Treatment Plant
ZP	Zeta Potential

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Chapter 1 Introduction

1.1. Project Rationale

Many utilities in northeastern North America and Europe face a unique set of conditions in which successful efforts to reduce atmospheric pollution have led to the phenomenon of Lake Recovery, leading to increases in pH, natural organic matter (NOM), cyanobacterial and algal blooms in surface water supplies. One of the significant and widespread drivers for these water quality changes is the reduction in atmospheric discharge of acidic gases. In particular, the emission of sulfur oxides from the combustion of fossil fuels has greatly decreased in recent decades as seen in **Figure *1* Error! Reference source not found.**.

Figure 1: (A) National emissions of oxidized nitrogen (NOx) and sulfur dioxide (SO2) through U.S. (B) Annual Wet deposition of Sulphur (S) and nitrogen (N) since 1979 as measured by the Atmospheric Deposition Program at Huntington Forest. Obtained from *Sullivan, et al., (2018)*

These long-term changes are problematic for treatment plants that were designed under fundamentally different source water quality conditions, leading to increased treatment costs, the addition of treatment processes, increased residuals handling and reducing operational reliability and resilience.

In connection with this concept of Lake Recovery, is a broad scale statistically significant increase in Dissolved Organic Carbon (DOC) and pH of surface waters across the areas impacted by lower sulfur oxide deposition. In addition to DOC and pH, many utilities have reported higher levels of cyanobacteria along with their unwanted products, cyanotoxins, and taste & odor compounds. There is strong evidence that these phenomena are mechanistically linked and that water quality changes will continue to progress well into the future (Erlandsson, et al., 2011).

The impacts of the successful air pollution controls on source surface water quality are currently being observed by water plants and are being dealt with reactively. However, these impacts have not yet been translated into effects on water treatment plant operations and future process modifications or upgrades. Current treatment processes either are currently or will soon be inadequate to address these changes in source water quality, and an analysis of current and future design needs based on source water quality projections is required. **Figure *2*** captures the high level impacts of Lake Recovery on operations of water treatment facilities. However, in-depth analysis is required to understand the exact impacts on every component of the water treatment process.

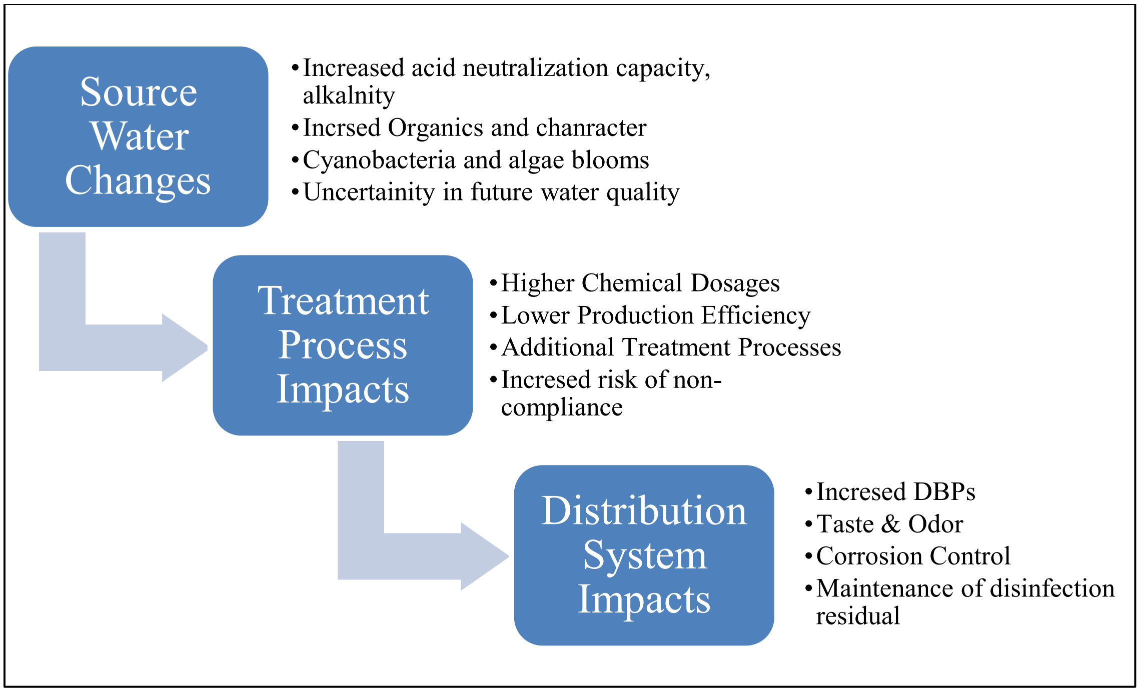

Figure 2: High-Level Impacts of Lake Recovery: Watershed to Tap

Halifax Water is already experiencing source water quality changes that are challenging existing treatment plant capabilities. The pH and color in both their source waters (Pockwock Lake and Lake Major) for large water plants have been trending up over the last fifteen years. **Figure *3*** and **Figure *4*** show the increase in pH and colour observed over the last two decades.

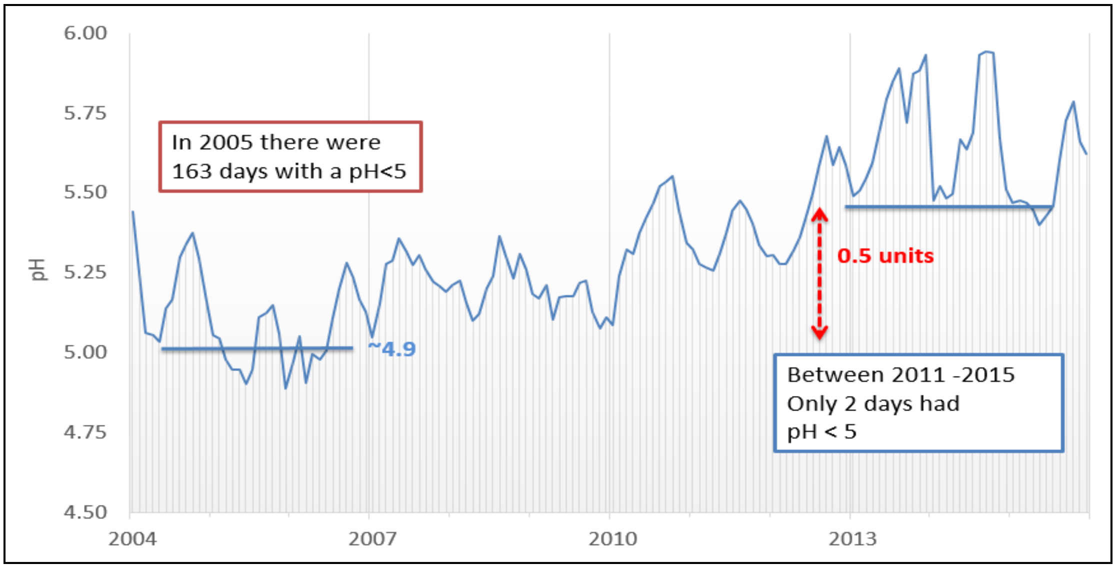

Figure 3: pH trend for Pockwock Lake between the years 2004 and 2015 showing an upward rise. (Source: Halifax Water, 2018)

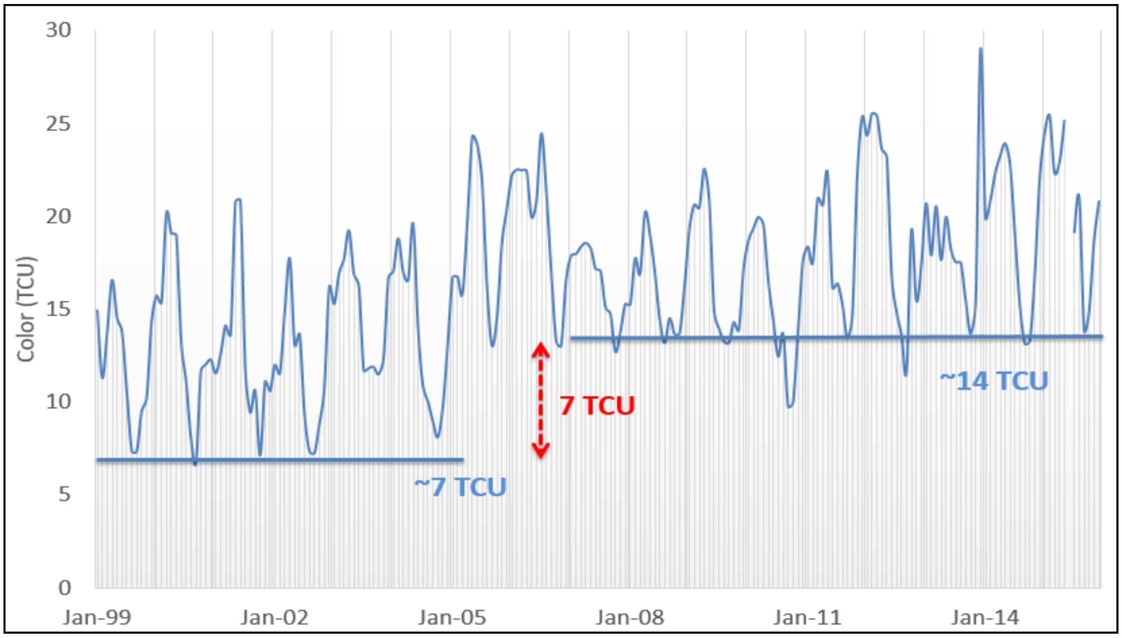

Figure 4: Color (TCU) trend for Pockwock Lake (Source: Halifax Water, 2018)

Although Lake Recovery effects are being felt at both Halifax Water plants, this research is focused particularly on the challenges faced by the JD Kline Water Supply Plant (JDKWSP). It is the largest drinking water plant in Atlantic Canada and is a direct filtration plant. Water quality changes were first noticed with the occurrence of seasonal geosmin (2012 to present), and thorough examination of historical water quality it is now evident that natural organic matter (NOM), colour and pH are also increasing. In light of these water quality changes, JDKWSP is reaching the limits of its direct filtration water treatment plant design.

In the last few years, the JDKWSP has started to face some challenges which have been linked to the source water quality change due to Lake Recovery. These incidents span across geosmin (taste and odour) to filter problems (turbidity and filter clogging algae). **Figure** *5* shows chronologically two of the major Lake Recovery impacts and other significant milestones that the plant has experienced since 2012.

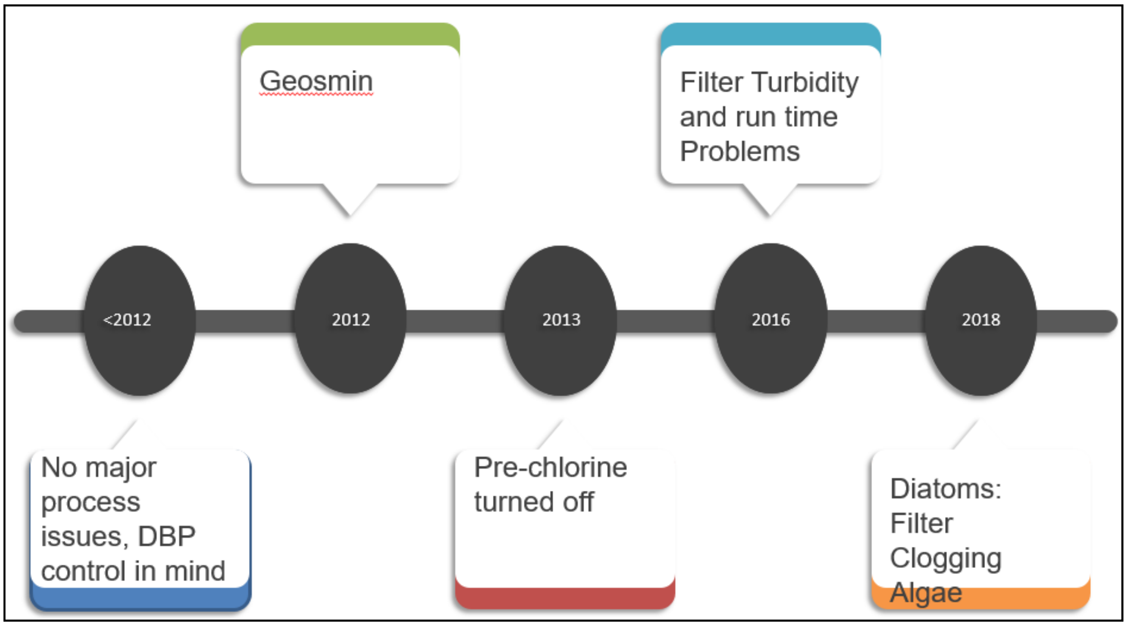

Figure 5: Series of water quality events at JDKWSP from 2012 to 2018.

As shown in **Figure** ***5***, JDKWSP did not have any major issues until 2012. The utility was constantly looking for opportunities to further lower the disinfection by-products (DBPs). In 2012, Geosmin was detected in the source water for the first time and has continued to appear seasonally in late fall to early winter almost every year since then. In 2013, after significant research, pre-chlorination was stopped in the plant to reduce DBPs and the decision was made to run the filters in a passive biological filtration mode. In 2016, over a very windy and rainy night, the turbidity in the source water increased from 0.300 NTU to 0.500 NTU and the plant was not able to handle it resulting in all seven active filters requiring backwash in a very short period of time. This incident showed how vulnerable the plant is to source water changes. In 2018, the plant was faced with algal diatoms which blanketed the filters and rendered the production from each filter so low that it was not able to fully meet the water demand of the city. Out of all these milestones/events, geosmin and algal diatoms can directly be linked to Lake Recovery impacts to source water and hence been studied in detail for this thesis.

A proactive approach must be taken to understand the source water changes and properly document the impacts on treatment plant so the short- and long-term decisions for upgrades can be taken. This research has documented the plants' challenges faced because of Lake Recovery. In addition, this research also discusses some of the opportunities that JDKWSP can consider in order to make the plant robust and resilient to future water quality changes. The findings from this thesis can help JDKWSP and other surface water drinking water treatment plants experiencing Lake Recovery be in a better position to face the challenging water quality.

1.2. Research Objectives

The objectives of this research can be summed into the following:

1. Document the treatment challenges faced by JDKWSP over the years by the impacts of Lake Recovery and how these challenges have evolved.

2. Provide immediate, short and long-term recommendations on potential process change and upgrades to extend the life of the existing plant.

1.3. Research Outcomes

1. Highlight the Lake Recovery effects on a water treatment plant, put them in perspective of treatment challenges.
2. Help surface water plants identify Lake Recovery impacts and challenges, provide opportunities and recommendations to optimize the current treatment process and plan future upgrades.

1.4. Thesis Organization

Chapter 1: outlines the research rationale, research objectives, and research outcomes.

Chapter 2: provides a literature review on Lake Recovery and how the changes in regulations around air pollution have helped the lakes in North America and Europe start to come back to their eutrophic state. This chapter also explains the chemical and biological response of the lakes to Lake Recovery and provides a local flavor by discussing water quality for the two large systems in Halifax.

Chapter 3: explains the study site: JDKWSP and the treatment process the plant currently follows. It also discusses the materials and methods used in this research.

Chapter 4: discusses the two major Lake Recovery impacts faced by JDKWSP: Geosmin (2012 – present) and algal diatoms (2018).

Chapter 5: discusses some of the immediate, short term and long term process changes or upgrades that could provide opportunities to make JDKWSP more resilient and robust to Lake Recovery impacts.

Chapter 6: summarizes and concludes the thesis.

Chapter 2 Literature Review

2.1. Introduction

This chapter starts with the explanation of the effect of stringent air quality guidelines on acid rain. It explains how decrease in air pollutant concentrations responsible for acid rain has helped the lakes and water bodies to recover from the effects of acidic deposition. In addition, it links the role of Lake Recovery to chemical and biological water quality changes by looking at lakes in Europe and North America. The objective of this chapter is to represent the connection between acid rain to Lake Recovery and ultimately to the changing raw water quality, the problem that is currently being experienced by many drinking water treatment plants.

2.2. Acid Rain

Controlling environmental pollution has been one of the major objectives for various environmental protection agencies especially in developed nations. This can be air, water, soil or noise pollution. One of the themes that has captured significant notice in terms of controlling air pollution is acid atmospheric deposition (often referred to as "acid rain") in Europe and North America (Garmo, et al., 2014). United States Environmental Protection Agency (USEPA) defines acid rain as

"A broad term that includes any form of precipitation with acidic components, such as sulfuric or nitric acid that fall to the ground from the atmosphere in wet or dry forms. This can include rain, snow, fog, hail or even dust that is acidic."

Polluted air masses containing sulphur and nitrogen compounds travel long distances across national boundaries. Acidifying compounds thus affect surface waters, groundwaters, and acid-sensitive soils far beyond their country of origin. According to USEPA, 2019, the primary origin of these sulphur and nitrous oxide compounds are:

1. Burning of fossil fuels to generate electricity. Two-thirds of sulphur dioxide (SO_2) and one-fourth of nitrous oxides (NO_X) in the atmosphere come from electric power generators.
2. Vehicles and heavy equipment.
3. Manufacturing, oil refineries and other industries.

In the early 1970s, researchers started to observe the hazardous impacts of acid rain on fish habitat. In response, the regulators in the United States and Canada started to develop strategies on controlling it. This lead to the Convention on Long-Range Transboundary Air Pollution (CLRTAP), United States Clean Air Act, Canada-Wide Acid Rain Strategy for post 2000 and international (1991 Canada-United States Air Quality Agreement) emission control policies aimed at reducing acid deposition (Garmo et al., (2014); Strock et al., (2014); Keller et al., (2007).

Locally, Nova Scotia is often termed as the "tailpipe of North America" meaning the province receives the bulk of its air pollution effects from the eastern United States and central and eastern Canada (Nova Scotia Environment, 2017). The application of stringent air quality regulations through the guidelines mentioned above has helped significantly decrease the air pollutant deposition in Nova Scotia. **Figure *6*** shows how sulphur dioxide deposition has reduced in Halifax, Nova Scotia over the last 30 years.

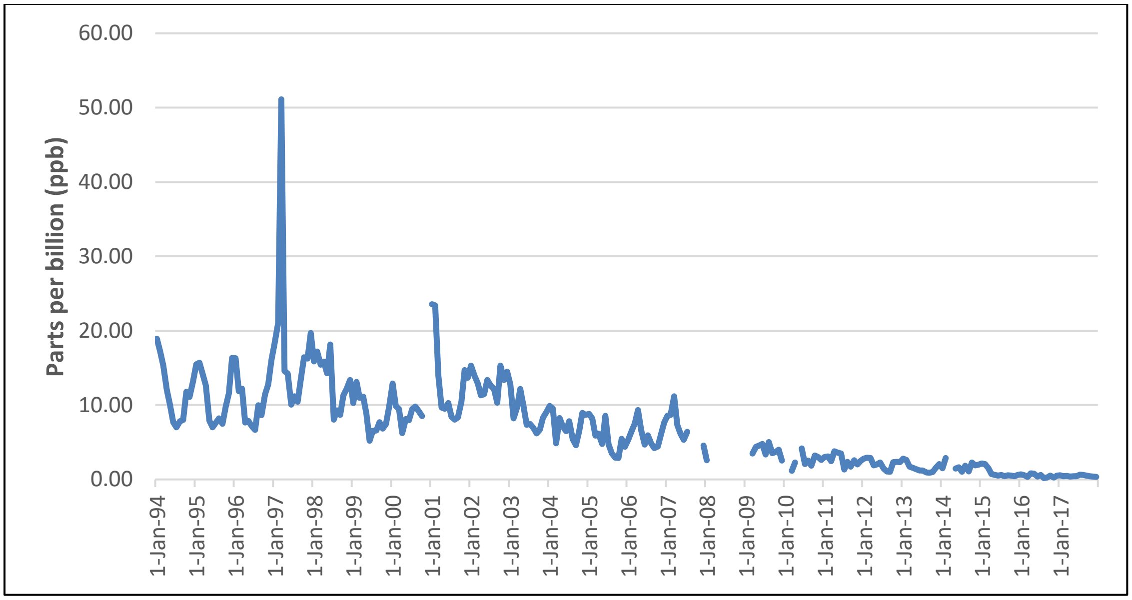

Figure 6: Monthly average SO2 concentration in Halifax (Source: data.novascotia.ca, data obtained on Nov 5, 2019)

It can be observed from **Figure *6*** that the stringent air quality emission guidelines have had a positive impact on air quality by reducing the pollutants. The current concentration of SO_2 is close to zero ppb.

