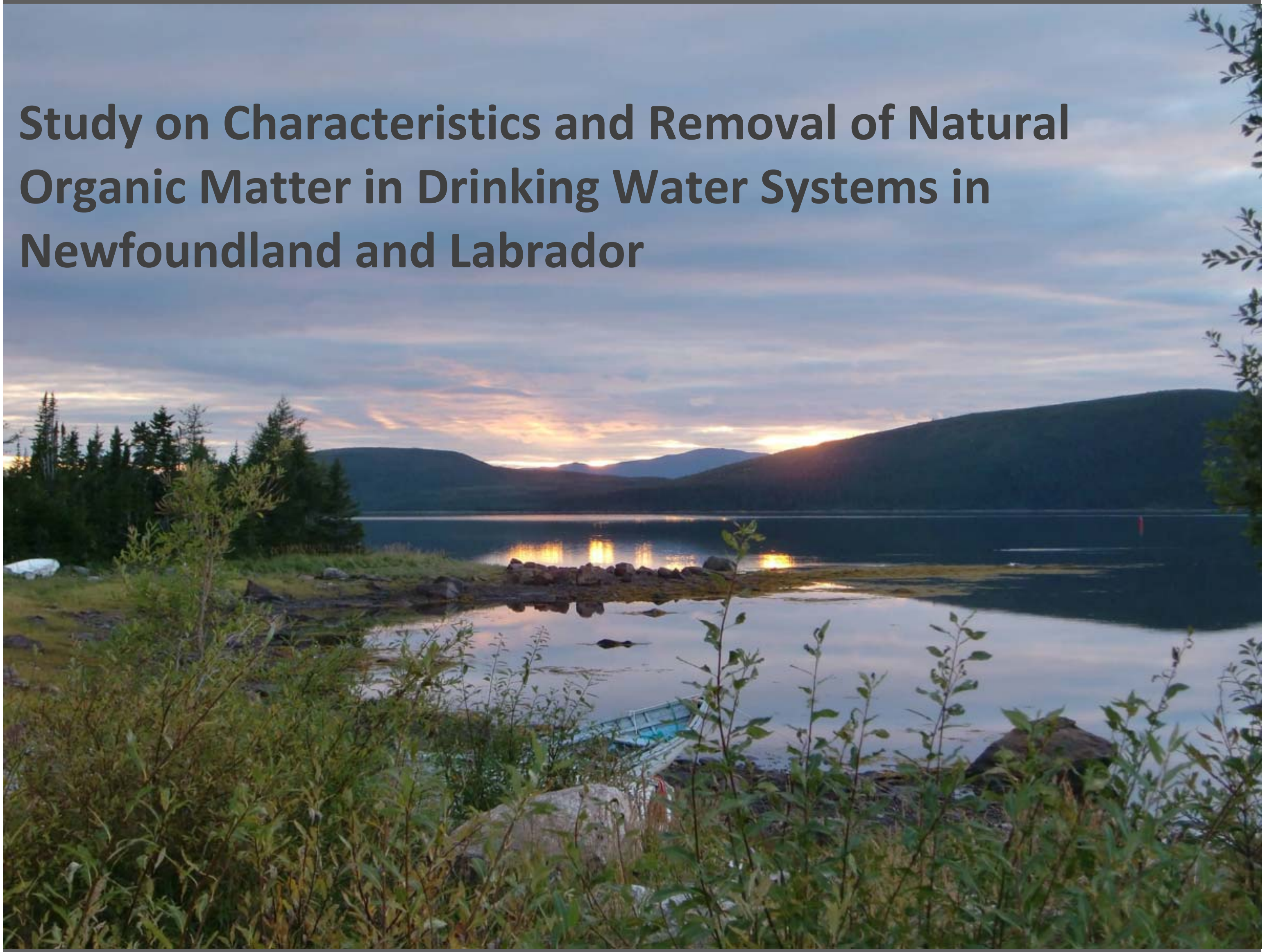
Study on Characteristics and Removal of Natural Organic Matter in Drinking Water Systems in Newfoundland and Labrador



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Water Management Division

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EXECUTIVE SUMMARY

Background

Natural Organic Matter

Natural organic matter, or NOM, refers to a group of carbon-based compounds that are found in surface water and some groundwater supplies. They are the product of various decomposition and metabolic reactions in the water supply and its surrounding watershed. Common NOM compounds include proteins, polysaccharides, and humic substances. Though NOM does not pose a risk to human health on its own, some NOM compounds are known to react with chlorine and chloramines to produce disinfection by-products (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAA) that are thought to be carcinogenic and/or genotoxic.

Some NOM occurs as particulate matter or is adsorbed to particulate, but in most water supplies in Atlantic Canada the majority of NOM exists as dissolved compounds and is often measured as dissolved organic carbon (DOC). It is commonly accepted that some NOM compounds, notably those with light-absorbing chemical structures such as aromatic rings, are the most likely to react to form DBPs. These structures are known to absorb UV light at specific wavelengths, including 254 nm. Therefore, it is also common to quantify NOM by measuring the amount of UV light it absorbs (UV254). UV254 can be normalized to DOC to yield a specific UV absorbance (SUVA) value, which can be used to predict the aromaticity and treatability of the NOM being measured. True and apparent colour are also used as rough estimates of NOM content.

NOM can be further characterized by separating it into different fractions that are characterized by their acidity and hydrophobicity using resin fractionation. These include hydrophobic acids (HOA), hydrophilic acids (HIAs), hydrophobic bases (HOBs), hydrophilic bases (HIBs), hydrophobic neutrals (HONs), and hydrophilic neutrals (HINs). The molecular weight (MW) of the different NOM fractions can be determined using high pressure size exclusion chromatography (HPSEC) or a series of membranes with specific MW cut-offs. The former was used in this study.

The quantity and reactivity of NOM in a water sample is determined by the characteristics of the water supply and its watershed. For example, smaller water bodies have been observed to have higher NOM content than larger ones, and moving water bodies (rivers, etc.) have been observed to have more variable NOM content than more stagnant ones. Wetlands, coniferous forests, and heather in the watershed have all been identified as being correlated with elevated NOM levels. Human activities that impact the drainage pattern and land cover of the watershed (i.e., forestry, development, etc.) have also been shown to increase the amount of NOM in some water supplies.

NOM levels are known to vary seasonally with changes in temperature and precipitation. In Atlantic Canada, NOM levels usually peak in the summer and fall. Long term increasing trends in NOM levels have been observed in parts of the northern hemisphere, including some water bodies in Newfoundland and Labrador. This may be as a result of climate change, human activities, or changes in rain water quality.

Treatment Considerations

Many common and emerging water treatment processes can be used to remove NOM. These include coagulation-based systems such as conventional treatment, dissolved air flotation, direct filtration, and various proprietary packaged systems. Oxidation-based systems (ozone and filtration, ozone and biological filtration, advanced oxidation processes) membrane-based systems (low pressure membranes proceeded by coagulation, high pressure membranes working through size exclusion), and adsorption-based systems (activated carbon, resins) have also been used to remove or reduce the reactivity of NOM.

It must be emphasized that the effectiveness and cost of any treatment system are highly dependent on the water demand exerted by the community and the quality of the raw water. The presence of inorganic parameters can also complicate the design and operation of an organic treatment process significantly, resulting in increased capital and ongoing costs.

Project costs can be influenced by site conditions. For example:

- Where is the community located?
- How far is the site from the raw water source?
- Does an intake have to be built?
- Are intake pumps required?
- Does a transmission main have to be installed?
- Does a building have to be constructed?
- Is there sufficient land owned by the municipality to accommodate the plant?
- What improvements must be made to the site before construction?
- Is a packaged system available or will the process need to be designed from the ground up?
- Who will build the plant?
- Who will operate the plant?
- How will residuals be disposed of?
- What kind of monitoring plan is required?
- What are the current and projected costs for media/coagulant/chlorine/power?

These and other questions often drive the decision making process during the pre-design, detailed design, and construction phases of a project and will dictate which NOM removal process is most appropriate for a given community.

Methodology

Water samples were collected from six water supplies and two water treatment plants in the province of Newfoundland and Labrador. These were analyzed for TOC, DOC, UV254, and colour and the NOM they contained was fractionated using resins into HOAs, HIAs, HOBs, HIBs, HONs, and HINs. The molecular weights of the NOM compounds in the bulk and fractionated samples were determined using HPSEC.

Additional investigations were conducted on water quality records provided by the Department of Environment and Conservation (ENVC).

Results

Province-wide Water Quality Trends

Many communities in Newfoundland and Labrador rely on small surface water supplies for drinking water. Most of the surface water in the province is high in DOC, colour, and UV254 and few of the smaller communities have water treatment processes designed to remove NOM. Most use chlorine for disinfection. The combination of these factors can lead to high levels of THMs and HAAs in the water distributed to customers.

The low transmittance and high chlorine demand of much of the surface water in the province makes it difficult to change disinfection practices, particularly in small communities, without compromising human health. Water treatment for NOM removal in the water would minimize THM and HAA formation by reducing the amount of NOM available to react with chlorine and by making it easier to achieve compliance with the province's disinfection requirements without adding large amounts of chlorine.

Water Treatment Systems in Newfoundland and Labrador

In general, the coagulation-based treatment systems in the province have been successful at reducing the formation of THMs and HAAs, though some communities are still experiencing DBP levels above those recommended by the province. All have been maintaining colour under 10 TCU. NOM breakthrough has been observed at some of the plants, which may indicate design or operations-based problems with the treatment system. Further investigation is required to confirm the cause of the poor NOM removal.

The ozone-based systems have been less successful overall, though both have managed to drive average THMs below the province's guideline value of 100 µg/L. The one nanofiltration system achieved excellent organic removal when it was operational. Finally, the systems that rely on thread or microfiltration have not experienced any improvement in THMs or HAAs.

In some communities DBP levels increased after the construction and commissioning of the WTP. This might reflect the changes made to the disinfection systems in these WTPs to improve pathogen inactivation (i.e., increased chlorine). Detailed tables listing the DOC, colour, THMs, and HAA5 measured in the tap water of each community are provided in Appendix F.

Surface Water Supply Characteristics in Participating Communities

The characteristics of a water body and the watershed that surrounds it are known to influence the quantity and distribution of NOM found in a surface water supply. The type of water supply does not, however, appear to be have been related to the distribution of NOM fractions or MWs in the water samples analyzed in this study.

Watershed Characteristics in Participating Communities

The watersheds of the six water supplies evaluated in this study are very similar to one another. All contain wetlands and most contain forests and/or barrens. Soil and vegetation types are similar. Watersheds with coniferous forests, heaths, and wetlands were no more likely to have high levels of DOC or colour in their water supplies.

A comparison of the NOM fractions found in these water supplies sheds a bit more light on the influence of the watershed on water quality. Only one of the water supplies is located in Labrador (Community B). Unlike the others, it is characterized by stunted forests and palsa bogs. The NOM in the sample collected from the water supply is particularly acidic and contains a disproportionate amount of HIAs compared to the rest of the samples. These are usually smaller and more easily degraded than HOAs and may reflect the types of vegetation in the surrounding area or a long retention time in the pond.

All of the watersheds receive large amounts of precipitation and, for the most part, experience similar temperature ranges throughout the year, so these factors are unlikely to be responsible for the differences in NOM quantity and characteristics measured in water samples from each water supply. The one exception is Community B, which is located in Labrador and has colder temperatures. This may (or may not) influence the distribution of NOM fractions in its water supply.

The type and amount of human activity in the watershed does not appear to be connected to the type of NOM present in each water supply. The one possible exception is Community E, which is known to suffer from variable water quality in part because of the impact of the seasonal water demand from a nearby tourism hub. It was not possible to link this empirical observation to any of the data obtained in this study.

The characteristics of each watershed have undoubtedly impacted the quantity and characteristics of the NOM in each of the six participating water supplies; however, it is difficult to tease out which factor dominates in each case. In order to truly assess their impact(s) in individual watersheds it would be necessary to compare NOM levels before and after changes have taken place.

Tap Water Quality Records and Disinfection Practices in Participating Communities

All six participating communities have had difficulties maintaining TTHM and HAA5 levels below the provincial recommended values of 100 µg/L and 80 µg/L, respectively. The treatment plants in Community C and Community D have both successfully reduced the average TTHM and HAA5 results, but both continue to record exceedances. Community A has the lowest TTHM and HAA5 values, which is likely due to the low DOC, colour, and UV254 measured in their water supply and tap water. Large variations between the average and maximum values in the three remaining communities likely reflect seasonal changes in NOM levels, chlorine dosing adjustments, and changing water demands (i.e., retention time) in the community.

The characteristics of the disinfection systems in the participating communities and recommendations for DBP control are discussed in greater detail in Section 5.2 of this report. Though some reduction in DBP formation might be achieved by minimizing the amount of chlorine added for disinfection, the high chlorine demand exerted by the NOM and other parameters makes it difficult for many of the operators to maintain a free chlorine residual at the ends of the distribution system. Minimization of this chlorine demand, whether it is related to NOM/metals in the raw water or the piping in the distribution system, should be a priority to reduce the formation of DBPs in these communities.

Laboratory Results – Raw Water

The results of the bulk water, resin fractionation, and HPSEC analyses show that the NOM matrix in each of the six communities reacted differently upon chlorination. Though the samples from communities with high DOC, colour, UV254, and SUVA were frequently found to have higher THMfp and HAAfp, this did not always hold true in all of the samples.

The majority of the absolute THMfp and HAAfp in most communities was associated with the HOA fraction, though in some communities the HON and HIA fractions also contributed. When THMfp and HAAfp were divided by DOC (‘normalized’ to DOC) results suggest that the remaining fractions were also DBP precursors. As they were not as well represented in the matrix they had less of an effect on the overall absolute THMfp and HAAfp.

Hydrophobic compounds in general were found to be more likely to react with chlorine to form THMs and HAAs in most of the communities, though there were some exceptions. The normalized DBPfps of the hydrophilic fractions were often higher than their absolute DBPfps. Acidic compounds (including HOAs and HIAs) were more likely to form DBPs in most of the communities, however, neutral fractions also contributed in many of the water samples. Though little DBP-specific information was gleaned from the HPSEC results, it was noted that all of the water samples contained large molecular weight HOAs, which have been found by other researchers (Section 2.1.4.2) to be important DBP precursors.

Overall, it was established that the effects of chlorination on the water samples collected in the study was very source specific. Though the overall trends suggest that HOAs are the main contributors to THMfp and HAAfp, this was not the case in every community. Also, though hydrophobicity, which is often associated with aromaticity and can thus be measured using UV254 or SUVA, is frequently associated with THMfp and HAAfp, this was not true of all of the water samples. This suggests that some DBP mitigation strategies might not be appropriate in every case and that care should be taken when generalizing the results of this and similar studies to water supplies in other communities in Newfoundland and Labrador.

Laboratory Results – Coagulation-based WTP (Community C) and Ozone and Filtration (Community D)

Raw and treated water samples were collected from the WTPs in two of the communities that participated in the study. One employs a proprietary packaged coagulation-based treatment system for

NOM removal while the other relies on ozone and filtration for colour and DBPfp reduction. The TOC, DOC, true and apparent colour, UV254, THMfp, and HAAfp of the bulk water samples were measured and the NOM in the samples was separated into six fractions using resin fractionation. The DOC, THMfp, and HAAfp of each fraction were also measured. Finally, the MW of the NOM in the bulk water and of each individual NOM fraction was measured using HPSEC.

TOC, DOC, UV254, colour, and SUVA were lower in both treated water samples than in the raw water samples from each community. The coagulation-based treatment system removed more DOC than the ozone and filtration system but both were able to reduce UV254, colour, and SUVA by over 50%. THMfp and HAAfp were also reduced by both treatment systems. The ozone and filtration system was particularly effective at reducing both HAAfp and HAA reactivity (HAAfp/DOC).

The results show that the coagulation-based treatment process preferentially removed the large MW hydrophobic acids that are widely assumed to be the most important DBP precursors. This follows trends observed by numerous other researchers. Despite this, the treated water still had substantial THMfp and HAAfp. These were mostly linked to the HIN fraction, which was poorly removed by the WTP and moderately reactive towards chlorine.

Treatment with ozone and filtration appears to have reduced the overall MW of the NOM present in the raw water and converted the highly reactive HOA fraction into less reactive fractions (HIAs, HIBs, and HOBs). This resulted in reduced THMfp and HAAfp. These results are similar to established trends.

Despite the close alignment between the results of this study and similar published studies, the results in this section are source specific and should not be generalized to other water sources or WTPs in Newfoundland and Labrador.

Application of Findings

General Impacts on Design and Operation of Water Treatment Facilities

Despite its cost, NOM fractionation can provide system designers and operators with a wealth of useful information. For example, water from supplies characterized by high levels of HOAs is more readily treated using coagulation-based processes. These systems may also benefit from online UV254 monitoring, which would allow operators to adjust the process to adapt to changing NOM levels in the water supply.

Communities where THMs and/or HAAs regularly exceed recommended limits but whose water supplies are characterized by low SUVA and/or UV254 readings will benefit more from less selective treatment processes such as high pressure membrane filtration, which works by size exclusion, or processes that remove hydrophilic and/or small MW NOM compounds (i.e., HIAs, HIBs, etc.) such as ozone with biological filtration or some resin-based systems.

Organic Water Quality Indicators

Given the expense associated with NOM fractionation, designers and operators usually have to rely on indicator parameters that can be related back to specific NOM fractions, in particular the HOA fraction. Linear regressions performed on data provided by the ENVC did not find strong significant relationships between DOC or UV254 and THMs or HAAs. Data obtained under more controlled conditions in the laboratory indicated significant relationships between:

- DOC and UV254;
- DOC and THMfp;
- DOC and HAAfp;
- UV254 and THMfp;
- UV254 and HAAfp;
- UV254 and DOC of HOA fraction;
- SUVA and DOC of HOA fraction;
- UV254 and THMfp of HOA fraction;
- UV254 and HAAfp of HOA fraction;
- UV254 and % THMfp associated with HOA fraction; and
- SUVA and % THMfp associated with HOA fraction.

Most of these had r^2 values between 0.50 and 0.75, indicating moderate strength relationships. The only exceptions were DOC vs. UV254 and UV254 and the THMfp of the HOA fraction, which both had r^2 slightly above 0.9. A larger dataset would be required to develop reliable predictive equations for the province.

Considerations for Existing Guidelines, Piloting Requirements, and Pre-design Requirements

A decision-making framework has been developed for the selection of an appropriate NOM removal process in communities in Newfoundland with organic DBP exceedances. This framework includes four potential steps:

- Review of existing water quality records;
- Raw water characterization study;
- Bench scale testing; and
- Pilot testing.

This framework could be used as the backbone of a pre-design study as defined in the province's design guidelines or adapted for use in the proposed generic terms of reference being developed by the Department of Municipal Affairs (DMA). It may be possible to omit one or two of the three last steps in some communities, though this is not recommended unless reliable long-term and seasonal DOC, UV254, THMfp, HAAfp, and treatability data is available for the community's water supply and/or a very similar one.

LIST OF ACRONYMS

BDCM	Dibromochloromethane
CT	Measure of disinfection effectiveness
DALY	Disability adjusted life years
DBP	Disinfection by-product
DCAA	Dichloroacetic acid
DAF	Dissolved air flotation
DOC	Dissolved organic carbon
EBCT	Empty bed contact time
GAC	Granular activated carbon
GC	Gas chromatograph
HAA	Haloacetic acid
HAA5	Sum of MCAA, DCAA, TCAA, bromoacetic acid and dibromoacetic acid
HI	Hydrophilic
HIA	Hydrophilic acid
HIB	Hydrophilic base
HIN	Hydrophilic neutral
HPSEC	High pressure size exclusion chromatography
HO	Hydrophobic
HOA	Hydrophobic acid
HOB	Hydrophobic base
HON	Hydrophobic neutral
MCAA	Monochloroacetic acid
MF	Microfiltration
MIEX	Magnetic ion exchange

MTBE	Methyl tert-butyl ether
MW	Molecular weight
NF	Nanofiltration
NOM	Natural organic matter
PAC	Powdered activated carbon
PWDU	Potable water dispensing unit
RO	Reverse osmosis
SUVA	Specific UV absorbance at 254 nm
TCAA	Trichloroacetic acid
TDS	Total dissolved solids
THAA	Total haloacetic acids
THM	Trihalomethane
TTHM	Total trihalomethanes
TOC	Total organic carbon
UF	Ultrafiltration
UV254	Ultraviolet absorbance at 254 nm
UVA	Ultraviolet absorbance
UVT	Ultraviolet transmittance
WTP	Water treatment plant

CHAPTER 1 INTRODUCTION

1.1 Project Background

Surface water sources in Newfoundland and Labrador are generally characterized by low pH, low alkalinities and high concentrations of natural organic matter (NOM). Very few communities in the province are equipped with water treatment equipment optimized for NOM removal. Consequently, what NOM exists in the raw water can interact with chlorine used for disinfection to form disinfection by-products (DBPs) including trihalomethanes (THMs) and haloacetic acids (HAAs). Elevated NOM levels can also compromise the effectiveness of UV disinfection systems by absorbing the UV light that would otherwise be able to inactivate pathogens.

Some NOM species are more likely to react with chlorine to form DBPs and/or absorb significant amounts of UV light. NOM is naturally heterogeneous, with molecular weights ranging from less than 100 to over 10,000 Daltons. As a result, it is generally categorized based on reactivity.

In 2010, the Water Resources Management Division of the Department of Environment and Conservation (ENVC) of Newfoundland and Labrador initiated a study to investigate how watershed characteristics, treatment system type and design and disinfection practices can influence the distribution of NOM fractions in raw and treated water. The impact of NOM size and reactivity on the formation of DBPs was also to be investigated. Six representative communities were designated to participate in the study. The selected communities are located throughout the province and include a variety of source water types, watershed characteristics, and water treatment strategies.

1.2 Objectives

This project addressed one of the most intractable problems faced by small rural communities in Newfoundland and Labrador – the effective characterization and removal of DBP precursors.

The original request for proposals listed the following project objectives:

- Characterize NOM in the source water of six representative public drinking water systems in the province;
- Identify common watershed characteristics that might influence the type and total amount of NOM and, consequently, the formation of DBPs;
- Determine which DOC fraction has the highest DBP formation potential (THMs and HAAs);

- Evaluate the efficiency of DOC removal at existing water treatment plants in the province;
- Uncover statistical predictive relationships and correlations between colour, DOC, TOC, UV254, THMs, HAAs, and SUVA based on existing data collected by the ENVC;
- Elucidate seasonal and long term NOM trends in surface water sources in the province; and
- Review the Guidelines for the Design, Construction, and Operation of Water and Sewerage Systems and make recommendations for improvements to the sections relating to the optimization of treatment systems for NOM removal.

Further discussion between CBCL Limited and the technical committee yielded the following additional objectives:

- Characterize the distribution of NOM in the treated water from two water treatment plants;
- Determine the effects (if any) of intake location on the level of DBP precursors in the influent raw water;
- Identify surrogate parameters for the quantification of DBP precursors; and
- Describe the design, operation, and NOM removal efficiency of common water treatment processes, including conventional treatment, oxidation (ozone and filtration), membrane filtration, granular activated carbon, and ion exchange.

1.3 Report Organization

An in-depth review of current scientific literature on the subjects of NOM, DBP formation, and the optimization of treatment systems for NOM/DBP precursor removal is provided in Chapter 2. Chapter 3 describes the project methodology. Chapters 4, 5, and 6 describe the results of the desktop and lab portions of the study with respect to source water quality, DBP formation, and the effectiveness of various water treatment processes. An analysis of the project findings is provided in Chapter 7. Chapter 8 presents the conclusions of the study and recommendations for future study. Additional information and water quality data is provided in the appendices.

CHAPTER 2 BACKGROUND

2.1 Natural Organic Matter

2.1.1 Introduction

The term natural organic matter, or NOM, refers to a wide spectrum of chemical compounds that result from natural processes in the environment, including the decomposition of organic matter and algal metabolic reactions. Proteins, amino acids, polysaccharides, and humic and fulvic acids are all examples of NOM. All of these compounds share some common characteristics, but vary widely in size and reactivity. The heterogeneous nature of NOM makes it difficult to quantify and characterize.

The concentration and reactivity of the NOM present in any given water source can be influenced by the characteristics of the watershed, seasonal changes in temperature and precipitation, long term climatic changes, and human and animal activities. In particular, surface water in areas where wetlands make up a large percentage of the groundcover tends to have high concentrations of coloured aromatic NOM.

The water treatment industry has taken a keen interest in the characterization and removal of NOM because it is associated with the formation of disinfection by-products (DBPs). Trihalomethanes (THMs) and haloacetic acids (HAAs) can be formed when certain NOM species react with chlorine or chloramines. Many of the compounds that fall into these categories are suspected carcinogens and/or teratogens. The Canadian Drinking Water Quality Guidelines (CDWQG) recommend specific limits on many DBPs, including total THMs and HAAs.

Some drinking water treatment processes can be optimized to remove NOM before it has the chance to react with chlorine to form DBPs. Coagulation-based processes, including conventional treatment, direct filtration, and dissolved air flotation, use metal salts to induce NOM molecules to agglomerate so that they can be removed using clarification or filtration. Oxidation processes such as ozonation transform NOM into smaller and/or less reactive species that are less likely to form DBPs. High pressure membrane filtration processes can remove NOM molecules through size exclusion. Finally, adsorption processes that employ activated carbon or various resins can also be used to remove some types of NOM before disinfection.

Though DBP formation is the most commonly discussed and researched NOM-related topic in the water treatment industry, NOM can also interfere with the operation and/or effectiveness of many water treatment and disinfection processes including membrane filtration (low and high pressure), ion exchange, and UV disinfection.

For example, fouling negatively impacts the performance of membrane filtration units by restricting the passage of water through the system. Ion exchange units designed to remove inorganic species (arsenic, uranium, etc.) can also be fouled by NOM, which can compete with the target parameter for exchange sites.

UV disinfection works by irradiating pathogens with enough UV light to interfere with their ability to reproduce and thus essentially 'inactivate' them. This is only effective when the pathogens are exposed to a large amount of radiation. The total amount of radiation provided by a UV disinfection unit is dependent on the strength of the bulbs that it contains. This is usually referred to as the 'dose' with units of mJ/cm^2. For example, a dose of 11 mJ/cm^2 is required to achieve 3-log inactivation of *Giardia* cysts. The amount of the radiation that reaches a pathogen is also affected by the presence of parameters that block or absorb UV light. Particles (measured as turbidity) tend to block UV light while light absorbing chemical structures (chromophores) present in some NOM species can absorb UV light. The amount of light that passes through a water sample is referred to as the 'transmittance'. Most manufacturers only assure disinfection at transmittance levels above 70% (many units require a transmittance of 75%) and a specified flow rate. Water with high levels of turbidity and/or NOM rarely meets these criteria.

2.1.2 Measurement and Characterization

The total concentration of NOM is usually measured as total organic carbon (TOC) or dissolved organic carbon (DOC). The species most likely to react with chlorine to form DBPs are thought to be those that absorb visible and/or UV light at certain wavelengths. Colour and UV absorption (UVA) are therefore thought to indicate the reactivity of the NOM within a given water sample. A summary of these parameters and the analytical methods used to measure them is provided in Table 2.1.

Table 2.1 Common organic parameters

	Total Organic Carbon	Dissolved Organic Carbon	Colour	UV Absorption
	mg/L	mg/L	True Colour Units (TCU)	cm^{-1}
Analytical Method	Catalytically aided combustion oxidation non-dispersive infrared detector	Catalytically aided combustion oxidation non-dispersive infrared detector	Colorimeter	UV spectrophotometer
Filter Required	None	0.45 µm	0.45 µm	0.45 µm
Species or Structure Detected	All organic carbon compounds	All dissolved and/or colloidal organic compounds	Coloured compounds	UV light absorbing chemical structures (ex. double bonds)
Interferences			Iron, manganese, copper, turbidity	Turbidity

Specific UVA, which is calculated by normalizing UV254 by DOC (Equation 2.1), has been suggested as a possible alternative to DOC or UVA for the detection of DBP precursors.

$$\text{SUVA} = \frac{\text{UV254}}{\text{DOC}} \qquad \text{Equation 2.1}$$

It can also be a useful predictor of whether a given sample of NOM would be removed through coagulation. Given that coagulation is known to be effective for the removal of DBP precursors, it seems intuitive that SUVA could be used to predict DBPfp. The evidence for this is split; some researchers have found significant relationships between SUVA and THMfp and HAAfp (Kitis et al., 2002) while others have not (Garvey and Tobiason, 2003).