2.3. Lake Recovery in North America and Europe

2.3.1 Chemical Response

Monteith et al., (2007) have researched extensively on the decrease of acid rain, the phenomenon of Lake Recovery and its associated changes to the Dissolved Organic Carbon (DOC) of the water. The focus of their study has been in Europe and Eastern North America. They determined that the response a particular lake or reservoir provides to the decrease in acid rain is dependent on both topology and geology. In response to the reduction in these sulphur and nitrous oxides, the pH and color of the lake have shown an increasing trend as well. This has been confirmed by analyzing water quality for various lakes. Locally, the two water supply lakes in Halifax have shown an upward trend for pH and color (Anderson, Krkosek, Stoddart, Trueman, & Gagnon, 2017). Work done by Monteith, et al., 2007 (**Figure** *7*) showed that there was a variable increase in DOC in mg/l/yr on various water bodies which is a result of their geological nature.

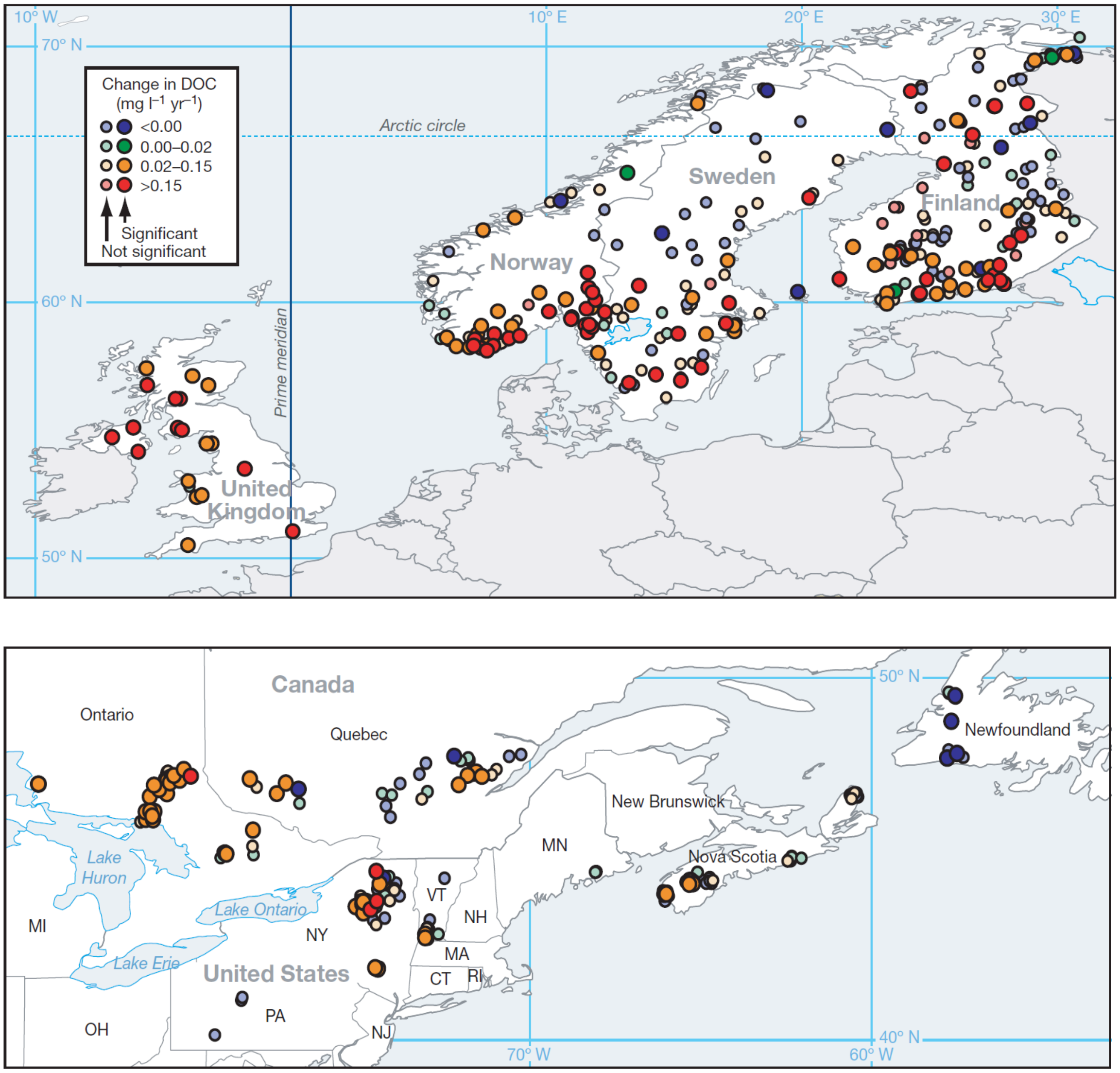

Figure 7: Trends of Dissolved Organic Carbon (mg/l/yr). Upper panel shows sites in Europe and lower shows North America. (Obtained from: Monteith, et al., 2007)

The figure above illustrates that a significant number of lakes have observed an increase in DOC of 0.15 mg/l/year. Similar trends of increasing DOC is seen in research done by Keller (2009) who has focused their study area in Sudbury, Ontario, Canada. The results are displayed below in **Figure *8***.

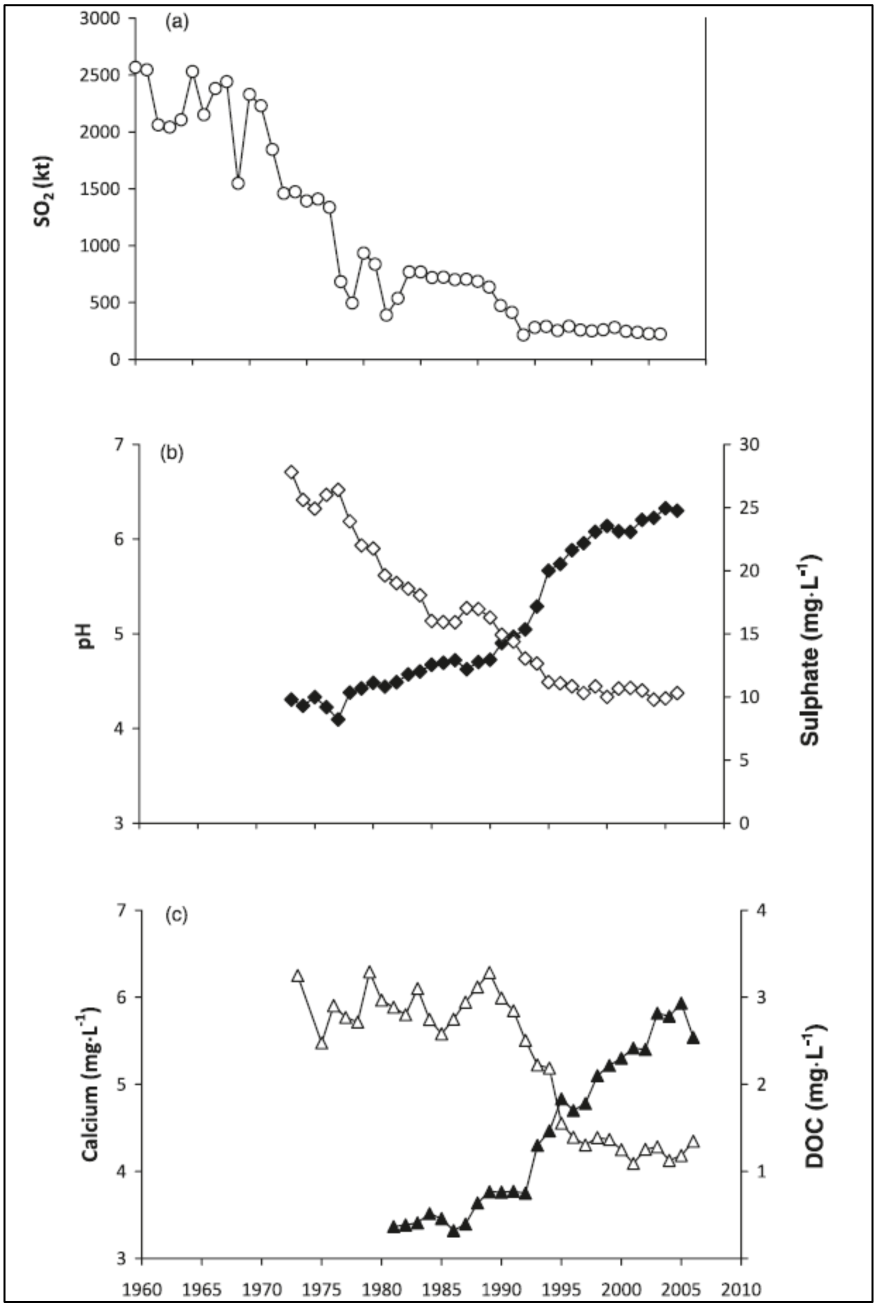

Figure 8: (a) Annual S0$_2$ emissions in kilotons from Sudbury smelters; (b) average annual pH-left axis and sulphate concentrations – right axis; (c) calcium concentration – left axis and DOC concentration – right axis. Obtained from Keller et. al., (2007).

As observed and confirmed by the figures above, as the SO$_2$ concentration decreases, there is an increase in the pH and the DOC levels in lakes around Sudbury. Research conducted by Monteith, et al., 2007 has also drawn correlation between changes in concentration of SO_4^{2-} (μe/l/year) vs the associated increase in the change of DOC (%/year). The research suggests that there is a positive correlation between the two as indicated in the **Figure *9*** below.

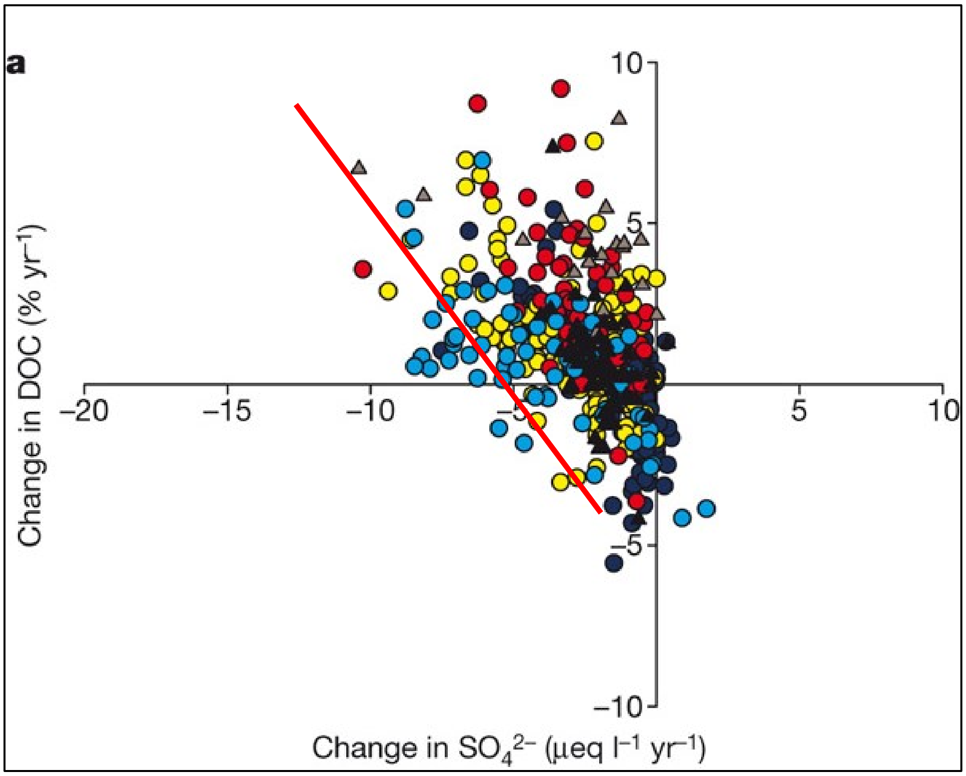

Figure 9: Relationship between % ΔDOC and Δ SO_4^{2-} . Dark blue circles represent data from Canada, yellow circles represent Finland, red circles represent Norway, light blue represent Sweden, grey triangles represent UK and USA data is represented by black triangles. (Obtained from Monteith, et al., 2007)

2.3.2 Biological Response

Previous sections focused primarily on the chemical response in terms of water quality indicators, i.e., DOC, pH, color, and sulphur concentration. This section describes how this chemical response has affected the overall biology of the lake or waterbody ecosystem. It is very important to understand that majority of the lakes affected by acid rain around the years of 1970 to 2000 had a pH of less than 5 whereas the threshold for sustaining fresh water systems is a pH of 6 (Nova Scotia Environment, 2017). Hence, as the pH of these lakes trend towards 6, it is going to encourage growth of a more diverse ecosystem.

Keller et al., (2007) researched on the biological modification of Clearwater Lake and surrounding lakes in Sudbury, Ontario from Lake Recovery. Their research showed evidence of biological recovery as lakes start to recover from acidification. They observed recolonization of various populations of acid and/or metal-sensitive invertebrate species, including many common crustacean zooplankters such as Daphnia mendotae, Skistodiaptomus oregonensis, Epischura lacustris, and Eubosmina longispina. Additionally, they observed that the phytoplankton communities in lakes around Sudbury are returning to the communities that were observed earlier in the pristine environments in pre-1970 era. **Figure *10*** shows the various factors that are involved in either restoring the community to the pre-acidification stage of the lake or creating a new community. The study also discussed that for any given lake, there could be multiple factors at play to determine how fast or slow the lake recovers from acidification effects as displayed in **Figure *10***.

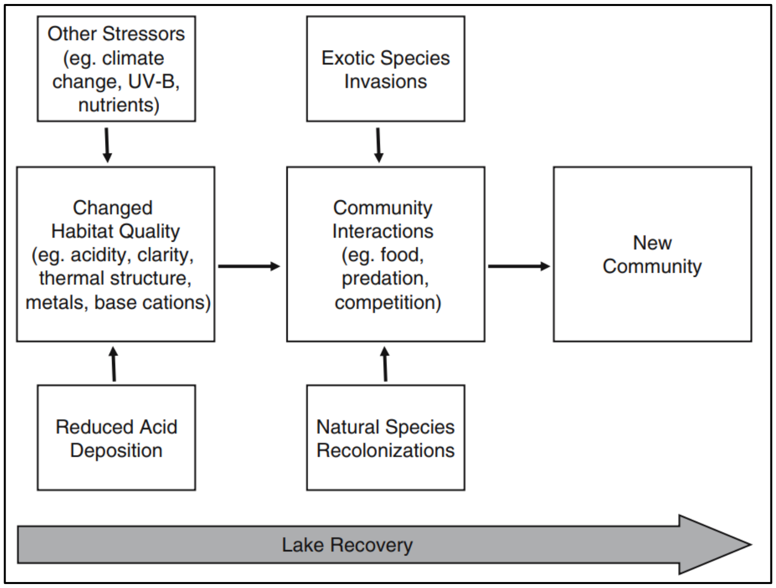

Figure 10: Relationships between some factors influencing the recovery of lakes from acidification. Obtained from: Keller et al., (2007).

Figure *10* above demonstrates that both chemical and biological factors contribute towards the recovery of aquatic communities from acidification. There is evidence that some of aquatic biota, zooplankton, phytoplankton are remerging in the lakes post Lake Recovery. Conversely, there are still severely damaged species that will recover at a slower pace. Evidence of large-scale biological recovery of aquatic organisms from anthropogenic acidification in North America and Europe has not been properly documented and is still being completely understood to the dynamics involved. However, it is clear that with improvements in water quality, biological and analytical recovery, changes will persist (Shead, 2007).

2.4. Impact of Lake Recovery on Water Treatment Plants

The water quality changes due to Lake Recovery happen at a very slow pace. Additionally, these changes are so subtle that they are hard to detect using traditional source water monitoring programs (Strock, Nelson, Kahl, Saros, & McDowell, 2014).

Water quality changes gets noticed only when there is an upset in the plant or through thorough examination. Climate change further complicates identification of reason for this change in water quality and adds another dynamic influencing water quality. Increases in pH, natural organic matter (NOM), temperature and longer seasons caused by climate change result in higher temperatures and prolonged thermal stratification within lakes which are preferred growth conditions for cyanobacteria, algae and other biological species (Betts, 2018).

Drought conditions can also be beneficial to cyanobacteria if periods of intense rainfall occurred prior to the drought, which would affect nutrient flow into watersheds and prolong stratification in lakes (Betts, 2018). Apart from cyanobacteria challenges, the water plant can also face algae problems as these predominantly start to appear with increasing pH and warmer temperatures. Algae can occur in various species which can cause variable degrees of treatment challenges (American Water Works Association, 2010). For example, JD Kline Water Supply Plant (JDKWSP) started to experience geosmin problems in 2012 which was only an aesthetic problem. However, the algal diatoms in 2018 event was so severe that it caused JDKWSP's filter clogging issues which rendered the plant not meeting the city's water demand. Other plants such as Taihu Lake in China have observed harmful algae in terms of cyanotoxins which have resulted in plant shutdowns (Ghernaout, Ghernout, & Saiba, 2010). Some other types of algae can also lead additional formation of disinfection by-products such as trihalomethanes (THMs) and haloacetic acids (HAAs) acids (Joh, Yang Soon, Shin, & Lee, 2011).

2.5. Local connection to Lake Recovery

Halifax Water operates two large water supply plants – JDKWSP and Lake Major WSP (LMWSP) drawing raw water from Pockwock Lake and Lake Major respectively. Since 2000, the pH in both water supplies has been increasing, and more importantly the source water pH has been trending towards a pH of 6 which is selected as the threshold pH for sustaining healthy fish and biological habitat in Atlantic Canadian lakes (Nova Scotia Environment, 2017). Additionally, the cutoff pH for cyanobacteria presence is 5 (American Water Works Association, 2010). In 2002 there were 153 days where pH was less than 5 in Lake Major; whereas for the period between 2010 and 2015, there were less than 10 days in total when the pH was lower than 5. Similarly, in Pockwock Lake there were 162 days in 2005 where pH was less than 5, and from 2010 to 2015 there were only 7 days in total that had a pH < 5 (Anderson, Krkosek, Stoddart, Trueman, & Gagnon, 2017).

Both water supplies were historically considered to have low colour (true colour) and the treatment plants were primarily designed for particle removal. The colour in Lake Major has increased from an average of 22 to 48 TCU, and for Pockwock Lake the colour has increased from an average of 12 to 21 TCU from 1999 to 2015. Similarly total organic carbon has increased by about 1 mg/L in each of the lakes from 1999 to 2015, from 4 to 5 mg/L in Lake Major, and from 2.4 to 3.4 in Pockwock Lake (Halifax Water, 2018). The behavior of these parameters is exactly in line with what has been seen around the world in terms of Lake Recovery as explained earlier in this chapter.

In terms of biological response of the lake, in the fall of 2012, Pockwock Lake started experiencing the presence of geosmin for the first time in the plant's history. Since then geosmin has become an annual issue, and is present in the water for between 6 weeks and 6 months every year, starting in August/September. The average concentration when geosmin is present is 10 ng/L, which leads to a significant increase in customer complaints about water quality (Halifax Water, 2019). Geosmin was the first instance of the biological response due to increasing pH of the lake and the re-presence of algal communities in the lake. More recently, and the core of this thesis is the episode JDKWSP had with the algal diatoms which are known to clog filters. This is discussed in more details in subsequent chapters.

The water quality changes have had major impacts to the plant operations. Average coagulant dosages at the LMWSP showed a significant increase during the period between 1999 and 2015. The average alum dose at the LMWSP increased by nearly four times from 15 mg/l to 60 mg/L. Statistical test results show that alum dose at the LMWSP was increasing at a similar rate to color concentration in Lake Major, and therefore it is likely that this increase in organics resulted in additional coagulant demand. (Anderson, Krkosek, Stoddart, Trueman, & Gagnon, 2017). The JDKWSP has been experiencing reduced filter run times, and in the past few years, and for the first time in 35 years, have had to start increasing the alum dose from 8 to 12 mg/L. The changing water quality in Pockwock Lake is approaching the limits of design for a direct filtration facility (Colour ≤ 20 TCU and TOC ≤4 mg/L) (Halifax Water, 2018). This increase in alum dose generates added cost for the utility, and there is also associated additional chemical demand for pH & alkalinity adjustment as well as residuals handling in response to additional alum. Furthermore, the increased alum dose can adversely affect filter run times by faster head loss development.

2.6. Summary

Stringent air quality regulations have lowered acid rain precipitation which in turn has affected lakes across various parts of the world to recover from acidification. The lakes have seen a constant increase in DOC concentrations. However, the change in DOC of a particular lake or water body depends on different factors including geology and topology. Some lakes have seen an increase in pH and DOC at a faster pace than others. The two local water supplies in Halifax have also observed the effects of Lake Recovery; however, since JDKWSP is a direct filtration plant, the impacts of these effects can be higher than a conventional filtration plant. The next chapter explains the treatment process of the JDKWSP and provides an insight into the shortcomings of the plant that makes it vulnerable to Lake Recovery effects. Lessons learned from this plant can be applied to others experiencing similar water quality changes due to Lake Recovery.

Chapter 3 Methods and Materials

3.1 Description of the study site

The study site used this thesis is the JD Kline Water Supply Plant (JDKWSP). JDKWSP is the largest drinking water treatment plant in Atlantic Canada and supplies water to the mainland Halifax, Bedford and Sackville parts of Halifax Regional Municipality (HRM). It is located in the Upper Hammonds Plains area of HRM as shown in **Figure 11**. The plant draws its raw water from Pockwock Lake, a fairly pristine water supply that falls under a protected watershed with negligible anthropogenic influence. The watershed is split by Hants and Halifax Counties. The plant sees a seasonal water temperature variation from ~1 to 23°C, with temperature maxima and minima occurring in August and January, respectively.

The JDKWSP was commissioned in 1977 and is a direct filtration surface water treatment plant with a capacity of 220 ML/day (currently supplies ~ 82 ML/day), located on Pockwock Lake. This lake has very low alkalinity (<1 mg/L as $CaCO_3$) which is typical of the surface waters in Nova Scotia.

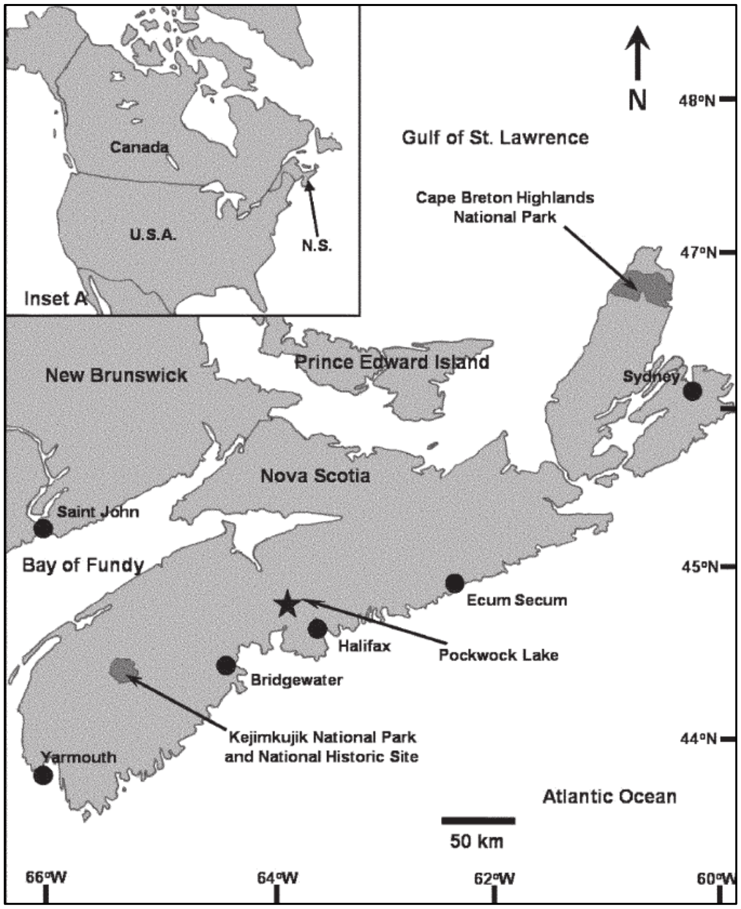

Figure 11: Location of JDKWSP in reference to Atlantic Canada and North America (Obtained from: Tropea, Ginn, Cumming, & Smol, 2007).

As presented earlier in Chapter 1 (**Figure *3***), the pH has been increasing from 5 and is trending towards 6 slowly. A similar trend has been seen for organics (color). ***Table 1*** shows a typical water analysis of JDKWSP in comparison to The Canadian Drinking Water Quality Guidelines (CDWQG).

Table 1: Water quality reported by the JDKWSP in 2019 and its comparison to the Guidelines for Canadian Drinking Water Quality (CDWQG). Units of measurement are mg/L unless otherwise noted. (Halifax Water, 2019)

Parameters	**JDKWSP**		**CDWQG**	
	Raw Water	**Treated Water**	**Maximum Acceptable Concentration**	**Aesthetic Objective Concentration**
Alkalinity (as CaCO3)	<5.0	21.0	-	-
Aluminum	0.102	0.105		0.2
Calcium	1.0	4.2	-	-
Chloride	7.2	8.9	-	≤250
Colour (True colour Units)	14.5	<5.0		≤15.0
Hardness (as CaCO3)	4.3	12.0	-	-
Iron	<0.05	<0.05	-	<0.3
Lead (µg/L)	<0.50	<0.50	5.0	-
Manganese	0.024	0.011	-	≤0.05
pH (pH units)	6.5	7.5	-	7-10.5
Turbidity (NTU)	0.4	<0.11	0.2/1.0*	≤5
HAAs	-	0.020	0.080	-
THMs	-	0.034	0.100	-

*0.2/1.0 means that the plant must produce water with a turbidity of <0.2 NTU 95% of the time and <1.0 NTU 100%.

The water quality presented in ***Table 1*** shows that the finished water produced at JDKWSP meets or exceeds the CDWQG. However, it does not demonstrate the challenges that the plant faces when there is a change in the raw water quality (for example lake turnovers, sudden turbidity fluctuations). It is very important to put forward process changes and upgrades in order to meet the challenging water quality of the future and make the plant more resilient and robust.

3.2 JD Kline Treatment Process

Raw water is pumped into the direct filtration facility through a 1.2 m (48") inlet pipe and flows under gravity into the subsequent treatment processes. The treatment process starts with three rapid mix tanks (namely mix tank # 1, #2 and #3) in series, four parallel trains of three-stage hydraulic flocculators, eight direct dual media rapid filters in parallel, followed by finished water chemical injection for pH adjustment, fluoride and corrosion control. Lime (Calcium Hydroxide) is added to boost the alkalinity of the raw water followed by potassium permanganate ($KMnO_4$) for taste & odor control and oxidation) in the first mix tank. The pH at the end of pre-mix tank #1 is approximately 10.

The water is allowed to further react and mix in mix tank 2. At the end of this mix tank and the start of next, aluminum sulphate (alum) and carbon dioxide (CO_2) are added. Alum is the main coagulant that is used at the plant. CO_2 is added to lower the pH and bring it in the range for proper coagulation which for this plant has traditionally been between 5.6 and 6.0. Alum dose for the plant for its first 35 years of operation has been 8.0 ±0.5 mg/L. However, due to the increase in the organics, it has been slowly raised over the last seven years to 12±0.5 mg/L. Additionally, during the colder time of the year (December to May), a non-ionic polymer (0.025–0.065 mg/L) is added as a coagulant aid.

Since JDKWSP is a direct filtration plant, an increase in alum dose can result in faster headloss development on filters due to formation of a heavier and bigger floc. Knowles (2011) carried out bench and pilot scale experiments to trial other coagulants such as ferric sulfate, polyaluminum chloride (PACl) and aluminum chlorohydrate (ACH) against aluminum sulfate (alum) using variable coagulation dosage and pH conditions. The study showed that although alternative coagulants can lower the DOC and subsequent DBP formation potential, they can also result in lower filter runs and unit filter run volumes (UFRV). Thus until further research and pilot trials can be performed, alum is the preferred coagulant in the plant.

The plant had pre-chlorinated the water at the rapid mix (mix tank # 3) stage since its commissioning in 1977 to 2013. Pre-chlorination was stopped in 2013 based on research conducted by Stoddart & Gagnon (2015). This research proved that when prechlorine is removed, adenosine triphosphate (ATP) concentrations on the filter media increased from ~50 to ~200–500 ng/cm3 which showed that the filters converted from conventional to passive biofilters. Filter performance analysis revealed that conversion increased the filter effluent turbidity and reduced the filter head loss accumulation rate. Unit filter run volumes and filter run times were maintained. Water quality monitoring indicated that finished water total disinfection by-products were reduced by ~10–20 µg/L for trihalomethanes and ~6–10 µg/L for Haloacetic acids. However, as described elsewhere in the subsequent chapter, pre-chlorine was turned back on in July 2018.

The water exits the Mix Tank 3 into a common flocculated water channel and goes into four identical flocculation trains where three-stage tapered hydraulic flocculation occurs. Flocculation tanks are 5.0 × 5.0 × 7.8 m each (L × W × D), with a typical retention time of 22 min each (Stoddart & Gagnon, 2015). Vadasakkari and Gagnon (2011) evaluated these flocculators and showed the water short-circuiting a preferential path in the flocculation tanks. One of the reasons is the low mixing intensity (G-Values) in these tanks which is low due to the plant operating at less than half of its design capacity. The design and shortcomings of these flocculators are further discussed in Chapter 5. The velocity of water reduces as it passes through these trains.

The floc water is then dispersed between seven (eight on-site, however only seven used at any given time under normal operating conditions) anthracite and sand media filters. From bottom to top, each filter contains 300 mm of silica (0.45 mm effective size) sand and 600 mm of anthracite (0.9 mm effective size) respectively. Halifax Water is currently undergoing a project to rehabilitate all eight filters since they were original to the plant. Recent filter surveillance data showed that the media had rounded over the 40-year use. In June 2018, when the diatoms started to cause filter clogging, only two out of eight filters were rehabilitated and the remaining six still had old media and underdrain systems. Operating the old filters is challenging because as media gets more rounded, it changes its characteristics in terms of effective size and porosity which then translates into substandard filtration or a filtration process that is not robust enough to handle water quality upsets. Small changes in coagulation pH and coagulant dose could have bigger impacts on the effluent turbidity and filter runs. As per the approval to operate permit[1], the filters are run until one of the parameters is reached, i.e., either headloss reaches 2.15, turbidity reaches 0.1 or filter run time reaches 80.0 hours. Although ageing filters are not an issue that is brought on by Lake Recovery, the impacts of age are however magnified by the water quality upsets due to Lake Recovery.

The filtered water goes into clearwell from where it is sent to the city for distribution. As the water is leaving the clearwell, it is dosed with chlorine for disinfection, sodium hydroxide (NaOH) to bring the final pH to 7.4, zinc/ortho-polyphosphate as a corrosion inhibitor, and hydrofluorosilicic acid to aid in dental health. **Figure 12** shows a schematic of the process for JDKWSP.

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[1] Approval to Operate is a permit issued by Nova Scotia Environment that gives guidelines for the plant to stay in compliance with the drinking water guidelines set out by the province.

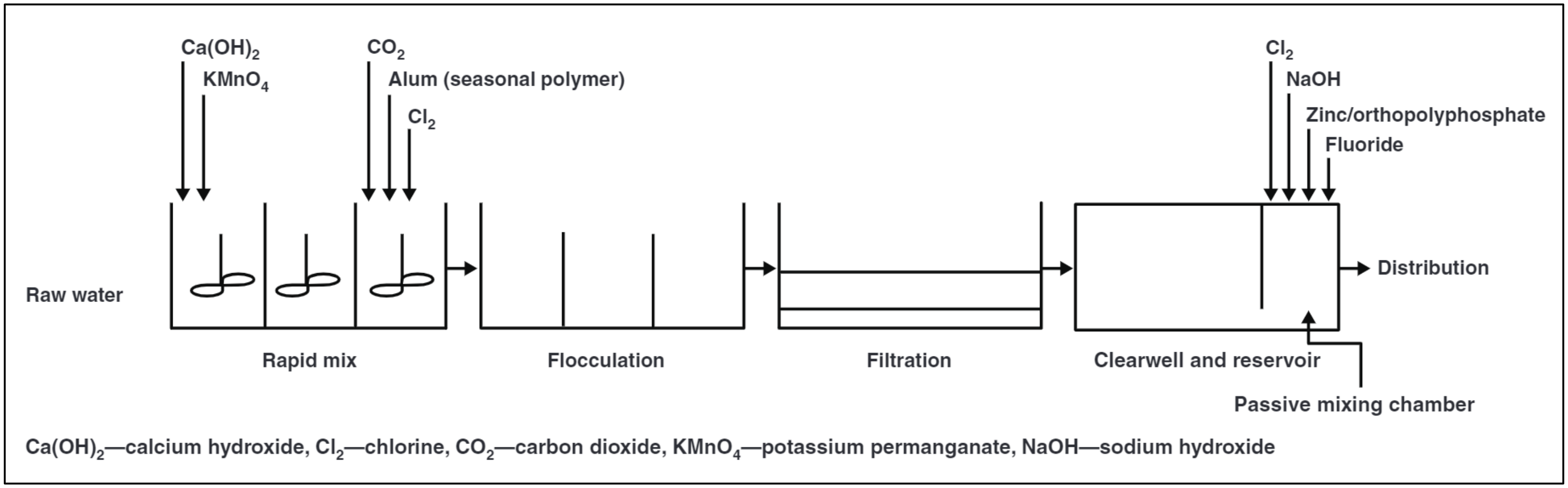

Figure 12: JD Kline WSP Process Schematic Diagram (Obtained from: Stoddart & Gagnon, 2015)

3.3 Data Collection and Analysis

3.3.1 Plant Data

The majority of the plant data discussed in this thesis has been downloaded using PI Datalink add-in for Microsoft Excel. The source of the data is the PI data historian used by Halifax Water for the majority of their plant and distribution attributes. The plant staff conducts laboratory measurements in accordance with Standard Methods for the Examination of Water and Wastewater (APHA, 2012). Procedures unavailable in this text are executed in accordance with the equipment manufacturer description. Experimental parameters that were measured throughout this research include pH, turbidity, TOC, DOC, UV254, trihalomethanes formation potential (THMFP), haloaceticacids formation potential (HAAFP), true color, chlorophyll-a, algal enumeration.

3.3.2 Analytical Water Quality

During the period of this research, plant staff used a Hach 11D pH meter to record pH values. Turbidity has been measured by either HACH 2100AN or TU52 for benchtop and Hach 1720E for inline turbidity measurements. True color was measured on samples filtered through a 0.45 μm polysulfone filter membrane (GE Water and Process Technologies) that was pre-rinsed with 500 mL Milli-Q water. A HACH DR/4000, 5000 or 6000 UV/VIS spectrophotometer was used to measure true color.

TOC and DOC samples were collected head-space free in 40 mL pre-cleaned glass vials and preserved with concentrated phosphoric acid to pH <2. DOC samples were filtered through a 0.45 μm polysulfone filter membrane (GE Water and Process Technologies) primed with 500 mL Milli-Q water. TOC and DOC measurements were performed using a TOC-V CPH analyzer with a Shimadzu ASI0-V autosampler and a catalytically aided combustion oxidation non-dispersive infrared detector (NDIR) having a method detection limit of 0.08 mg/L (Shimadzu Corporation, Kyoto, Japan).

3.3.3 Biological Water Quality

Chlorophyll-a numbers were obtained using a water quality sonde YSI -6600 V2 which provided temperature as well. Geosmin testing was conducted by a third party lab, SGS Canada Inc. using their method code ME-CA-[ENV]GC-LAK-AN-012.

3.4 Pilot Plant

Alternative filter media effective size and higher alum dose study was conducted in the pilot plant at JDKWSP using source water from Pockwock Lake. Source water quality was described earlier in this chapter. The pilot plant was operated to emulate the full-scale treatment process at the study site, which is also described earlier in this chapter. The pilot plant (Intuitech Inc., Salt Lake City, Utah) is comprised of two identical and parallel treatment trains. Raw water from Pockwock Lake entered the first of three premix tanks where mechanical mixing occurred. Lime is added in the first premix tank to adjust the pH for oxidization with potassium permanganate ($KMnO_4$). Carbon dioxide (to reduce the pH to the coagulation target which ranges from approximately 5.8±0.1. Alum is added to the final pre-mix tank. The control side of the pilot received the same alum dose as the full-scale plant (11.5 mg/l ±0.5 mg/l). The experimental side of the pilot plant received an alum dose of 15 mg/l ±0.5 mg/l. Each premix tank had a detention time of approximately 1 minute. Coagulation is followed by 3stage flocculation at G-values of 30, 20, 10 s, respectively. Flocculation stage detention times ranged from 16 to 19 minutes per flocculation basin. Flocculated water then entered the filtration skids. Each side of the pilot has three filtration columns. However, for this work, only the first filter column (F110) on the control side and third column on the experimental side (F230) was used for the evaluation of effluent turbidities and organics. F110 had the same media design as a full-scale plant whereas F230 had the experimental media design with higher effective size (ES) and depth. The filter media designs for F110 and F230 are shown in ***Figure 13***.

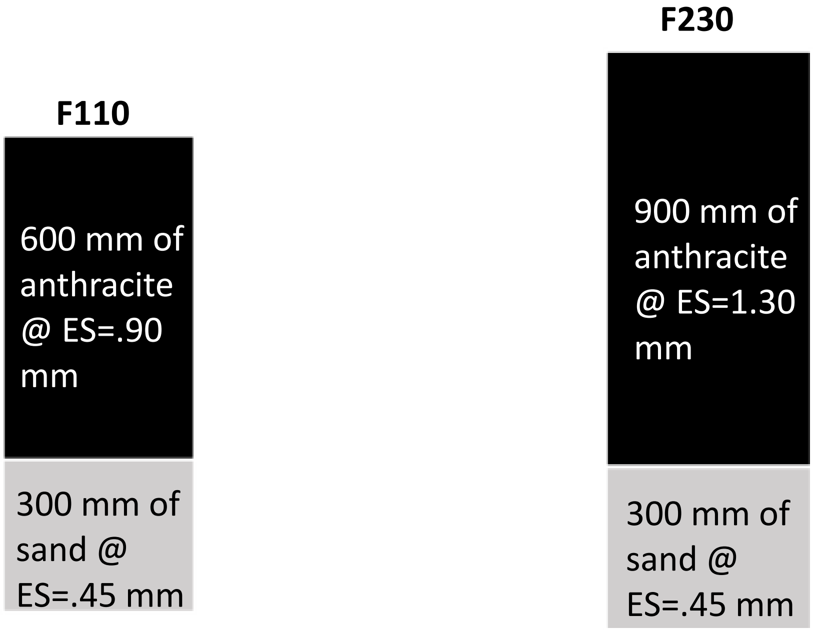

Figure 13: Filter media designs for control and experimental sides of the pilot plant

Filter loading rate for this experiment was 4.4 m/h for an EBCT of 12.5 minutes. The pilot filters are equipped with continuous monitoring for filtration performance and operational parameters including effluent turbidity, particle count, head loss, filter run time and flow. In agreement with full-scale plant operational criteria, filters were equipped with automatic shutoffs and operated to not exceed effluent turbidity of 0.2 NTU, ahead loss of 2.15 m or filter run time of 80 hours. Filters were backwashed with filter effluent. Backwash consisted of an air scour phase, a combined air scour and water wash phase and three water wash phases. Previous research at this facility demonstrated that parallel pilot plant trains could produce reasonably equivalent water quality to each other and to the full-scale water treatment plant (Knowles, Mackay, & Gagnon, 2012 and Stoddart, 2017).

Chapter 4 Identifying Challenges Faced by JD Kline WSP in Light of Lake Recovery

4.1 Introduction

This chapter discusses the challenges that JD Kline WSP (JDKWSP) has faced or is currently facing due to the changing water quality as the lake recovers from acid deposition. There are two major events that have caused significant challenges for the plant and Halifax Water – Geosmin (2012-present) and the algal diatoms (June – Aug 2018). Geosmin is known to cause an earthy musty smell in the water. The threshold for detection for the normal population is 10 ng/L. However, a utility can start to receive taste and odor complaints at as low as 4 ng/L. Algal diatoms are known to cause a variety of issues from taste and odour, increasing coagulant demand to clogging the filters. The species of diatoms that were predominant for JDKWSP in 2018 was *tabellaria fenestrate*. This species is known to clog filters by forming a rebar like structure on top and thus not allowing floc particles to penetrate through the whole filter bed. The objective of this chapter is to examine the water quality impacts brought on by Lake Recovery and document the challenges faced by a drinking water plant. This research will help translate water quality changes due to Lake Recovery to impacts on the operation of a water plant. In addition, other utilities facing Lake Recovery gain an appreciation for what could happen and put measures in place to be ready in advance.