The *Guidelines for Canadian Drinking Water Quality* (GCDWQ) does not recommend specific TOC, DOC, UV254, or SUVA levels for drinking water. They do, however, suggest an aesthetic objective of 15 TCU for colour. Colour can negatively impact users' perception of water safety and quality and their confidence in their municipal water system. This can result in users' turning to bottled water or unprotected raw water sources to fulfil their potable water needs. Note that in practice, most users can detect as little as 5 TCU of colour in water so utilities should aim to reduce it as low as is feasible.

NOM can also be categorized based on biodegradability. NOM compounds that can be metabolized by bacteria are referred do as biodegradable organic carbon (BDOC) or assimilable organic carbon (AOC). BDOC is quantified by comparing the DOC of the raw water to that remaining in a vial inoculated with authochthonous bacteria. AOC is measured by growing bacteria in an environment where organic carbon is the limiting nutrient. The amount of bacterial growth that occurs under this condition can be related back to the amount of useable (assimilable) carbon available.

Utilities generally aim to reduce BDOC as much as possible because its presence in the treated water can result in increased bacterial re-growth in the distribution system. The formation of BDOC and AOC is desirable in ozone treatment systems, however, as this makes NOM easier to remove using biological filters.

These straightforward analysis methods are useful indicators of overall water quality but do not differentiate between NOM compounds with different sizes and compositions. Certain categories of compounds tend to behave similarly, however, so instead of separating individual species, researchers often divide NOM into various fractions based on their reactivity. For example, proteins and amino acids are bases, which can be hydrophilic or hydrophobic depending on their makeup. NOM fractions in water can be separated from one another using a technique known as resin fractionation. In this process, each sample is passed through a series of different resins, each of which adsorbs one specific NOM fraction at a given pH.

A list of common NOM fractions and their associated molecular weights is provided in Table 2.2.

Table 2.2 Summary of NOM fractions (adapted from Imai et al., 2001)

Fraction	Abbreviation	Example	Molecular Weight Range
Hydrophobic Neutral	HON	Hydrocarbons	100 to 70,000 D
Hydrophobic Base	HOB	Proteins, Amino Acids	250 to 850 D
Hydrophobic Acid	HOA	Humic and Fulvic Acids	450 to 1,000 D
Hydrophilic Neutral	HIN	Polysaccharides	120 to 900 D
Hydrophilic Base	HIB	Proteins, Amino Acids	100 to 1,000 D
Hydrophilic Acid	HIA	Fatty Acids	250 to 850 D

The molecular weights (MWs) of various NOM species can be determined using UF membranes with specific MW cut-offs or using high pressure size exclusion chromatography (HPSEC). The latter is often used in conjunction with resin fractionation to determine the range of molecular weights found in the different NOM fractions.

The analytical methods touched upon in this section are discussed in greater detail in Chapter 3 – Project Methodology.

2.2 NOM in the Natural Environment

2.2.1 Types and Sources of NOM

NOM is ubiquitous in surface water. Lakes, ponds, rivers, and streams all receive inputs of NOM from their surrounding watersheds and from the metabolic activities of the microorganisms they contain. The NOM that enters from outside the water supply is referred to as allochthonous while that which is created within it referred to as autochthonous. The proportion of each type of input varies from source to source.

The total amount of allochthonous NOM present in a water supply is difficult to control but can sometimes be minimized through watershed management. For example, soil erosion can result in increased allochthonous NOM transport into the water supply. By limiting human activities that contribute to soil erosion in the watershed NOM transport can be mitigated to some degree.

Algae contribute to the total amount of autochthonous NOM in a water supply both through their metabolic reactions and their eventual demise and decay. Thus the loading of autochonous NOM in a water supply can to some degree be controlled by minimizing algal growth. Algae thrive in water supplies with high concentrations of nutrients such as nitrogen and phosphorus. The most common sources of these compounds are human, industrial, and agricultural wastes. Nutrient levels can be minimized by limiting the influx of these waste streams into the water supply through watershed protection and wastewater treatment.

Some researchers have suggested that allochthonous NOM is more aromatic than authochthonous NOM (Zumstein and Buffle, 1989). Croué et al. (2000) found that samples from a water source dominated by allochthonous NOM were highly aromatic and hydrophobic while that from a source with mixed allochthonous and autochthonous NOM contained a higher proportion of hydrophilic compounds, Aromaticity, often quantified by UV254 or SUVA, is generally associated with the hydrophobic acid fraction of NOM. Water sources with high concentrations of allochthonous NOM would thus be expected to have larger concentrations of aromatic hydrophobic acids, as measured by the DOC of the HOA fraction and/or the UV254 and SUVA of the bulk water. Though this has been suggested by the results of a few studies, other researchers have pointed out that other factors including the effects of long-term exposure to sunlight, biodegradation, and natural filtration, may result in erroneous correlations between parameters (Imai et al., 2001).

2.2.2 Characteristics of the Water Supply

The total amount of NOM present in a given water source is a function of its overall water quality, size, and the characteristics of its watershed. NOM tends to degrade through photochemical and biochemical reactions over time so water supplies with larger surface areas are less likely to have high concentrations of NOM (Rasmussen et al., 1989). The NOM they contain is also more likely to be diluted by precipitation. Rivers and streams can have more variable NOM levels than ponds and lakes because of their changeable flow patterns.

Some communities in Newfoundland and Labrador have created raw water reservoirs by flooding low-lying areas. If plant material (biomass) is not adequately removed before the area is flooded it oftentimes results in high levels of NOM in the reservoir water. The watershed surrounding the reservoir can also contribute to NOM loading and should be carefully assessed before flooding.

Garvey and Tobiason (2003) found that the relationships between common organic parameters that many researchers take for granted are not valid in all water sources. Their study compared the water quality results from two water sources gathered over a two year period. They found that though significant positive relationships existed between UVA and DOC, TOC and THMfp, and UVA and THMfp in one water source, they were absent in another source. These results suggest that the relationships between organic parameters vary by water source. In this particular case, the researchers suggested that the differences might be due to different proportions of allochthonous vs. autochthonous NOM in the two sources. Specifically, the significant relationships between the various organic parameters were only observed in the water source that was assumed to have a higher ratio of allochthonous to autochthonous NOM.

Some researchers have used resin fractionation to more effectively characterize the NOM compounds found in different surface water supplies. For example, Imai et al. (2001) analyzed the NOM fractions found in four rivers and one large lake in Japan. DOC was higher in the lake water than in the river water. Both types of water were found to contain mostly humic substances (hydrophobic acids) and hydrophilic acids, with smaller amounts of hydrophobic and hydrophilic neutral and basic species. The ratio of HOAs to HIAs was lower in the lake water than in the river water. The researchers attempted to link this ratio and that between DOC and UV254 to the source of the NOM within the watersheds with limited results. Bourbonniere (1989) fractionated the NOM from six water supplies in eastern Canada and found that the HOA fraction generally dominated by weight.

2.2.3 Characteristics of the Watershed

Allochthonous NOM enters surface water through multiple pathways including leaching from soils and algal activity (Krasner et al., 1996). Thus, the characteristics of the watershed, including vegetation, soils, topography, and land use, can affect the amount and reactivity of NOM in a given water supply.

Peat bogs in particular have been shown to contribute large amounts of organic matter to surface water (Urban et al., 1989). Eckhardt and Moore (1990) drew a positive relationship between the percent wetland in a watershed and the resulting concentration of DOC in surface water. They noted, however, that regional differences in the relationship between percent wetland and the concentration of DOC were apparent in the dataset. Wetland composition (fen vs. bog vs. swamp), water quality (pH, hardness, etc.), and land use patterns were offered as possible explanations for this observation.

Engstrom (1987) conducted a survey of various surface water sources in Labrador and found that the types of vegetation and soils present in the watershed influenced the apparent colour measured in the lake. He found that the colour of the water lakes in watersheds characterized by peatland or boreal forest was elevated compared to those in watersheds characterized by tundra or spruce woodlands. Cronan and Aiken (1985) suggested that coniferous forests were more likely than deciduous forests to contribute humic substances to surface water. Armstrong et al. (2010) reported that the presence of heather increased NOM levels in surface water.

2.2.4 Seasonal Trends

The total quantity and chemical characteristics of NOM vary seasonally in many water supplies. Heavy precipitation, snowmelt, and algal blooms are seasonal events that can increase the total amount of NOM in a water source. Usually, measurements of all organic parameters are higher in the summer and fall than in the winter and spring, though this is not always the case. For example, Garvey and Tobiason (2003) found that NOM levels increased in the summer and fall in both a river water supply and a lake water supply, though the trend was less pronounced in the lake. A study by Imai et al. (2001) found that the concentration of DOC in a large lake was highest in the fall whereas that in the rivers feeding into it peaked in the late spring.

Seasonal changes can also impact the relative distribution of NOM fractions in water source, though this is not always the case. For example, Owen et al. (1993) observed that though the absolute concentration of NOM varied from season to season, the relative proportions of hydrophilic vs. hydrophobic compounds and large and small MW compounds was constant in all but two of the water sources being investigated. Large reservoir systems were the most stable. The two outliers were a river source and a high DOC groundwater source. Other researchers have observed significant seasonal changes in the relative proportions of hydrophilic vs. hydrophobic NOM (Croué et al., 2000) or the MW distribution, which may be reflected in changes in treatability. It has also been noted that variations between water supplies can be greater than the seasonal changes within each supply (Bourbonniere, 1989).

Sohn et al. (2007) found that the total amount of DOC and UV254 removed in a treatment process consisting of coagulation, sand filtration, ozone, and biological activated carbon changed over the course of one year (experiments were conducted in March, April, July, and September). Owen et al. (1993) also noted this trend and recommended averaging the results from different seasons in order to detect differences between surface water sources. A similar study by Brinkman and Hozalski (2011) found that permeability of a hydrophilic low pressure membrane changed over the course of a year. Decreased permeability was associated with increased UV254 in the raw water.

2.2.5 Long Term Trends

An increasing trend in the NOM content of surface water has been noted by many researchers in Europe and North America. This increase is thought to be related to changing watershed conditions related to human activities and/or climate change. Analysis of data collected through the Canada-Newfoundland Water Quality Monitoring Agreement showed that the colour of the water in 35 rivers and lakes in Newfoundland and Labrador increased between 1986 and 2001. There was no overall trend for DOC, though levels did increase in 14 of the 65 sources investigated (Dawe, 2006).

A wide-ranging evaluation of existing research and water quality records available through the UK Acid Waters Monitoring Network conducted by Evan et al. (2005) confirmed that DOC levels in the lakes being monitored increased over time. They suggested that this could be explained by changes in acid deposition and/or climatic changes, depending on the source being assessed. The former was as a result of the recovery of many ecosystems from the impacts of acid rain whereas the latter could be associated with climate change. The researchers pointed out, however, that the exact mechanisms underlying the observed increases were still very much up for debate. A similar hypothesis was advanced by Clark et al. (2010), who noted that the differences between the various watersheds and lakes being investigated made it difficult to establish whether deposition, climatic changes, or land use patterns were to blame for the increase in DOC.

These and similar studies have used non-parametric statistical methods that corrected for the influence of seasonal changes to establish long term trends.

2.2.6 Human Activity in the Watershed

Various human activities have been linked to increased levels of NOM in surface water supplies; particularly those that lead to increased erosion as this can cause higher NOM loadings throughout the watershed that eventually make their way into the water supply. For example, the drainage of peatlands has been linked to increased concentrations of NOM in surface water (Armstrong et al., 2010). Forest fires and the clearing of land through forestry or for agricultural reasons can increase runoff into surface water supplies. Housing development, tourism and recreation can impact the amount of NOM entering a water supply because of the deforestation and wetlands drainage that can be associated with these activities. Finally, though not usually practiced in Newfoundland and Labrador due to the proximity of the ocean, the release of untreated wastewater or wastewater treatment plant effluent into surface water bodies can increase and change the characteristics of NOM in the water.

Some jurisdictions have attempted to rehabilitate watersheds that have been negatively affected by human activities. One watershed rehabilitation method that has been used successfully in the United Kingdom is peatland drain blocking. Blocks can be made from a variety of materials including plastic, wood, and straw. The blocks are placed in the ditches originally used to drain the peat. A study by Armstrong et al. (2010) found that blocked drainage ditches in peatlands contributed less NOM (DOC and UVA) than unblocked ditches. In Australia, the application of gypsum to soils in the watershed was shown to slow the transport of NOM into water supplies (CRC, 2005). The researchers warned that this improvement in organic water quality may be offset by an increase in manganese levels. Other methods that can be used to reduce the impact of human activities on NOM levels in a water supply include source water protection, reforestation and limiting development.

2.2.7 Intake Considerations

The location of the intake within a lake or river can impact the total concentration of NOM entering a community's water supply system. The first and most important consideration is the choice of water supply. Small ponds, surface water sources surrounded by wetlands, and man-made raw water reservoirs are often characterized by high levels of allochthonous NOM. If possible, these and other potential supplies that are found to have high and/or variable levels of NOM should be avoided. Autochthonous NOM is associated with the activity and decay of algae and macrophytes so conditions favourable to their growth should be avoided (i.e., high nutrient levels, particularly phosphorus).

Once the water source has been chosen, the intake should be installed in such a way as to minimize impacts from point source (i.e., wastewater outfalls) and non-point source (i.e., agricultural runoff, inputs from bogs/peatlands) NOM inputs. The location of the intake can also be influenced by other factors, including NOM levels. To establish an ideal site for the intake, water samples should be taken at various locations within the water source and at different depths. Testing should be conducted over several seasons to ensure that seasonal trends are taken into account.

If NOM concentrations are known to vary seasonally, communities may consider drawing large amounts of water from the water source during periods when NOM levels are low to be used at a later date, as outlined in the ENVC design guidelines (ENVC, 2005).

Temperature stratification and lake turnover can impact the distribution of NOM in the water supply and should be taken into account during the siting of the intake. Lake stratification occurs when the temperature of the water supply begins to vary based on depth as a result of conditions at the surface of the lake and total lake depth. For example, increasing temperatures in the epilimnion (top layer) of the lake over the course of the summer months can result in the growth of algae and macrophytes. Lake turnover, which occurs either once (monomictic) or twice (dimictic) a year in most lakes, redistributes water, nutrients, and organic matter throughout the lake. This can make it difficult to establish a consistently ideal location to install an intake to maximize water quality.

Algae and macrophytes release small MW bioavailable organic compounds as part of their metabolism. As they die they fall into the deeper, colder part of the lake (hypolimnion) where they decompose and add to the NOM loading at the bottom of the lake. The NOM that results from the decay of the organisms themselves is more likely to be more hydrophobic, of larger MW, and less bioavailable than that produced by the algae and macrophytes during their short lives. When the lake turns over in the fall (and often once again in the spring) this NOM is transported to all layers of the lake.

Allochthonous NOM enters the water supply from tributaries and the surrounding watershed. Periods of high run-off are associated with increased levels of allochthonous NOM. The NOM initially enters the epilimnion but subsequently sinks to the bottom of the lake where it joins the NOM created internally through the metabolism and decomposition of algae and other microorganisms.

All of this suggests that NOM can be present at all levels of a surface water supply, though the total concentration at any given level is likely to vary by season and by supply. For example, a study by Bukaveckas et al. (2007) found that samples taken from the hypolimnion had higher THMfp than those taken from the epilimnion. The difference was most pronounced in the fall months. Much of the NOM measured in the reservoir and tributaries under investigation was associated with algal growth and decay. Note that the watershed surrounding the reservoir in question was mostly agricultural (high nutrient export), whereas watersheds in Newfoundland and Labrador are generally characterized by wilderness, recreation, and some industry.

Some of the water quality concerns associated with lake stratification and turnover can be mitigated by installing a multi-level intake. This type of intake allows utilities to draw water from different levels within the water supply at different times of the year based on water quality. Multi-level intakes are more expensive and must be coupled with raw water quality monitoring systems to ensure that operators know when to open a different section of the intake. This would be particularly complex with respect to NOM because of the multiple factors that can affect the distribution of NOM throughout the lake and the difficulties associated with the quantification and characterization of NOM.

Though NOM levels should be considered when siting and designing the intake, other considerations are arguably more important. These include:

- Pathogen levels;
- Water temperature;
- Turbidity;
- Ice formation;
- Nutrients;
- Sediment deposition;
- Changes in water levels;
- Water velocity; and
- Impacts on aquatic organisms.

The design of the intake structure itself should follow the requirements laid out by the federal Department of Fisheries and Oceans.

2.3 Disinfection By-products

2.3.1 Common Disinfection By-products

The NOM compounds commonly present in raw and treated drinking water do not pose a human health risk, however, they are known to react with free chlorine and chloramines to form disinfection by-products (DBPs). These compounds have been linked to the development of various cancers and birth defects. Common DBPs include trihalomethanes (THMs), haloacetic acids (HAAs), and haloacetonitriles (HANs), though there are many others. THMs and HAAs are regulated in many jurisdictions while HANs are considered 'emerging' DBPs and are still being studied to establish the best approach to minimizing their effects on human health. Brominated DBPs are widely considered to be more dangerous than non-brominated DBPs, but they are usually present in smaller concentrations because they only form in the presence of bromide.

2.3.1.1 TRIHALOMETHANES

The presence of trihalomethanes (THMs) in chlorinated drinking water was first reported by Rook et al. (1974). Subsequent research established that THMs caused the development of tumours in animal models (NCI, 1976). As the results of these studies were disseminated, countries around the world began to recommend or require that utilities limit the formation of THMs, usually by optimizing their treatment and disinfection processes.

Four THMs are addressed in the majority of guidelines and regulations; chloroform, bromoform, bromodichloromethane, and chlorodibromomethane. Chloroform generally dominates because the three brominated compounds form only in the presence of naturally occurring bromide (Richardson et al., 2007). A summary of the prevalence, possible health effects, and detection limits of four THMs is provided in Table 2.3.

Table 2.3 Characteristics of common trihalomethanes (adapted from Richardson et al., 2007 and WHO, 2008)

Trihalomethane	Prevalence	Health Effects
Chloroform	High	Carcinogenic
Bromoform	Moderate	Carcinogenic, genotoxic
Bromodichloromethane	Moderate	Carcinogenic, genotoxic
Chlorodibromomethane	Moderate	Carcinogenic, genotoxic

Recent studies have suggested that some of the health effects associated with THMs might be more likely to result from dermal and inhalation exposure (ex. during showering and bathing) than due to the ingestion of drinking water containing DBPs (Leavens et al., 2007).

The formation of THMs can be prevented by treating the water using a process known to remove DBP precursors (i.e., NOM), eliminating pre-chlorination, or switching from free chlorine to an alternative disinfectant. Preformed THMs can also be removed by passing the treated, chlorinated water through a granular activated carbon filter (GAC) (Lykins et al., 1998), though this may not be feasible at full-scale.

The detection limits for the various THM species range from 0.1 to 0.2 µg/L.

2.3.1.2 HALOACETIC ACIDS

Like THMs, haloacetic acids (HAA) are formed through reactions between chlorine and NOM. They can also be formed in disinfection processes employing chloramines or chlorine dioxide. Though nine HAAs are known to occur in drinking water systems, only five are regulated in most jurisdictions. These are mono-, di-, and trichloroacetic acid, bromoacetic acid, and dibromoacetic acid. The five regulated HAAs vary in genotoxicity and carcinogenicity and, as with THMs, most studies have concluded that the brominated HAAs are the most toxic (Richardson, 2007). The prevalence, health effects, and detection limits of the five regulated HAA compounds are provided in Table 2.4.

Table 2.4 Characteristics of common haloacetic acids (adapted from Richardson et al., 2007 and WHO, 2008)

Haloacetic Acid	Prevalence	Health Effects	Detection Limit
Monochloroacetic Acid	Moderate	Genotoxic	2 to 5 µg/L
Dichloroacetic Acid	High	Carcinogenic, genotoxic	1 µg/L
Trichloroacetic Acid	High	Carcinogenic	1 µg/L
Bromoacetic Acid	Moderate	Genotoxic	
Dibromoacetic Acid	High	Carcinogenic, genotoxic	

Levels of HAAs in drinking water can be reduced by removing HAA precursors (i.e., NOM), switching from free chlorine disinfection to an alternative method, minimizing water age, or using biologically active carbon (BAC) filters or granulated active carbon filters (GAC) (Xie and Zhou, 2002).

2.3.1.3 N-NITRODIMETHYLAMINE

N-Nitrosodimethylamine, or NDMA, is an emerging DBP that has been identified as a probable human carcinogen based on its effects in animal models. It is usually found in the distribution systems of utilities that use chloramines for secondary disinfection, although it can also be formed during other water treatment processes including chlorination and anion exchange (WHO, 2008). Aqueous NDMA can also be present in the effluent from sewage treatment plants and various industrial processes. It is estimated that only 10% of total NDMA exposure occurs due to the ingestion of drinking water (Fristachi and Rice, 2007); the rest is from food.

NDMA is formed when organic nitrogen precursors interact with monochloramine, dichloromine, or chlorine in the presence of ammonia (WHO, 2008). Research suggests that NDMA can be destroyed by UV irradiation (WHO, 2008). As with all DBPs, however, the most effective way to minimize human exposure to NDMA is to focus on the reduction of its precursors, namely organic nitrogen compounds and ammonia, in the water being disinfected.

The current detection limit for NDMA ranges from 0.03 to 0.04 ng/L depending on the analytical method used.

2.3.1.4 OTHER DISINFECTION BY-PRODUCTS

Disinfection by-products can be formed by alternative disinfectants such as ozone and chlorine dioxide. The precursors for these DBPs are inorganic. For example, bromate can form when ozone reacts with naturally occurring bromide in the raw water. Some of these inorganic DBPs, including bromate, are regulated in many jurisdictions as discussed in Section 2.4.3.

2.3.2 Quantifying Human Health Risks Related to Disinfection and Disinfection By-products

The debate between the relative impacts of pathogens vs. DBPs on human health is ongoing. Most researchers, policy makers, and regulators have chosen to take a quantitative risk management approach, that is, to statistically compare the overall disease burden associated with each contaminant.

This approach quantifies the amount of risk associated with a particular parameter by estimating the total amount of disability and loss of life attributable to it. This risk is generally communicated as the total disability-adjusted life years per person (DALY/person). The WHO recommends a target of 10-6 DALY/year when developing guidelines/standards for individual water quality parameters (WHO, 2008). A detailed explanation of the quantitative risk assessment method is provided in Quantifying Public Health Risk in the WHO Guidelines for Drinking-Water Quality (WHO, 2003).

The disease burdens associated with disinfection by-products such as THMs, HAAs, and bromate are still being investigated but preliminary assessments suggest that THMs and bromate have health burdens ranging from 1 to 5 DALY/1000 people. A study in the Netherlands conducted by Havelaar et al. (2000) compared the annual impact of *Cryptosporidium* infection with that of renal cancer caused by bromate exposure in a hypothetical drinking water supply using ozone oxidation for pathogen inactivation. They concluded that the net impact of ozone disinfection of *Cryptosporidium* on health would be approximately +0.70 DALYs/mpy (million people per year). This means that the overall health impacts of cancers caused by bromate were found to be less than those resulting from infection with *Cryptosporidium.* Their assessment relied on a number of major assumptions about the number of oocysts present in the source water, the risk of exposure to pathogens, and the incidence of gastrointestinal illness and renal cancer in the population due to *Cryptosporidium* infection and bromate exposure.

The greatest drawback to the use of quantitative risk assessment to compare the risks associated with different water quality parameters are: the lack of appropriate epidemiological data; an overreliance on animal models; and the sheer number of assumptions made during the risk assessment process. If these drawbacks are addressed, future studies will more accurately elucidate the relative risks associated with various human pathogens vs. disinfection by-products.

2.3.3 Regulation of Disinfection By-products

The 2010 version of the Guidelines for Canadian Drinking Water Quality (GCDWQ) recommend a maximum acceptable concentration (MAC) of 100 µg/L for THMs and 80 µg/L for HAAs. Bromate and chlorate have been assigned MACs of 10 µg/L and 1 mg/L, respectively. A MAC of 0.04 µg/L has been proposed for NDMA and is currently under review.

The government of Newfoundland and Labrador has adopted these guideline values as recommendations and is actively investigating ways to help communities in the province comply with the recommended limits. Some other provinces have adopted the GCDWQ, including the DBP MACs, as law.

In the United States, common DBPs such as THMs, HAAs, bromate and chlorite are regulated by the US EPA Stage 1 Disinfectants and Disinfection Byproducts Rule (Stage 1 D/DBPR). Compliance is based on annual running averages (US EPA, 2002). Until recently, the running average was calculated by pooling DBP measurements from throughout the entire distribution system. The new Stage 2 D/DBPR was promulgated in 2005 and requires that utilities measure DBP levels at a number of sites within their distribution systems to establish locational running annual averages (LRAAs) for THMs and HAAs (US EPA, 2005).

The WHO also publishes guideline values for various water quality parameters, including a number of DBPs. In contrast to those in Canada and the United States, the WHO guidelines for THMs and HAAs are broken into individual compounds. Instructions for developing a total THM limit are provided in the guidelines (WHO, 2008). The European Union has chosen to adopt some of the WHO recommendations, but only regulates total THMs and bromate. Strategies for minimizing the formation of other DBPs, but no specific guidelines values are listed (CEU, 1998).

A summary of the DBP recommendations and requirements discussed in this section is provided in Table 2.5.

Table 2.5 Disinfection by-product guidelines and regulations (GCDWQ, 2010; US EPA, 2002; WHO, 2008; CEU 1998)

Disinfection By-product	Guidelines for Canadian Drinking Water Quality	US Environmental Protection Agency Regulations	World Health Organization Guidelines	European Union Standards
	(2010)	(2002)	(2008)	
Total Trihalomethanes	100 µg/L	80 µg/L	none[a]	100 µg/L
Chloroform			*300 µg/L*	
Bromodichloromethane			*60 µg/L*	
Chlorodibromomethane			*100 µg/L*	
Bromoform			*100 µg/L*	
Haloacetic Acids	80 µg/L	60 µg/L	none[b]	none
Monochloroacetic Acid			*20 µg/L*	
Dichloroacetic Acid			*50 µg/L*	
Trichloroacetic Acid			*200 µg/L*	
Monobromoacetic Acid			*none*[c]	
Dibromoacetic Acid			*none*[c]	
Bromochloroacetic Acid			*none*[c]	
Bromate	10 µg/L	10 µg/L	10 µg/L (provisional)	10 µg/L
Chlorite	1000 µg/L	1000 µg/L	700 µg/L (provisional)	none
Nitrosodimethylamine	0.04 µg/L[d] (proposed)	none	0.01 µg/L	none

[a] $\frac{C_{bromoform}}{GV_{bromoform}} + \frac{C_{DBCM}}{GV_{DBCM}} + \frac{C_{BDCM}}{GV_{BDCM}} + \frac{C_{chloroform}}{GV_{chloroform}} \leq 1$ (WHO, 2008)

[b] no total value provided

[c] insufficient information available for guideline derivation

[d] 9 ng/L in Ontario

The variation in recommended and required DBP limits reflects the limited amount of data available on DBP formation and the effects of individual DBPs on human health. Over 600 different DBPs have been identified by researchers, but only a few of these have been studied in great detail. The majority of the DBP studies that have been conducted to date have been limited to animal models whose findings may not translate to significant health effects in humans.

2.4 Predicting Disinfection By-product Formation Potential

The formation of DBPs is impacted by multiple factors including the:

- Concentration of NOM;
- Concentration of chlorine;
- Concentration of bromide;
- pH;
- Temperature; and
- Reaction time.

Most of these are easily measured, but the heterogeneous nature of NOM makes it difficult to predict the amount of DBPs that will be formed during the disinfection process. Some common water parameters, including TOC, DOC, UV254, and SUVA have all been proposed as suitable surrogates for DBP forming NOM. The effects of hydrophobicity, acidity, and molecular weight on DBP formation potential have also been investigated.

2.4.1 Surrogate Parameters

Numerous researchers have attempted to predict the formation of DBPs based on the characteristics of the water being disinfected and the conditions of the disinfection process. Sadiq and Rodriguez (2004) have prepared an extensive review of many of the better known models. Most of these are based on laboratory data and are rarely accurate when applied to full scale systems. Many also fail to take into account seasonal changes in NOM concentrations.