4.2 Geosmin: 2012 to present

The JDKWSP experienced its first outbreak of geosmin in the fall of 2012. It was detected when Halifax Water started to receive multiple phone calls from customers for an earthy musty smell in the water. Upon further investigation and lab tests, it was identified as geosmin. Initially, that incident was treated in isolation and was not thought of as a product of Lake Recovery as it was not a well-known concept at that time.

The chemical name of geosmin is trans-1,10-dimethyl-trans-9 decalol ($C_{12}H_{22}O$) and it is a chemical composition illustrated in **Figure *14*** (below). It is a common taste and odour compound that has become a significant concern for utilities all over the globe especially North America as the lakes become more eutrophic due to Lake Recovery. It produces an earthy, musty-type taste and odour in the water (Srinivasan, Sorail, 2010).

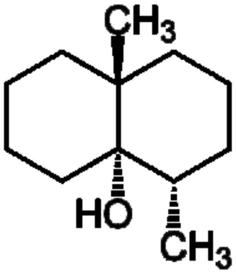

Figure 14: Chemical structure of Geosmin

Cyanobacteria, also known as blue-green algae, synthesizes geosmin throughout the life cycle and eventually releases or store the odorant depending on the phase or surrounding environmental factors. Upon death and biodegradation of the cells, geosmin is released into the environment. Favorable conditions that influence geosmin outbreaks usually consist of excessive nutrients and warmer temperatures, which coincide with cyanobacteria blooms (Elhadi, Huck, & Slawson, 2006). More recently, the summers have been dryer and have lasted longer in the region which has made conditions viable for blooms. In addition, as the pH of the lake trends towards 6, the ecosystem in the lake is becoming healthier to support the conditions required for blooms. Therefore, outbreaks tend to occur in late summer to early fall. With Pockwock watershed being very large and multiple tributaries feeding into the lake, the effects and concentration of geosmin are subsequently detected during late fall and into early winter months.

Geosmin was first detected in the treated water from the JDKWSP in October 2012. This was the first detected occurrence of geosmin in over 35 years of operating the Pockwock water system. Halifax Water was unaware of the problem until taste and odour related customer complaints started to overwhelm the call center. For the first year, geosmin concentrations fluctuated between 7 to 14 ng/L in both the raw and treated water throughout the months of October through December. Levels decreased gradually beginning in January 2013 and dropped to below detection limits (<3 ng/L) in May 2013. ***Figure 15*** below shows a plot of the quarterly average values for geosmin from 2012 to the present. The highest value recorded for geosmin is 38 ng/l in November 2013.

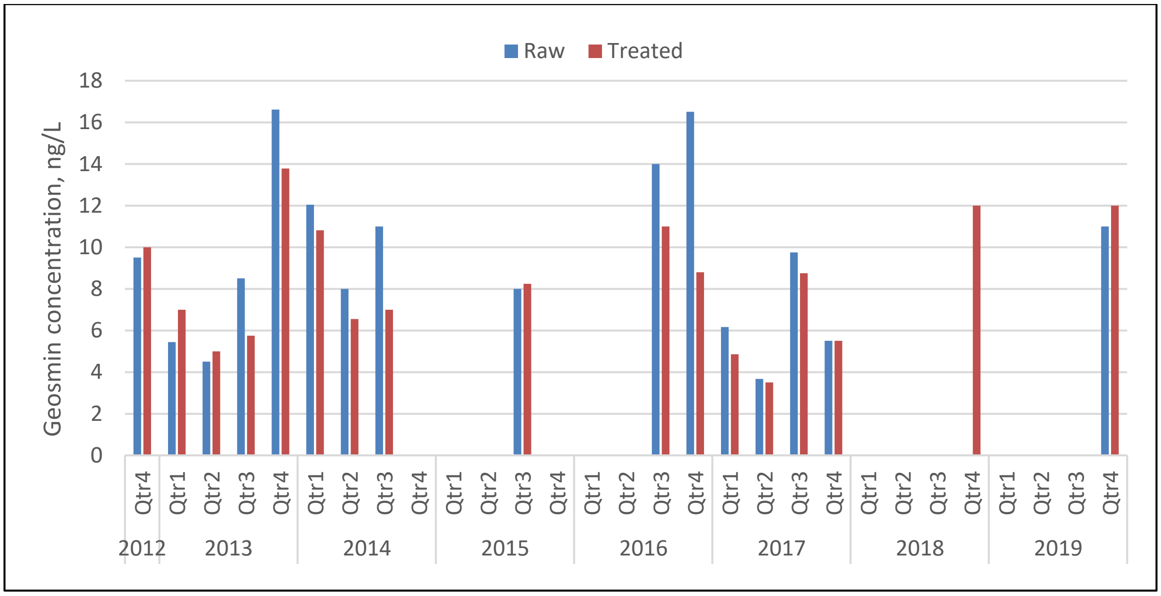

Figure 15: Average quarterly geosmin concentrations for raw and treated water at JDKWSP

Conventional treatment methods (coagulation, flocculation, & filtration) lack the ability to remove geosmin to levels undetectable by humans. Since the initial geosmin outbreak at JDKWSP in 2012, the plant converted to passive biofiltration through the removal of pre-chlorination. The objective of removing pre-chlorine from the pre-treatment (rapid mix) was to reduce chlorinated disinfection byproduct (DBP) formation. It was hypothesized that by removing prechlorine, the anthracite sand filters would remove particles as well as operating biologically (Stoddart & Gagnon, 2015). Even with the change in pre-treatment, geosmin continued to persist which led to the inquiry of alternative treatment options at JDKWSP. **Figure *15*** also shows that there is no significant difference between the raw and treated geosmin concentrations and the numbers are normally within ±2 ng/L.

One of the biggest challenges the utilities run into while investing a taste and odour problem is funding for the project. There are always competing priorities, some of which are more crucial than an aesthetic objective. However, taste and odour do form the customer's confidence that they have in the utility. In the case of Halifax Water, it can be observed that as soon as there is Geosmin detected in the water, the customer complaints about taste and odour start. The increase in geosmin correlates to the number of phone calls received by the utility for taste and odour. From **Figure *16***, it is evident that the calls start at a geosmin level of as low as 4 ng/L. Halifax Water, so far, has been able to keep the customer calls regarding geosmin related taste and odour complaints to a manageable level through proactive messaging and customer education. However, it will be crucial to keep the taste and odour treatment in future capital upgrade planning as this holds a very important customer confidence factor.

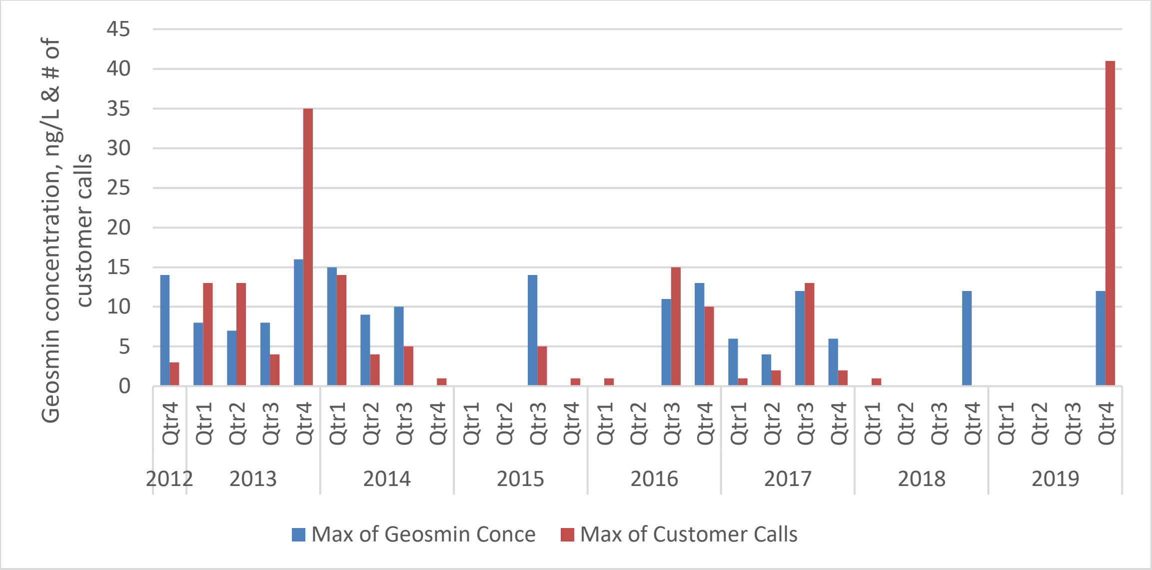

Figure 16: Maximum concentration of treated water geosmin at JDKWSP vs the # of calls received for taste and odour at the Customer Call Center

4.3 Filter Clogging Diatoms: June – August 2018

Filter clogging diatoms have been the most significant and serious incident of Lake Recovery's impact to the treatment plant. In early June 2018, the plant started to experience some uneven filter runs. Under optimal conditions, the plant filters are run according to the following terminal parameters (as per the Approval to Operate permit issued by Nova Scotia Environment):

- Headloss = 2.15 m
- Turbidity = 0.1 NTU

Filter Run Hours = 80 hours

A filter is backwashed if either of the above parameters reaches the terminal point. Typically, the filter at JDKWSP runs between 65 to 80 hours. **Figure** ***17*** represents the Filter Run Hours on a particular filter run for Filter #1 at JDKWSP from 2010 to 2017. **Figure** ***17*** shows the filter runs were typically 70 hours ±5 h. There are a few filter runs where the run time dropped to 50 hours but that can be attributed to various operational anomalies and were isolated incidents and did not last long.

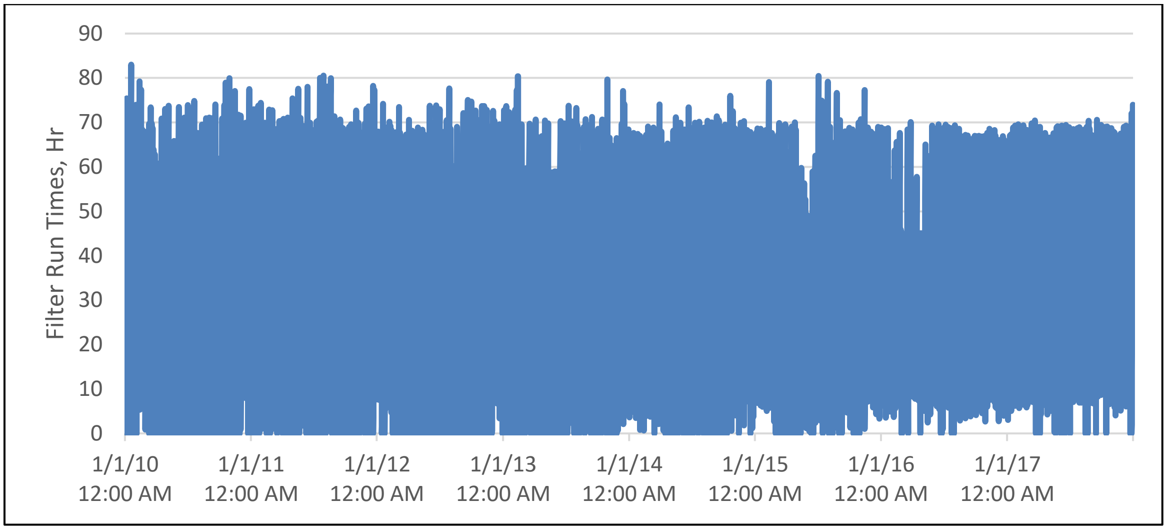

Figure 17: Filter # 1 run hours from 2010 to 2017 at JDKWSP.

In early June 2018, the headloss on filters started to develop much faster and the filters had to be taken out of service for backwashing much sooner than the typical 70 hours. Filters started to go off on headloss from 30 to 50 hours as shown in **Figure 18**. The filter run times were uneven with some runs lasting 70 hours and others terminating at 30 hours.

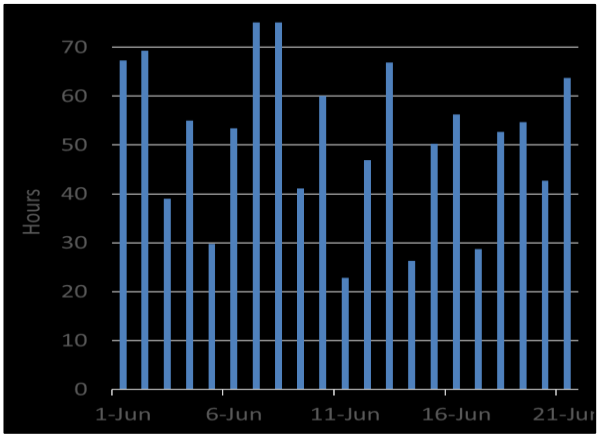

Figure 18: Uneven filter runs. Filters being backwashed anywhere from 25 to 70 hours. Data is for Filter # 1.

Originally, the uneven filter runs were believed to be happening due to the fact that the treatment chemistry may not be optimized. The plant staff tried to optimize the CO_2 – lime chemistry in order to make sure there was enough alkalinity for alum coagulation. Additionally, they tried to make other minor pH adjustments to see if longer filter runs could be achieved but the problems still persisted and kept getting worse as seen in **Figure *19***. The filter runs shortened to mere 20 hours. It became very difficult to keep up with the backwash and distribution of water demand.

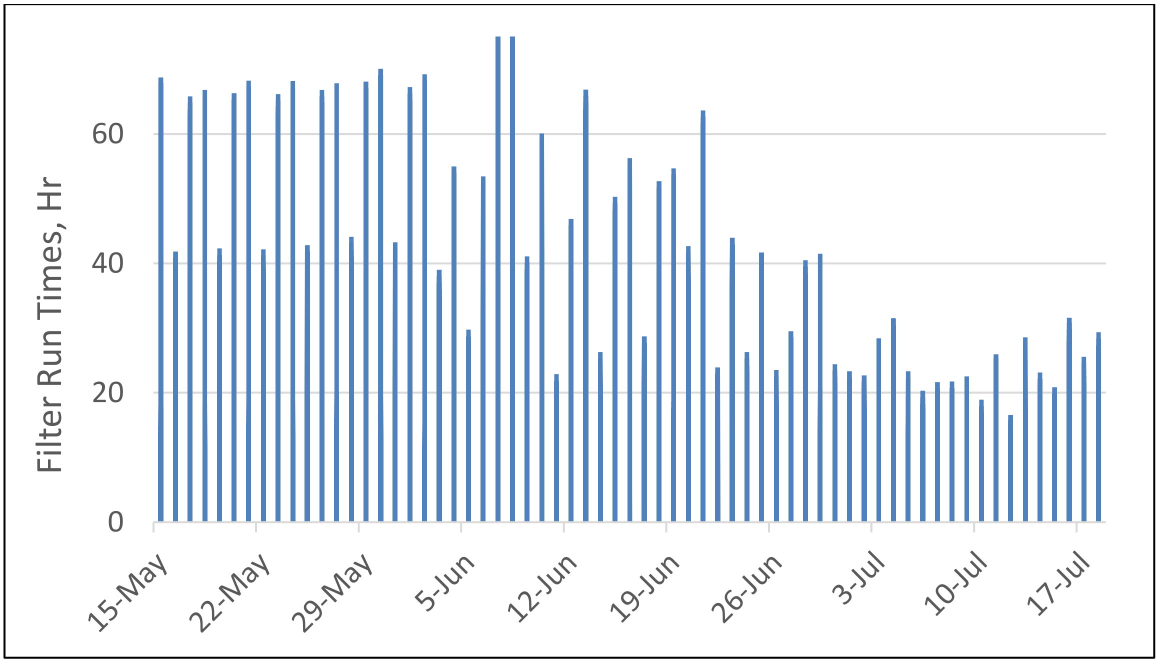

Figure 19: Filter run hours keep going down. Data is for Filter # 1, obtained from Plant PI Historian

To have a fair comparison for filter performance, one of the industry-preferred techniques is comparing Unit Filter Run Volumes (UFRV). The UFRV is the volume of water produced by the filter during the course of the filter run divided by the surface area of the filter. UFRVs of 200 m^3 per m^2 or greater are satisfactory, and UFRVs greater than 300 m^3 per m^2 are desirable (Environmental Protection Agency, Ireland, 1995). **Figure *20*** shows the comparison of UFRV (m^3/m^2) for Filter # 1 at JDKWSP. As it is evident from the data, the plant's normal production from a filter is a UFRV of 250 ±25 m^3/m^2. There were filter run problems (not part of this research) because of a turbidity event in March 2016 which brought the UFRV down. Besides that, the plant maintained its UFRV. In 2018, it can be observed that the UFRV came down as low as <50 m^3/m^2.

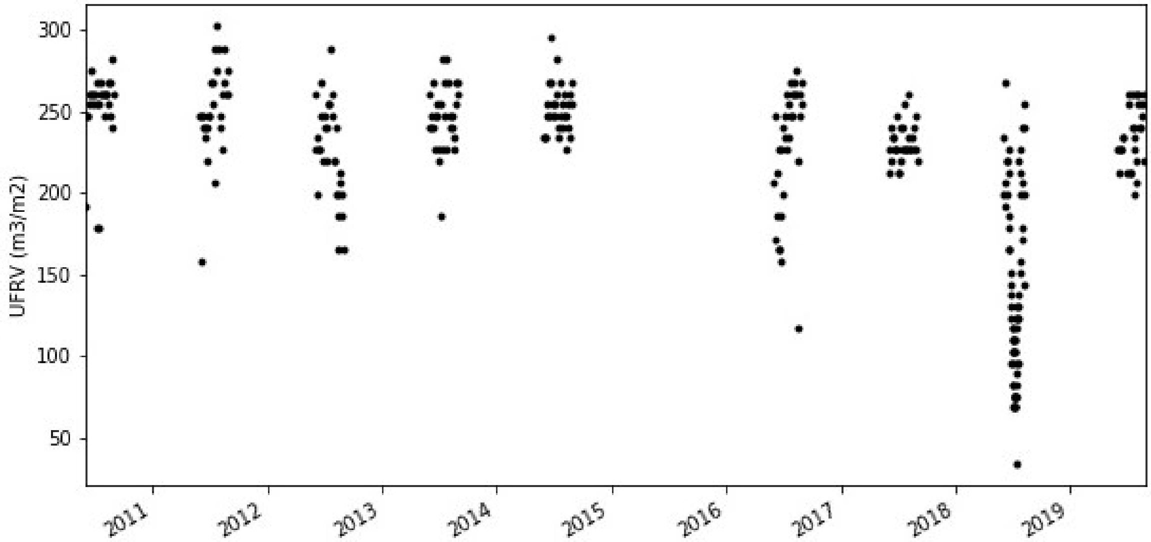

Figure 20: UFRV comparisons over the months of June to August every year from 2010 to 2019 for Filter# 1. (2015 data omitted as it was incomplete). On average, 30 filter runs assessed every year from June to August.

4.4 Water Quality Evaluation

This section explains various water quality evaluations or assessments that were performed to identify the root cause of the plant upset as the plant staff had not experienced such a significant drop in filter production earlier. Organics and biological water evaluations were done to gain a deep understanding of the raw water quality.

4.4.1 Organics

It was evident through the literature and the organics concentration obtained from the laboratory testing that NOM in the lake is increasing (***Figure 4***). The JDKWSP being a direct filtration plant is at the extreme ends of its treatment capabilities for handling this quantity of NOM. The plant staff needs to go one step further by not only quantifying the

NOM but also looking at it qualitatively using NOM fractionation in order to better understand the hydrophobic vs hydrophilic fractions.

NOM consists primarily of two substances: Hydrobhobic and Hydrophylic. Hydrophobic substances (acids, bases, and neutrals) largely represent humic and fulvic acids which may be naturally present from neighbouring vegetation. This type of material has a high molecular weight and is highly absorbable and removed by coagulation. Hydrophilic substances (acids, bases and neutrals) are largely biogenically produced by macro- and micro-organisms in aquatic systems. These types of organic molecules have low molecular weight and are poorly removed by coagulation - but can be removed through oxidation (Matilainen, et al., 2011).

Based on recent fractionation work, the quality of NOM is changing. Comparison of data from 2009, 2010 and 2018 has shown that there has been a slight increase in hydrophobic material from 2018 from 2009. Hydrophilic material was almost the same in 2009 and 2010 and is now doubled in 2018 (Anderson L. , 2020). The fractionation work needs to be repeated for different seasons and also needs to be one of the consistent measurements for the raw water. This will help develop a baseline and more datasets to compare.

4.4.2 Increased biological activity

One of the interesting things observed during this period was that the Chlorophyll-a numbers were elevated at the height of the incident. Chlorophyll-a is a pigment contained in chloroplasts of photosynthetic organisms and is a commonly used indicator for phytoplankton biomass. As the summer progressed, Chlorophyll-a started to drop as illustrated in **Figure *21***. Chlorophyll-a is a very good indicator of the biological activity in the plant (Joh, Yang Soon, Shin, & Lee, 2011).

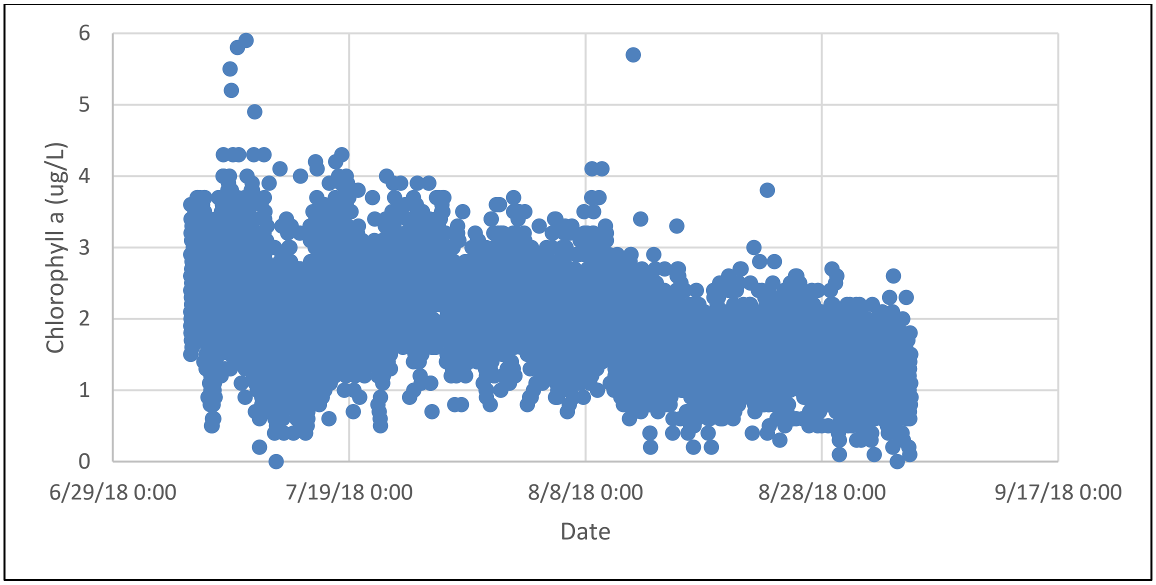

Figure 21: Chlorophyll-a in the lake over summer 2018. Data obtained by using a water quality sonde deployed in front of the raw water pump station intake.

Figure *22*, a depth profile for the Chlorophyll-a data, revealed there was an increase for the Chlorophyll-a in the thermocline layer of the lake. Coincidentally, this is the depth where the plant derives all its water. This seemed to provide some evidence to the problems faced by the plant and could be linked to the increased biological activity. The plant staff also conducted an examination of water under a microscope and were able to identify a particular type of algae was in the raw water. The same algae species seemed to be trapped in the flocculated water and on top of the filter beds. Further enumerations were able to classify these species as Tabellaria fenestrate (Tabellaria), a type of algal diatom.

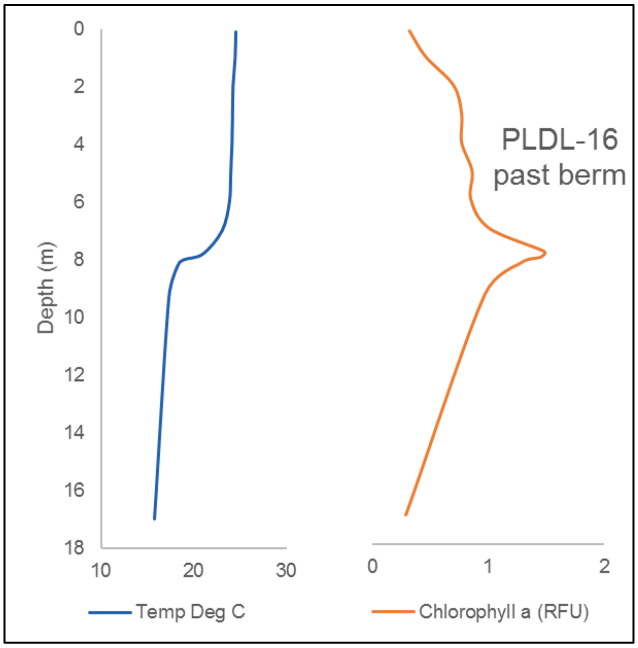

Figure 22: Depth profile of Chlorophyll-a in the lake with depth, Aug 1, 2018. Data obtained by using a water quality sonde deployed in front of the raw water pump station intake.

Tabellaria is one of the organisms causing most filter run problems and is likely to be found in water all year round except for January and February. Additionally, it is known to be found in low turbid waters such as Pockwock Lake (American Water Works Association, 2010). Tabellaria has a silica wall structure that essentially forms a glue-like structure on top of the filter bed. Tabellaria has known to reduce the filter runs in treatment plants down to one hour in Chicago and Michigan back in the 1960s (American Water Works Association, 2010). **Figure *23*** shows a sample of the flocculated water from JDKWSP confirming presence of Tabellaria.

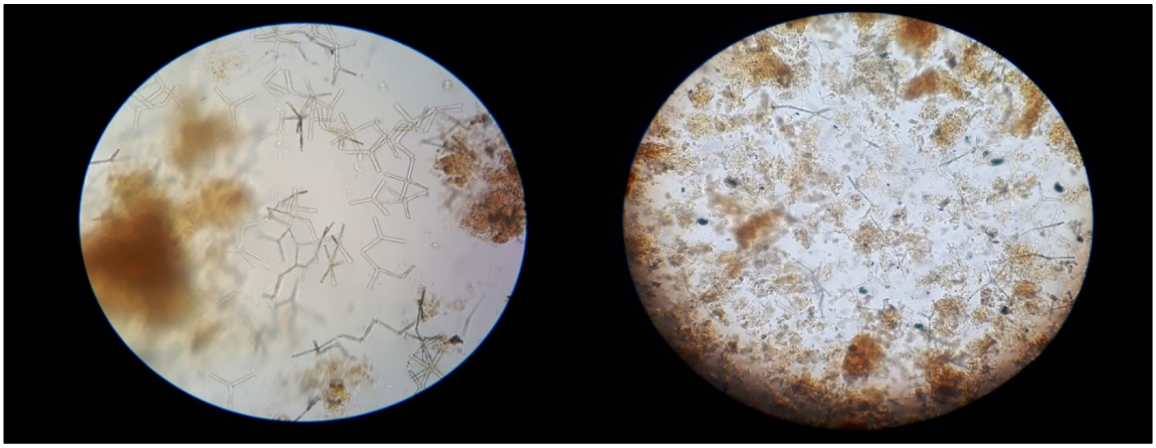

Figure 23: Tabellaria identified under a microscope from JDKWSP flocculated water (Magnification: 10X, July 1, 2018)

Waters that have a presence of Tabellaria, impose a significant demand on the coagulant as they can drop the zeta potential to as low as -40 millivolts (mv) (Joh, Yang Soon, Shin, & Lee, 2011) whereas JDKWSP typically operates around a zeta potential of -6 to -10. Hence, presence of Tabellaria changes the charge through the coagulation and flocculation process which in turn does not let the coagulated material to not settle. Additionally, Tabellaria forms a chain-like structure and acts like a rebar in floc particles. The cells are generally united in zigzag chains by gelatinous cushions at the corners. The zigzag arrangement and the gelatinous cushions, which can be stretched, make the length of the chain flexible, and this helps to prevent these chains from breaking on the filter surface. These chains, therefore, may be more effective than long filamentous algae in producing a clogging membrane on the top of the filter (American Water Works Association, 2010). This does not allow the floc particles to penetrate deep into the bed and hence the filter starts to gain head loss quickly. This is exactly what was experienced by JDKWSP with their shortened filter run times. The surface sweeps for the backwash cycle and the backwash pumps themselves were only able to remove Tabellaria from the top of the filter as the material was too gelatinous/heavy. This was evident when filter surveillance of one of filters was done and the samples were sent to the lab for assessment. These results are depicted in **Figure *24*** which shows that Tabellaria was primarily stuck on the top layer of the filter media and did not let floc particles to penetrate through the whole filter column.

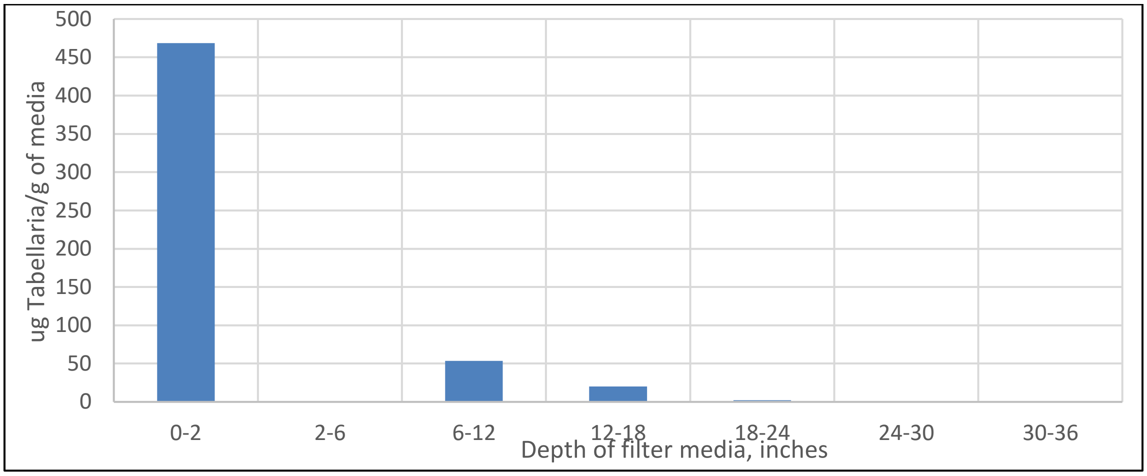

Figure 24: Tabellaria concentration with the depth of filter media. Data is for Filter # 5. Dirty Bed, Date of Sample – July 5, 2018.

It was also observed that the diatom concentration continued to dominate throughout the summer in the raw water. **Figure *25*** and **Figure *26*** show Tabellaria concentrations and **Error! Reference source not found.** shows the algal taxonomy for J uly and August 2018. The highest concentration of Tabellaria was observed for the July 31st sample at approximately 1100 mg/m^3.

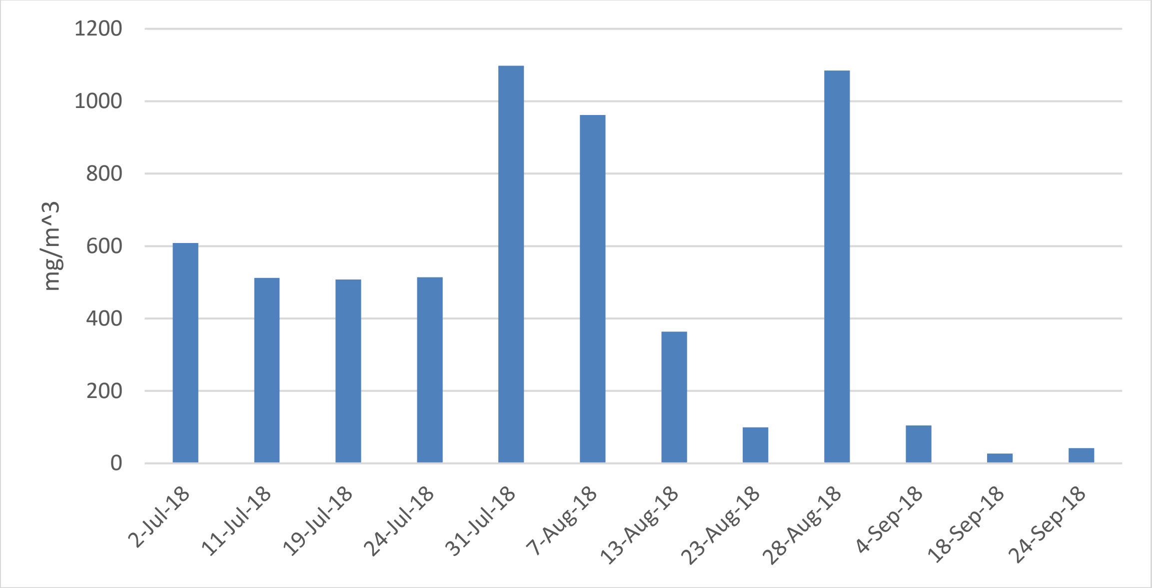

Figure 25: Tabellaria Concentrations from July to September 2018

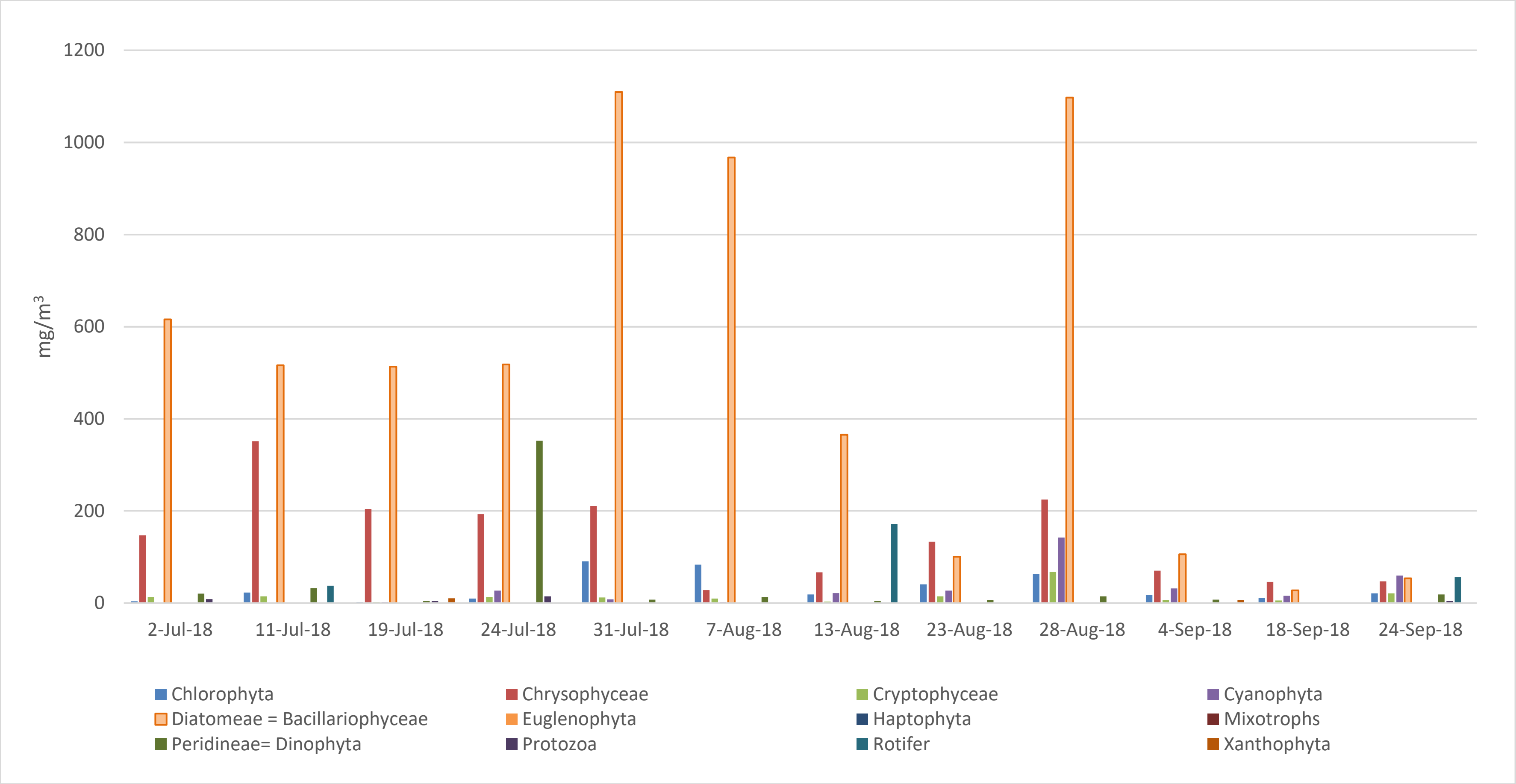

Figure 26: Algal Taxonomy of JDKWSP raw water from July to September 2018

4.5 Summary/ Discussion

Chapter 4 examined two of the major Lake Recovery effects that JDKWSP has observed so far. The first was the presence of geosmin in the raw water which has been a recurring issue ever since its first occurrence in 2012. The second effect was the presence of filter clogging algae, in particular, *Tabellaria fenestrata*. Geosmin numbers in the raw water have fluctuated over the years with the worst year being 2013. An initial study conducted by Halifax Water on a treatment solution for geosmin did not make financial sense since it is an aesthetic objective with no harm to human health. Hence, Halifax Water has been able to educate customers about geosmin and have been able to manage customer expectations. However, with the pH of the lake trending towards 6, and with the warmer and hot season, it would be prudent to budget for a treatment solution in the long term. This is discussed in the next chapter where potential treatment solutions have been recommended to make the plant more robust and resilient.

The second effect observed from Lake Recovery and JDKWSP was the filter clogging diatoms. It was observed that the filter production dropped significantly in light of these algal diatoms (Tabellaria being the dominant species). Tabellaria is known as a filter clogging diatom which is a thick silica-rich cell wall and forms short rebar like chains. The result is that the whole depth of filter media and filter runs shorten. At the peak of the tabellaria episode in June-Aug 2018, the UFRV of the filters went from 250 m^3/m^2 in early June to less than 50 m^3/m^2 in early July and hence the plant faced significant production issues. There were various solutions (discussed in Chapter 5 – 5.2) tried by the plant staff with the available resources to extend the filter run times and thus bring the plant back to production.

Chapter 5 Opportunities to Build Plant Resiliency in Response to Lake Recovery

5.1 Introduction

Chapter 4 discussed the two major impacts of Lake Recovery on the JDKWSP: geosmin and filter clogging algae. This chapter proposes opportunities for plant optimization and capital upgrades to make the plant resilient to such events. This chapter is broken into three timeframes: immediate, short term and long term upgrades. Immediate opportunities are the process and instrumentation optimizations along with minor chemical adjustments that the plant staff can take immediately. Most of these opportunities have already been trialed or implemented during the algal diatoms period from June to Aug 2018. Short term actions are steps or possible plant optimization/upgrades within the next two years. Long term actions are recommendations on bigger capital upgrades in the plant from year 3 and onwards.

5.2 Immediate Actions

This section describes some of the opportunities that can be implemented immediately. Some of these were already trialed or implemented during the algal diatoms period from June to Aug 2018. The options that have been already implemented are marked by an asterisk (*).

5.2.1 Pre-treatment Actions

1. **Oxidant - Permanganate dose (*)**

The plant normally runs at a permanganate dose of 0.15 mg/l. To increase the oxidation capabilities, it was thought that an increase in permanganate dose would help filter turbidities and production. After doing some preliminary tests, the dose was increased from 0.15 to 0.25 mg/l. However, the excess manganese dose was observed in the clearwell indicating that the increase did not help. This was further confirmed with the data from the pilot plant as seen in **Figure** *27*. The filter effluent turbidity stayed above the guideline of 0.2 NTU when the permanganate dose was at 0.25 mg/l. As the dose dropped to 0, there was an improvement in filter turbidity.