2.4.1.1 TOC AND DOC

TOC represents all of the non-purgeable organic carbon compounds in a water sample. This includes all NOM species. Dissolved (and colloidal) organic carbon species that pass through a 0.45 µm filter are collectively referred to as DOC. Many organic DBP precursors are present in water in dissolved or colloidal form and consequently, can be quantified by measuring DOC.

Some researchers have found reasonably strong correlations between TOC and/or DOC and DBPfp (Chowdhury and Champagne, 2008) while others have found that these relationships are more tenuous (Owen et al., 1993). These differing findings are explained by the fact that the analytical methods used to quantify TOC and DOC are unable to differentiate between NOM species. In some source waters, nearly all of the NOM present will be able to react with chlorine to form DBPs and in such a case, TOC and DOC are good surrogates for DBP precursors. This is not true for water supplies with smaller proportions of reactive NOM species. Of particular concern are source waters where the proportion of reactive to non-reactive NOM changes over the course of the year.

2.4.1.2 UV ABSORBANCE AND SUVA

Many DBP precursor molecules such as humic acids are known to absorb ultraviolet light at specific wavelengths (Owen et al., 1993). Studies by Edzwald et al., (1987), Najm et al. (1994), White et al. (2003) and Chowdhury and Champagne (2008) have shown strong positive relationships ($r^2 > 0.9$) between UV absorbance at 254 nm and THMfp. The results of a study by Krasner et al. (1994) suggest that care should be taken not to assume that this will be the case under all conditions. They found that UV254 and actual THM concentrations were not strongly correlated in treated water samples. They hypothesized that this was due to variations in the disinfection strategies employed by different utilities; noting that the actual measured concentration of THMs in the field often differs from that found in formation potential tests run in the laboratory. Other studies have been less conclusive. For example, Kitis et al. (2002) found strong relationships between SUVA and both THMfp and HAAfp while Shorney et al. (1999) did not.

2.4.1.3 NOM FRACTIONS

Not all NOM compounds react with chlorine to form halogenated DBPs. For example, proteins are generally oxidized to form aldehydes and organic acids while polysaccharides are known to be less reactive than other NOM species and thus unlikely to react with oxidants. Current research suggests that it is the aromatic rings found on some NOM molecules that react with oxidants to form halogenated DBPs such as trihalomethanes and haloacetic acids. Thus, it would be expected that water samples with a high proportion of proteins (HOBs, HIBs) or polysaccharides (HINs) would be less likely to form DBPs than those where HOAs were more common. Recent research, however, suggests that in practice this is not always the case.

Numerous studies have been conducted to try to establish the THMfp and HAAfp of different NOM fractions. Owen et al. (1993) found that the total hydrophilic fraction (HI) was as reactive (normalized THMfp/HAAfp) as the total hydrophobic fraction (HO) – though the analysis was complicated by the higher concentration of bromine in the samples with more hydrophilic NOM. A study by Kristiana et al. (2010) found that large hydrophobic molecules were more likely to react to form DBPs, but that smaller, less aromatic compounds formed more brominated DBPs. Croué et al. (2000) found that the HOA fraction had the highest THMfp, DCAAfp, and TCAAfp, though all of the other fractions contributed as well, in particular the acidic ones. Kitis et al. (2002) noted that the hydrophobic and hydrophilic fractions both made large contributions to the overall DBPfp, particularly when the SUVA of the water was low. The HO fraction was found to be more reactive irrespective of the SUVA of the water sample. Finally, Panyapinyopol et al. (2005) studied NOM fractions from a WTP in Bangkok and found that the HIN and HOA fractions contributed the majority of the THMfp of the treated water, but that the HIB and HOB fractions had the highest normalized THMfp.

Summaries of these findings are provided in Table 2.6 and Table 2.7.

Table 2.6 Summary of absolute and normalized THMfp from different fractionation studies

Study	Fraction(s) with highest absolute THMfp (ug/L)	Fraction(s) with highest normalized THMfp (ug/L)
Owen et al. (1993)	HO	HO and HI
Croué et al. (2000)	HOA	HOA, HIA
Kitis et al. (2002)	HO and HI	HO
Panyapinyopol et al. (2005)	HIN, HOA	HIB, HOB

Table 2.7 Summary of absolute and normalized HAAfp from different fractionation studies

Study	Fraction(s) with highest absolute HAAfp (ug/L)	Fraction(s) with highest normalized HAAfp (ug/L)
Croué et al. (2000)	HOA	HOA, HIA
Kitis et al. (2002)	HO and HI	HO

The contradictory results obtained by different researchers highlight how it can be difficult to predict THM and HAA formation using surrogate parameters. The relative mass of each NOM fraction differs from source to source, as does the distribution of compounds within each fraction. This leads to variations in the reactivity and DBPfp of each fraction from source to source, making it difficult to generalize the results of one study to different water supplies.

Another interesting finding by Owen et al. (1993) was that when they separated the hydrophobic and hydrophilic fractions from one another the sum of their chlorine demands (and resulting THM formation) was greater than those of the bulk water. This suggests that some fractions may have inhibitory effects on one another while they are in bulk solution.

2.4.1.4 MOLECULAR WEIGHT

Larger MW fractions are often hydrophobic and aromatic in nature, suggesting that they are more likely to contribute to the formation of DBPs. The relationship between MW and DBP formation does not always hold true. For example, many large HONs (>10,000 Daltons) are polysaccharides, which are unlikely to react with chlorine to form DBPs (Chow et al., 2005). Smaller molecules, such as amino acids (HIBs, HOBs) are thought to be less likely to react to form DBPs (Singer and Reckhow, 2011).

Kristiana et al. (2010) found that larger MW NOM fractions were more likely to form DBPs than smaller compounds. The smaller compounds also formed DBPs, however, and were particularly common precursors for brominated DBPs. Kitis et al. (2002) found no relationship between MW and DBPfp.

2.4.1.5 OTHER PARAMETERS

As described in previous sections, chlorine demand, bromide levels, temperature, reaction time, and pH can impact the formation of THMs and HAAs. For example, the rate of THM formation is higher at high pH but this relationship does not hold true for HAAs (Krasner et al., 1989). Shorney et al. (1999) found that chlorine demand was significantly correlated to both THM and HAA formation and Gang et al. (2002) used it as the basis of their DBP formation predictive model.

Though an in-depth discussion of the effects of these parameters is outside of the scope of this project, it should be kept in mind that differences in DBP levels among utilities may be affected by factors other than the amount of NOM available.

2.4.2 DBP Formation Models

Numerous researchers have attempted to develop equations to predict the formation of THMs and HAAs based on water quality parameters (TOC, DOC, UV254, bromide, etc.) and operational conditions (chlorine dose, retention time, etc.). Sadiq and Rodriguez reviewed 25 DBP formation models in their

2004 report for the National Research Council of Canada. Some of the simpler models developed over the past 30 years are summarized in Table 2.8.

Table 2.8 DBP formation models (adapted in part from Sadiq and Rodriguez, 2002)

Source	Data Type	Equation
Minear and Morrow (1983) Morrow and Minear (1987)	Laboratory	$\text{TTHM } (\mu\text{mol/L}) = -3.91 + (\text{Br}^{-})^{0.15} + 0.23 \log(\text{D}) + 0.24 \text{ pH} + 10^{0.009\text{T}} + 0.26 \text{ NVTOC}$
Amy et al. (1987) Chowdhury et al. (1991)	Laboratory	$\text{TTHM } (\mu\text{mol/L}) = 0.0031(\text{UV} \cdot \text{TOC})^{0.44} \text{D}^{0.409} \text{t}^{0.265} \text{T}^{1.06} (\text{pH} - 2.6)^{0.715} (\text{Br} + 1)^{0.036}$
Chang et al. (1996)	Laboratory	$\text{TTHM } (\mu\text{g/L}) = 12.7(\text{TOC})^{0.291} \text{t}^{0.271} \text{D}^{-0.072}$
Amy et al. (1998)	Laboratory	$\text{TTHM } (\mu\text{g/L}) = 0.00412(\text{DOC})^{1.1} \text{D}^{0.152} \text{Br}^{0.068} \text{T}^{0.61} \text{pH}^{1.60} \text{t}^{0.26}$
Rodriguez et al. (2000)	Field Laboratory	$\text{TTHM } (\mu\text{g/L}) = 1.392(\text{DOC})^{1.092} \text{pH}^{0.531} \text{T}^{0.255}$ $\text{TTHM } (\mu\text{g/L}) = 0.044(\text{DOC})^{1.030} \text{t}^{0.262} \text{pH}^{1.149} \text{D}^{0.277} \text{T}^{0.968}$

*D = chlorine dose (mg/L), t = reaction time (h), T = temperature (^{o}C), TTHM = total trihalomethanes (ug/L), THAA = total haloacetic acids (ug/L)

Additional models have been proposed that take into account the impacts of chlorine demand (Gang et al., 2002), chlorophyll-a (Golfinopoulos, 1998), and seasonal variations (Golfinopolous and Arhonditsis, 2002).

While many of these models performed very well ($r^2 > 0.9$) in the researchers' own studies none have been universally adopted by the water industry because many of them were developed in laboratories under controlled conditions, were limited by a small sample size, and/or were specific to the water supplies evaluated.

2.5 Water Treatment for NOM Removal

2.5.1 Coagulation Processes

Coagulation is the most well-established method of removing NOM. Coagulants, which may be aluminium or iron based, are chemicals that can be added to water to induce dissolved and colloidal species to agglomerate into larger particles known as flocs. These flocs are removed in a clarification step, which may be based on gravity or buoyancy. The clarified water is then filtered through media to remove any remaining flocs. Some coagulation processes do not include a clarification step, relying exclusively on filtration for floc removal.

During coagulation, it is widely believed that NOM is removed from the water through complexation, precipitation, agglomeration, and/or adsorption, though there is still some debate as to which process(es) dominate. Edzwald elucidated the mechanisms of coagulation in his 1993 paper *Coagulation in drinking water treatment: Particles, organics, and coagulants*. The concepts presented in this paper have influenced the understanding of coagulation processes in the water industry, particularly with respect to the removal of NOM.

There are three different coagulation strategies used in the water industry: sweep flocculation; enhanced coagulation; and optimized coagulation. The terms 'enhanced' and 'optimized' coagulation are often used interchangeably though they differ slightly from one another. Sweep flocculation occurs when a large amount of coagulant is added the water resulting in the formation of large amorphous hydroxide flocs. Particles, microorganisms, and other contaminants become enmeshed with or adsorbed to these large flocs during the flocculation process and are eventually removed in the clarification and filtration steps. The US EPA defines enhanced coagulation as "the process of improving the removal of disinfection byproduct precursors in a conventional water treatment plant" (US EPA, 1999).

Researchers, however, have defined enhanced coagulation as a process that relies on exact dosing of coagulant to neutralize the charges that would usually keep particles at a distance from one another. Once the charges are neutralized, the particles are encouraged to agglomerate through flocculation and removed through clarification and/or filtration. Finally, optimized or optimum coagulation refers to the strategy of optimizing both the coagulant dose and the pH to ensure that NOM, turbidity, pathogens, and aluminum are all minimized in the treated water (Edzwald and Tobiason, 1999). All three processes can be used to remove NOM but the last two are most effective.

Most experimental work on coagulation has focused on alum ($Al_2(SO_4)_3.14H_2O$). When alum is added to water, it ionizes and reacts with naturally occurring alkalinity to form aluminum hydroxide, which will precipitate out of solution under certain conditions. Minimum solubility occurs at a pH of 6.2 at 25^oC and 6.7 at 4^oC (Edzwald, 1993), though the optimum pH for NOM removal may vary from 5 to 7 based on temperature and DOC levels (Gregory and Edzwald, 2011).

Although alum has historically been the most commonly used coagulant, there are numerous alternatives available. Some of these are summarized in Table 2.9.

Table 2.9 Coagulants used for water treatment

Coagulant	Advantages	Disadvantages
Alum	Widely available	Limited pH range
Polyaluminum chloride* (PACl)	Effective over wide pH and temperature ranges	Proprietary
Ferric chloride	Widely available	Unsuited to cold climates

*numerous proprietary products available

Coagulation has frequently been found to reduce THMfp and HAAfp. It is known to target humic acids, which usually make up a large proportion of the hydrophobic acid fraction and this fraction is often associated with the formation of THMs and HAAs. Work by Owen et al. (1993) showed that coagulation reduced THMfp and HAAfp by 20% to 30% in water samples from two of three participating communities. Croué et al (2000) coagulated individual NOM fractions and found that the HOA fraction was particularly well removed by coagulation with alum as measured by DOC and UV254 (48% to 80% and 74% to 95%, respectively). The other acidic fractions (ex. HIA) were also removed effectively. Larger molecular weight compounds are more effectively removed by coagulation than smaller molecular weight compounds (Owen et al., 1993; Sohn et al., 2007).

Edzwald (1993) propounded the use of SUVA as an indicator of the hydrophobicity, aromaticity, and molecular weight of the DOC compounds in a given water sample, suggesting that a high SUVA was associated with a high proportion of HOAs within the water sample. He hypothesized that water with a SUVA above 4 L/mg.min would be amenable to coagulation while that with SUVA below 3 L/mg.m would not be. These findings have since been expanded upon and are presented in tabulated form in Chapter 3 of the most current version of Water Quality and Treatment, published by the AWWA (Edzwald and Tobiason, 2011).

When the source water contains fewer HOAs (low SUVA), coagulation is less likely to be effective. This has been demonstrated in numerous experiments. For example, Sohn et al. (2007) were only able to remove 5 to 10% of the influent DOC from raw water with a SUVA between 1.8 and 2.5 using coagulation.

It has been demonstrated that bromine is not effectively removed through coagulation (Sohn et al., 2007). This may result in the preferential formation of brominated DBPs after coagulation treatment.

Some common water treatment processes that employ coagulation are sedimentation with filtration, direct filtration, dissolved air flotation with filtration, and coagulation with low pressure membrane filtration.

2.5.1.1 CONVENTIONAL

For many years, the most common design for water treatment plants consisted of coagulation followed by flocculation, settling, and filtration. This eventually became known as ‘conventional’ treatment because of its ubiquity and to differentiate it from newer treatment processes. Conventional treatment is effective for the removal of turbidity, pathogens, and NOM. It generally has a large footprint relative to other treatment processes, however, and is relatively chemical and energy intensive.

An aluminium or iron based coagulant is added at the very beginning of the process. It is often accompanied by a pH control chemical (soda ash, lime, etc) to ensure that a pH conducive to the formation of aluminium or iron precipitates is maintained throughout the process. The water is mixed vigorously and then flows through a series of flocculation tanks where it is mixed at decreasing intensities to promote the formation of large, settleable flocs. The majority of these flocs are removed through gravity in the sedimentation basin. Any flocs that do not settle out in the sedimentation basin travel with the clarified water to the filter, where they are removed through size exclusion.

Packaged conventional-style treatment processes are commercially available and in use in some communities in Newfoundland and Labrador. For example, both Ramea and Channel-Port aux Basques employ the Degremont Pulsa-pak. This treatment system is often labelled ‘conventional’ but in fact incorporates a number of innovations meant to decrease the overall footprint of the plant. For example, the Pulsa-pak system relies on solids contact instead of gravity-driven sedimentation for floc removal. Packaged systems can be less flexible to operate than more traditional-style systems, and must therefore be sized carefully to avoid compromising treated water quality.

A process flow diagram of a standard conventional treatment system is provided in Figure I.1 in Appendix I.

2.5.1.2 DISSOLVED AND AIR FLOTATION

The dissolved air flotation (DAF) process is identical to the conventional treatment process except that clarification is accomplished using flotation rather than sedimentation. DAF is thought to be more effective than conventional treatment for NOM removal from soft, low pH, low turbidity water sources because flocs formed mainly from the interactions between the coagulant and hydrophobic NOM tend to have relatively low densities (Zabel, 1985). Thus, they can be induced to float, rather than sink, by introducing a stream of air-saturated water at the bottom of the clarification chamber.

The introduction of a stream of recycled treated water that has been saturated with air results in a stream of bubbles that forces the flocs up to the top of the chamber as they enter from the final flocculation chamber. The flocs form a sludge blanket on top of the water and are skimmed off by a mechanical device. The clarified water is sent through a media filter before being disinfected and distributed. The footprint of DAF system is considerably smaller than an equivalent conventional sedimentation system, which makes the process more attractive when a new treatment plant is being designed. The process is also less sensitive to water temperature than conventional treatment (Gregory and Edzwald, 2011), making it an ideal choice for cool climates.

A process flow diagram of a DAF treatment system is provided in Figure I.2 in Appendix I.

2.5.1.3 DIRECT FILTRATION

Some water treatment facilities have dispensed with clarification processes in favour of straight filtration. The flocs formed in the coagulation and flocculation steps are driven directly against media filters and removed through size exclusion. Direct filtration processes have a smaller footprints than conventional or DAF processes. Chemical costs are often lower because the required floc size is smaller – resulting in less coagulant use. Filter runs can be shortened due to fouling, however, which can lead to increased backwashing.

A process flow diagram of a direct filtration treatment system is provided in Figure I.3 in Appendix I.

2.5.2 Membrane Filtration

Membrane filters are now well-established in the water industry as an alternative to traditional media filters. They can be used in conjunction with coagulation, adsorption, and oxidation processes or combined with one another to produce high quality drinking water without chemical addition. The four main types of membrane processes are:

- Microfiltration (MF);
- Ultrafiltration (UF);
- Nanofiltration (NF); and
- Reverse osmosis (RO).

Each is defined by its ability to remove species that fall into a given size range, as shown in Figure 2.1.

2.5.2.1 LOW PRESSURE MEMBRANE FILTRATION

Low pressure membrane filters are used to remove particles, colloids, and some dissolved species from raw water. The process relies on pressure driven size exclusion. Water is forced against the surface of a semi-permeable membrane. Any particles or molecules larger than the membrane's pores are retained on the surface. Water and any molecules smaller than the pores pass through the membrane surface and into the permeate stream.

Membrane filters can remove much smaller particles than conventional media filters because of the small size of the pores the membrane surface. They also have very small footprints relative to many of the other processes used to remove NOM. In most applications the enhanced level of filtration can be accomplished without increasing the overall energy consumption of the process.

Low pressure membranes are labeled as MF or UF depending on the size of their pores. MF membranes have pore sizes ranging from 0.1 to 0.2 µm while UF membranes have pore sizes ranging from 0.01 to 0.05 µm. In practice, however, there is often an overlap in the pore size distribution between MF and UF membranes from different manufacturers.

The pores on MF membranes are too large to reliably remove NOM, though some larger molecules can be removed by UF membranes depending on the manufacturer. UF membranes with set pore sizes have traditionally been used in the laboratory to separate NOM based on molecular weight but are not available commercially at the municipal scale. Membranes are frequently charged; having either a hydrophobic or hydrophilic character. This can influence the NOM species removed and the type and extent of membrane fouling. For example, hydrophobic membranes have been found to experience surface fouling by hydrophilic and neutral compounds (Gray et al., 2007).

A process flow diagram of a standard low pressure membrane filtration system is provided in Figure I.4 in Appendix I.

2.5.2.2 LOW PRESSURE MEMBRANE FILTRATION WITH PRE-TREATMENT

Coagulation or powdered activated carbon (PAC) may also be added to the membrane process to help remove organic matter present in the raw water.

Only a small amount of coagulant is required to induce the formation of flocs large enough to be removed by the membrane. Removal of DOC, UV254, THMfp, and HAAfp is improved by the addition of coagulation pre-treatment. It can also minimize membrane fouling (Farahbakhsh and Smith, 2002). Conventional, DAF, and rapid mix coagulation pre-treatments have all been used ahead of low pressure membranes to improve NOM removal.

Pre-treatment with PAC has been shown to increase organic removal, but not as dramatically as coagulation pre-treatment. It has also been shown to result in increased membrane fouling (Lahoussin-Tourcaud et al., 1990; Farahbakhsh and Smith, 2002).

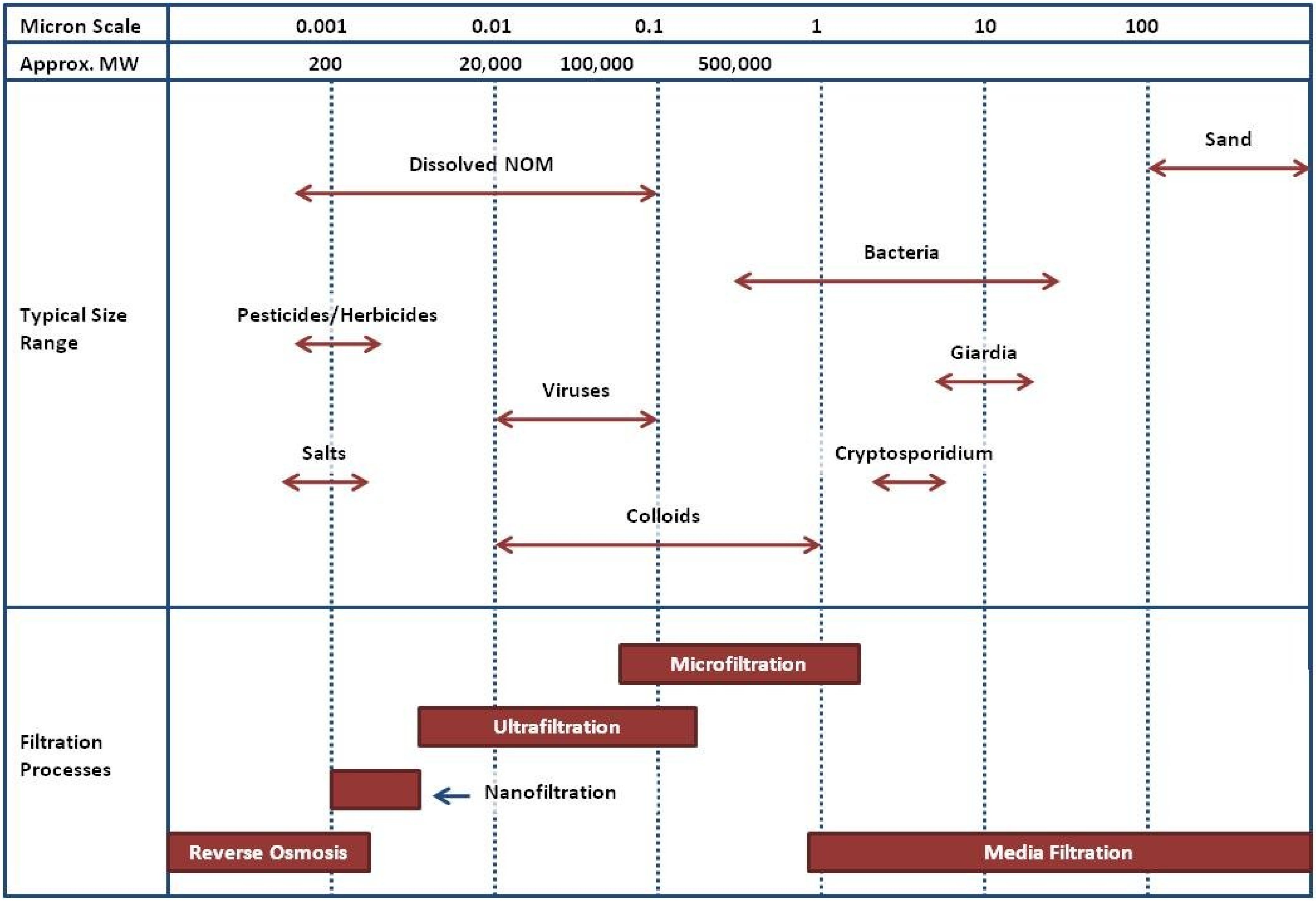


Figure 2.1 Filtration processes (Adapted from Duranceau and Taylor, 2011 and Osmonics, 1996)

Low pressure membrane filtration systems that employ pre-treatment for organic removal are capable of removing the same types of NOM (MW, charge, etc.) as their parent processes. Removal is often more effective than with the parent process alone because membrane filters can remove smaller flocs. Low pressure membrane filtration with coagulation pre-treatment is used in at least two communities in Nova Scotia, both of which use surface water sources with high DOC and colour and low pH, alkalinity, and turbidity. A similar system was successfully piloted in the Town of Come by Chance.

A process flow diagram of a low pressure membrane treatment system with coagulation pre-treatment is provided in Figure I.5 in Appendix I.

2.5.2.3 HIGH PRESSURE MEMBRANE FILTRATION

High pressure membranes, which include NF and RO processes, are defined by their MW cut-offs. Both NF and RO membranes have MW cut-offs below the MWs of most NOM molecules. This means that NOM is essentially removed through size exclusion.

RO allows filtration to occur at a molecular level, thereby removing dissolved species and ions. NF membranes evolved as a form of RO but use a larger pore structure, operating at lower feed pressures, and removing fewer ion species from feed water. Both technologies achieve complete removal of dissolved organic matter, metals, turbidity, and associated compounds.

High pressure membranes are easily fouled by particles and some inorganic species such as calcium and manganese (i.e., hardness), iron, and manganese. As a result, some form of pre-treatment is usually required before feed water can be sent against a high pressure membrane. This may include media or low pressure membrane filtration for turbidity removal, softening for ion removal, or oxidation with filtration for iron and manganese removal. Combination UF/NF treatment systems have become more popular in recent years; at least three have been installed in small communities in Nova Scotia that have high levels of colour and DOC in their raw water. All of these have proven effective at reducing THMfp and HAAfp.

High pressure membrane systems are energy and water intensive but rarely require chemical addition. They can be used at the small and very small scale. For example, four of the existing potable water dispensing units (PWDUs) in Newfoundland and Labrador use RO membranes. One small community in the province recently piloted a tubular NF unit and found that the membrane was very effective for NOM removal.

2.5.3 Oxidation Processes

Chlorine, potassium permanganate, ozone, and air (oxygen) are all examples of oxidants used in the water treatment industry. Reactions between these and common water quality parameters can be both useful and challenging in a water treatment process. All of the aforementioned oxidants can be used to convert reduced (dissolved) iron and manganese species into oxidized (particulate) species that can then be removed through filtration. Oxidants can also react with certain components of the cell walls of microorganisms during the disinfection process; killing or disabling them. Finally, large colour-causing NOM compounds can be oxidized to form smaller, less coloured ones. Unfortunately, reactions between

NOM and certain oxidants (i.e., chlorine) can also result in the formation of halogenated DBPs such as THMs and HAAs.

Common oxidation processes used for NOM removal in the drinking water industry include:

- Ozone and filtration;
- Ozone and biological filtration;
- Ozone and slow sand filtration; and
- Advanced oxidation processes (AOPs).

2.5.3.1 OZONE AND FILTRATION

Ozone is one of the strongest gas oxidants used in water treatment. Through a series of chemical reactions, ozone will oxidize organic matter and metals while providing a level of chemical disinfection. The oxidized by-products of ozonation can be filtered through conventional media, GAC, biologically active GAC, or a slow sand filtration unit.

Using ozonation and filtration to remove organics requires the installation of an ozone generation unit, injection system, contact vessel and a subsequent filtration system. The ozone generators used at a small scale are usually air fed. At larger scale ozone generation efficiency is often improved by using an oxygen feed, which necessitates the addition of an oxygen concentrator to the treatment process. Irrespective of the feed, ozone is produced on-demand and injected either into a side-stream flow that carries the dissolved gas to the main point of application or is applied directly to the main process stream. An ozone dose of 1.0 mg/L O3 to 1.0 mg/L DOC followed by a minimum of 5 to 10 minutes of reaction time is considered standard.

Studies, including one by Hesse et al. (1999) have shown that large hydrophobic NOM molecules can be converted to smaller, more biodegradeable ones through oxidation. Others have also noted that ozonation increases the hydrophilic fraction while decreasing the hydrophobic fractions. For example, Sohn et al. (2007) observed an increase of 12% in the hydrophilic fraction and a decrease of 9% in the hydrophobic fraction after ozonation. They also found that ozonation reduced normalized THMfp and HAAfp significantly. Experiments conducted on water samples from four different water sources in the US showed that though DOC remained constant in most cases, UVA decreased after ozonation (Owen et al., 1993). The same study noted that the proportion of biodegradeable NOM increased after ozonation. A study by Chowdhury et al. (2008) suggested that the effects of ozonation may differ from one source water to the next. They applied ozone to two source waters in British Columbia and found that THMfp and HAAfp were reduced in one but not the other. They traced the difference in HAAfp to the tendency of the water to form dichloroacetic acid (DCAA).

Conventional multimedia filters can be used to remove the particulate formed during the oxidation of some dissolved inorganic species such as iron and manganese. GAC and biologically active GAC have proven more effective at removing the products of the oxidation reactions between ozone and NOM. The first works mainly through adsorption while the second depends on biodegradation by the microorganisms attached to the media.

Slow sand filters are large, gravity-driven systems that operate by size exclusion and biodegradation. They have a large footprint but require no energy or chemicals and very little operation and maintenance. Their limited ability to remove NOM means that they can only be used in communities with high quality (i.e., low TOC) source water. Recently, however, a company in Ontario has designed a slow sand filtration system that incorporates ozone and roughing filters to improve NOM removal. An independent study of the system conducted in Maine showed a 67% reduction in TTHM when ozone was included while a more recent pilot conducted in Northern Ontario showed a 30% reduction in DOC and 80% reduction in colour, suggesting that the more aromatic/hydrophobic NOM species were being removed and/or transformed.

Ozone-based processes can be employed at all scales. Two communities in Newfoundland and Labrador, one with 10,000 people and the other with 1,500 people, have installed full-scale ozone and filtration treatment plants. The technology can also be applied at the very small scale - three of the seven PWDUs in the province make use of ozone to produce high quality drinking water. Other small scale treatment systems employ ozone to improve organic removal.

Despite its ability to reduce THMfp and HAAfp, ozone treatment has some important drawbacks. Ozone itself is highly corrosive to organic materials such as wood and rubber. As a result, ozone treatment equipment, piping, and housing must be made of more resistant material such as stainless steel (304/316 SS). Such materials tend to be more expensive.

Ozone residuals in water are short-lived. The gas, however, is harmful if inhaled and can present an occupational health and safety risk when used in treatment if the proper precautions are not taken. The US EPA currently recommends a maximum of 0.12 ppm ozone exposure for one hour and an eight-hour exposure maximum of 0.075 ppm. OSHA and NIOSH recommend an eight-hour exposure maximum of 0.1 ppm while Health Canada has a recommended eight-hour exposure limit of 0.02 ppm for residential indoor air. The American Conference of Governmental and Industrial Hygenists (ACGIH), whose guidelines are widely used across North America, recommend values between 0.05 ppm and 0.2 ppm depending on the time of exposure and amount of exertion. Table 2.10 compares the limits recommended by different organizations and regulatory bodies.

Table 2.10 Recommended ozone exposure limits

Organization/Regulatory Body	Exposure Limit
US EPA	
One hour	0.12 ppm
Eight hour	0.075 ppm
OSHA and NIOSH	
Eight hour	0.1 ppm
Health Canada	
Eight hour (residential)	0.02 ppm
ACGIH	
Eight hour (heavy work)	0.05 ppm
Eight hour (moderate work)	0.08 ppm
Eight hour (light work)	0.10 ppm
Two hour	0.20 ppm

To ensure that operators are not exposed to excessive ozone the treatment area must include ozone monitoring equipment and an alarm system. Public health can also be impacted as the reaction of ozone with naturally occurring bromide can result in the formation of bromate, a well-known DBP. Finally, it can be difficult to measure in-stream ozone levels, which can negatively impact the operator's ability to quantify the dose being applied or the level of pathogen inactivation. All of these drawbacks are of particular concern in small communities, which generally have less access to monetary or human capital.

2.5.3.2 ADVANCED OXIDATION PROCESSES

The behaviour of ozone in water is complex. Though ozone on its own is able to oxidize many parameters, it can also decompose spontaneously to form other oxidant species such as hydroxyl free radicals. These radicals are highly reactive but non-selective, meaning that they react quickly with most parameters in the water. The total oxidation that occurs when ozone is added to water is partly due to reactions with ozone and partly due to reactions with these hydroxyl radicals.

Hydroxyl radicals can be formed through spontaneous ozone decomposition, ozone decomposition brought about by the addition of hydrogen peroxide or a catalyst (ex. O_3-H_2O_2), or by irradiating hydrogen peroxide with UV (UV-H_2O_2). Treatment systems based on the second and third reactions have been labelled advanced oxidation processes (AOPs). The O_3-H_2O_2 process can reduce ozone demand by promoting increased conversion of O_3 to the hydroxyl radical. The UV-H_2O_2 process eliminates ozone entirely; minimizing the size and operating costs of the treatment system.

Acero and Von Gunten (2001) reported that an O_3-H_2O_2 process improved the performance of an ozone system effectively when the water being treated was high in alkalinity and low in NOM. The opposite was true when the water had a higher concentration of TOC. Speitel et al. (2000) found that the addition of hydrogen peroxide to an ozone treatment system did not improve TOC reduction, biodegradation, or DBPfp in two waters that had been pre-treated to achieve a starting TOC concentration of 2.7. They did note, however, that there was less bromate formation in their O_3-H_2O_2 system than in their pure O_3 system. In Newfoundland, the O_3-H_2O_2 process is likely to be of most use in communities with pre-existing ozone systems who have high levels of bromate in the treated water.

The UV-H_2O_2 process may be of particular interest to smaller communities in Newfoundland and Labrador because it is much simpler to operate than the ozone-based processes. Speitel et al. (2000) showed that a UV-H_2O_2 + biologically active GAC system was nearly as effective at reducing TOC, UV254, and DBPfp as a more traditional ozone + biologically active GAC system. Also, depending on the transmittance of the water being treated, UV-H_2O_2 systems can double as disinfection units. Like all processes, however, there are drawbacks. Most importantly, operating costs can be high (depending on your point of reference), particularly for systems that do not include a post-filtration step that can remove transformed NOM compounds and/or quench residual hydrogen peroxide (Mowat and Hofmann, 2009). This might contribute to the formation of DBPs if precursors are not sufficiently oxidized.

2.5.4 Adsorption and Ion Exchange Processes

Adsorption occurs when one species attaches itself to another through intramolecular forces (i.e., dipole interactions, hydrogen bonds). It is mainly used to transfer a chemical species from a liquid or gaseous phase onto a solid one. The solid species is referred to as the adsorbent and the species that is removed from the gas or liquid phase is called the adsorbate. Numerous adsorbent media have been developed for use in the water industry. Ion exchange processes work in a similar manner, but rely on both adsorption and the exchange of charged species between the media and the bulk water.

The total amount of adsorbate that can be adsorbed onto the media is determined by the media's capacity and the amount of time the water spends in contact with it. The latter is referred to as the 'empty bed contact time' (EBCT). In general, removal improves with increasing EBCT (Summers et al., 2011). The amount of water that can be treated by a given adsorbent is expressed as the concentration of the adsorbate in the filtrate after a given volume, time, or number of bed volumes. This last is used most frequently because it allows designers to compare different size treatment systems (Summers et al., 2011). The point at which the concentration of adsorbate in the filtration exceeds a set acceptable value is referred to as 'breakthrough'.

The surface of an adsorbent media can be positively or negatively charged, which will impact the types of compounds it can remove. Many NOM fractions are charged at ambient conditions and thus can be removed through adsorption. The hydrophobic acid fraction, which is the most extensively studied, is negatively charged at a neutral pH. Consequently, it is most effectively adsorbed when the media is positively charged. Common adsorbents used for NOM removal include activated carbon, ionic resins, and metal oxides. The first two are the most commonly used in the water treatment industry.

2.5.4.1 ACTIVATED CARBON

Activated carbon is used to remove numerous organic and inorganic parameters, including NOM. Preformed DBPs including chloroform, dibromochloromethane (BDCM), dichloroacetic acid (DCAA), and trichloroacetic acid (TCAA) can also be removed by activated carbon (Summers et al., 2011). Removal is accomplished mainly through adsorption. Activated carbon is made by 'carbonizing' (charring) natural products such as coal, wood, or coconut shells. It is commercially available as a powder (PAC) that can be added to the water directly or a granular media (GAC) that can be used in a fixed bed filter.

Though activated carbon is known to be effective for the removal of most organic compounds, it often cannot be relied upon for complete removal of DOC or TOC because some sizes and fractions of NOM are adsorbed more easily than others, specifically smaller humic and fulvic acids (McCreary and Snoeyink, 1980). Larger molecules are less likely to gain access to the pores of the media because of size exclusion (Summers and Roberts, 1988; Newcombe, 1999). Experiments by Owen et al. (1993) found that GAC adsorbed larger MW hydrophobic NOM and allowed non-humic and lower MW to pass through the filter.

Solution pH and ionic strength can impact the adsorption of NOM by activated carbon. At lower pH NOM molecules are smaller and less charged, which can result in changes in the interactions with the adsorbent. One study found that significantly more NOM was adsorbed onto an activated carbon media at a pH of 3 than at a pH between 7 and 8 (Newcombe, 1999). Increasing ionic strength is associated with more effective adsorption on negatively charged surfaces but less effective adsorption on positively charged surfaces (Summers and Roberts, 1988).

A biological layer tends to develop on the surface of GAC media over time. This has been observed to enhance the removal of biodegradeable NOM, which may represent from 10 to 15% of the total

(Summers et al, 2011). Biologically active GAC filters are frequently employed after ozonation because the oxidation process transforms some of the larger, non-biodegradeable NOM compounds into small, biodegradable ones. This may be less effective in cold environments as the biological activity in the filter is temperature-sensitive.

There are three important drawbacks to the use of activated carbon for NOM removal. First, there can be significant differences in the adsorptive capacity of the media from one manufacturer to another and even from batch to batch due to the natural variability of the starting material. No matter the quality of the media, its capacity for NOM adsorption is often low and/or easily interfered with by other parameters that have a greater affinity for the media. Finally, the adsorbate (NOM) is also variable. As discussed at length in previous sections, the quantity and composition of NOM varies seasonally in most surface water sources. This can make it difficult to predict the amount of NOM removal or the frequency with which the media must be regenerated. Utilities seeking to employ GAC filters for NOM removal should pilot the technology over an extended period of time to evaluate the effectiveness of the process as the NOM loading changes over the course of the year.

A detailed explanation of NOM removal by activated carbon is provided by Summers et al. (2011) in Water Quality and Treatment, published by the American Water Works Association.

2.5.4.2 ION EXCHANGE

Often referred to as ‘softening’, ion exchange resins have been used to remove unwanted ionic species from water for many years, particularly at the very small scale (groundwater, point of use, etc.). The resin is made up of a cross-linked polymer matrix with covalently linked charged functional groups (Clifford et al., 2011). Different applications rely on strong acid and weak acid cationic or strong base and weak base anionic resins.

Ion exchange works by literally switching out one ion for another. The first is initially held on the resin while the other is present in the bulk water. Unlike most other adsorption processes, ion exchange resins remove parameters with a similar, rather than opposite, charge. Many NOM molecules contain carboxylic acid structures, which make them anionic in nature. Therefore, they can often be removed using anionic exchange resins. Ion exchange reactions are usually reversible, meaning that the resin can be regenerated periodically to improve removal. Once the target ion ‘breaks through’ the filter the resin is regenerated with a salt solution; reversing the original ion exchange. This can result in a much longer media life than other adsorbents such as activated carbon. The amount of water treated between regeneration events depends on the type of resin used and the parameter being removed.

The resin is usually held in a fixed bed reactor, however, this is not always the case. One commercially available technology that has become more popular in recent years is magnetic ion exchange, or MIEX. MIEX differs from other ion exchange processes because it uses resin beads rather than a traditional column design. The beads, which are made a of strong base anion exchange resin impregnated with magnetic iron oxide, are added to the influent water in a continuously mixed reactor. The small size of the beads increases the surface area available for exchange while the presence of magnetic iron oxide causes the beads to agglomerate together over time allowing for easy removal once the treatment is complete. Once the beads have been recovered they are regenerated using a salt solution.

Bench-scale studies have suggested that high SUVA, hydrophobic NOM compounds are most effectively removed by MIEX (Boyer and Singer, 2006). It is only recently that researchers have assessed the effectiveness of the technology at the pilot and full-scale rather than at the bench-scale. This has allowed them to evaluate the impacts of resin regeneration and changing water quality on the removal of NOM.

Singer et al. (2007) demonstrated that THMfp and HAAfp were significantly reduced in a pilot-scale MIEX process. The same study presented data showing that the MIEX process removed hydrophobic fractions more effectively than hydrophilic factions but that the latter were reduced to some degree in some of the tests. The researchers also demonstrated that larger molecular weight compounds (> 1,000 Daltons) were removed more effectively than smaller molecular weight compounds.

A different study by Mergen et al. (2008) found that the resin's ability to remove these high molecular weight hydrophobic compounds was not maintained over time as the MIEX beads were regenerated and reused. This trend was not apparent for the smaller hydrophilic compounds, 40% to 60% of which were removed during the treatment process. The researchers hypothesized that the large molecular weight compounds were blocking the adsorption sites, preventing further ion exchange. They also noted that bulk water NOM parameters such as DOC and UV254 were poorly correlated to treatability with MIEX. A study by Hesse et al. (1999) found that smaller MW compounds were removed more effectively than large MW ones.

A more recent pilot-scale study by Drikas et al. (2010) found that all charged compounds (very hydrophobic, slightly hydrophobic, and charged hydrophilics) were removed by the MIEX process but neutral fractions were unaffected. Other studies have shown otherwise (Cornellisen et al., 2008). Drikas et al. also demonstrated that the use of MIEX as a pre-treatment for a conventional treatment process and a low-pressure membrane process improved DOC and SUVA removal.

Until recently, most MIEX studies were conducted in the United States and Australia using raw water with high pH and low DOC relative to that found in Newfoundland and Labrador and the rest of the Atlantic Provinces. Researchers at Dalhousie University are currently studying potential applications of MIEX in Atlantic Canada. So far they have found that the a bench scale MIEX process was more effective than coagulation with alum for reducing the THMfp and HAAfp of the soft, highly coloured water found in one Nova Scotia community. Some of their preliminary studies have also shown that organic removal can be enhanced by adding a MIEX pre-treatment step ahead of a coagulation-based process. Additional benefits associated with the combined treatment process included an increase in the number of BVs treated before breakthrough in the MIEX pre-treatment step and a reduction in the amount of coagulant required in the main treatment step (Walsh et al., 2009).

Some disadvantages of ion exchange processes include interference and pore blocking by other species, particularly sulphate (Boyer and Singer, 2006; Mergen et al., 2008; Clifford et al., 2011), source specific removal rates (Mergen et al., 2008), resin specific removal rates (Cornelissen et al., 2008) and the difficulties associated with the disposal of the spent brine solution.

2.5.5 Bank Filtration

Bank filtration systems, often referred to as infiltration galleries, have been in use for thousands of years, but it is only in the past century that they have been specifically engineered to help achieve defined water quality objectives. A well or gallery is drilled in the vicinity of a surface water source (river or lake) and the raw water is drawn through the subsurface into the cleared space and then directed towards the treatment and/or disinfection system. In some instances, bank filtration systems have been shown to be able to remove turbidity, microorganisms, nutrients, and organic materials (Sharma and Amy, 2011). The effectiveness of a bank filtration system is strongly influenced by the hydrology of the aquifer (permeability, mineralogy, etc.) and the characteristics of the water source (flow, quality, temperature) (Tufenkji et al., 2002).

Numerous chemical, biological, and physical processes contribute to the removal of undesirable water quality parameters during bank filtration. For example, hydrophobic NOM can be adsorbed onto aquifer materials and subsequently biodegraded depending on the characteristics of the subsurface filtration area. The degree to which this occurs depends upon the distribution of NOM fractions in the bulk water. For example, a SUVA reduction of 26% was observed in a source water with high levels of biodegradable NOM (Weiss et al., 2004). Another study by Weiss et al. (2003) found that THMfp and HAAfp were reduced by between 50% and 80% in three systems in the United States.

Seven public water systems in Newfoundland and Labrador include infiltration galleries. No water quality data was provided or collected during this study to judge the effectiveness of these systems but anecdotal evidence suggests that their ability to remove NOM is limited. The consultant's experience with infiltration galleries in Nova Scotia suggests that while infiltration galleries are effective at removing turbidity, they are not capable of removing significant amounts of NOM. It is anticipated that these results are soil and source water specific and may not hold true for all systems.

Six case studies of bank filtration systems in Europe and the United States are presented in Chapter 15 of the most recent version of Water Quality and Treatment: A Handbook on Drinking Water, published by the AWWA (Sharma and Amy, 2011).

2.5.6 Anticipated Costs

The treatment processes described in previous sections vary with respect to treatment effectiveness equipment costs, footprint (space required), operating costs, and operating complexity. These factors and many others contribute to the total lifetime cost of a WTP. Local conditions will dictate which processes are most appropriate for any given community. These are discussed in greater detail in Chapter 7 of this report.

2.5.7 Summary

Table 2.11 summarizes the information presented in sections 2.5.1 through 2.5.5.

Table 2.11 Effectiveness of water treatment processes used for NOM removal

Method	Effectiveness	Fraction(s) Targeted	MW Range Targeted
Coagulation-based Systems			
Conventional	Moderate	Hydrophobic	All, particularly larger MW
DAF	Moderate	Hydrophobic	All
Direct Filtration	Moderate	Hydrophobic	All, particularly larger MW
Membrane-based Systems			
MF or UF	Low		> 10,000 Daltons
MF or UF w. Coagulation	High	Hydrophobic	
Spiral-wound NF or RO	High	All	>300 Daltons
Tubular NF	High	All	> 300 Daltons
Oxidation-based Systems			
Ozone and Filtration	Moderate	Hydrophobic	All, particularly larger MW
Ozone + Slow Sand	Moderate		All, particularly larger MW
AOPs	Moderate	Hydrophobic	All, particularly larger MW
Adsorption-based Systems			
Activated Carbon	Low	Variable	Variable
Ion Exchange	High	Variable	Variable
MIEX	High	Variable	Variable
Natural Treatment Methods			
Bank Filtration	Low	Variable	Variable

Please note that other parameters can interfere with the operation and effectiveness of many of these treatment processes. For example, researchers have observed that bromide is not removed effectively by coagulation or activated carbon. This can result in the preferential formation of brominated DBPs (bromodichloromethane, dibromochloromethane, etc.) over non-brominated DBPs such as chloroform and dichloroacetic acid in water treated with coagulation and/or GAC (Owen et al., 1993; Sohn et al., 2007). Bromide can also react with ozone to form bromate, a dangerous DBP. It is essential, therefore, to remove bromide using a separate treatment process before applying chlorine or ozone to the water.

Iron and manganese can also complicate treatment, particularly when they are present in dissolved form. Like NOM, these parameters exert an oxidant demand. Thus, if both NOM and metals are being treated using a single oxidation step the oxidant dose will have to be increased. This may result in larger equipment and power costs for the utility.

pH can affect the operation of many NOM reduction processes. Coagulation, which is dependent on the behaviour of aluminum or iron salts, is strongly impacted by changes in pH. Most coagulants only operate within a small range of pH values. Optimized coagulation, which is used to target NOM, depends on electrostatic interactions between NOM molecules and the coagulant. Both of these are impacted by pH. The majority of coagulation-based treatment processes optimized for NOM adjust the pH of the influent water to between 6 and 7 before coagulant addition.

Membrane filtration processes are also impacted by pH. Membrane surfaces are charged (either hydrophobic or hydrophilic), as are NOM molecules. The amount of fouling and, to some degree NOM removal, in a membrane filter is affected by the electrostatic interactions between NOM molecules and the membrane surface, which are themselves dependent on pH. The overall charge on the surface of a clean membrane kept at a neutral pH will vary from one manufacturer to another while the charges on the NOM molecules will vary in each water source. Thus, the influent pH should be optimized on a site by site basis.

CHAPTER 3 PROJECT METHODOLOGY

3.1 Desktop Study

A desktop study was conducted in the months following the award of the project. The following aspects of the water systems in each of the six participating communities were evaluated where feasible:

- Historical water quality;
- Watershed characteristics;
- Source water quality;
- Water supply system;
- Water treatment/disinfection system;
- Water distribution system;
- Tap water quality; and
- System operation.

The results of the desktop portion of the study were used to develop an information collection sheet that was used by CBCL staff during their site visits. The sheets include a series of questions for the operator, instructions for collecting water samples, and a list of pictures to be taken during the site visit. A copy of the information collection sheet is provided in Appendix A.

3.2 Field Program

The field program took place between September 2010 and February 2011. The site visits were staggered throughout the year to accommodate the limitations of the fractionation equipment and the requirements of the research assistant conducting the laboratory work.

Site visits were conducted by CBCL engineers and/or civil technologists. Each site visit lasted approximately half a day and included a tour of the water system and watershed, an interview with the system operator(s), and an assessment of the intake, water treatment, and disinfection systems. CBCL staff also collected 20 L of raw water and, where available, 20 L of treated, non-chlorinated water.

A list of the sites visited and the water samples collected at each is provided in Table 3.1.

Table 3.1 Summary of site visits and samples

Site	Date of Visit	Samples Collected
Community E	September 2010	20 L raw
Community C	September 2010	20 L raw, 20 L treated
Community B	September 2010	20 L raw
Community F	December 2010	20 L raw
Community D	January 2011	20 L raw, 20 L treated
Community A	February 2011	20 L raw

3.3 Laboratory Analyses

3.3.1 Fractionation

Using the fractionation procedure developed by Leenheer (1981) and later modified by Marhaba et al. (2003), the dissolved organic matter from the raw and filtered water was separated into six organic fractions; hydrophobic acid (HON), base (HOB) and neutral (HON) and hydrophilic acid (HIA), base (HIB), and neutral (HIN). Diaion WA10 resins and Supelite™ DAX-8 resins were procured from SUPELCO. AG-MP 50 resin was procured from Bio-Rad Laboratories. New DAX-8 resins were passed through a 500 µm sieve to remove large resins. The resin was then stored in 0.1 N NaOH for 24 hours before sequential 24 hour cleanings with hexane and acetone using a soxhlet extractor (Leenheer 1981). The clean resins were then packed into 2.5 x 120 cm Kontes Chromaflex chromatography columns. The resins were further cleaned and prepared by passing methanol, 0.1 NaOH, 0.1 HCl and MilliQ through each column (Leenheer, 1981). Resin quantities in each column were determined using the resin absorption quantities calculated by Leenheer (1981). Additional resin cleaning and preparation instructions for Diaion WA10 and AG-MP 50 resins can be found in Leenheer (1981).

Before passing the sample through each column, the conductivity and absorbance (UV254) of the MiliQ effluent were determined to ensure a conductivity of < 10 µs/cm and an absorbance < 0.001. Additionally, DOC samples were collected to determine the DOC of the resin bleed prior to passing the water sample through. Figure 3.1 describes the experimental procedure used in this study. The left-hand axis describes the pH to which the sample is adjusted prior to passing through the columns. The right hand axis describes the eluent used to desorb the desired organic material from the resins. The horizontal axis describes the order in which water is passed through each of the five columns. A photograph of the actual column setup is shown in Figure 3.2.

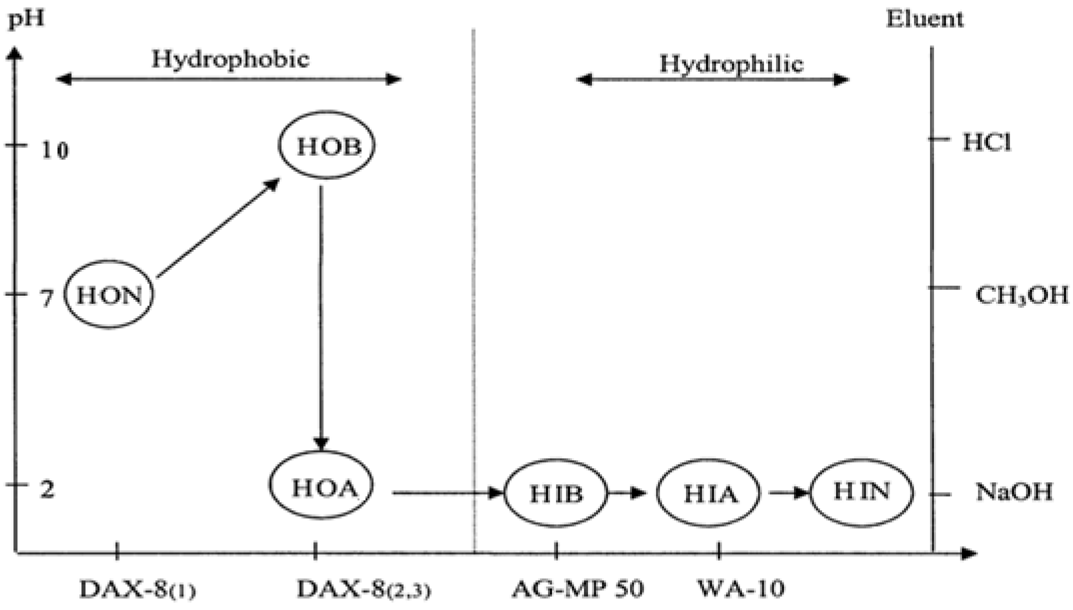


Figure 3.1 Schematic of the resin fraction procedure described by Marhaba *et al.* (2003) with the new DAX-8 resin as opposed to the XAD-8 resin previously used

Figure 3.2 Experimental setup of the fractionation procedure

3.3.2 Size Exclusion Chromatography

The molecular weight distribution of organic fractions was determined using high pressure size exclusion chromatography (HPSEC or SEC). Samples were brought to a pH of 3-7 and passed through a 0.45 µm filter membrane (GE Water & Process Technologies). Samples were evaluated using a TSK G3000SW column (7.5 mm X 300 mm) with a TSKgel SW guard column (7.5 mm X 70 mm). The media in the TSK column consisted of silica with a pore size of 10 µm. These columns were connected to the Perkin Elmer Series 200 Autosampler and the Perkin UV/Vis detector which was set at 254 nm. Samples of 20 µl were injected and passed through the columns at a flow rate of 0.7 mL/min. A sample run time of 30 min was established, whereby all of the compounds in the sample had passed through the column. The molecular weight (MW) of organics was determined by size calibration using four sodium polystyrene sulfonate standards (Scientific Polymer Products Inc) with different molecular weights; 14,900, 7,540, 5,180 and 1,530 Daltons. A coefficient of determination $r^2 > 0.90$ was consistently achieved.

3.3.3 Total and Dissolved Organic Carbon

The TOC samples were prepared by placing the sample in 50 mL head-space free vials and acidified below a pH of 2 with phosphoric acid. DOC samples were first filtered through a 0.45 µm filter paper (Cole-Parmer® Nylon Membranes) before acidifying and placing it in the vial as described in Standard methods for the Examination of Water and Wastewater (APHA, AWWA, and WEF, 1998). Measurements were performed using a TOC-V CPH analyzer with a Shimadzu ASI-V autosampler and catalytically aided combustion oxidation non-dispersive infrared detector (NDIR) having a method detection limit of 0.08 mg/L (Shimadzu Corporation, Kyoto, Japan). Operating conditions for TOC measurements were TOC standard platinum catalyst; injector volume 50 µL; oven temperature 680°C; carrier gas flow 150 mL/min; potassium hydrogen phthalate standards 0-10 mg/L; correlation >0.99. For any given analysis, approximately one standard was prepared for every 10 samples.

3.3.4 UV Absorbance and Colour

UV absorbance at a wavelength of 254 nm and colour were measured using a HACH DR/4000 UV/VIS spectrophotometer (Hach Company, Loveland, CO).

3.3.5 Conductivity, Temperature and pH

Conductivity, temperature and pH were measured using an Accumet Excel XL50. Both the conductivity and pH probes were calibrated daily using standard buffer solutions from Fisher Scientific. The temperature probe was also calibrated daily using a mercury thermometer.

3.3.6 Disinfection By-product Formation Potential

Trihalomethane and haloacetic acid total formation potentials (THMfp and HAAfp) were analyzed under uniform conditions (Summers et al. 1996). Samples were buffered to a pH of 8 with borate, dosed to ensure a 1.0 ± 0.4 mg/L of free chlorine after a 24 hour incubation period at 20ºC. After 24 hours samples were drawn and preserved for THM and HAA extractions.