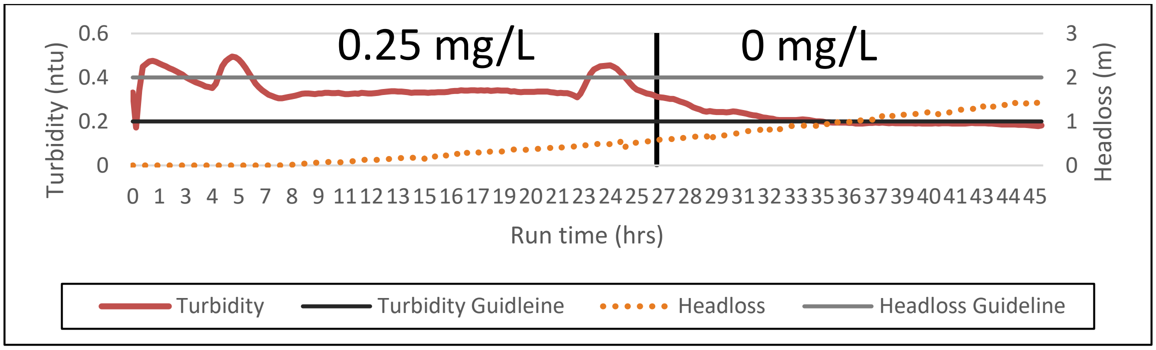

Figure 27: Increased Oxidant experiment in the pilot plant.

Although there were no significant improvements observed during the algae incident for altering the $KMnO_4$ dose (**Figure** *27*), it would be advisable to do permanganate demand tests seasonally to determine the optimal dose rather than running the plant at a constant 0.15 mg/L all year around.

5.2.2 Coagulation/Flocculation

1. Dose (*)

The JDKWSP uses alum as its main coagulant. The dose historically has been kept at 8 mg/l ±1.0 mg/l for the majority of its 40-year operation. A nonionic polymer is added during the colder parts of the year as a coagulant aid. An incremental dose increase from

7.5 mg/L to 9.5 mg/l showed that as the alum dose increased; the filter effluent turbidities improved. This demonstrates the coagulant demand was not being met. However, with increased alum dose, comes higher filter loadings and hence the filter loss of head rose faster. The plant staff had to find a balance of an alum dose that would yield filter turbidity in the range of 0.16 NTU. This would allow them some room to stay below the regulated 0.2 NTU and obtain filter runs in the range of 24 hr ± 2 hr. Another aspect of higher coagulant dose with an alternative filter media design is discussed later in this chapter in Section 5.3.4.

2. Hydraulics (*)

The JDKWSP was initially designed for a flow of 220 MLD. The plant currently operates at 96 MLD under normal conditions and at 67 MLD when ramped down. The design of the flocculation tanks is such that as water progresses through the three tanks in each train of the hydraulic flocculators, the velocity gradients are tapered to decrease as water goes through. A layout of this is shown in **Error! Reference source not found.** b elow. However, since the plant is operating at less than half its design capacity, it is not getting the hydraulic energy required to promote an efficient flocculation regime as intended or designed (Vadasarukkai, Gagnon, Campbell, & Clark, 2011).

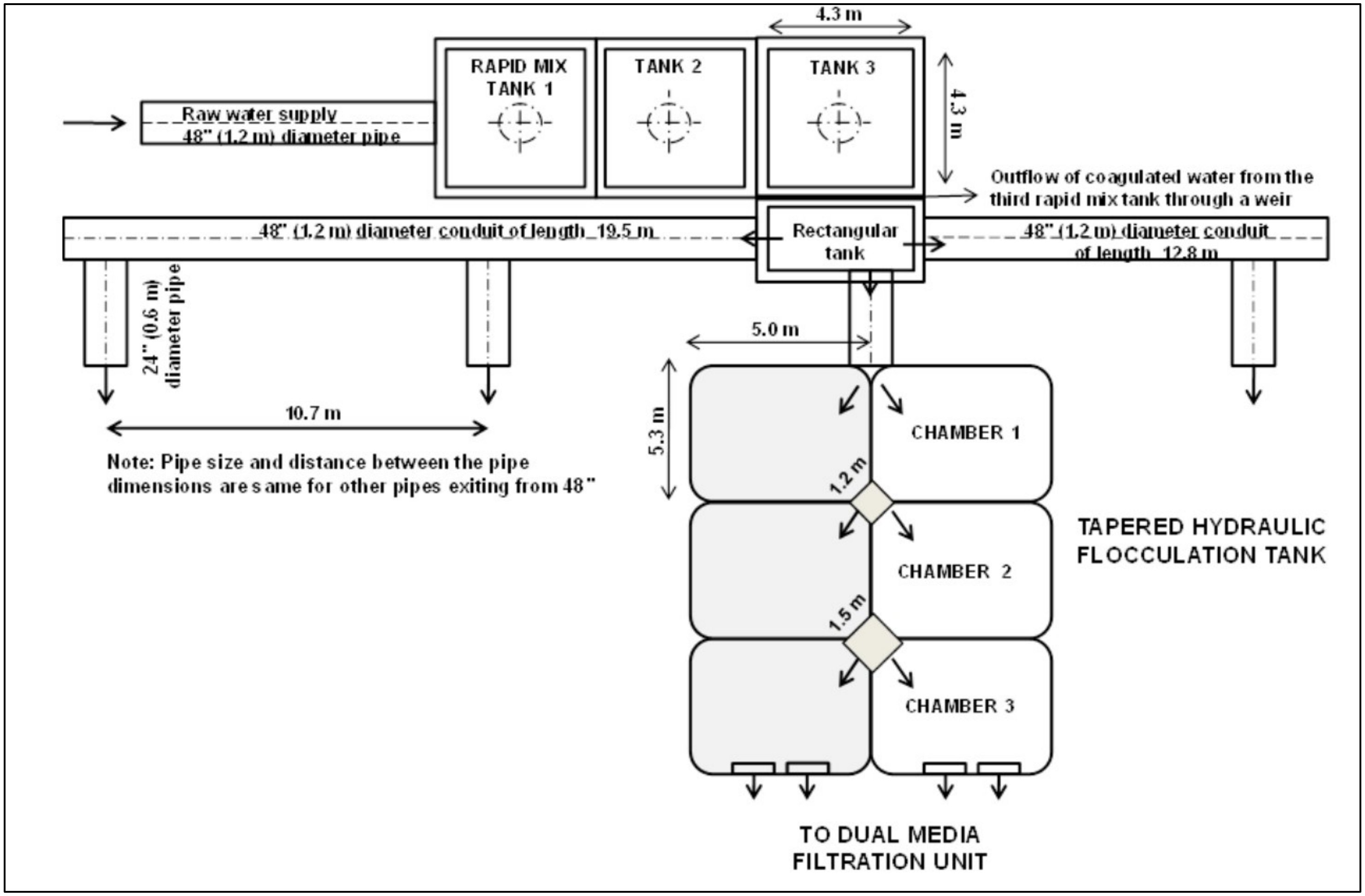

Figure 28: Schematic overview of the front end of the treatment train at JDKWSP (Vadasarukkai, Gagnon, Campbell, & Clark, 2011)

Vadasarukkai et. al., (2011) found two major findings from the research on the flocculators at JDKWSP. The first was that the velocity gradient substantially decreases from the first stage to the second stage. Additionally, being at half the design capacity, the hydraulic retention time in the flocculators is significantly higher than anticipated. Hence, during the algal diatoms period between June and August 2018, the plant staff tried to operate the plant with one or two flocculators shut in order to increase the mixing energy and operate the plant as close to design as possible. However, no real advantage was observed on the filter run times which was the focus at that time. It will be beneficial to operate the plant with only two flocculators under normal plant operating phase for an extended period to observe if there are any benefits to be realized. According to the Atlantic Canada Guidelines for Water Treatment Plants, the flocculation velocity gradient should be in 50 to 100 s-1 range. It was seen by Vadasarukkai et. al. (2011) that the G values in the flocculation tanks were 10, 3 and 2 s-1 respectively.

The second finding from Vadasarukkai et. al. (2011) was that there was uneven flow between the four trains of flocculators. This research showed through CFD modeling that the outside two flocculators receive more flow than the inside two. This pattern thus makes the water more prone to uneven retention times and velocity gradients. Hence, the plant might need to investigate the flow splitting in more detail and try to achieve an even flow distribution. Although operating the plant on two or three trains of flocculators rather than all four did not show any positive results during the algae incident, it will be wise to try this again when the plant is operating in a steady-state to investigate whether it is possible to receive positive results by improving mixing intensities.

5.2.3 Proactive Chemical Dosing Control

There have been many technological advancements in the water industry to give the operators timely and accurate information about various parts of the processes. This data can be about pumps, motors, flows and other analytical parameters. It is very important to make use of these advancements for the benefit of running the treatment process as optimal as possible. Following are some of the recent advancements that JDKWSP made in order to make the process operate better:

1. **Use of flowmeters on chemicals (*):**

JDKWSP has always relied in the past on the four-hour operator rounds of the plant to collect the information on tank levels and convert to dosages. However, the drawback of doing this is that the dosage information is available only after a four hour delay which is usually too long. This becomes even more critical when the chemical in question is as important as the coagulant. Hence, by using flow meters on chemical feed lines, the plant is able to run in 'live' mode which makes it easier to adapt to process upsets.

2. **Automatic pump adjustment on dosage:**

With the addition of flowmeters and live dosage information, the plant should take it one step further by introducing automatic pump adjustments to match the target dose. This has been successfully tried at other Halifax Water plants through a proportional–integral–derivative (PID) loop where the plant PLC automatically adjusts the pump up or down based on the flowmeter dosage. This will ensure accurate and consistent dosing at all times.

5.2.4 Filtration and Backwashes

There were several things tried by plant staff to maximize the production from the filters. Following were the changes in filtration/backwashing methodology that were implemented:

1. **Conditioning (*)**

As seen in earlier schematics of the plant, JDKWSP is not equipped with the filter-to-waste feature in their filtration setup. Hence, it is very important to control the initial filter ripening turbidity spike. In the approval to operate permit, the JDKWSP has to rest a filter for a minimum of one hour and start the filter into production with a flow no more than 4.5 MLD. This is done as a measure to lower the risk of any particle breakthrough through the filter in the initial part of the run in lieu of filter to waste. This approach was verified by the work conducted by Follet et al. (2011). During the algal diatoms period, it was difficult for the plant to keep the initial turbidity spike below 0.2 NTU. One of the solutions tried was to add alum solution at 1 mg/L into the influent troughs to help promote some floc over the top of the filter with the freshwater. The thought is that this fresh influent water with a slightly higher alum dose will mix with the water column of clean clearwell water after backwash and promote some floc formation in order to lower the initial turbidity spikes. To pictorially understand this, refer to **Figure *29*** obtained from Amburgey et al., (2003) below. The higher alum water would be in the TB to TM range and would try to lower the turbidity with some floc generation in that area. The results of this experiment were unfortunately inconclusive. It can be assumed that it provided marginal help as it was very difficult for the fresh incoming water to mix with the layer of clearwell water that already existed after the backwash on top of the filter. A better approach could have been adding alum to the backwash water.

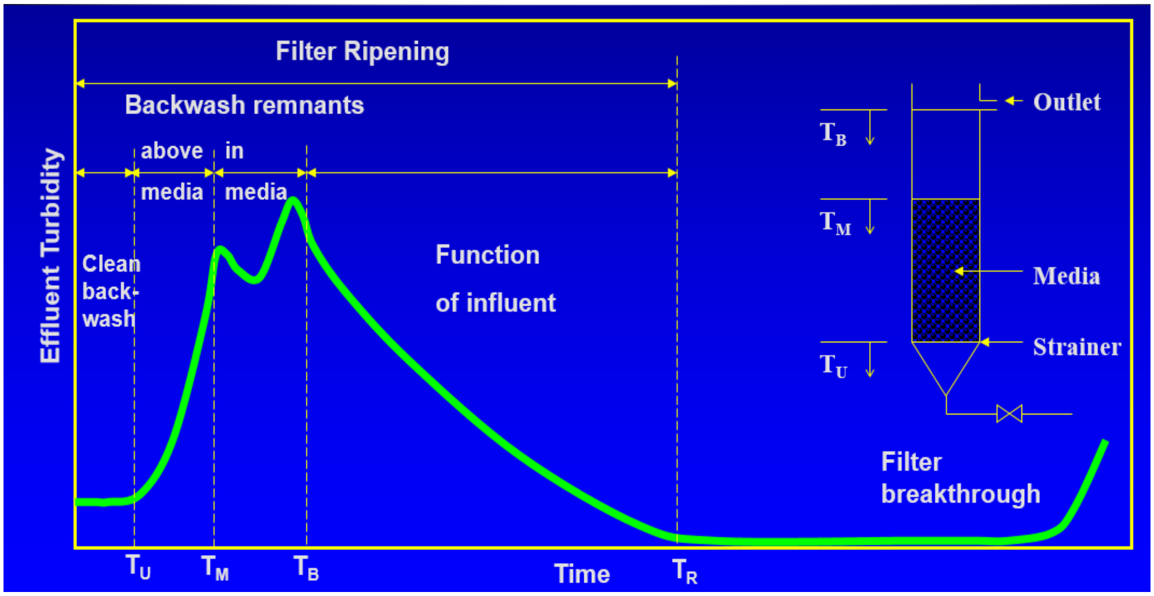

Figure 29: Typical filter operation from putting in service after a backwash to its full run until filter breakthrough. Obtained from Amburgey et al., (2003)

5.2.5 Pre-chlorination (*)

To overcome the problems associated with algal blooms, water supply plants commonly use pre-chlorination (48%), increased coagulant doses (24%), PAC treatment (16%) and regularly change coagulants (4%) (Joh, Yang Soon, Shin, & Lee, 2011). Also, pre-chlorination has been employed in various water supply plants all across the world primarily as an oxidant at the head of the plant to oxidize metals and other taste and odour compounds. In addition, chlorine also helps in controlling the biological growth within the treatment processes at the plant. Biological growth was observed at JDKWSP during the diatom event. Further analyses were performed to find out how the biology was progressing within the treatment plant, it was found that Adenosine triphosphate (ATP) (***Table 2***) was higher in the flocculation tanks than the incoming raw water. This meant that the diatoms were reproducing within the plant. Hence, the plant needed a treatment step right at the start of the process. The JDKWSP used to operate with pre-chlorination up until 2013. Fortunately, all the plumbing and pipework to restart the pre-chlorination still existed in the plant.

Table 2: ATP values within the plant on July 12 and 13, 2018 before pre-chlorination was turned on

	cATP pg/mL	
	July 12	**July 13**
Raw Water	96	97
Floc	140	130
On top of filters	125	78
Clearwell	-	3

There were three main factors that provided some hesitancy in going with this option:

Increase in DBPs in the distribution system

JDKWSP specifically shut down pre-chlorination in 2013 as a measure to lower the DBPs. Shutting down pre-chlorination provided a 40% reduction in DBPs (Stoddart & Gagnon, 2015). Turning pre-chlorination back on meant that the DBPs in the distribution system would increase close to the maximum allowable concentration (MAC).

Loss of the biological active filters and turn them into rapid dual media filters

Since the shutdown of pre-chlorination, the filters slowly converted themselves into biologically active filters. Research shows that there has been growth in the biomass within the filters with stable effluent water quality and a marginal reduction in DOC (Stoddart A. , 2017). The additional negative side of starting pre-chlorination again was that it was unknown how the biomass would react or whether it would slough off and create effluent water quality problems.

Possibility of lysing algal cells and releasing algal toxins if blue-greens are present

Samples were sent to the lab and it was confirmed no algal toxins were released after chlorine treatment. Hence, addition of pre-chlorination was possible.

Considering all factors above and after pilot testing, pre-chlorination was turned on July 16, an initial dose of 1.5 mg/L, to maintain 0.1-0.2 mg/L on top of the filters. Alum was adjusted and increased by 0.5 mg/L in order to maintain the same zeta potential value as it was before the pre-chlorination. It made immediate impacts as can be seen in **Figure *30*** indicating the filter run hours started to increase as soon as the pre-chlorination started. **Figure *31*** and **Figure *32*** provide evidence that chlorination was able to control the biology within the plant. **Figure *31*** shows the ATP as water proceeds through the plant after turning pre-chlorination on. **Figure *32*** illustrates a comparison of the ATP before and after chlorination.

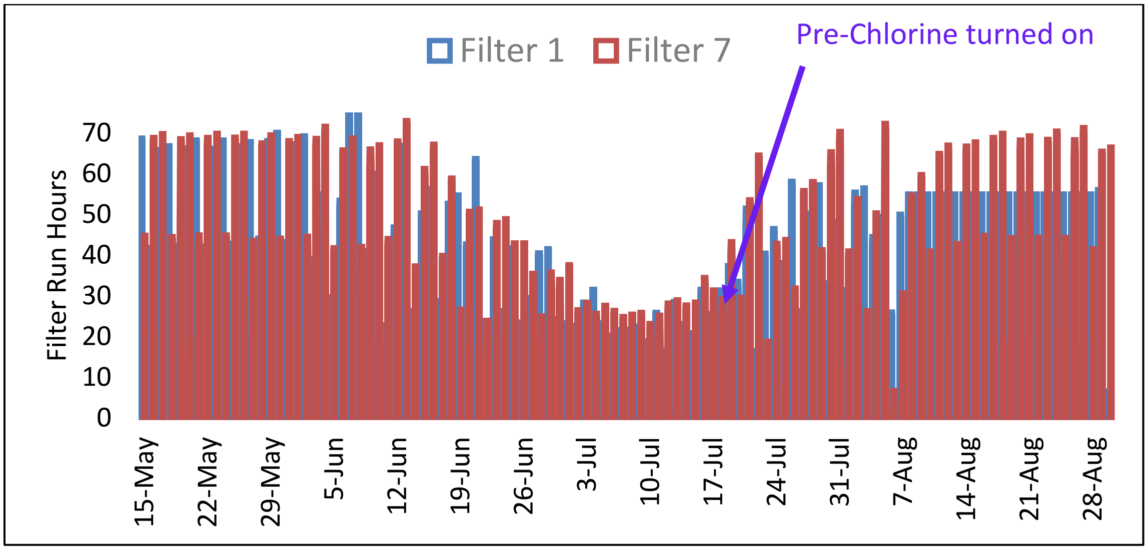

Figure 30: Filter Run hours before and after pre-chlorination

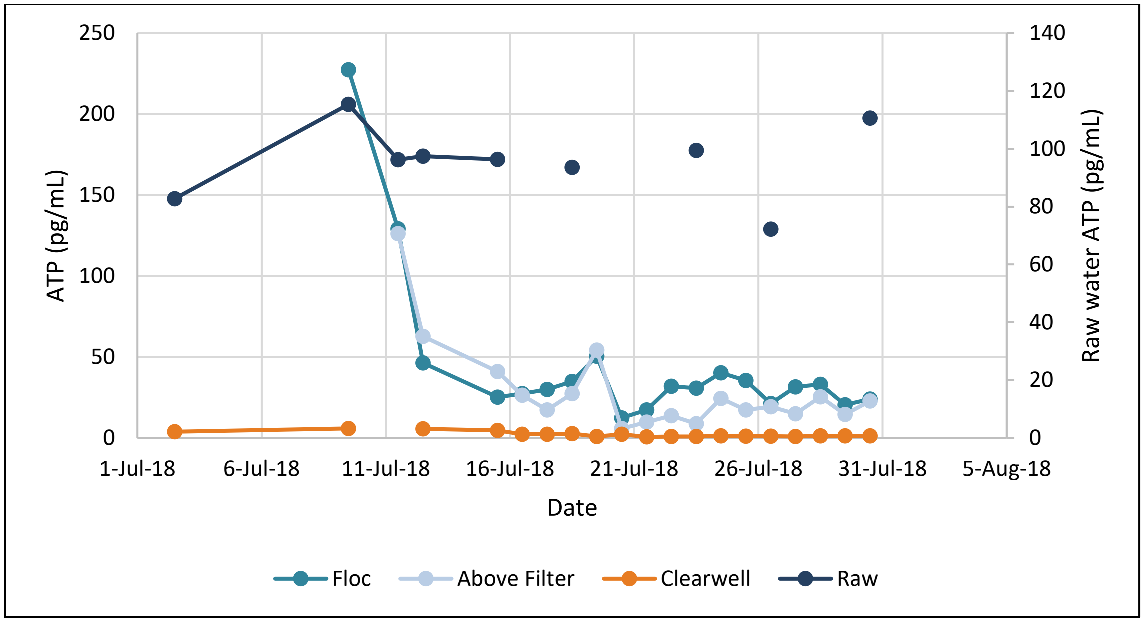

Figure 31: Biological activity at JDKWSP before and after turning pre-chlorination on