THMs were measured using EPA Method 551.1, which employs liquid-liquid extraction and gas chromatography with electron-capture detection (LLE/ECD) (U.S. EPA, 2005). This method uses pentane as a solvent to extract an aliquot of sample, which is injected into a gas chromatograph (Varian CP-3800 GC and Varian CP-8400 autosampler) with an electron capture detector for separation and analysis.

Samples were analyzed for 4 trihalomethane compounds: chloroform, bromodichloromethane (BDCM), dibromochloromethane (DBCM) and bromoform compounds.

For THM determination, the gas chromatograph (GC) operating conditions were as follows: standard concentrations of 6, 10, 50, 100, 140, 240, 460 µg/L, injector temperature 220°C; detector temperature 320°C; injection volume 1µL; flow rate 1 mL/min; sample injected at 50°C and held for 7 minutes, temperature increased to 115°C at a rate of 5 C/min with no hold, temperature increased to 295°C at a rate of 50 C/min and held for 0.5 minutes. A coefficient of determination $r^2>0.95$ was consistently achieved for all four THM compounds.

HAAs were measured following Standard Method 6251B (APHA et al., 2005), which utilizes micro liquid–liquid extraction with methyl tert-butyl ether (MTBE) at acidic conditions. Sodium sulphate and sulphuric acid are added to samples to increase extraction efficiency. HAA extracts were analyzed using a gas chromatograph (Varian CP-3800 GC and Varian CP-8400 autosampler) with an electron capture detector for separation and analysis. Samples were analyzed for 9 haloacetic acid analytes (HAA9): monochloroacetic acid (MCAA), monobromoacetic acid (MBAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), bromochloroacetic acid (BCAA), dibromoacetic acid (DBAA), bromodichloroacetic acid (BDCAA), chlorodibromoacetic acid (CDBAA), tribromoacetic acid (TBAA).

For HAA determination, the GC operating conditions were as follows: standard concentrations of 10, 20, 30, 40, 60, 80, and 100 µg/L; injector temperature 200°C; detector temperature 300°C; injection volume 1µL; flow rate 1 mL/min; sample injected at 35°C and held for 10 minutes, temperature increased to 65°C at a rate of 2.5 C/min with no hold, temperature increased to 85°C at a rate of 10 C/min with no hold, temperature is increased to 205°C at a rate of 20 C/min and held for 7 minutes. A coefficient of determination $r^2>0.95$ was consistently achieved for all nine HAA analytes.

To validate the precision and accuracy of the THM and HAA methods, method blanks (milli-q water) and quality control (QC) samples (milli-q spiked with a known amount of standard mixture) were prepared for every 15 samples, for any given analysis. Acceptable recoveries were 80-120% for the QCs.

3.4 Participating Communities

The study aimed to identify and describe the NOM fractions present in six surface water sources and the filter effluent from two water treatment plants in Newfoundland and Labrador and establish which were most likely to react with chlorine to form THMs and HAAs. Six representative water supplies were identified by the ENVC at the beginning of the study. The communities are scattered across the province and their water systems service populations ranging from approximately 400 to 10,000. Only two of the six communities have formal water treatment systems. All of them use some form of chlorine to achieve the province’s disinfection requirements. A summary of the characteristics of the participating communities is provided in Table 3.2.

Table 3.2 Summary of the characteristics of the participating communities

Community	Region	Serviced Population	Source Type	Water Treatment	Disinfection
Community A	Eastern	4,723	Pond	None	Chlorine gas
Community B	Labrador	522	Pond	None	Calcium hypochlorite
Community C	Western	4,319	Pond	Conventional packaged	Chlorine gas
Community D	Central	9,651	Lake	Ozone and filtration	Chlorine gas
Community E	Western	394	Brook	None	Chlorine gas
Community F	Central	1,029	Pond	None	Chlorine gas

CHAPTER 4 WATER QUALITY IN NEWFOUNDLAND AND LABRADOR

4.1 Source Water Quality

4.1.1 DOC

A contour map showing the distribution of DOC in the surface water in Newfoundland and Labrador was prepared as part of an agreement between the ENVC and Environment Canada. A copy is provided in Figure 4.1. The colours on the map represent average values measured at various sampling sites across the province. The sites are indicated on the map by the black markers.

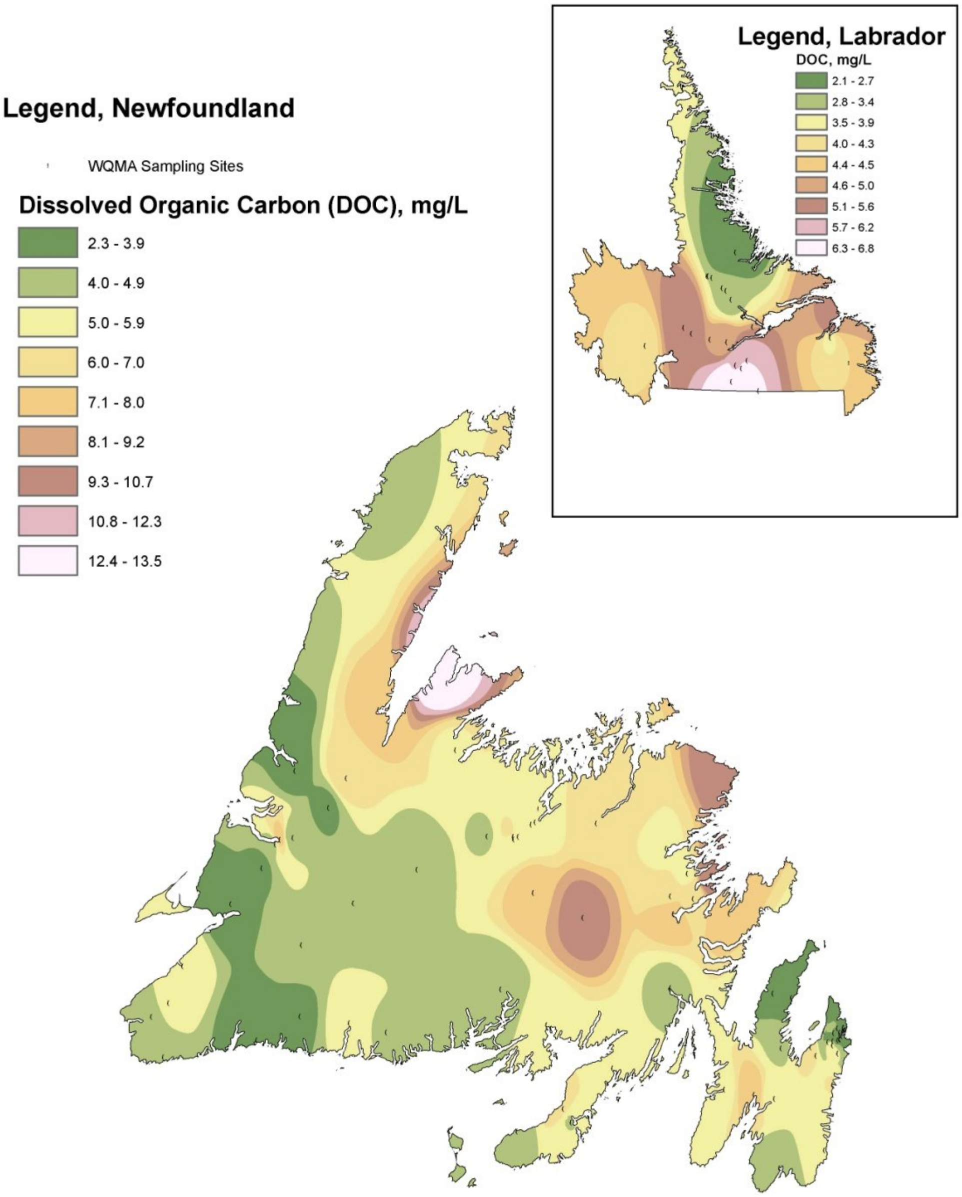
The contour map shows that the surface water on approximately two thirds of the landmass of the province has average DOC levels above 5 mg/L. Surface water sources in four areas of the province are characterized by average DOC levels above 9 mg/L. Surface water sources on the island often have higher DOC levels than those in Labrador. Some areas, in particular the western portion of the island and the northern coast of Labrador, have relatively low average DOC levels compared to the rest of the province.

The contour map provides a good starting point but does not reflect the effects of seasonal variations in water quality. Though it can be used as a general guide to the water quality expected in different parts of the province, it should not be used as the basis for system design.

4.1.2 Colour

A second contour map showing the average colour measured at various sites in the province is provided in Figure 4.2. For the most part, the distribution of colour in the surface water of the province is similar to that of DOC. The only large exception is the south coast of Labrador, which has moderate DOC levels accompanied by low colour.

Dissolved Organic Carbon Contours Based on Canada-Newfoundland Water Quality Monitoring Agreement Data



A contour map displays regions, each of which represents a constant value for a particular parameter. These regions are approximations based on average recorded values at WQMA sites for all data collected between 1985-2000. The contour regions were estimated using a geostatistical approach known as Inverse Distance Weight (IDW), with a power of 5. The maps will be updated for every five years of new water quality data collected. Values are compared against the Canadian Council of Ministers of the Environment Water Quality Guidelines for the Protection of Aquatic Life.

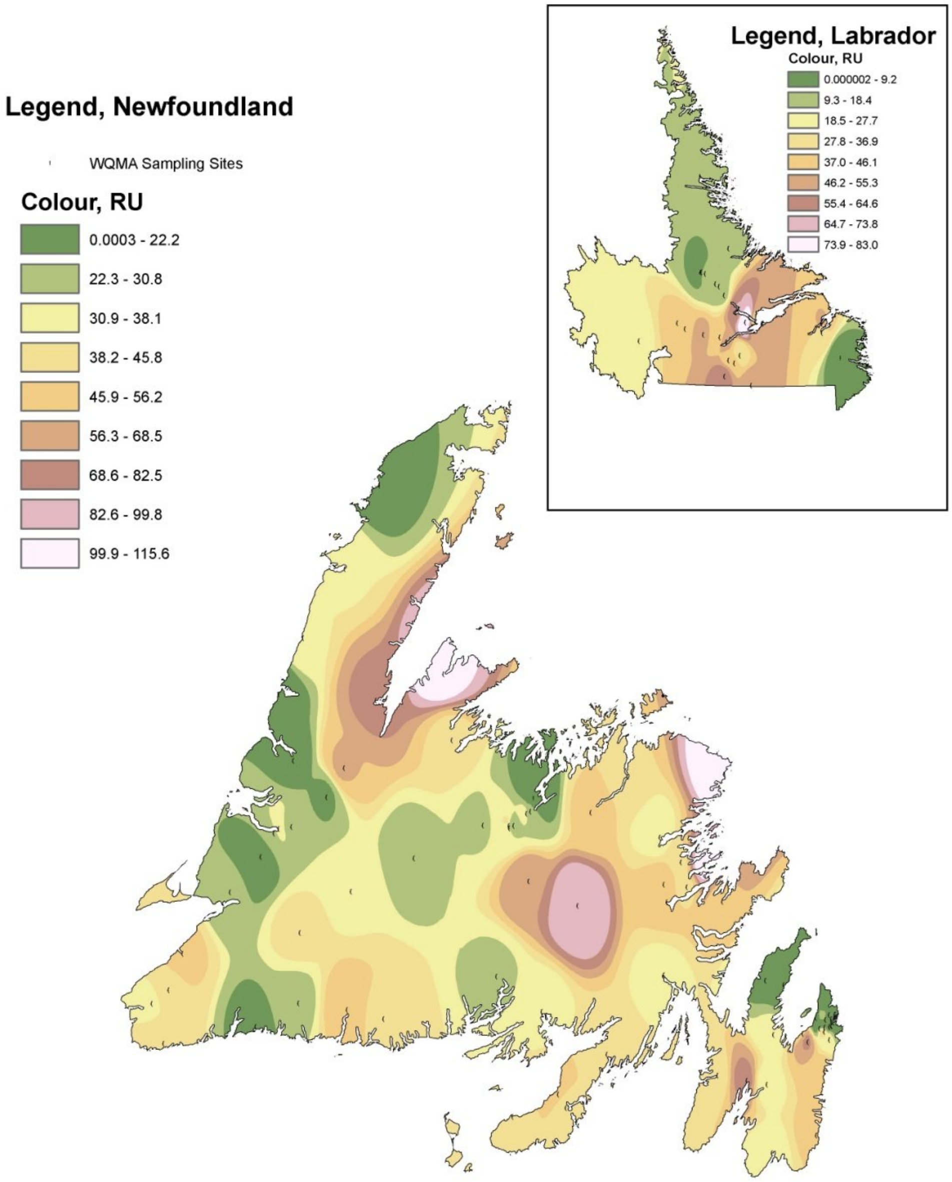
Dissolved Organic Carbon (DOC) includes soluble carbohydrates, amino acids, and other acids whose sources include photosynthesis, leaching from plant leaves and roots, and soil organic matter. Levels are naturally high in the province due to the abundance of bogs and marshes. Increased levels of DOC can be a result of forest harvesting or the discharge of sewage. There is no DOC guideline for the Protection of Aquatic Life.

Government of Newfoundland and Labrador
Department of Environment and Conservation
Water Resources Management Division

Environment Canada Environnement Canada

Figure 4.1 DOC contour map

Colour Contours Based on Canada-Newfoundland
Water Quality Monitoring Agreement Data



A contour map displays regions, each of which represents a constant value for a particular parameter. These regions are approximations based on average recorded values at WQMA sites for all data collected between 1985-2000. The contour regions were estimated using a geostatistical approach known as Inverse Distance Weight (IDW), with a power of 5. The maps will be updated for every five years of new water quality data collected. Values are compared against the Canadian Council of Ministers of the Environment Water Quality Guidelines for the Protection of Aquatic Life.

A water body may be perceived as being unclean due to high colour (i.e. brown or green), but this is not necessarily the case. Large amount of bogs and marshes in this province result in a high organic content in most waterbodies, which can cause high colour. In addition, geology can influence water colour (i.e. if there is a high iron or copper content in surrounding bedrock). Industrial waste from pulp and paper production and mining operations can also add substantial colour to water. There is no colour guideline for the Protection of Aquatic Life.

Government of Newfoundland and Labrador
Department of Environment and Conservation
Water Resources Management Division

Environment Canada Environnement Canada

Figure 4.2 Colour contour map

4.1.3 Algal Blooms

Possibly due to the province's cool climate and limited agriculture, water supplies in Newfoundland and Labrador have not experienced the same levels of eutrophication as those in other parts of the country. Nonetheless, in 2007 residents near four small ponds on the Avalon Peninsula reported blue-green algae blooms. A field survey was conducted to determine the cause(s) of the blooms but the results were inconclusive. Most notably, nitrogen and phosphorous levels in most of the affected ponds were at background levels or below the detection limits. The authors hypothesized that the blooms may have resulted from temporarily increased nutrient loading during a heavy precipitation event related to Tropical Storm Chantal. In the wake of the field survey the provincial government established a blue-green algae monitoring plan. No algal blooms have been reported in the province since 2007.

4.2 Tap Water Quality

4.2.1 History of Exceedances

The high levels of DOC, colour, and UV254 measured across the province (Section 4.1), combined with a reliance on chlorine for disinfection, has historically made it difficult for many communities in Newfoundland and Labrador to meet the recommended TTHM and HAA5 guidelines of 100 µg/L and 80 µg/L, respectively.

For many years the ENVC has tracked the number of water samples taken and the number of DBP exceedances found in communities across the province. Currently, THM and HAA samples are taken four times a year. Unlike most other parameters, THM and HAA compliance is determined based on a running average calculated over the course of the entire year, so each exceedance represents a single community. Table 4.1 summarizes the total number of samples taken and exceedances noted in 2008 and 2009.

Table 4.1 Total number of THM and HAA exceedances detected in 2008 and 2009 (ENVC, 2008 and ENVC, 2009)

	2008	2009
THM		
Total Samples	957	1,130
Frequency of Sampling (samples / year)	4	4
Serviced Areas Sampled	239	283
Exceedances	111	128
% Exceeded	46%	45%
HAA		
Total Samples	316	1,528
Frequency of Sampling (samples / year)	4	4
Serviced Areas Sampled	79	382
Exceedances	n/a	144
% Exceeded	n/a	38%

The number of communities sampled was determined by dividing the number of samples taken by four, since sampling is conducted quarterly. In some cases, however, a community may have been sampled less frequently due to individual circumstances and therefore, the number of communities sampled listed in Table 4.1 might represent a slight underestimate.

In both 2008 and 2009 approximately 45% of the communities sampled had a running THM average above 100 µg/L. The HAA guideline only came into effect in 2008, so no record of exceedances was published for that year. In 2009, however, approximately 38% of the communities exceeded the guideline value of 80 µg/L.

A more detailed discussion of the THM results from 2008 is provided in the Water Resource Management Division's 2008 Annual Report. The writers of the report established that the 111 communities that reported a running THM average above the recommended limit in that year represented a total of over 80,000 people, mostly in communities with fewer than 1,000 people (ENVC, 2008). In 2009, over 130,000 people were impacted by THMs that exceeded the GCDWQ and 161,000 were affected by HAAs that exceeded the GCDWQ (ENVC, 2009). Most of these people were from communities with fewer than 1,500 people.

4.2.2 Statistical Relationships Between Measures of Organic Quality

UV transmittance at 254 nm was measured in the tap water from 133 distribution systems in Newfoundland and Labrador during the fall of 2010. UV254 was calculated as the log of UV transmittance and plotted against various other parameters. The results were provided to CBCL by the ENVC.

Water samples for other parameters, including colour, DOC, turbidity, THMs, and HAAs were taken at the same time. Linear regressions were performed to determine whether significant relationships existed between the various organic parameters and DBPs. The results are summarized in Table 4.2.

Table 4.2 Summary of regression statistics obtained during the analysis of ENVC water quality data

y	x	r^2	p	Linear Equation*	n
Organic Parameters					
UV254	DOC	0.78	< 0.05	$y = 0.045x - 0.07$	133
Colour	DOC	0.47	< 0.05	$y = 0.06x + 5.39$	133
Colour	UV254	0.84	< 0.05	$y = 216.6x - 17.3$	131
UV254	Turbidity	0.17	< 0.05	$y = 0.74x + 0.43$	127
DBPs					
TTHM	DOC	0.22	< 0.05	$y = 15.2x + 25.3$	100
TTHM	UV254	0.06	< 0.05	$y = 166.7x + 103.7$	101
TTHM	SUVA	0.00	> 0.05		98
TTHM	Colour	0.00	> 0.05		100
TTHM	pH	0.02	> 0.05		100
TTHM	Chlorine	0.05	< 0.05	$y = 39.6x + 113.4$	109
THAA	DOC	0.17	< 0.05	$y = 25.4x + 27.6$	97
THAA	UV254	0.04	< 0.05	$y = 263.0x + 161.5$	98
THAA	SUVA	0.00	> 0.05		96
THAA	Colour	0.01	> 0.05		97
THAA	pH	0.04	> 0.05		95
THAA	Chlorine	0.23	< 0.05	$y = 160x + 118.5$	108

*equations are only displayed for pairs of variables that are significantly correlated to one another

A significant positive linear relationship was found between the UV254 and DOC results ($r^2 = 0.78$, $p < 0.05$). This indicates that UV254 is a moderately good proxy for DOC in the water supplies used in the province; a useful finding that also suggests that much of the NOM present in surface water supplies in the province is aromatic in nature (likely falling into the hydrophobic acid fraction). An even stronger relationship ($r^2 = 0.84$, $p < 0.05$) was found to exist between UV254 and colour. The strength of these relationships is surprising because the UV transmittance measurements were conducted on unfiltered tap water samples, while the DOC and colour measurements were made on samples that had been filtered through a 0.45 µm filter. The unfiltered samples would be expected to contain solids, which can lower the UV transmittance measured by the technician.

The existence of a strong correlation between UV254 and DOC despite the differing lab procedures can explained by the fact that most surface water in Newfoundland and Labrador is low in turbidity but high in NOM. Thus, the filtered water sample is usually expected to be very similar to the unfiltered sample. Nonetheless, there was indeed a weak but significant relationship between turbidity and UV254 measured in the fall of 2010 ($r^2 = 0.17$, $p < 0.05$), which may have weakened the correlation between UV254 and DOC to some degree.

DOC was found to be weakly correlated to both TTHM and THAA at a 95% confidence interval ($r^2 = 0.22$ and 0.17, respectively). The fact that the relationship was significant is not surprising as the total amount of organic DBPs formed during chlorination is dependent on the amount of carbon available for reaction. The low r^2 values, however, indicate that other factors (NOM reactivity, chlorine dose, reaction time, etc.) also have an influence on DBP formation.

Linear regressions were also performed on the UV254, THM, and HAA results from the 2010 UVT/UVA sampling program. Very weak but significant positive relationships were found between UV254 and TTHM and UV254 and THAA. As with DOC, the poor correlation between these parameters was likely as a result of differences in chlorine dose, residence time, or other important parameters between communities.

The relationships between DOC and DBPs were stronger than those between UV254 and DBPs, perhaps due to interference in the UVT measurements by turbidity or because DBPs were being formed by NOM species that don't absorb UV light at 254 nm. Differences in chlorine dose, retention time, and overall water quality likely also contributed to the poor correlations among variables. Significant positive relationships similar to those found by other researchers (Edzwald et al., 1987; Najm et al., 1994; Shorney et al., 1999; White et al., 2003; Chowdhury and Champagne, 2008) would be expected between these parameters under controlled conditions.

4.2.3 Treatability

The suitability of coagulation and UV disinfection can be predicted using SUVA and UVT, respectively. As discussed in Section 4.2.2, the ENVC conducted two sampling programs in 2008 and 2010 to establish the UV transmittance (UVT) of various water supplies across the province. In both cases, unfiltered tap water samples were analyzed using a handheld instrument. The results of the eastern portion of the 2008 sampling program are summarized in a report prepared by the ENVC entitled 'UVA and UVT Investigation: Eastern Region of Newfoundland and Labrador' (ENVC, 2008). In 2010, water samples were also tested for other water quality parameters such as DOC, colour, turbidity, pH, and alkalinity. Measured UVT ranged from 13.1% to 99.9% during the 2010 sampling program.

Edzwald (1993) discussed the use of SUVA as an indicator of the tendency of the NOM in a given water sample to respond to coagulation with metal salts. Specifically, it indicates whether the coagulation process is controlled by the concentration of DOC, which is the ideal situation for NOM removal through coagulation. The SUVAs of the water samples analyzed during the aforementioned ENVC study are summarized in Figure 4.3. In his paper, Edzwald cited previous work that showed that a SUVA above 4 is indicative of this condition. 61% of the water supplies for whom a SUVA value could be calculated had a SUVA above 4, indicating that coagulation would likely be a successful treatment option for NOM removal in these communities. These communities are listed in Appendix D.

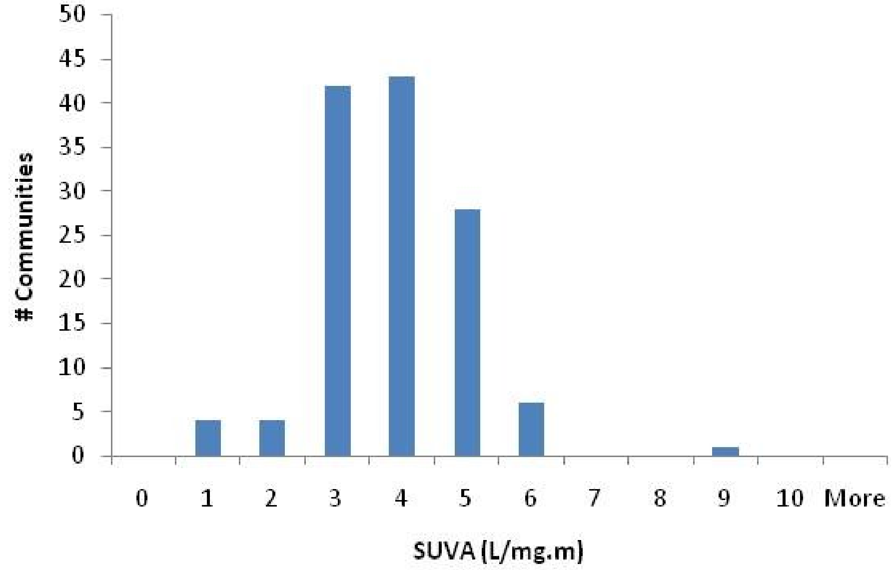


Figure 4.3 SUVA of tap water analyzed in 128 communities in Newfoundland and Labrador in the fall of 2010

UV disinfection is only feasible if the water has a transmittance above 75% at 254 nm. The choice to measure the UVT of the unfiltered water was appropriate for the study being conducted at the time, which sought to establish the feasibility of using UV disinfection in different communities in the province. The majority of the UVT results fell below the usual cut-off of 75% transmittance for UV disinfection units, as shown in Figure 4.4.

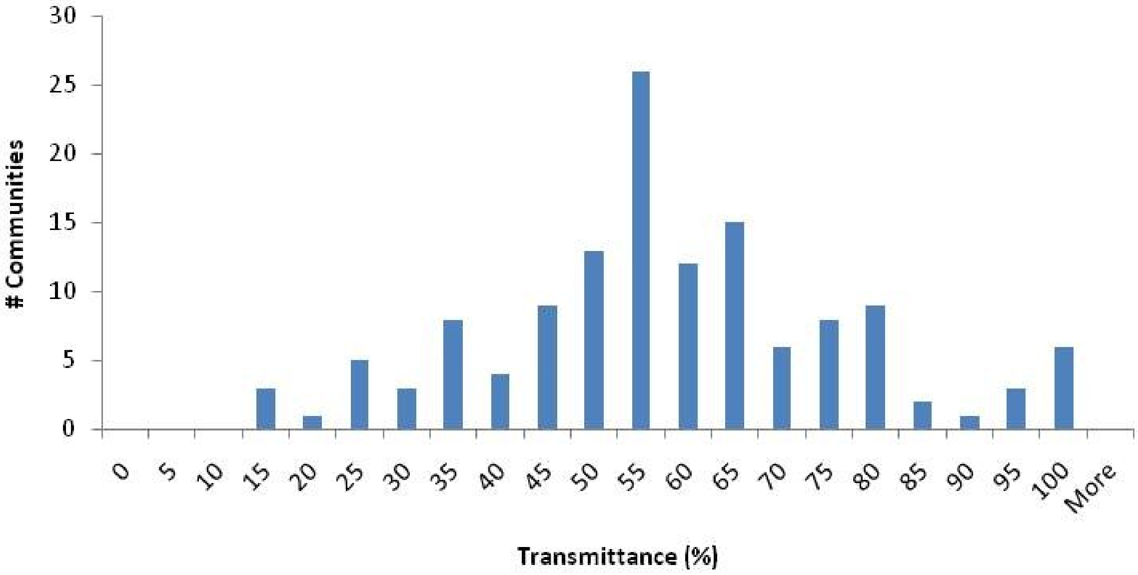


Figure 4.4 Tap water transmittance measured in 134 communities in Newfoundland and Labrador in the fall of 2010

Of the 134 water systems sampled for UVT, only 22 had high enough transmittance to justify the use of UV disinfection. A summary of these is presented in Appendix D.

The SUVA and UVT results presented in this section represent only one sampling event and thus do not take into account seasonal or other variations in water quality. Consequently, they should not be assumed to provide a complete picture of the range of water quality experienced in each community. Further sampling (preferably monthly) should be conducted before drawing any definite conclusions about the suitability of coagulation or UV disinfection in these communities.

4.3 Evaluation of Existing Treatment Plants

Sixteen water treatment plants (WTPs) are currently in operation in Newfoundland and Labrador. A seventeenth is still in commissioning but is expected to come online shortly. The ENVC provided CBCL with historical water quality records for each of the sixteen operational WTPs along with some information about the characteristics of the systems, including their year of commissioning. These are summarized in Table 4.3.

Table 4.3 Summary of water treatment processes

Community	Treatment Process(es)	Commissioned
Channel – Port aux Basques	Packaged Conventional	1988
Clarenville	Conventional	2007
Conne River	Membrane (NF)	2006
Deer Lake	Thread filtration (3 µm)	2001
Gander	Ozone and filtration	2006
Grand Falls	Conventional	1996
Happy Valley – Goose Bay	Semi-conventional*	2002
Heart’s Delight – Islington	Conventional with mixed oxidants	2001
Lourdes	Semi-conventional**	2004
Lumsden	Conventional	1972
Musgrave Harbour	Conventional	1996
Pasadena	Thread filtration (3 µm)	2002
Placentia	Ozone and dual-media filtration	1991
Ramea	Packaged Conventional	2002
St. John’s – Big Bay Bulls	Ozone and dual-media filtration	1978
St. John’s	Membrane (MF)	2007

*groundwater - oxidation followed by greensand filtration

**cyclone filters, periodic coagulation, and multimedia filtration

Five of the most important parameters used to assess organic removal and predict the likelihood of DBP formation are DOC, colour, turbidity, pH, and bromide. Table 4.4 presents a summary of the average values of these parameters measured in the water sources used to supply the sixteen water treatment plants in the province.

Table 4.4 Average raw water quality in participating communities (ENVC, 2000-2009)

Community	Source Type	DOC	Colour	Turbidity	pH	Bromide
		mg/L	TCU	NTU		mg/L
Channel-PAB	Pond	7.3	99	0.78	5.32	0.01
Clarenville	River	6.4	52	0.53	6.46	0.01
Conne River	Brook	5.0	47	0.47	5.39	0.04
Deer Lake	Lake and canal	3.2	23	0.36	6.92	0.02
Gander	Lake	5.4	44	0.45	6.41	0.02
Grand Falls	Lake	4.9	36	0.65	6.43	0.01
Happy Valley - Goose Bay	Groundwater	1.3	32	12.15	7.05	0.27
Heart's Delight	Pond	7.0	42	0.50	6.11	0.01
Lourdes	Brook	6.2	51	1.07	7.95	0.02
Lumsden	Pond	10.0	143	1.44	5.39	0.02
Musgrave Harbour	Pond	11.4	134	4.33	5.90	0.02
Pasadena	Pond	4.1	25	0.42	7.07	0.02
Placentia	Pond	6.2	40	0.57	6.00	0.02
Ramea	Pond	9.4	174	1.57	5.56	0.14
St. John's BBB	Pond	3.2	21	0.61	6.15	0.01
St. John's	Lake	2.2	6	0.50	6.13	0.01

Tap water quality varies between communities and despite the existence of WTPs, many communities continue to experience high levels of THMs and HAAs, as shown in Table 4.5.

Table 4.5 Average tap water quality in participating communities (ENVC, 2000-2009)

Community	DOC	Colour	Turbidity	pH	THMs	HAAs
Units	mg/L	TCU	NTU		ug/L	ug/L
Channel - PAB	2.3	1	0.5	5.8	56	125
Clarenville	2.1	5	0.6	7.1	61	63
Conne River	3.5	15	0.3	6.3	139	154
Deer Lake	3.5	17	0.3	6.6	51	66
Gander	6.0	23	0.4	6.5	187	107
Grand Falls-Windsor	2.5	2	0.5	6.8	83	100
Happy Valley-Goose Bay	0.6	1	0.3	7.1	63	42
Heart's Delight	3.8	9	0.3	6.9	111	89
Lourdes	6.3	19	0.9	7.4	176	180
Lumsden	3.6	8	0.8	6.9	62	87
Musgrave Harbour	4.2	5	1.1	6.4	101	182
Pasadena	5.1	13	0.3	6.7	106	189
Placentia	8.0	29	0.8	6.5	94	96
St. John's BBB	3.3	8	0.4	6.7	20	53
St. John's	2.0	3	0.4	6.5	40	45
Ramea	2.1	4	0.7	6.7	279	62

In general, communities with higher historical concentrations of DOC and colour were found to have higher levels of THMs and HAAs, though this was not always the case. For example, TTHMs in Ramea have averaged 279 µg/L while DOC has averaged only 2.1mg/L in the tap water. The high rate of THM formation could be related to the relatively high pH, which can favour the formation of THMs, or the water supply's elevated bromide levels. Alternatively, the apparent lack of correlation between DOC and THM results for Ramea may simply reflect a sampling schedule where these two measurements were taken at different times of the year. Other factors, such as the distribution and reactivity of NOM species, chlorine dose, and system retention time, can also impact the formation of THMs and HAAs and may help to explain the imperfect relationship between DOC and DBPs in the town's tap water.

For most of the communities in the study, the underlying distribution of the parameters presented in Tables 4.4 and 4.5 is skewed to the left (low values) with infrequent outliers to the right (high values). This highlights the variable nature of the water quality found in most of these raw water supplies. Nonetheless, an average value has been calculated for each parameter so that communities can be compared to one another. It should be kept in mind, however, that most of the communities being profiled experience large fluctuations in water quality, which partly explains their occasionally poor performance. Tables of minimum and maximum values for DOC, colour, turbidity, pH, and bromide parameters detected in each water supply are provided in Appendix E.

Average DOC, colour, TTHMs, and HAA5 from before and after the commissioning of these and the other thirteen WTPs in Newfoundland and Labrador are provided in Appendix F. Each table also includes the p-values obtained when a student's t-test was used to determine the significance of the differences in pre- and post-WTP water quality.

The following four case studies present a more detailed analysis of the effects of different water treatment processes on tap water quality in towns in Newfoundland and Labrador.

4.3.1 Case Study – Ozone and Filtration

The Town of Gander commissioned their ozone and filtration plant in early 2007. Since then the concentrations of THMs and HAAs have decreased, though they are still frequently above the recommended guideline values of 100 µg/L and 80 µg/L respectively. The data presented in Figure 4.5 shows this clearly.

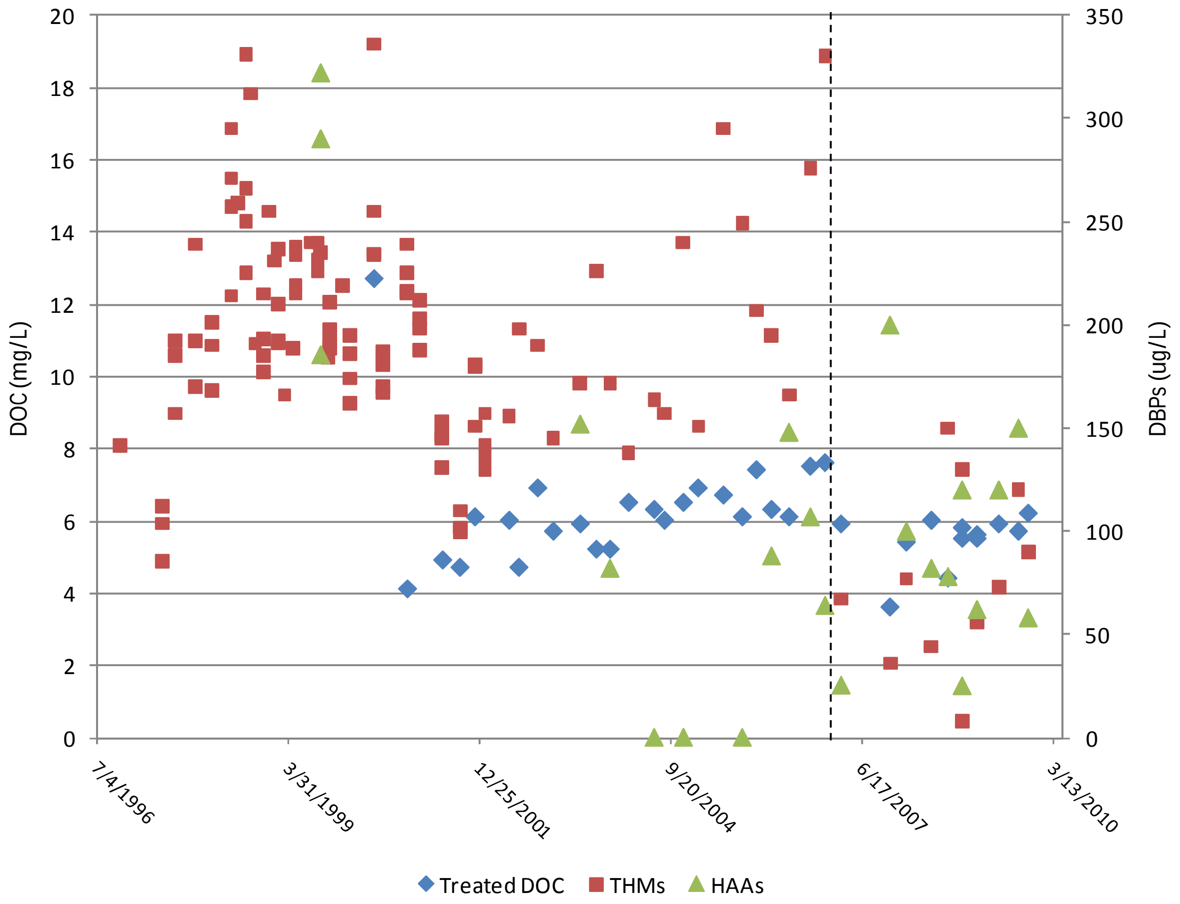


Figure 4.5 DOC, THMs, and HAAs in the tap water in Gander (ENVC, 1996-2009)

Ozone is known to react with large, aromatic NOM species and convert them to smaller, less reactive compounds (Section 2.5.3). As a result, the ozone treatment system should not be expected to decrease the total amount of DOC in the water but rather should reduce the amount of THMs and HAAs formed when chlorine is added for primary or secondary disinfection. This trend is apparent in the historical water quality dataset from Gander.

The slight reduction in DOC apparent after the commissioning of the treatment plant may be related to adsorption or biodegradation of ozonated NOM species in the media and/or GAC filters that follow the ozone contact chamber. It may also be due to seasonal changes in water quality.

The total concentration of THMs measured in the tap water decreased dramatically after the commissioning of the treatment plant, dropping from an average of 186 µg/L to 77 µg/L. A student's t-test conducted on the data confirmed that the decrease was significant ($p < 0.05$). The average HAA5 dropped from 120 µg/L to 93 µg/L, but this change was not found to be significant. Interestingly, however, the addition of ozone did change the types of HAAs being formed. Trichloroacetic acid (TCAA) dropped from an average of 82 µg/L to 37 µg/L and monobromoacetic acid increased from undetectable to an average of 6.1 µg/L. This suggests that the ozone treatment was indeed affecting the reactivity of the NOM.

4.3.2 *Case Study – Conventional Treatment*

Conventional treatment systems, which include coagulation, flocculation, sedimentation, and filtration steps, have been used for NOM removal for many years. The effectiveness of a conventional system is dependent on its ability to induce NOM to precipitate out of solution and remove the resulting particulate through sedimentation and/or filtration. If a system is not achieving good organic removal the problem can often be traced back to the coagulation conditions.

The Town of Heart's Delight-Islington relies on a conventional WTP to treat their potable water. The DOC, THM, and HAA results from the past ten years are shown in Figure 4.6.

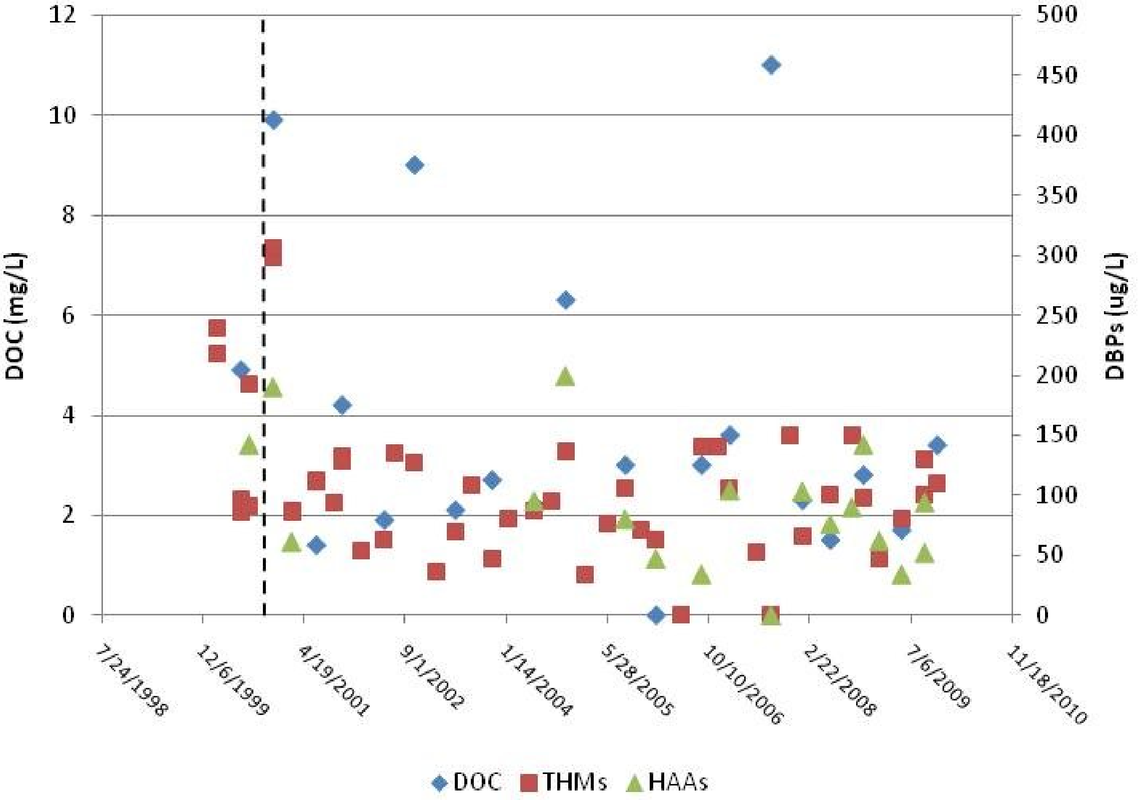


Figure 4.6 DOC, THMs, and HAAs in the tap water in Heart's Delight-Islington (ENVC, 1999-2009)

Overall, the DOC of the tap water has hovered between 2 and 4 mg/L, though on occasion it has been as high as 11 mg/L. The average DOC of the tap water did not decrease significantly after the plant was commissioned but it is lower than the overall average raw water DOC. It is difficult to confirm the latter, however, as the raw and tap water DOC readings were rarely performed on the same day. The few paired data points suggest that DOC removal has ranged from 0% to 65%.

Inadequate organic removal can often be traced back to the coagulation step. Factors such as pH, overall water quality, coagulant dose, and mixing intensity can impact the effectiveness of the coagulation process. Very little information was available during this study to determine the exact reasons behind the poor organic removal at the Heart's Delight WTP, but the low pH and turbidity of the raw water suggest that water quality is not to blame. The system should be assessed in greater detail to establish whether the poor performance is a result of system design, system operation, or a combination of the two.

Average THM and HAA concentrations have decreased since the WTP came online, though both parameters are still frequently above the recommended guideline limits of 100 µg/L and 80 µg/L, respectively. As described in Chapter 2, coagulation processes are often assumed to remove, rather than transform, NOM species, so it is somewhat surprising that DBP levels have decreased over time while DOC has remained constant. One possible explanation is that the mixed oxidants used for disinfection are interacting with whatever NOM molecules that are not removed in the coagulation process and transforming them into less reactive species. It is not possible to confirm this possibility with the water quality data provided for the study.

4.3.3 Case Study – Membrane Filtration

Conne River is located on the Bay d'Espoir Penisula on the Southern Coast of Newfoundland. The community is First Nations and administered by the federal government, but the ENVC still conducts regular water quality sampling. The WTP includes sand filters and a spiral-wound nanofiltration membrane for NOM removal. It was commissioned in 2006 but the dramatic improvement in water quality apparent in late 2004/early 2005 suggests that the system was operational before this point. In 2008, the system was taken offline due to operational problems. Historical DOC, TTHM, and HAA5 results are provided in Figure 4.7.

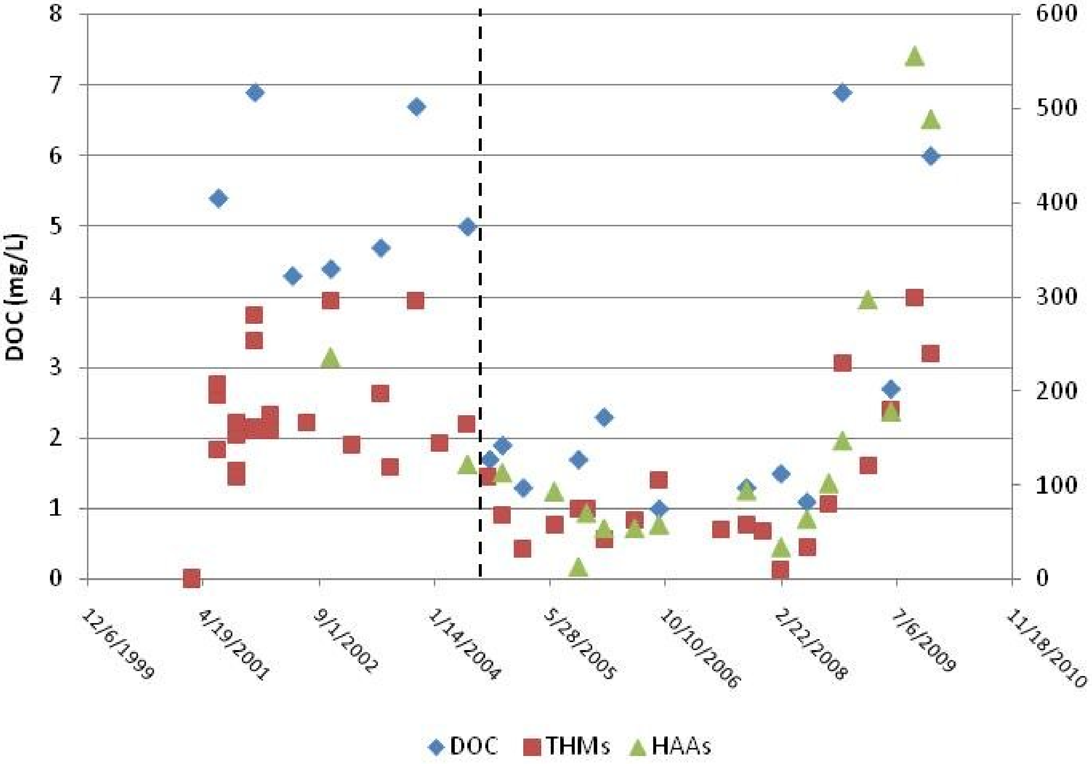


Figure 4.7 DOC, THMs, and HAAs in the tap water in Conne River (ENVC, 2001-2009)

Tap water DOC, TTHM, and HAA5 decreased dramatically when the WTP was brought online. All three increased once again when the system went offline. This shows that the nanofiltration system was effective at removing DBP precursors when it was operating.

4.3.4 *Case Study – Thread Filtration*

A few WTPs in the province rely on thread filtration units for turbidity removal. Like most filters, these work on a size exclusion basis. In the water industry, anything below 0.45 µm is considered dissolved. The thread filters used in Newfoundland and Labrador has been designed to have a specific cut-off of 3 µm, and thus would not be expected to remove any dissolved parameters such as NOM.

Figure 4.8 shows the ENVC DOC, TTHM, and HAA5 records from Deer Lake.

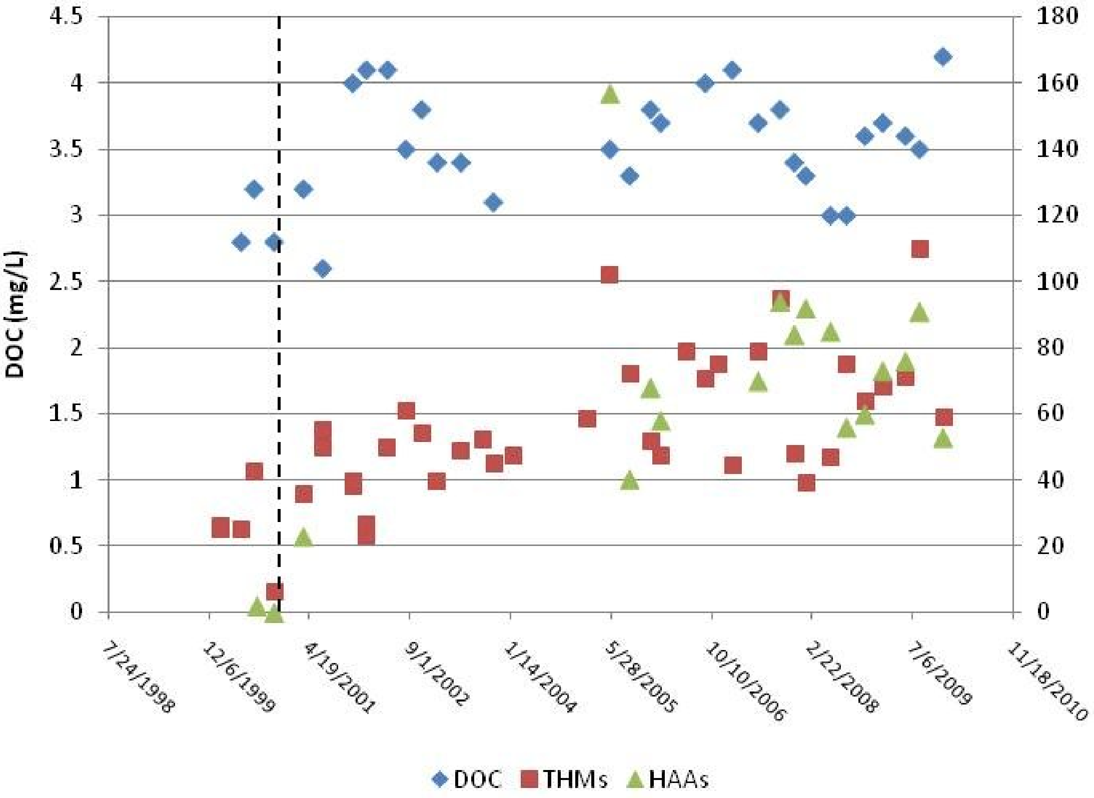


Figure 4.8 DOC, THMs, and HAAs in the tap water in Deer River (ENVC, 1999-2009)

As expected, the addition of the thread filter in Deer Lake did not result in decreased concentrations of DOC, THMs, or HAAs in the tap water. In fact, both THMs and HAAs appear to have increased over time. Since the DOC did not increase over time, it is possible that the increase in DBPs is as a result of improvements in the disinfection system. A more thorough assessment of the system might yield better information about the increase in DBPs over time.

CHAPTER 5 PARTICIPATING COMMUNITIES

5.1 Watershed and Source Water Characteristics

The information in this section was drawn from:

- Observations by CBCL staff during site visits;
- Operator questionnaires completed during site visits;
- The Newfoundland and Labrador Ecoregion Brochures project;
- Municipal documents (watershed protection plans, etc.);
- ENVC water quality and watershed characteristics records; and
- ENVC operator training records.

5.1.1 Community A

Community A draws water from a pond located to the west of the community. It is fed by several nearby ponds. The surrounding watershed covers an area of 25.6 km^2 and has a perimeter of 20.7 km. The watershed is 76% land, 20% water and 4% wetland.

The town is located in the Northeastern Barrens Subregion of the Maritime Barrens Ecoregion. This subregion is made up mostly of barrens with some pockets of bogs and forested areas. This includes slope bogs, basin bogs and fens. The forested areas are made up of balsam fir, black spruce and white birch. Mosses, heath, and berries are also present. The soil in the subregion consists mainly of humo ferric podzols and ferro humic podzols. The former occur in drier areas and are made up of mostly inorganic matter while the latter are more common in wetter areas and contain higher levels of organic matter.

The region receives an average annual rainfall of 1,250 mm to 1,300 mm. Summer temperatures generally fall between 13^{o}C and 16^{o}C while winter temperatures hover between -8^{o}C and -3^{o}C. Human activities within the watershed are generally confined to summer cottages and tourism.

Water flows from the pond to the chlorination building by gravity. The transmission main that connects the two includes portions of 450 mm (18”) concrete and 300 mm (12”) ductile iron pipe and extends over 2 km. The operator reports that the maximum raw water flow is 6,250 LPM (1,650 USgal/min).

Table 5.1 provides a summary of some of the water quality parameters measured in samples collected by ENVC from the Community A water supply between 1987 and 2009.

Table 5.1 Summary of historic water quality in the Community A water supply

Parameter	Alkalinity	Colour	pH	Turbidity	DOC	Aluminum	Iron	Lead	Manganese
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L	mg/L	mg/L	mg/L	mg/L
Average	4.1	12	6.5	0.31	2.9	0.05	0.02	0	0.01
St. Dev.	3.1	4.5	0.2	0.17	0.72	0.04	0.02	0	0
Maximum	17	21	6.9	0.70	5.1	0.21	0.05	0.002	0.02
Minimum	0	3	6.1	0.01	1.8	0.01	0	0	0

As shown in the table, over the sampling period the pond has had a pH slightly below neutral (6.5 ± 0.2) and low alkalinity (4.1 ± 3.1 mg/L as $CaCO_3$). Colour has ranged from 3 to 21 TCU, with an average of 12 TCU, which is below the GCDWQ aesthetic objective of 15 TCU. Levels of aluminum, iron, lead and manganese have also been within GCDWQ limits. DOC levels in the pond have ranged from 1.8 to 5.1 mg/L, averaging 2.9 mg/L. During the site visit the operator stated that the raw water quality tends to remain constant throughout the year.

Recent research (Section 2.2.4) suggests that DOC levels are increasing in surface water bodies throughout the northern hemisphere, possibly as a result of changes due to the recovery from acid rain and/or climate change. Figure 5.1 shows DOC and colour readings measured over time in the Community A water supply.

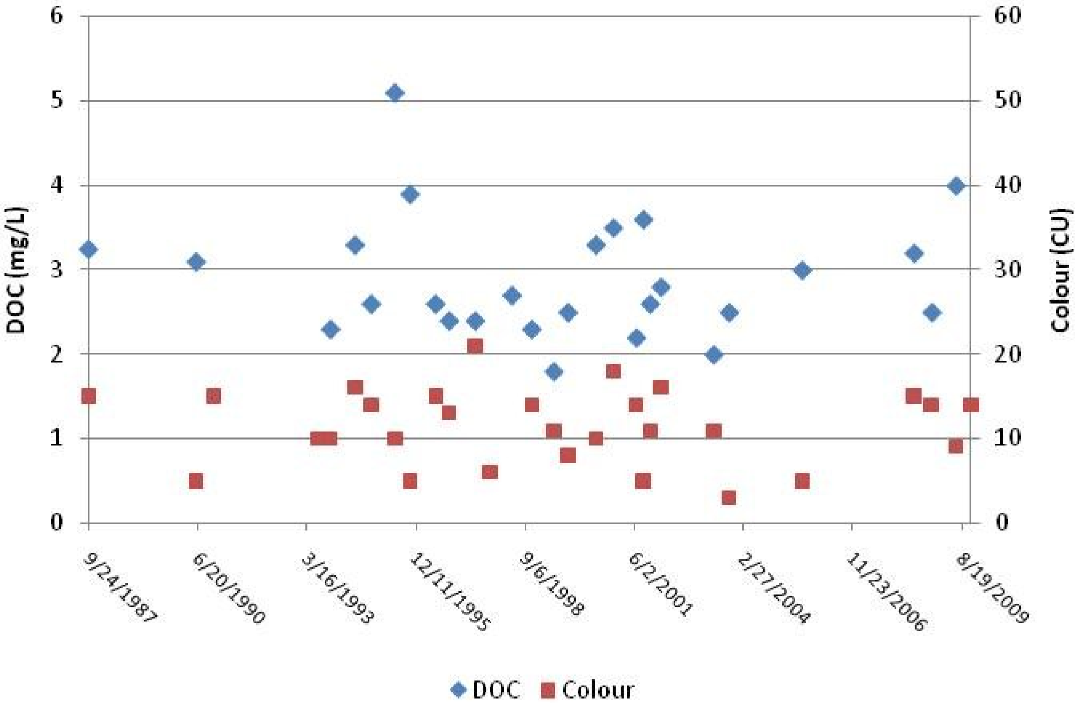


Figure 5.1 DOC and colour measured in the water supply in Community A (1987 – 2009)

No increasing trend is apparent for either parameter. This may mean that the characteristics of the water source and watershed have not changed significantly over the past twenty years or that insufficient data has been collected to date to show any important trends.

5.1.2 Community B

A nearby pond acts as the water source for Community B, which is located on the coast of Labrador. The total serviced population is listed as 522 (ENVC, 2010). The pond is in fact a man-made reservoir that was created by flooding a low-lying area near the town. This may help to explain the high levels of NOM that are regularly measured in the raw water.