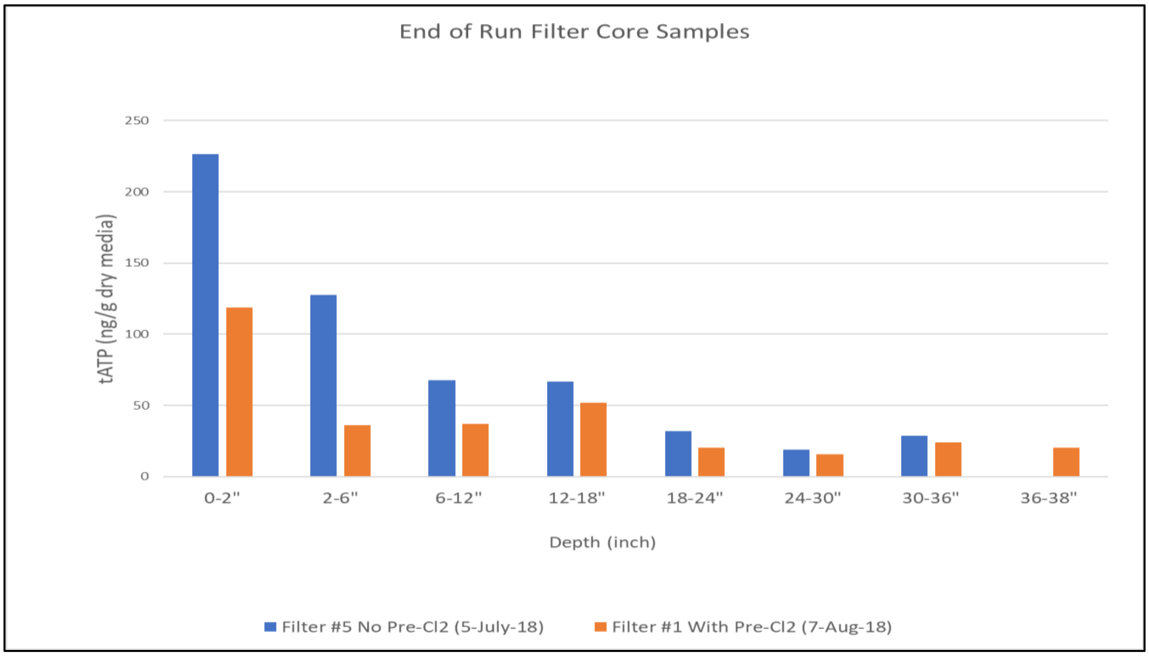

Figure 32: ATP numbers through the filter column before and after turning pre-chlorination on

Additionally, it was observed that even though the diatom concentration increased in August as the summer progressed; there was no effect on the filter run time once the pre-chlorination began. **Figure *25*** shows how the diatoms concentration was over the event. Comparing this to **Figure *30***, it can be observed that although the diatoms concentration was highest on Aug 1, 2018, there was no effect on filter run times.

It is important to note in the above sections for immediate action plans that most of the items have already been tried either prior to or during the algae incident. However, some of the actions, like hydraulics changes, alternative coagulant dose and pH were not run for any significant amount of time due to time constraints. It is important to revisit these changes at a time when the plant is running at a stable condition, as there might be efficiencies and process enhancements that can be observed when the plant process has stability.

5.3 Short Term Recommendations

This section describes some of the opportunities for plant resiliency that can be considered within the next two years for the JDKWSP.

5.3.1 Source water monitoring

Water treatment plants nowadays have the need to obtain near real-time water quality information. This does not only apply to the water quality parameters within the plant but it starts at the source water. This additional and real time data provides plant staff with the capability to detect changing conditions, such as developing algal blooms or turbidity upsets, which require immediate action for efficient, cost-effective water treatment. Sometimes, algal blooms and other biological incidents happen far away from the intake in the watershed. However, water flow, wind and sudden runoff events can quickly bring these contaminants towards the intake for the treatment plant. It is, therefore, necessary to ensure that the source water monitoring program is evaluated to optimize the sampling locations, parameters, sampling frequency. Data tracking and interpretation systems will also need to be in place to closely monitor and detect subtle water quality changes to ensure plant performance can be optimized. This will allow the utility to be proactive in response to the need for potential water quality changes.

One of the better advancements in technology has been the introduction of water quality sondes, buoy- and piling-mounted water-column profilers useful in monitoring biological and physical-chemical parameters throughout the entire water column. These devices collect water quality information as often as once per minute which is a major upgrade from manual field measurements which typically for source water are done monthly or seasonally. Additionally, these sondes can test for multiple parameters. This could have slightly higher initial costs in terms of purchase and set up, but definitely pays off as the time goes on as they provide real-time data (American Water Works Association, 2010). Water quality measurement of the whole column is very important, as even simple parameters like water temperature have extended effects on the quality of coagulation. Also, profiling the whole depth of the column gives the plant staff the knowledge of where to draw water from at certain times of the year (if they have the capability such as a multi-level intake). Extended deployment water quality instruments equipped with anti-biofouling measures have pigment-specific sensors that allow real-time monitoring of algal biomass as relative chlorophyll-a or phycocyanin fluorescence. Halifax Water had a consultant develop a sampling plan for various parameters in the source water to get advanced warnings on water quality changes as well as start to develop some baselines. The sampling schedule is shown in **Table 3**. This sampling should be done in addition to the deployment of water quality sondes in the lake to monitor for parameters 24x7.

Table 3: Sampling parameters and frequency for the source water.

Sampling Parameter	Frequency
• Algal enumeration/taxonomy • Chloride	Biweekly
• Nutrients o Silica o Iron, nitrate, nitrite, ammonia, ortho-phosphate, total phosphorus	Biweekly
• Taste & Odor o GEO, MIB	Monthly
• Cyanotoxins o Microcystin (SGS Laboratories) o On-site visual verification	Monthly
• Using a microscope This is typically done after preliminary taxonomy results are received, and a select few species were identified as dominant.	

In addition to the parameters mentioned in **Table 3**, the NOM fractionation work needs to be repeated for different seasons and also needs to be one of the consistent measurements for the raw water. This will help develop a baseline and more datasets to compare and understand the seasonal chemical adjustments.

5.3.2 Pre-treatment

The equipment and tankage at the JDKWSP are original to the plant and there have been no modifications or upgrades done at the facility since its commissioning in 1977. In

2010, Halifax Water engaged consultants to take a look at some of the process components and identified the following inefficiencies:

1. The current pretreatment mix tanks have low G-value. At a flow of 95 MLD (which is normal operating flow at JDKWSP), the mixing intensity in the pre-treatment tanks is approximately 300 s^{-1}. As per the Atlantic Canada Guidelines for Water and Wastewater Plants, the G Value in the pre-mix tanks shall be between 600-1000 s^{-1}.
2. After this rapid mixing stage, from pre-mix tank # 3 to the channel for pretreated water, the water surface elevation drops significantly, over a weir, up to 3-feet at normal maximum flow. This drop could be further damaging to the floc, as the shear forces on the floc particles are elevated when the water falls.

The recommendations out of this 2010 report called for upgrading the mixers to provide better velocity gradients (intensities), to match the Atlantic Canada guidelines. Additionally, the design of the weir that transfers water from the end of pre-mix tank # 3 to the distribution header of floc tanks should be reviewed. Both of these solutions should be considered to promote better floc formation and decrease the risk of floc shearing to already created floc particles.

5.3.3 Filter Control Methodology

The plant runs at half the capacity of its original design as discussed in the chapters 3 and 4. This presents an opportunity to examine how many filters should be run at any given time and optimize filter loading. Additionally, the water quality has changed significantly over the years and hence the terminal filter run hours should be fine-tuned.

This section explains the various options that the plant staff may try in order to manage the filters better.

1. Filter Run time (FRT) vs. Unit Filter Run Volume (UFRV)

Historically, JDKWSP has managed to get anywhere from 70 to 80 hours filter runs. 80-hour filter runs were common up until 2014 but due to changing water quality, achieving 80-hour filter runs has not been feasible. Additionally, the 80 hours run time was based on the water quality that the plant had for the first 25 years of its operation. With the organics in the source water doubled from 1.7 mg/l to 3.4 mg/l, it will be a worthwhile exercise for the plant staff to set a new baseline.

Also, in its current operating procedure, the filter effluent flow is reduced if it either reaches a threshold turbidity (0.1 NTU) or headloss (2.15 m) value. This elongates the filter run hours of the filter but reduces the amount of water it is producing. Hence, at the end of the filter run, it makes it look like the filter has run for a longer duration of time. However, it has not produced as much water. Therefore, it would be prudent to lower the expectations on filter run hours and take the filter out of production sooner. It will be important to operate the filters based on UFRV. UFRVs of 200 m^3/m^2 or greater are satisfactory, and UFRVs greater than 300 m^3/m^2 are desirable (Environmental Protection Agency, Ireland, 1995). The advantage of using UFRV vs filter run time can be seen below in **Figure *33***. The analysis was done in February 2019, at a point where the JDKWSP had rehabilitated four out of the eight filters. In the comparison of their run times and UFRV, it is seen that there were occasions when the filter run times for both new and old filters very close to 70 hours. However, a comparison of the UFRV suggests that the old filters are producing 50 m^3/m^2 less than new. Hence, using FRT alone as the gauge for filter efficiency can provide a false positive on filter performance.

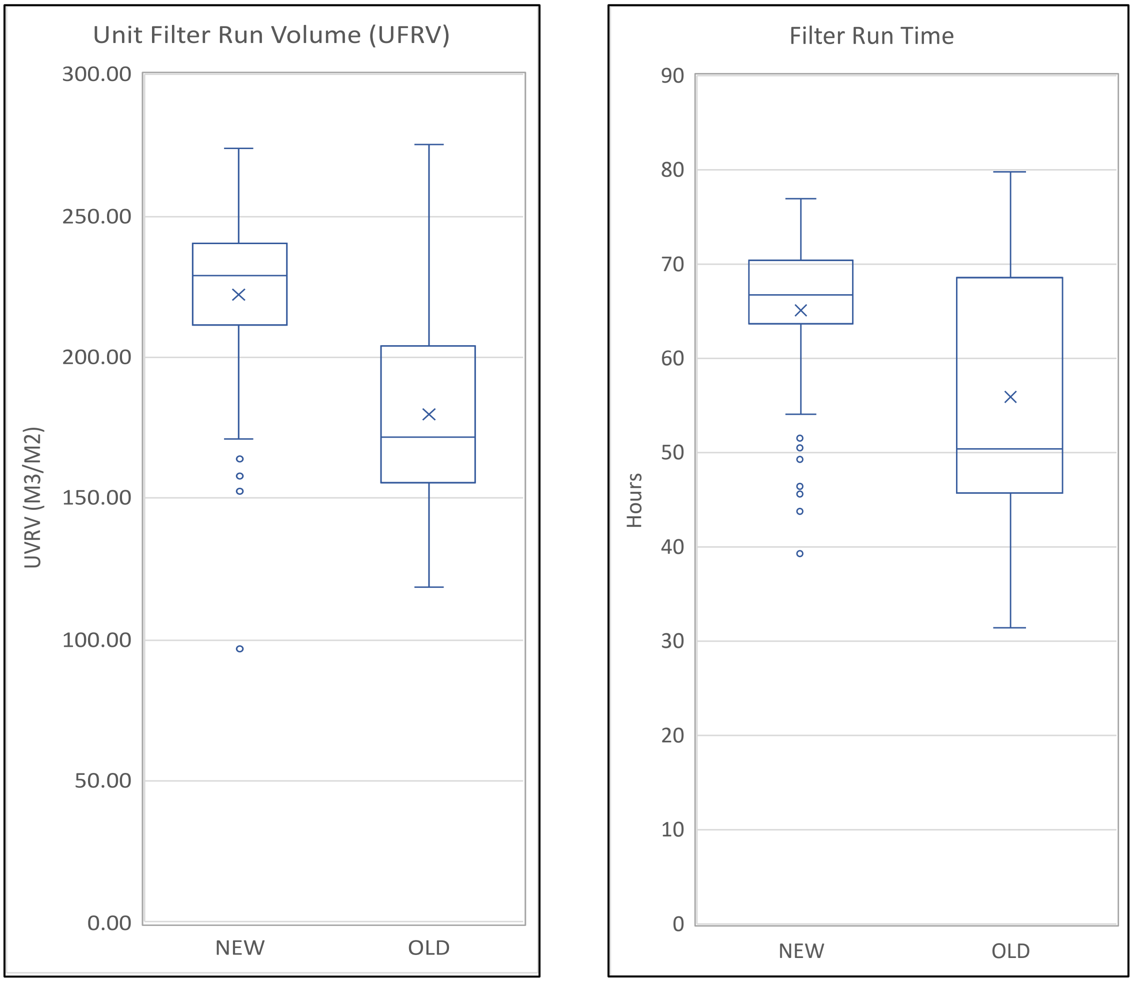

Figure 33: UFRV vs Filter Run time comparison (data from November 2018 to February 2019 for JDKWSP)

It should be noted in **Figure *33*** that although the new filters have better UFRV than old, they are still performing “average” in terms of what the industry standard is. However, examining from a filter run time perspective, one would be lead to believe that the plant is operating reasonably well for a direct filtration plant with run hours reaching 70 hours which is a unique case for direct filtration plants as most of these plants have 24 to 36 hours run times (Ratnayaka, Brandt, & Johnson, 2009).

2. New Filter Run Time Objective

This is a by-product of the discussion in the preceding section. It is important to understand that terminal filter run hour does have a place and need as this parameter ensures the plant stays complaint with the filter run times stipulated in the Approval to Operate permit. Also, it helps to ensure filters stay on a particular backwashing schedule. Historically, 80 hours has been the standard number that the plant staff have been using as the target. With changing water quality, this number has not been achieved for years. Hence, it will be prudent to come up with a terminal filter run hour time that is based on recent filter performances. As stated earlier, typical direct filtration plants have run hours in the range of 24 hours whereas Pockwock has historically run over three times that. Hence, a new Filter Run Time target should be set considering current water quality and operations regime. This number could be adjusted seasonably.

3. Backwash Optimization

The JDKWSP has two backwash pumps. The backwash valve controls the rate of incoming water for the backwash. This valve is original to the facility and modulates the flow at a very slow pace. **Figure *34*** shows the effect of this slow control valve on a current backwash regime where it can be observed that the filter was backwashed at the highest flow rate for only three minutes (30% of the backwash time). The overall water used in the filter backwash was close to 0.9 ML. In order to make this backwash regime more efficient, the controls of the backwash valve need to be upgraded so that there is a faster ramp up and down. This would enable the backwash regime to wash the filter at the highest flow rate longer and hence provide an efficient wash.

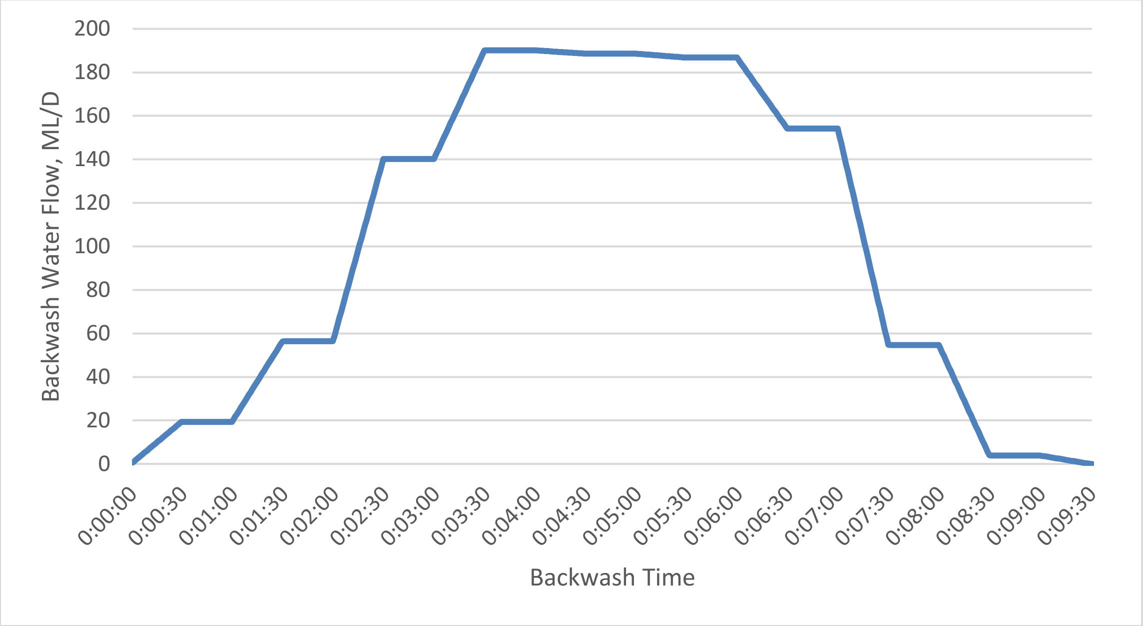

Figure 34: Backwash profile at JD Kline WSP

4. <u>Extended Terminal Subfluidization Wash (ETSW)</u>

ETSW is a procedure that can help lower the initial turbidity spikes during the filter ripening stage once a filter is put into operation after backwashing. It involves extending the normal backwash duration at a subfluidization flow rate for an amount of time sufficient to move one theoretical filter-volume of water through the filter box. The fundamental behind this procedure is that it removes already-detached particles produced during the fluidization portion of the backwash procedure from the filter box, and the decreased shear forces associated with the subfluidization flow rates do not detach significant quantities of additional particles to be left in the filter at the conclusion of the backwash procedure. It is the backwash remnant particles, due primarily to an upward shift in magnitude of their negative zeta potentials, which are now known to contribute a significant portion of the filter ripening turbidity spikes following the restart of a backwashed filter (Amburgey, Amritharajah, Brouckaert, & Spivey, 2003). In the current setup, the backwash valve is not able to keep the valve open at this very low flow that is required for ETSW. Upgrading the controls for the backwash valve as described in the previous section would also allow ETSW to happen.

5.3.4 Filter Media and Coagulant Modification

The current filters are being rehabilitated with new filter media. The new media has the same specification as the old media with 300 mm of sand over 600 mm of anthracite. The specification for the media is shown in **Table *4***.

Table 4: Existing filter media specification

Media Type	**Effective Size (mm) d10**	**Uniformity Coefficient**	**60% Passing d60**	**Specific Gravity**	**Media Depth (mm)**	**L/d ratio**
Anthracite	0.9	1.4	1.26	1.65	600	667
Sand	0.45	1.4	0.63	2.65	300	667
TOTAL					**900**	**1333**

One of the factors in not increasing the coagulant dose is that the current media, which has a finer anthracite layer, starts to develop headloss faster when the alum dose is increased as there are more solids being retained by the filter. One of the alternatives in the interim could be to try to get the same filter effluent water quality by using a deeper anthracite layer with a higher effective size. This still maintains the same L/d ratio for the filter but allows it more solids handling capacity because of being a deeper bed. The reason media specification was not altered was there was no piloting conducted at the time of project execution. However, in late 2018, one-month long piloting was conducted using a higher effective size media and a deeper bed and with an alum dose of 15 mg/l (3 mg/l higher than the production plant). The specifications of this new media were explained in Chapter 4 (Materials and Methods).

In order to evaluate whether increased alum would have an effect on removing more organics or not, an experiment was run in the pilot plant. The control side of the filter had the same media specification as provided in **Table *4*** whereas the experimental side had the filter design shown in **Table *5***.

Table 5: Experimental filter media specification

Media Type	**Effective Size (mm) d10**	**Uniformity Coefficient**	**60% Passing d60**	**Specific Gravity**	**Media Depth (mm)**	**L/d ratio**
Puracite Anthracite	1.3	1.4	1.82	1.4	900	692
Sand	0.45	1.4	0.63	2.65	300	667
TOTAL					**1200**	**1359**

The results of this experiment are shown in **Figure *35***. There was a definite improvement in the removal of DOC. **Figure *35*** shows that on average, there was 10% additional DOC removed on the experimental side than the control. This experiment shows the following two results:

1. There is additional coagulant demand in the water that is currently not being fully satisfied.
2. It shows positive results that a clarification step using a higher coagulant dose will be extremely helpful in further removing organics.