Community B is located in the Coastal Barrens Ecoregion. This ecoregion encompasses most of the coast of Labrador and is characterized by stunted forests of spruce, willows, and birch, as well as bogs and barrens. Soil cover is minimal, resulting in restricted plant growth. The region receives large amounts of rain (1,000 to 3,000 mm annually) and snow (3 to 4 m annually). Temperatures remain cool throughout the year, ranging from 9°C to 13°C in the summer and -19°C to -10°C in the winter. The watershed extends across 14.2 km^2, of which 11% is water, 3% is wetlands, and 86% is dry land. A picture of the watershed is provided in Figure 5.2.

The watershed for the Community B water supply differs noticeably from those in the other communities participating in this study. Average temperatures are lower, the growing season is shorter, and the area supports a very different set of plant species. These differences might be expected to contribute to the quantity and character of the NOM present in the town's water supply.

Figure 5.2 Vegetation in the Community B watershed

The raw water intake for Community B is located approximately 2 m below the surface of the water in the pond (6' to 8'). Water flows from the pond to the chlorination building by gravity through a 200 mm iron pipe for approximately 500 m.

The pond is high in colour and DOC and has low pH, low alkalinity and low turbidity, as shown in Table 5.2.

Table 5.2 Summary of relevant water quality parameters in the Community B water supply

Parameter	Alkalinity	Colour	pH	Turbidity	DOC	Aluminum	Iron	Lead	Manganese
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L	mg/L	mg/L	mg/L	mg/L
Average	1.3	98	5.5	0.9	10.0	0.26	0.49	0	0.01
St. Dev.	3.6	31	0.4	0.4	2.3	0.09	0.17	0	0
Maximum	12.0	170	6.2	1.4	14.0	0.40	0.82	0	0.02
Minimum	0	46	4.6	0.4	7.2	0.07	0.26	0	0

The historical record shows that DOC and colour levels vary considerably but pH, alkalinity and turbidity levels tend to be more consistent. During the site visit the operator confirmed that the colour of the raw water is worse during the summer than in the winter. The concentration of iron is above that recommended for potable water by the GCDWQ. Average and maximum levels of lead and manganese are within their respective GCDWQ limits.

The DOC and colour results shown in Figure 5.3 suggest that NOM levels have increased in the water supply. This trend is not as impressive as it may initially appear. First, only 11 data points were available in the historical records. Second, prior to 2005 all samples were taken in the middle of the summer. After 2005, the ENVC began collecting a second annual sample in October in addition to that collected in July. The four highest points on the graph represent the four October samples – otherwise the summer DOC and colour levels have remained constant since 2001.

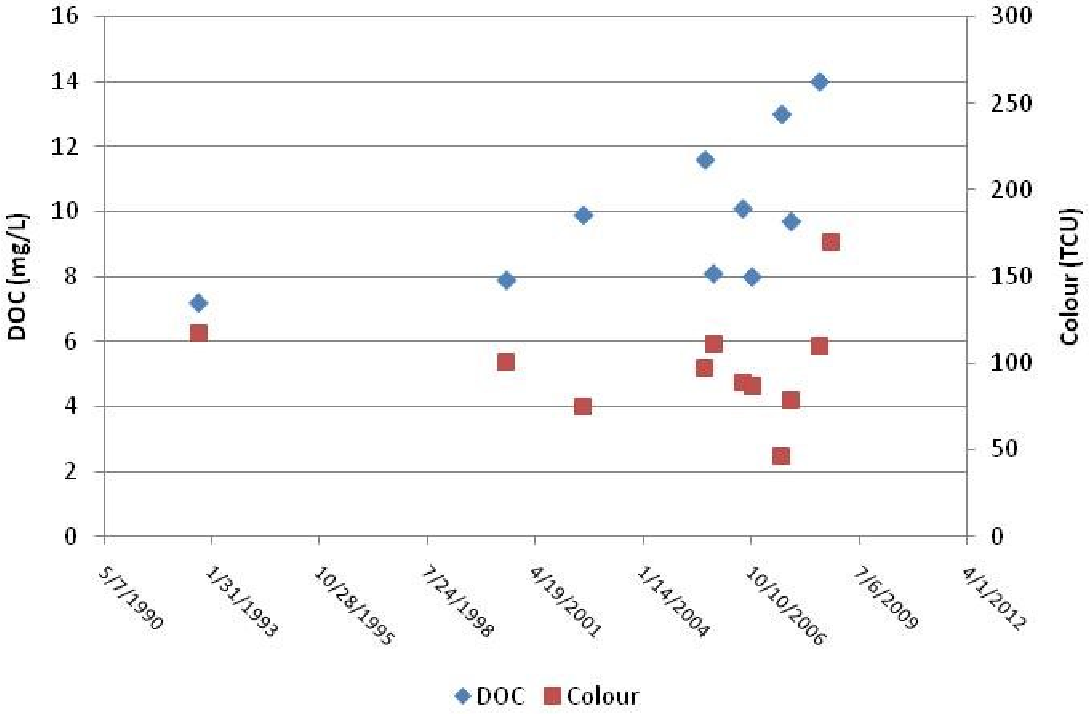


Figure 5.3 DOC and colour measured the Community B water supply (1992 – 2009)

5.1.3 Community C

Community C draws water from a reservoir style water supply. It was created by damming a small water system and flooding the surrounding area. The supply lies to the northeast of the town close to the WTP.

The land surrounding the water supply is mostly made up of barrens. Like many other parts of the province, these barrens are a relic from the time of European settlement when the colonists burned and/or cleared most of the trees. This changed the drainage patterns of the surrounding land and may help to explain some of the water quality issues that continue to plague the area. The watershed itself has an area of 11.19 km^2 and is made up of 11% water and 89% dry land, all of which can be considered barrens. The watershed is considered to be free of wetlands. Soils are mostly made up of inorganic humo ferric podzols and common vegetation includes dwarf shrub heaths, berries, and small pockets of forest in areas protected from the wind. Some researchers have drawn a connection between the presence of heaths in the watershed and high NOM levels, but insufficient data is available for this study to determine whether this has anything to do with the water quality in the Community C water supply. Figure 5.4 shows some of the land cover found in the Community C watershed.

Figure 5.4 Vegetation in the Community C watershed

Table 5.3 provides a summary of some of the relevant water quality parameters measured in water samples drawn from the Community C water supply as part of the ENVC water sampling program between 1988 and 2009.

Table 5.3 Summary of relevant water quality parameters in the Community C water supply

Parameter	Alkalinity	Colour	pH	Turbidity	DOC	Aluminum	Iron	Lead	Manganese
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L	mg/L	mg/L	mg/L	mg/L
Average	1.1	98	5.3	0.8	7.3	0.17	0.25	0	0.01
St. Dev.	1.9	51	0.5	0.6	2.8	0.08	0.11	0	0.01
Maximum	7.0	250	6.5	3.6	13.0	0.35	0.58	0.01	0.03
Minimum	0	35	4.6	0.1	0.4	0.03	0.11	0	0

During the sampling period the water from the water supply has been characterized by low pH, low alkalinity, and moderate turbidity. Colour and DOC have been high and variable, ranging from 35 to 250 TCU and 3.6 to 13.0 mg/L respectively. The concentration of aluminum has ranged from 0.11 mg/L to 0.58 mg/L. The average concentration of iron has remained below the aesthetic objective of 0.3 mg/L, but concentrations of up to 0.58 mg/L have been measured, suggesting that iron may periodically be a problem for the community. Lead and manganese results have both been below GCDWQ recommended levels in all samples collected by the ENVC.

The graph in Figure 5.5 shows DOC and colour results obtained from sampling between 1998 and 2009.

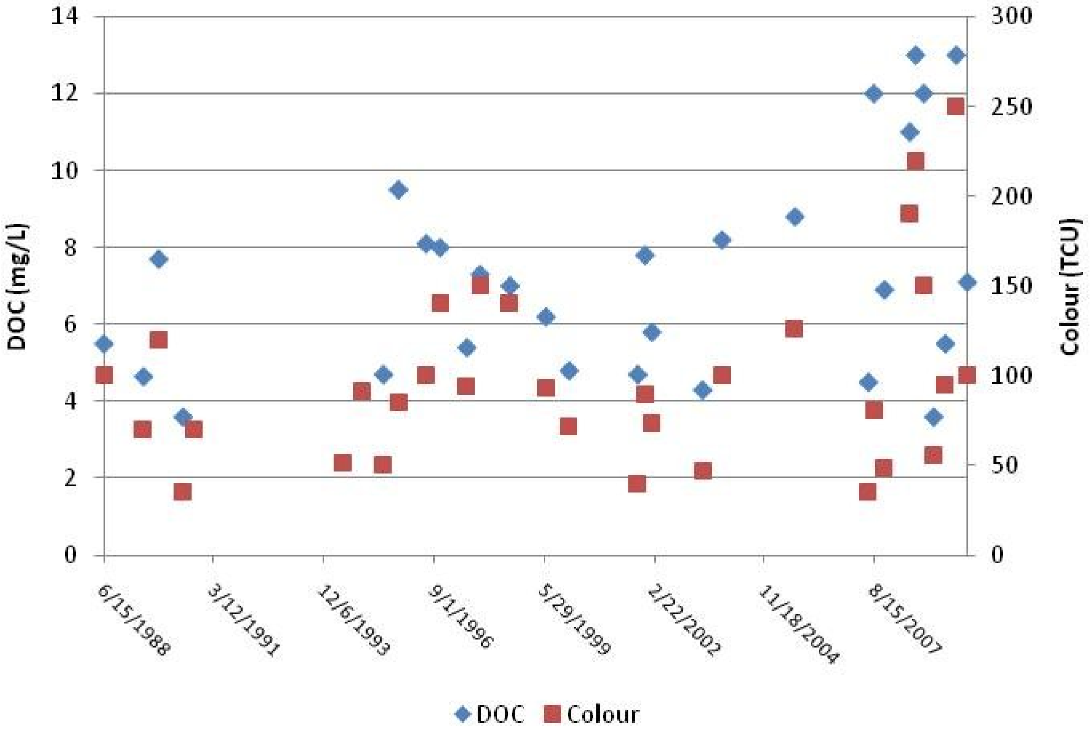


Figure 5.5 DOC and colour measured in the Community C water supply (1988 to 2009)

Both DOC and colour appear to have increased over time in the Community C water supply. This became particularly noticeable after 2007. This trend might be related to the expansion of the water supply. The original reservoir was formed by installing a dam on a pre-existing water system and allowing the surrounding area to flood. This supply proved to be unreliable due to seasonal fluctuations and was expanded in 2002 by installing a second dam approximately 46 m (150') from the original. This flooded a larger area and, according to the operator, led to deterioration in water quality, in particular NOM levels, at the inlet to the WTP. The dam system is shown in Figure 5.6.

Figure 5.6 Dam system on the Community C water supply

5.1.4 Community D

Community D draws its water from a large lake adjacent to the town. With a surface area of 112 km^2, this lake is one of the largest in the Central Region of the Island of Newfoundland. It is fed by two major rivers and a plethora of smaller streams. One river drains from the northwestern portion of the lake. The lake provides water for a number of other communities besides Community D.

A detailed assessment of the lake was conducted in 1995 and 1996 during the development of a watershed management plan for the area. The authors classified the lake as oligotrophic and dimictic, meaning that it is characterized by low biological productivity (minimal algal growth) and turns over twice a year (EDM, 1996).

Community D is located in the Central Newfoundland Forest ecoregion, in the North-Central Subregion. This subregion is known to be home to many tree species including black spruce, white spruce, trembling aspen and balsam fir. Mosses, lichens, and heath are also common. Bogs in the subregion are generally of the 'domed' variety. The most common type of soil is humo ferric podzols, though the area close to the town is known to have organic deposits as well.

The North-Central Subregion receives approximately 1,200 mm of rain and 3 to 3.5 m of snow each year. Winter temperatures generally range from -8°C to -4°C while summer temperatures are generally between 15 °C and 16°C, although highs above 20°C are recorded on occasion.

The watershed that surrounds the Community D water supply has a perimeter of 273 km and a surface area of 1,676 km^2. Wetlands make up 11% of the total land area. The main land uses in the watershed are forestry and recreation, including a large number of summer cottages. Additional information on the watershed can be found in its watershed management plan (EDM, 1996).

Table 5.4 provides a summary of the raw water quality in Community D Lake. The data was drawn from ENVC water quality records.

Table 5.4 Summary of relevant water quality parameters in the Community D water supply

Parameter	Alkalinity	Colour	pH	Turbidity	DOC	Aluminum	Iron	Lead	Manganese
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L	mg/L	mg/L	mg/L	mg/L
Average	4.5	43.8	6.4	0.5	5.4	0.12	0.05	0	0.01
St. Dev.	3.1	5.5	0.2	0.4	1.3	0.13	0.03	0	0.01
Maximum	13.0	58	6.9	1.8	7.5	0.73	0.12	0	0.02
Minimum	0	29	5.9	0	1.1	0.03	0	0	0

The raw water in the water supply is characterized by relatively low pH and alkalinity, moderate colour and DOC, slightly elevated aluminum and low levels of iron, lead, and manganese. Figure 5.7 shows the DOC and colour measured in the Community D water supply between 1993 and 2009.

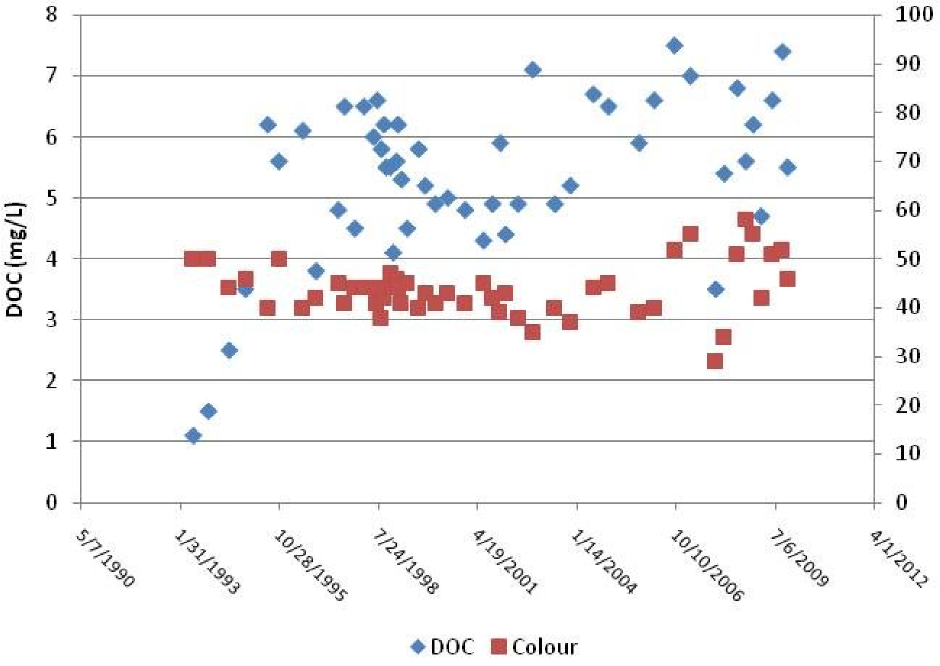


Figure 5.7 DOC and colour in the Community D water supply (1993 – 2009)

DOC appears to have increased during the early 1990s and then remained between 4 and 8 mg/L thereafter with no obvious increasing or decreasing trend. This might be related to changing watershed characteristics or, more likely, seasonal effects being masked by changes in the sampling schedule from year to year. In her 2006 study, which took into account seasonal effects, Dawe found evidence of increasing DOC in one of the inflows to Community D Lake but no such trend in one of the outflows.

Colour remained constant between 30 and 60 TCU throughout the ENVC sampling period (1993 to 2009). This contrasts with water quality measurements taken during the preparation of the town's watershed management plans. The colour measured in these samples, which were taken from 9 different locations in the lake in June and September of 1995, was reported to be between 0 (non-detect) and 38 TCU (EDM, 1996).

5.1.5 Community E

Community E draws its water from a nearby brook. The surrounding watershed is located in the Corner Brook Subregion of the Western Newfoundland Forest Ecoregion. This area is characterized by limestone geology and large forests. Balsam fir is the most common tree species, though pockets of black spruce, yellow birch, red maple, white pine, and black ash are also present. The soil is mostly made up of alkaline eutric brunisols and mostly inorganic humo ferric podzols. The region receives approximately 1,200 mm of rain and 2 to 4 m of snow each year. Summer temperatures range from 14°C to 16°C while winter temperatures range form -8°C to -5°C.

In 2005, Community E released a watershed management plan. This document outlines the characteristics of the watershed and evaluates the impacts of human activities within it. The watershed itself is 40.8 km in perimeter and has an area of 76 km^2. It is made up of 91% dry land, 3% wetlands and 6% water. Most of the dry land consists of bedrock, which is mostly forested or covered by shrub, as shown in Figure 5.8.

Figure 5.8 Community E water supply and watershed

Community E is adjacent to a ski complex, which is also supplied with water by the brook. In the winter, the resort uses higher volumes of water to provide water to guests and to make snow. The two systems used to share a common intake system, which split into two separate transmission mains before the chlorination building used to disinfect the water sent to the town. This resulted in poor water quality in town when the resort was operating. The single intake has recently been replaced by a pair of separate intakes to minimize these effects.

Fishing, hunting, and berry picking are other common recreational activities within the limits of the watershed. The forestry industry is also active in the area, though its impact has diminished in recent years.

As shown in Table 5.5, the water is high in DOC, colour, iron, and manganese. All of these are variable, as would be expected in a brook.

Table 5.5 Summary of water quality data from the Community E water supply

Parameter	Alkalinity	Colour	pH	Turbidity	DOC	Aluminum	Iron	Lead	Manganese
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L	mg/L	mg/L	mg/L	mg/L
Average	2.1	60	5.9	0.5	6.8	0.03	0.24	0	0.03
St. Dev.	2.2	16	0.4	0.3	2.6	0.35	0.15	0	0.05
Maximum	10.0	106	6.7	1.7	13.8	0.08	0.80	0	0.21
Minimum	0	34	5.1	0.1	4.2	0.13	0.09	0	0

It should be noted that to date no water samples have been collected during the winter months when increased tourism would be expected to impact water quality. Thus, the results presented in Table 5.5 may not be representative of worst-case conditions, particularly with respect to turbidity.

The total amount of NOM in the Community E water supply does not appear to have increased over time, as illustrated by the DOC and colour data presented in Figure 5.9.

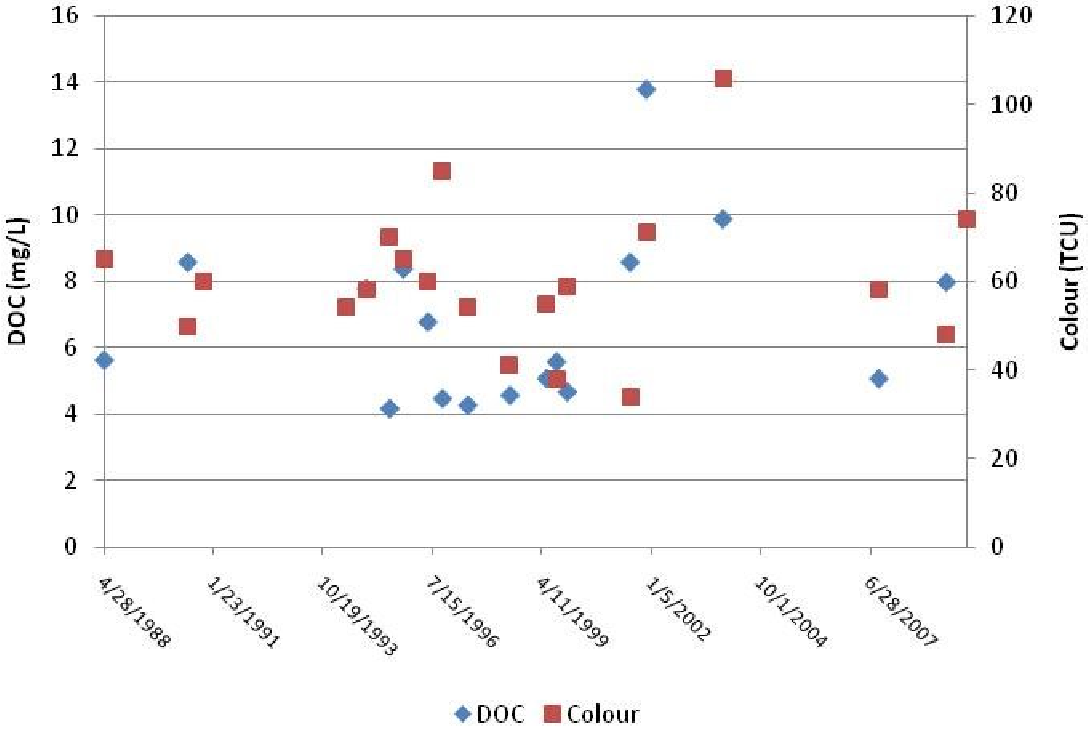


Figure 5.9 DOC and colour in the Community E water supply (1988-2009)

5.1.6 Community F

A nearby pond serves as the water supply for the Community F. A summary of water quality data from the pond obtained from the ENVC is presented in Table 5.6.

Table 5.6 Summary of water quality parameters measured in the Community F water supply

Parameter	Alkalinity	Colour	pH	Turbidity	DOC	Aluminum	Iron	Lead	Manganese
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L	mg/L	mg/L	mg/L	mg/L
Average	28.0	49	7.2	0.5	6.5	0.07	0.08	0	0.01
St. Dev.	3.4	11	0.3	0.4	2.6	0.05	0.08	0	0.01
Maximum	34.0	70	7.5	1.5	10.6	0.18	0.42	0	0.05
Minimum	20.9	21	6.6	0.1	1.0	0.01	0	0	0

The pond tends to have elevated levels of DOC and colour, moderate alkalinity and pH, low turbidity and lead, and moderate levels of iron, manganese and aluminum. TDS (shown in Appendix B) is high relative to the other water sources evaluated during the study, likely because the pond is located adjacent to the ocean.

Even more so than the water supplies in many of the other communities, the DOC measurements for the Community F water supply have been highly variable. There is no evidence, however, of an increasing trend in either DOC or colour, as shown in Figure 5.10.

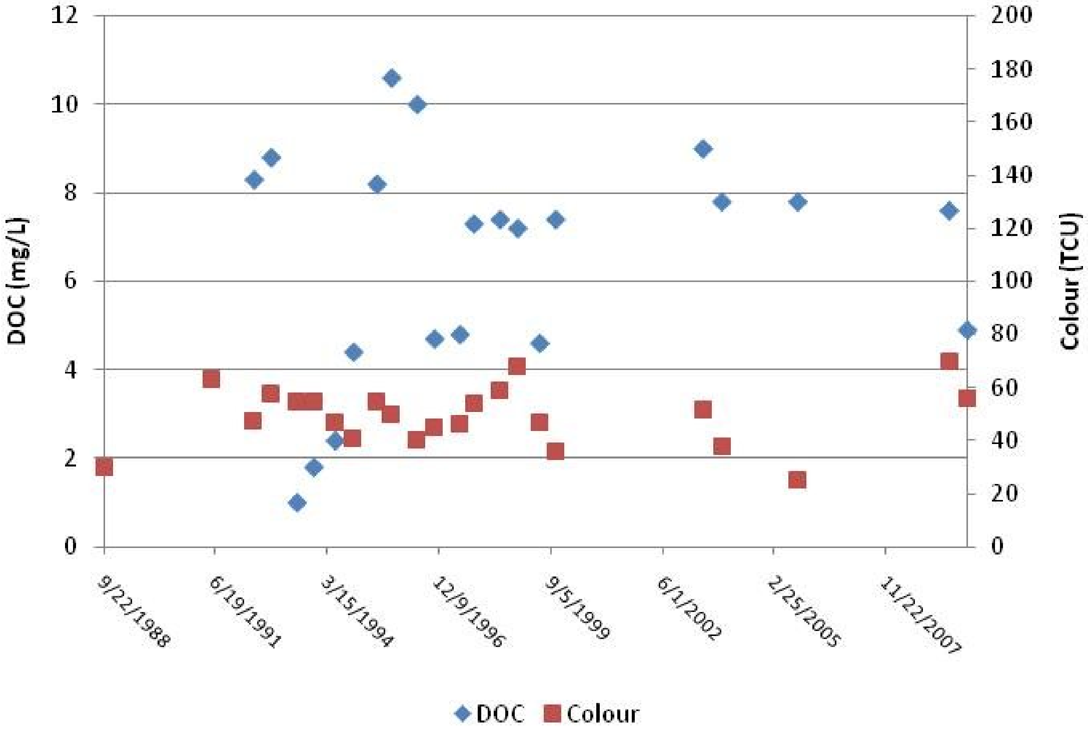


Figure 5.10 DOC and colour in the Community F water supply (1998 - 2009)

The Community F Pond watershed covers an area of 2.7 km^2, with a total perimeter of 11.2 km. The watershed is 8% water, 3% wetland, and 89% dry land. During the site visit the operator indicated that two or three brooks flow into the pond and there is only one outlet.

The watershed is located in the North Shore Forest Ecoregion, which extends across the north central coast of the island of Newfoundland from the Baie Verte peninsula to Bonavista Bay. The North Shore Forest, appropriately enough, is home to a variety of trees including black spruce, balsam fir, and white spruce. The area also includes stretches of swamps and barrens, which are home to smaller plants, including and variety of alders and berries. Soils in the area are generally made up of humo ferric podzols, organic fibrisols, and ferro humic podzols. The ecoregion receives between 1,100 and 1,300 mm of rain each year. There is little snow accumulation. The average summer temperature is approximately 16°C, while that in the winter ranges from -7 °C to -5°C.

5.1.7 Seasonal Effects

The importance of seasonal changes in NOM quantity and characteristics has been mentioned numerous times in earlier sections. Some examples of this are provided in Figure 5.11 and Figure 5.12, which show the average DOC measured in the water supplies for Community C and Community D at different times of the year. These communities were chosen because they both have large historical datasets. Error bars represent one standard deviation from the mean.