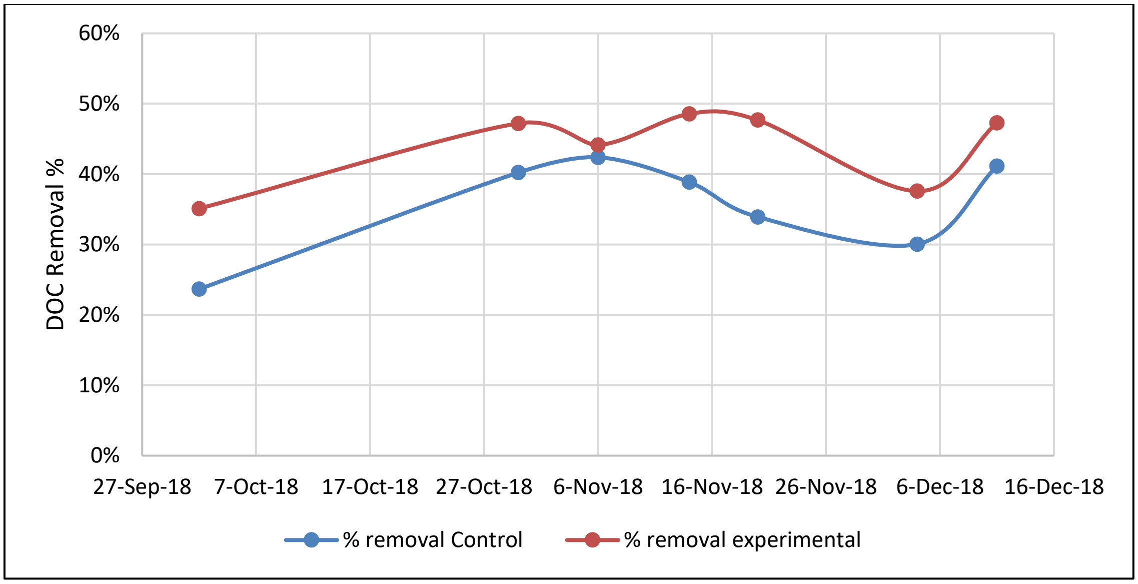

Figure 35: Percentage of DOC Removal over two different filter media specifications

5.4 Long Term Recommendations

This section describes some of the process and equipment upgrades that can be employed at the plant over the long term (year 2 and onwards).

5.4.1 Pump Station Optimization

Optimizing the pump station at a WSP can have great advantages to the subsequent processes, as this is the starting point of the treatment process. Some of the key considerations that the plant should investigate in terms of the pump station is discussed below.

1. **<u>Pumps on Variable Frequency Drives (VFDs)</u>**

The current pumps and motors are mostly original to the plant. There have been normal maintenance activities done to them as per the manufacturer's recommendations. However, the plant can only run at certain flow rates which means either the plant is running at 96 MLD or 67 MLD in order to make up to the 80 to 85 MLD distribution demand. This means is that the plant is being ramped up and ramped down at least once or multiple times a day. This repeated change in flow not only brings a few hydraulics challenges, but the filters are being ramped up and down continuously which has the potential to cause turbidity spikes. Some of the other challenges that can be faced are improper chemical mixing because the velocity gradients are lower when ramped down. Additionally, the chemical flow pacing is sometimes not linear as well and hence requires a close eye and manual intervention to ensure the proper amount of chemical is being dosed.

A better operation would be to have pumps that are on VFDs that can be run between flow rates of 75 MLD to 85 MLD to match the distribution demands and will eliminate ramp up and downs and make the process more stable.

2. **Multiple depth intake**

The current intake at the JDKWSP draws its water from the thermocline level of the lake and there is no flexibility to draw its water from an alternative depth. As was seen during the algae diatom period in 2018, there was an increase in the chlorophyll-a number in the thermocline layer indicating higher biological activity. Hence, it may be prudent for the JDKWSP to investigate a new multi-level intake deeper into the lake. There will be a need to do extensive water quality testing at various locations in the lake at various depths to properly evaluate the water quality. However, having a multi-level intake provides the water plant with alternative options as the water quality can vary significantly within the layers of lakes.

5.4.2 Conversion from a Direct Filtration to a Conventional Filtration Plant

As discussed the current water quality for JDKWSP is changing and the organics loading is increasing. When the plant was commissioned in 1977, the TOC was 1.7 mg/L, which was perfect for a direct filtration application. However, the current water quality is extending past the limits of a direct filtration plant. Hence, the treatment process at the plant needs to go from a direct filtration to a conventional treatment.

Based on the process selection graph (**Figure** ***36***) developed by Valade et.al (2009), the current water quality at JDKWSP fits right in the range for a Dissolved Air Floatation (DAF) process. The circle on **Figure** ***36*** indicates the source water quality when the plant was commissioned in 1977 whereas the triangle represents the current water quality.

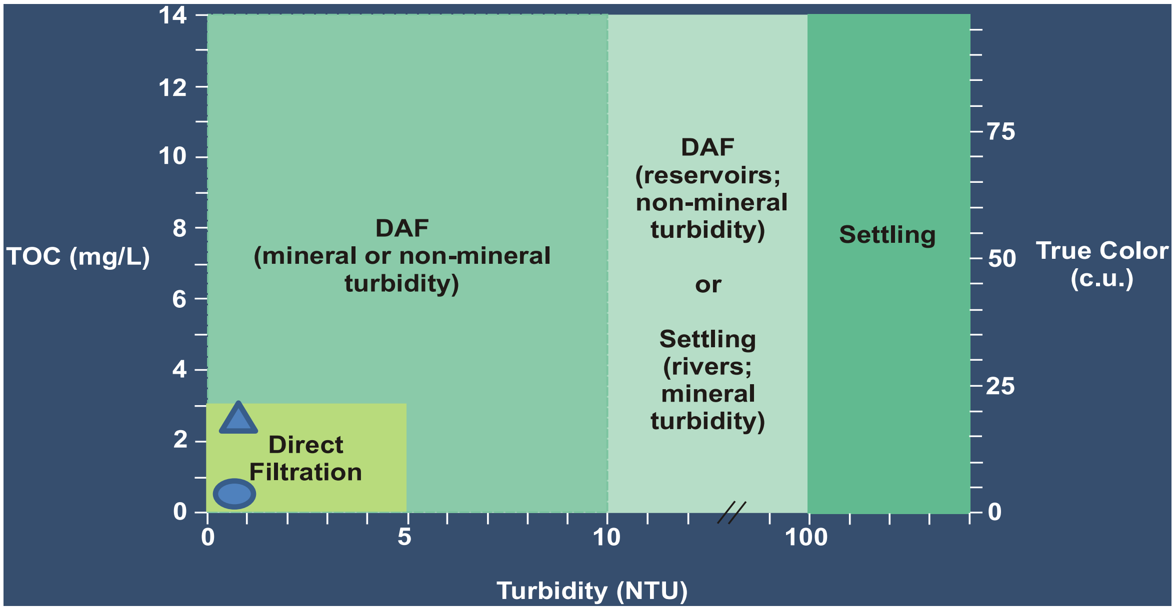

Figure 36: Process selection chart and Pockwock's water quality in 1977 and 2019. The red dot indicates TOC in 1977 and the blue dot represents 2019.

According to Ferguson et.al, (1993) who ran direct filtration and DAF comparisons on water similar to Pockwock Lake, the effluent water quality was much better coming out of filters if pre-treated with a DAF unit process. According to the pilot study done, filter run hour comparisons were 11 hours and 44 hours for direct filtration and DAF respectively (Ferguson, Logsdon, & Curley, 1995). Other studies done by Johnson, Gong, Bellamy, & Tran, 1995 on water quality similar to Pockwock Lake have also recommended DAF as the preferred clarification step.

DAF also has been proven to be an excellent technology to remove algae. Pilot studies conducted by Marston, Rupar, Cordaro, & VandeVenter (2015) have shown 98.9% removal of algal cells. This shows a very positive sign as the water quality for this pilot (New England area) was similar to Pockwock's.

5.4.3 Ozonation

The application of ozone in the water treatment industry dates back to the 1900s (American Water Works Association, 1991). Ozone was primarily introduced as a disinfectant. However, over the years Ozone has found multiple uses in the treatment processes. For example, it is used as a biocide, a classic oxidant and as a pretreatment to improve flocculation and other subsequent unit processes (American Water Works Association, 2012). The major uses of ozone so far have been for the following and all these uses can make JDKWSP more resilient to the changing water quality (Langlais, Reckhow, & Brink, 1991):

1. **Iron and Manganese Removal**

Ozone is an effective oxidizer. Most iron and manganese removal treatment processes incorporate oxidation to convert the dissolved forms of the metals to a solid, followed by a filtration process.

2. **Colour (organics) and turbidity removal**

Ozone has been used as an oxidant to remove oxidize the organics along with metals. According to various researchers, ozone in the dose of 1 – 3 mg/l has been effective in removing 100% true color in the water. Additionally, ozone is successful in removing 30 to 50% DOC at these dosages (American Water Works Association, 1991). Thus adding ozone to the treatment steps will enhance color and organics removal which in turn makes the plant more resilient.

3. Control Taste and Odours

As stated earlier in the thesis, JDKWSP has dealt with various episodes of geosmin since its first introduction in 2012. Results from various researchers have shown a reduction in geosmin in the range of 80% for an ozone dose of 2-3 mg/L (American Water Works Association, 1991). Ozone is not only limited to the removal of geosmin but other organic compounds as well.

4. Disinfection and Disinfection by-product control

Ozone has been known for its disinfectant capabilities. In fact, that was one of the reasons it was used from the onset of water plants. There are many plants across the world that use ozone as a disinfectant. It is a stronger disinfectant than chlorine and has been widely used if chlorinated disinfection by-products are a problem.

5. Algae Removal

Ozone does a similar work like chlorine in terms of effecting algal and plankton cells and destroying them. It can limit their growth within the plant and decrease biological activity as well.

6. Micro-Flocculation

Ozone is typically applied before the coagulant is added (lowers coagulant demand) or before the filters (develops micro flocs that help with filtration) (American Water Works Association, 2012).

Based on the multiple uses listed above, it is clear that ozonation can help make the plant be more resilient in terms of both short and long-term water quality changes. Any upgrades at the plant shall consider having ozonation in the future as a potential add on.

5.5 Summary

This chapter discussed various opportunities and alternatives that JDKWSP has in intermediate, short-term and long-term in order to make the plant more resilient to the changing water quality, especially to the aspect of Lake Recovery. These opportunities exist in the form of small plant operational adjustments such as setting up new baselines for filter run hours, using UFRV as filter efficiency measure to big capital upgrades of converting the current direct filtration plant to a conventional treatment plant by adding a clarification step in the treatment process. The majority of the immediate opportunities have been implemented by the plant staff such as adding flowmeters to chemical dosing, trying to vary operating the plants with one or two flocculation tanks off and pre-chlorination. Pre-chlorination was very effective for JDKWSP to cope with the algal diatoms as other immediate opportunities had marginal impacts. Some of the short-term opportunities are optimizing and setting new baselines for filter control methodologies, optimizing the backwash regime and setting up better source water monitoring programs. Long-term opportunities look at bigger multi-year capital upgrades to the plants in terms of pump station modifications, adding DAF clarifiers and adding ozonation into the treatment process. All these opportunities require proper resources and funding with proper implementation plans. It will be very beneficial for the JDKWSP to develop a comprehensive 10-year upgrade plan to look at all the opportunities holistically and factor in risks associated with each upgrade/project.

Chapter 6 Conclusions & Recommendations

6.1 Conclusions

Many European countries along with North America have been successful in implementing stringent air quality guidelines. This, in turn, has reduced the concentration of atmospheric gases such as SO_2 and NO_X significantly. Thus, there is less acid rain which has been the leading contributor to the lowering of the pH in lakes. The majority of these lakes had a pH of <5, thus making them less feasible for sustaining freshwater ecosystems. As a response to the decrease in acid deposition, lakes in Europe and North America are recovering from its effects. This phenomenon is known as Lake Recovery. As the pH recovers from <5 and approaches 6, it has led to a chemical and biological response from the lake. This thesis shows through literature review that lakes that are recovering from acid deposition have shown an increase in pH and DOC. The biological response of these lakes is observed by the occurrence of frequent algae and cyanobacteria blooms. These chemical and biological responses to Lake Recovery are having significant effects on water treatment plants.

The first objective of this thesis was to document the effects that a local water supply plant (JDKWSP) has observed in light of Lake Recovery. JDKWSP was commissioned as a direct filtration plant in 1977. At that time, the source lake had a pH of <5 and TOC of 1.7 mg/L. Since 2000, the pH and TOC in the lake have been increasing. Currently, the pH is close to 5.8 and TOC is at 3.4. The plant saw its first Lake Recovery impact in 2012 with an outbreak of a taste and odour compound: geosmin. Since then, geosmin has been a recurring problem for the JDKWSP which typically onsets in late fall and stays till mid-winter. Cyanobacteria synthesizes geosmin throughout the life cycle and eventually releases or store the odorant depending on the phase or surrounding environmental factors. Favorable conditions that influence geosmin outbreaks usually consist of excessive nutrients and warmer temperatures, which coincide with cyanobacteria blooms. The highest recorded geosmin concentration in the treated water at JDKWSP has been 18 ng/L. The customer complaints related to geosmin taste and odour can start to come at as low as 4 ng/L. The second Lake Recovery impact observed by the JDKWSP has been filter clogging algal diatoms from June to August 2018. The diatoms substantially lowered the filtered water production. The main species of diatoms in this period was Tabellaria fenestrata. Tabellaria forms rebar like structure on top of the filter and is gelatinous because of its silica-rich cell wall. This blocks the floc particles from filtering through the entire bed and traps them on top of the filter reducing the UFRV. In JDKWSP's case, the UFRV reduced to less than 50 m^3/m^2 when typically that number is around >200 m^3/m^2. This dip in production rendered the plant not meeting the water demand of the city and water from another plant had to be brought into its distribution system.

The second objective of this thesis was to recommend some immediate, short-term and long-term opportunities for JDKWSP in order to make it more robust and resilient to Lake Recovery impacts. The majority of the immediate opportunities were already addressed by the plant staff during the algal diatoms period in 2018. However, work needs to be done in the short and long term. Some of the immediate opportunities consists of adding flowmeters to chemical dosing, trying to operate the plant in various hydraulic loading rates and pre-chlorination. Pre-chlorination is very effective for

JDKWSP to cope with the algal diatoms as other immediate opportunities had marginal impacts. Short-term opportunities consist of optimizing and setting new baselines for filter control methodologies, optimizing the backwash regime and setting up better source water monitoring programs. Long-term opportunities look at bigger multi-year capital upgrades to the plants. These upgrades include pump station modifications, adding DAF clarifiers and adding ozonation into the treatment process.

6.2 Recommendations

Although the chemical and biological response of the lakes to the phenomenon of Lake Recovery have been documented, their translation to impacts on water supply plants is not well understood and is in its early stages of being studied. This is primarily because the effects of Lake Recovery are just being realized. Moreover, it can sometimes take a long time to link the symptoms to the cause. For example, in case of the JDKWSP, their first geosmin outbreak was in 2012. Initially, it was treated as an isolated occurrence and it was not until three to four years later that the utility started to link it to Lake Recovery. Now that the evidence exists linking Lake Recovery from acid deposition to increase in pH and DOC, it is very important for future work in this field to document the impacts on water treatment processes and upsets that are being faced by water supply plants. In addition to that, all future designs for water plants, whether new or retrofits, need to consider aspects of Lake Recovery in process selection.

This research recommends a variety of intermediate, short-term and long –term opportunities to build plant resiliency. Majority of the immediate opportunities were ad-hoc and in reaction primarily to the algal diatoms in 2018. **Figure *37*** and **Figure *38*** summarizes the short and long-term opportunities discussed in this thesis.

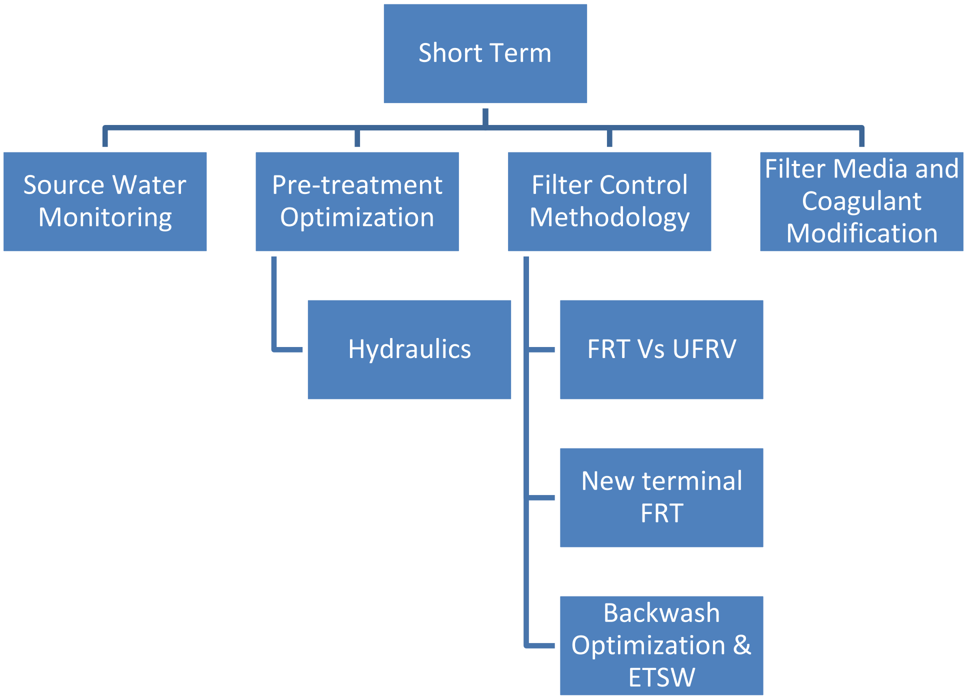

Figure 37: Summary of short-term recommendations

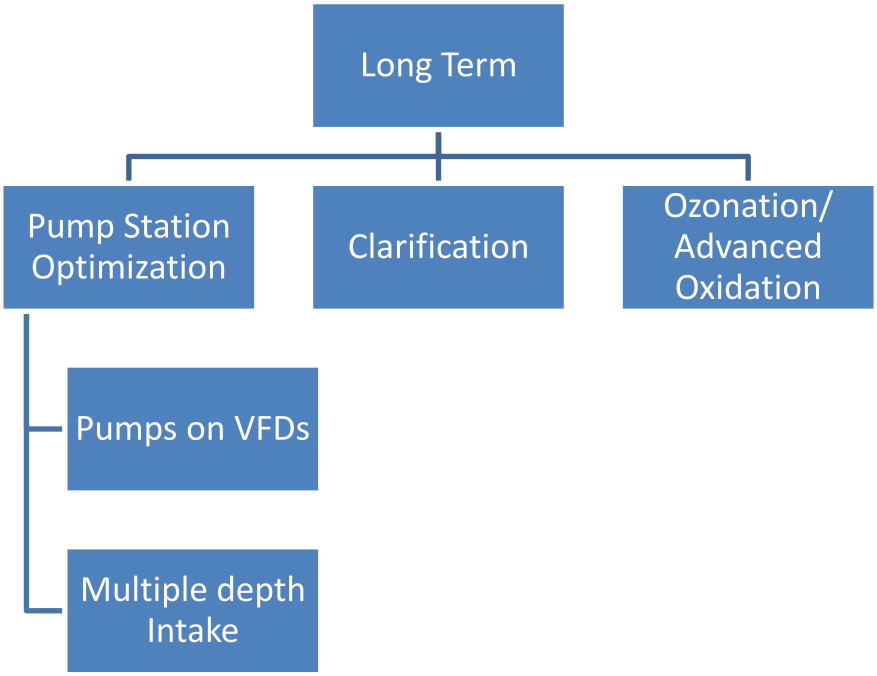

Figure 38: Summary of long-term recommendations

All these opportunities can be treated as discrete elements of a water plant and studied in depth via literature and piloting to prove the efficiency and applicability of each treatment opportunity. Additionally, future research should look into innovative technologies of retrofitting new infrastructure in old basins and footprints in order to reduce costs and make that next capital investment for a water utility more lucrative and feasible.

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