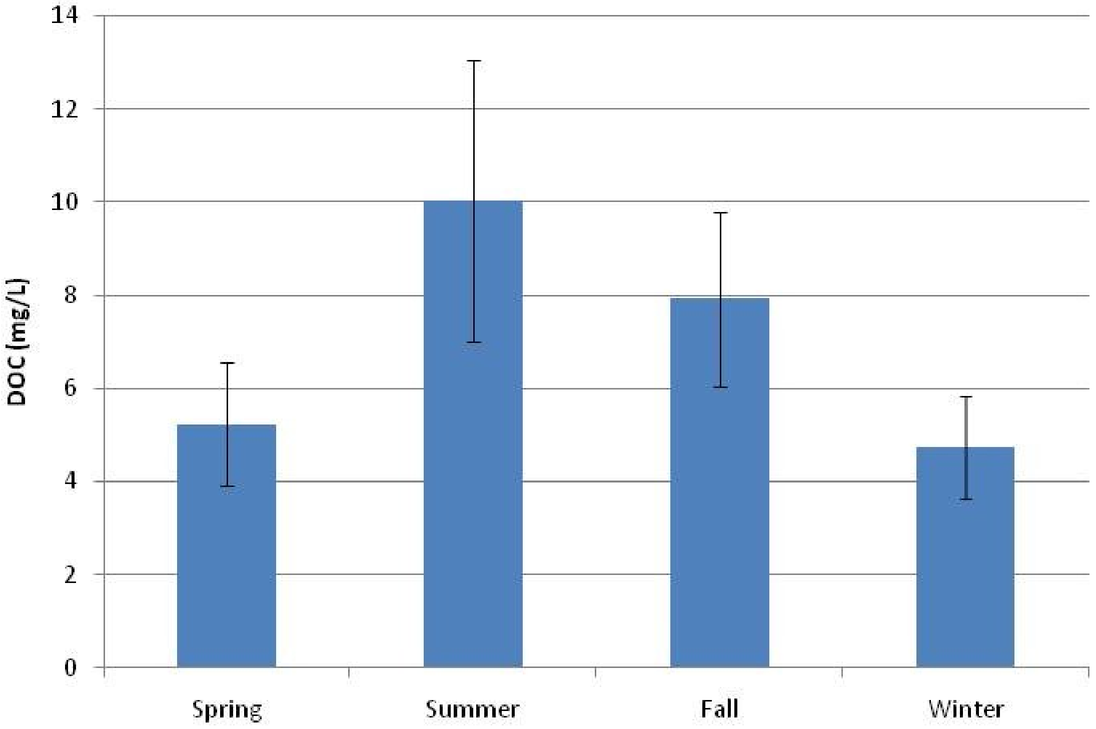


Figure 5.11 Seasonal DOC averages – Community C water supply (pond)

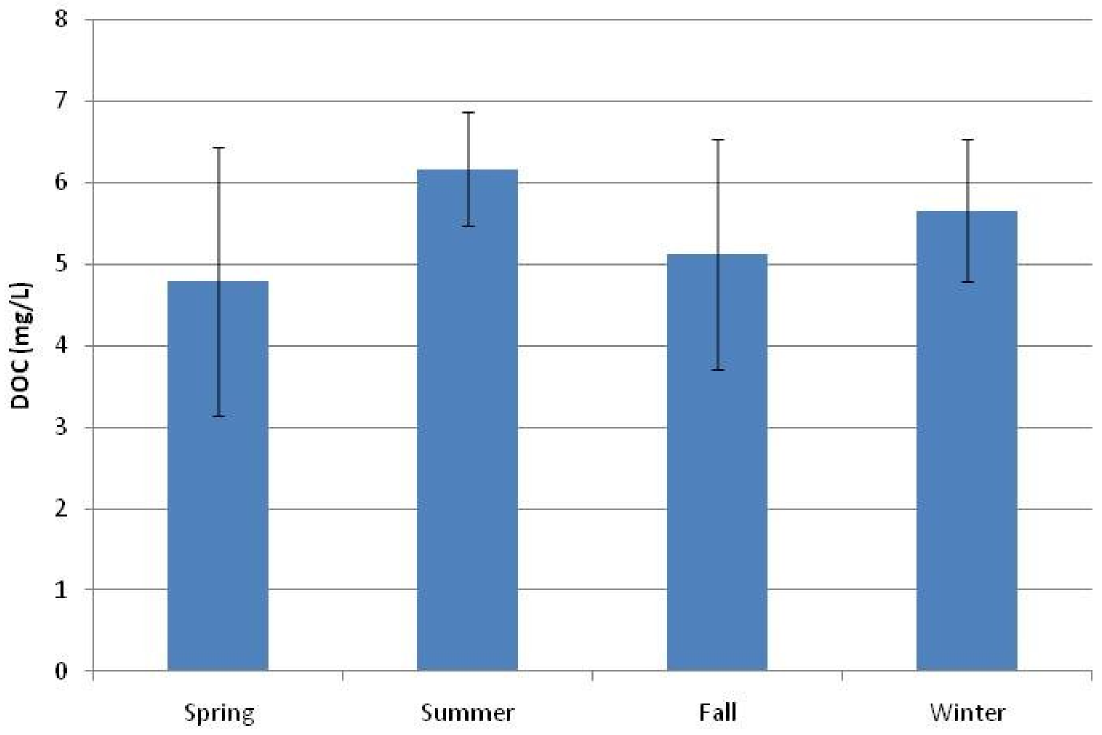


Figure 5.12 Seasonal DOC averages – Community D water supply (lake)

The average DOC has varied by season in both water supplies but the DOC of the water in the Community C supply (pond) has done so more than that in the Community D water supply (lake). Student t-tests conducted on the seasonal datasets from the former showed that the summer and fall averages were significantly different from the spring and winter averages. Average DOC was highest in the summer (10.0 mg/L) and lowest in the winter (4.7 mg/L). The average summer DOC was also highest for the Community D water supply (6.2 mg/L) but it is the spring average (4.8 mg/L) that is lowest. This is similar to the results of water quality sampling conducted during the preparation of the town's watershed management strategy (EDM, 1996). The summer average calculated using ENVC water quality records from Community D was significantly different from the spring and fall averages but not from the winter average.

Though numerous factors are undoubtedly at play in both water supplies, the most obvious difference between the two is their size. The lake water supply used by Community D is one of the largest water bodies in the province while the water supply in Community C was developed by flooding a small water body near the town. Its small size likely makes it more vulnerable to changes in temperature, pH, organic loading, and watershed use (Rasmussen et al., 1989).

5.1.8 Summary of Water Supply and Watershed Characteristics

Table 5.7 shows the type of surface water supply used in each of the six participating communities and provides a short summary of the average historical DOC, colour, and pH found in each.

Table 5.7 Characteristics of the water supplies in the six participating communities

Community	Source Type	DOC	Colour	pH
		mg/L	TCU	
Community A	Pond	2.9	12	6.5
Community B	Pond	10.0	98	5.5
Community C	Pond	7.3	99	5.3
Community D	Lake	5.4	44	6.4
Community E	Brook	6.8	60	5.9
Community F	Pond	6.5	49	7.2

Four of the six participating communities use ponds as water supplies. These ponds vary in water quality, though three of the four are indeed high in DOC and colour. The one lake water supply represented in the study has lower colour and more consistent water quality than most of the other sources. The river water supply has variable water quality.

A comparison of seasonal DOC averages (Section 4.2.7) showed that NOM levels in one of the pond water supplies (Community C) were more variable from season to season than those in the one lake supply (Community D). The notable summer/fall peak observed in both water supplies might help to explain why the water samples collected in the fall for this study had higher levels of DOC, UV254, and colour than those collected in the winter.

The percent dry land, wetland, and water in the watersheds of the participating communities are provided in Table 5.8.

Table 5.8 Summary of watershed characteristics – physical features

Community	Percent Dry Land	Percent Wetland	Percent Water
Community A	76%	4%	20%
Community B	86%	3%	11%
Community C	89%	0%	11%
Community D	11%	11%	78%
Community E	92%	3%	6%
Community F	89%	3%	8%

The watershed in Community D, whose lake has low DOC compared to many of the other water supplies, has the highest percent wetland of the six participating communities. This is the opposite of what would be expected based on previously published results. The culprit may be differing definitions of ‘wetland’, different watershed characteristics, or the influence of other factors such as climate or human activities (see Section 2.2).

Table 5.9 provides a summary of the common types of land cover, soils, and vegetation in the watersheds surrounding the water supplies in this study.

Table 5.9 Summary of ecoregion characteristics – soils and vegetation

Community	Land Cover	Predominant Soil Types	Predominant Vegetation
Community A	Barrens, bogs, forest	Humo ferric podzols and ferro humic podzols	Balsam fir, black spruce, white birch, mosses, heath
Community B	Stunted forest, palsa bogs, barrens	n/a	Spruce, willows, birch, peat moss
Community C	Barrens, bogs	Humo ferric podzols	Heaths, berries, alders
Community D	Forest, bogs	Humo ferric podzols, organics	Black and white spruce, balsam fir, aspen, mosses, lichens
Community E	Forest, swamps	Eutric brunisols, humo ferric podzols	Balsam fir, black spruce, yellow birch, red maple, ferns, flowers
Community F	Forest, swamps, barrens	Humo ferric podzols, ferro humic podzols, and organic fibrisols	Black spruce, white spruce, balsam fir, alders, berries

Table 5.10 summarizes the average precipitation and temperatures in each watershed.

Table 5.10 Summary of watershed characteristics – climate

Community	Average Rainfall	Average Summer Temperature	Average Winter Temperature	Other
Community A	1,275 mm	15^{o}C	-6^{o}C	
Community B	1,150 mm	12^{o}C	-15^{o}C	3 to 4 m of snow annually
Community C	1,625 mm	15^{o}C	-6^{o}C	
Community D	1,200 mm	16^{o}C	-6^{o}C	
Community E	1,200 mm	15^{o}C	-7^{o}C	2 to 4 m of snow annually
Community F	1,200 mm	16^{o}C	-6^{o}C	

Finally, Table 5.11 summarizes the human activities in each of the watersheds.

Table 5.11 Summary of watershed characteristics – land use

Community	Development	Recreation	Forestry	Industrial Activity	Other
Community A	Yes	Yes	No	No	
Community B	No	Limited	No	No	
Community C	No	Limited	No	No	
Community D	Yes	Yes	Yes	Yes	Airport
Community E	Yes	Yes	Yes	No	Ski resort
Community F	Yes	Limited	No	Limited	

5.2 Tap Water Quality

The information in this section was drawn from:

- Observations by CBCL staff during site visits;
- Operator questionnaires; and
- ENVC water quality records.

5.2.1 Common Water Quality Parameters

Table 5.12 presents the average alkalinity, colour, pH, turbidity, and DOC measured in the tap water of the six participating communities between 2000 and 2009. Note that Community C and Community D have WTPs designed to remove NOM. Consequently, their tap water is of noticeably higher quality than their raw water.

Table 5.12 Average levels of relevant parameters measured in the tap water of the six participating communities (2000 – 2009)

Community	Alkalinity	Colour	pH	Turbidity	DOC
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L
Community A	3	9	6.2	0.3	3.1
Community B	5	74	6.3	0.9	10.3
Community C	2	1	5.8	0.5	2.3
Community D	9	23	6.5	0.4	6.0
Community E	1	41	5.3	0.5	7.9
Community F	27	30	7.0	0.5	9.1

All but one of the communities have an average tap water alkalinity below 10 mg/L (as $CaCO_3$), which is standard for surface water in the province. These five communities also have low pH, ranging from 5.2 in Community E to 6.5 in Community D. The average colour of the tap water varies from 1 TCU in Community C to 74 TCU in Community B. DOC is distributed in much the same way except that Community F has a high average DOC vs. colour relative to the rest of the communities. All communities have average turbidity levels below 1 NTU in their distribution systems, meaning that they are, on average, in compliance with the provincial requirement of less than 1 NTU in the distribution system.

The maximum measured levels of the same five parameters are presented in Table 5.13.

Table 5.13 Maximum levels of relevant parameters measured in the tap water of the six participating communities (2000 – 2009)

Community	Alkalinity	Colour	pH	Turbidity	DOC
Units	mg/L as $CaCO_3$	TCU		NTU	mg/L
Community A	10	20	7.2	1.2	4.9
Community B	11	140	6.8	1.4	17.0
Community C	8	6	6.7	1.9	5.0
Community D	19	42	7.2	0.8	12.7
Community E	3	78	6.6	1.4	15.4
Community F	40	44	7.3	1.2	12.2

The values in Table 5.8 emphasize the variability observed in the overall tap water quality in these six communities.

5.2.2 Disinfection By-products – Occurrence and Potential Solutions

This section focuses on the occurrence and control of THMs and HAAs in five of the six communities who participated in this study.

5.2.2.1 COMMUNITY A

Community A screens the water that flows to the town from the water supply but lacks a formal water treatment plant. Consequently, the tap water quality is very similar to the raw water quality. In general, this is not of much concern because the raw water is low in colour and DOC. NOM is not removed before chlorination, however, leading to the formation of THMs and HAAs.

DBP levels have, for the most part, been below the GCDWQ limits of 100 µg/L and 80 µg/L for THMs and HAAs respectively, with the occasional high HAA reading. The total amount of THMs in the tap water has varied from a high of 80 µg/L to a low of just under 20 µg/L. The concentration of THMs decreased between 1999 and 2003, remained relatively constant between 2003 and 2008 and finally increased in 2009 and 2010. The operator was unable to explain the recent increase in THMs and HAAs during the site visit.

Linear regressions were performed on the available data. It was determined that the TTHM readings gathered between 1999 and 2010 were not significantly correlated to tap water DOC or colour readings taken during the same period. The lack of relationship between DOC and TTHMs is surprising, however, it may indicate that the DOC present in the water is not highly reactive with chlorine or that other factors, such as chlorine dose or contact time, are also controlling the rate of DBP formation. The historical dataset also fails to establish a strong correlation between TTHMs and colour, suggesting that the colour in the water in Community A may primarily be from non-organic sources.

HAAs have been sampled less frequently than THMs and as a result, it is more difficult to detect any important trends over time. The only real conclusion that can be drawn is that although the average HAA5 value is below the GCDWQ limit of 80 µg/L, HAA5 levels have been measured at or above this limit on three occasions. It can therefore be expected that increases in DOC or chlorine levels may result in dangerous levels of HAAs.

Chlorine gas is added to the water for disinfection. During the site visit the operator reported that 15.9 kg of chlorine is added to the water each day and that the average flow through the chlorination building is 6,250 LPM. This works out to a maximum chlorine dose of 1.8 mg/L and an average per capita demand of 1,600 Lpcd. The latter is well above that expected for communities in Newfoundland and Labrador. The disinfection equipment was replaced in August of 2010.

Disinfected water flows towards the town in a 300 mm ductile iron pipe. The first user is located approximately 600 m from the chlorination building. This works out to 42.4 m^3 of chlorine reaction volume. There is no storage ahead of the first user, so at the flow rate reported by the operator the total chlorine contact time is approximately 7 minutes. During the site visit the free chlorine residual measured at the first user was only 0.19 mg/L. Thus, the system is not in compliance with ENVC disinfection requirements and achieves a CT of only 1.33. This result should be confirmed by the ENVC through inspection of the water system and water use records.

The large difference between the applied chlorine dose and the residual measured at the first user suggests that the bulk water and/or the transmission main exert(s) a chlorine demand. Some of this is likely due to the NOM in the raw water, which reacts with the chlorine to form DBPs. As the chlorine dose and/or contact time cannot be reduced if the system is to comply with disinfection requirements, the formation of DBPs will likely continue at current levels unless some form of organic removal treatment process is installed. Alternatively, the community might consider installing a UV disinfection unit to achieve improved disinfection without increasing chlorine demand. The two UVT measurements made by the ENVC suggest that the water quality in Community A is high enough to justify this last option, though this should be confirmed through further sampling before the community is encouraged to pursue it.

5.2.2.2 COMMUNITY B

The water supply in Community B has elevated DOC levels and the town does not have a water treatment system designed to remove NOM. These two factors result in the formation of high levels of DBPs when the water is disinfected using calcium hypochlorite. The equipment is flow-paced but the operator still has a difficult time maintaining a chlorine residual in some parts of the distribution system. This problem is particularly acute when the local fish plant is operating. This has led to a long term boil water advisory in the community.

The distribution main that carries water from the chlorination building to the first user is 300 mm in diameter and between 300 and 400 m long. According to the operator, the max flow through the system is 1,700 LPM (350 gpm), which means that the water has nearly 60 minutes of chlorine contact time at peak demand. The chlorine residual at the first user was not measured during the site visit for this project, but was 2.0 mg/L during a site visit conducted for a related study. This means that the system was achieving a minimum CT of 120 at the time of the visit. The chlorine contact time, chlorine residual at the first user, and CT are all above those required in the Bacteriological Standard for Water Quality.

No evidence of a relationship was found between TTHMs and DOC or TTHMs and colour. The concentration of THAAs has been above the GCDWQ limit of 80 µg/L in most of the samples taken by ENVC over the sample period. The total amount of HAAs in the tap water has varied considerably since sampling began in 2001, however, there does not appear to be any positive or negative trend over time

As the operator has a difficult time maintaining a chlorine residual at the far ends of the distribution system it is not recommended that the town reduce its chlorine dose to minimize the formation of TTHM and HAA5. A chlorine booster station may help to alleviate the problems with the chlorine residual but is unlikely to bring DBPs to within recommended levels. UV disinfection is not feasible in Community B as the UVT is only 25%, well below the 75% required for most units. A treatment system optimized for organic removal will help to minimize DBP formation. The community could, however, also take measures to reduce retention time and the effects of short-term increased water demand from the fish plant.

5.2.2.3 COMMUNITY C

Community C relies on a conventional treatment train followed by chlorine gas to provide disinfection and reduce the formation of DBPs. Despite the WTP, THMs and HAAs are frequently detected at levels above the recommended guideline values of 100 µg/L and 80 µg/L, respectively. These exceedances may be due to NOM passage through the treatment plant, excessive chlorine addition, long retention time, or a number of other factors.

For example, during the site visit to the Community C conducted for this study the chlorine residual at the outlet of the WTP was 1.23 mg/L while that at the first user was 0.05 mg/L, reflecting a high chlorine demand and/or long retention time between these two points. At this time the operator reported that the peak flow was 2,600 m^3/day. Even assuming that minimal mixing occurs in the chlorine contact volume or the clearwell (baffling factor = 0.3) the system provides over 200 minutes of chlorine contact time and a CT of 288 to the water before it even leaves the plant. This is well above the provincial disinfection requirements and federal recommendations for virus and *Giardia* inactivation. Additional contact occurs in the transmission main to the community. This long contact time is excellent for disinfection but might be contributing to the formation of DBPs.

Figure 5.13 shows DOC measured in raw and tap water samples collected by the ENVC between 2001 and 2009.

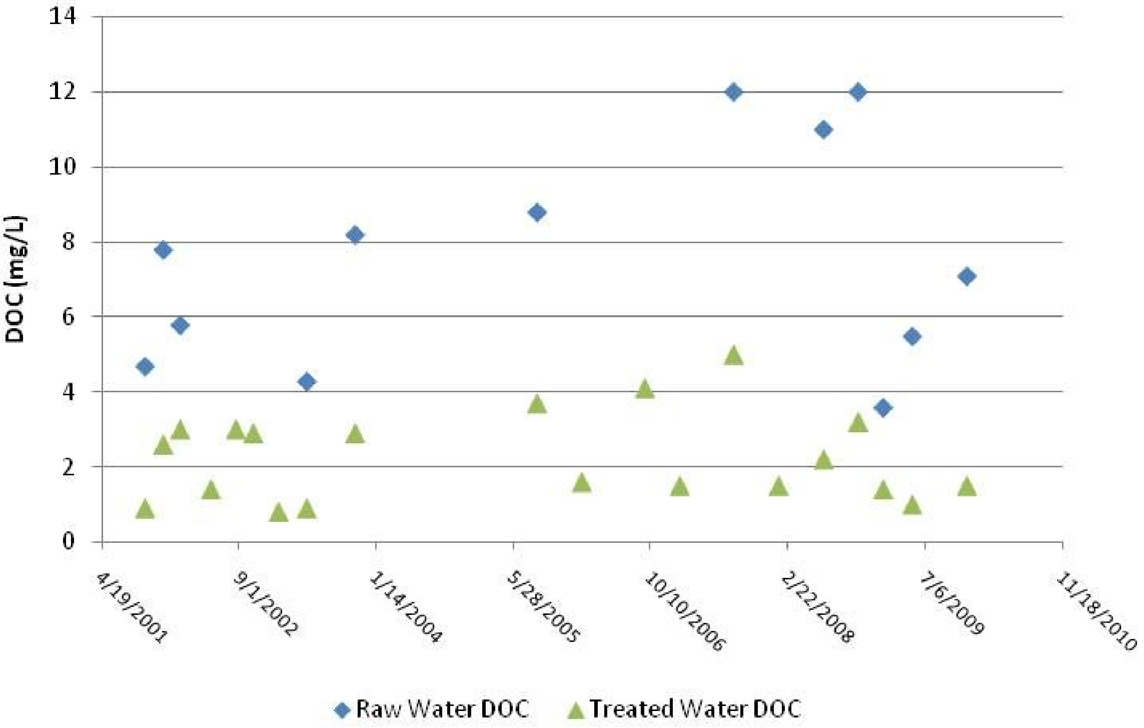


Figure 5.13 Raw and treated water DOC in Community C (2001 – 2009)

5.2.2.4 COMMUNITY D

Community D relies on a full-scale ozone and filtration system followed by chlorine gas and pH adjustment to provide disinfection, minimize the formation of DBPs, and prevent corrosion in the distribution system. The system was brought online in 2007 and has resulted in a noticeable reduction in DBPs, particularly THMs. It has not, however, reduced the amount of DOC in the tap water. This is not unexpected as ozone and filtration systems transform, rather than remove, DOC (see Section 2.5.3). A biological filtration step is often added after ozonation to remove the transformed DOC through biodegradation, but no evidence was available during the study to determine whether the GAC filter that follows the multimedia filters has biological characteristics.

Though the formation of both THMs and HAAs has decreased since the commissioning of the plant, both continue to exceed recommended limits periodically. The high DBP measurements may be related to short-term changes in the concentration and characteristics of the NOM in the raw water or due to excessive retention time in the storage tower during periods of lower demand.

The treatment system includes chlorine gas for disinfection. During the two site visits the operator reported that chlorine contact occurs in the transmission main and storage tank between the WTP and the first user. He also reported that the WTP usually treats approximately 300 m^3/hour, though during periods of high demand a second pump is brought online and the total flow increases to about 550 m^3/h. During one of the site visits the free chlorine residual measured at the first user was 0.65 mg/L. At peak flow conditions, the system is achieving a minimum of 401 minutes of chlorine contact time and a CT of 260 and during other times this is likely much higher.

In addition to organic and inorganic water quality parameters, ozone oxidizes components of microbial cells and can be used as a primary disinfectant. This means that the system in Community D is achieving even greater disinfection than that related to chlorine contact time. To further reduce the formation of DBPs, the town may choose to look into reducing the amount of chlorine added to the water and/or the retention time in the storage tank, which the town’s website lists as 18 hours. Alternatively, they could look into adding a biological filtration step after ozonation to remove some of the transformed NOM. This would reduce the amount of precursor material available for reaction.

An ENVC database provided to CBCL indicates that the storage tank is located after the first user. This should be updated to reflect the information provided by the operator.

5.2.2.5 COMMUNITY E

Though Community E has a Filtomat strainer to remove turbidity it does not have a WTP optimized for NOM removal. Consequently, during periods when the influent water has high a concentration of NOM there is increased formation of THMs and HAAs upon chlorination. THM and HAA concentrations in the tap water have increased in recent years and HAAs in particular are almost always above the guideline value recommended by the province. The concentration of DOC observed in the raw and tap water samples collected by the ENVC have not followed the same upward trend observed in the DBP measurements, so it is likely that the increase in DBPs is as a result of operational changes in the disinfection system.

Community E was visited by CBCL staff on two separate occasions to gather information for two different studies. Information relevant to the current study was collected on both occasions. During the site visits the operator reported that the community relies on chlorine gas for disinfection. He indicated that the most recent boil water advisory came about due to a combination of equipment failure, low chlorine levels, and high turbidity. He also mentioned that the chlorine dose was increased in response to the issuance of the boil water advisory, which likely explains the uptick in DBP levels.

The operator reported that water use in the community is usually around 285 LPM (75 USgpm), though this value is not recorded day to day. Approximately 1.36 kg (3 lbs) of chlorine is added to the water each day. This means that the maximum concentration of free chlorine in the water leaving the chlorination building is 3.3 mg/L. The system is flow paced to add a dose of 2.25 mg/L and during the site visit the CBCL staff member measured 2.19 mg/L of free chlorine in the disinfected water at the chlorination building. The total chlorine reading exceeded the measurement capability of the handheld machine used for analysis.

The concentration of free chlorine measured at the first user, who is located approximately 500 m from the chlorination building, was found to be 1.19 mg/L, indicating that the chlorine demand in the raw water was approximately 1 mg/L during the site visit. The transmission main that carries water from the chlorination building to the first user is 150 mm (6”) in diameter and there is no storage tank, so the chlorine contact time is approximately 123 minutes at the reported flow rate of 285 LPM. On the day of the first site visit the system was achieving a CT of 146, which corresponds to a 3-log inactivation of *Giardia* at the temperature and pH measured at the site. This is expected to decrease as demand increases, nonetheless, on the day of the first site visit the system was in compliance with provincial disinfection requirements and federal disinfection recommendations for viruses and *Giardia*.

The high chlorine demand in the system may be related to high NOM, iron, manganese, or turbidity in the raw water and a treatment process designed to remove some or all of these parameters could be installed ahead of the disinfection system. The poor and variable water quality of the water from Community E precludes the use of UV disinfection to improve disinfection and reduce the community’s reliance on chlorine. The town is currently conducting a groundwater investigation to assess the feasibility of replacing the current surface water supply.

5.2.2.6 COMMUNITY F

The Town of Community F also lacks a WTP, and as such, is unable to remove any of the NOM present in the raw water before the point where chlorine gas is added for disinfection. THMs and HAAs are regularly measured at levels above provincial recommendations. Linear regressions performed on the data points provided by the ENVC showed that both have increased significantly over time. DOC levels appear to have remained constant over time (with the exception of seasonal variations) so the increase in DBPs may be related to increased chlorine application or operational adjustments.

Chlorine gas is used for disinfection in Community F. The town lacks a chlorine reaction tank but does have a storage facility. A previous study found that the chlorine contact time between the point of disinfection and the first user is approximately 174 minutes at peak demand and that at a minimum chlorine residual of 0.3 mg/L the system is capable of achieving a CT of 52. During the site visit the free chlorine residual at the first user was determined to be 1.44 mg/L. Under these conditions, the system is able to achieve a CT of 250, well above provincial requirements and that required to ensure 3-log reduction of *Giardia* and 4-log reduction of viruses.

Community F is able to achieve disinfection levels well in excess of provincial disinfection requirements. It may therefore be is possible to reduce the amount of chlorine added to the water in order to minimize the formation of DBPs. This strategy should be applied cautiously as this may make it difficult for the operator to maintain an adequate chlorine residual at the end of the system. UV disinfection is unlikely to be feasible in Community F as the UVT has been found to be below the cut-off value of 75%.

5.2.2.7 SUMMARY

Table 5.14 summarizes the average and maximum TTHM and HAA5 measured in the tap water in various communities.

Table 5.14 Average and maximum TTHM and HAA5 measured in the tap water of participating communities (2000 – 2009)

Community	Average TTHM	Average HAA5	Max TTHM	Max HAA5
	ug/L	ug/L	ug/L	ug/L
Community A	37	64	78	108
Community B	231	334	449	688
Community C	56	125	190	249
Community D	187	107	336	322
Community E	83	249	200	302
Community F	133	147	340	190

Table 5.15 summarizes the characteristics of the disinfection systems in each of the six participating communities.

All but one of the communities were found to be achieving compliance with provincial disinfection requirements at the time of their site visit. This last was related to a low free chlorine residual at the first user, which could easily be remedied by increasing the chlorine dose slightly.

Table 5.15 Characteristics of the disinfection systems in participating communities

Community	Minimum Contact Time	Free Chlorine Residual at Outlet of Disinfection Volume	Calculated CT*	Recommended DBP Reduction Strategies
Community A	7 minutes	0.19 mg/L	1.3	Minimize chlorine demand, UV disinfection ahead of chlorination
Community B	58 minutes	2.0 mg/L	116	Minimize chlorine demand, decrease chlorine dose
Community C	200 minutes	1.2 mg/L	288	Improve organic removal, minimize retention time
Community D**	400 minutes	0.65 mg/L	260	Add biological filtration step to WTP, reduce chlorine dose, minimize retention time in storage tank
Community E	123 minutes	1.19 mg/L	146	Minimize chlorine demand, decrease chlorine dose, add chlorine booster stations
Community F	174 minutes	1.44 mg/L	250	Minimize chlorine demand, decrease chlorine dose, minimize retention time

*Calculated CT is based on reported flow (where available) OR an assumed peak flow based on population

**Ozone and chlorine used for disinfection – see Chapter 6

CHAPTER 6 NOM FRACTIONATION RESULTS

6.1 Source Water Quality

6.1.1 Bulk Water

Each bulk raw water sample collected during the field program was characterized based on DOC, UV254, and colour. The results are summarized in Table 6.1.

Table 6.1 DOC, UV254, apparent colour, and true colour measured in bulk water samples

Community	DOC	UV254	SUVA	Apparent Colour	True Colour
	mg/L	cm^{-1}	L/m.mg	TCU	TCU
A	3.6	0.128	3.6	10	8
B	7.7	0.452	5.9	54	41
C	10.8	0.815	7.5	99	92
D	7.0	0.281	4.6	23	22
E	8.3	0.425	5.1	164	36
F	9.0	0.410	4.6	41	27

The water sample from Community A had the lowest DOC, UV254, SUVA, and apparent and true colour of all of the participating communities. This is consistent with the historical water quality records for the community. It should be noted, however, that this sample was collected in the winter, which tends to coincide with low levels in organics in many surface water supplies. Though turbidity was not measured during this study, the close relationship between true and apparent colour suggests that the water sample did not contain a large amount of particulate.

On the other end of the spectrum, the water sample gathered from the water supply in Community C in September of 2010 had the highest DOC, UV254, SUVA, and true colour results. Both the DOC and true colour results are within the normal ranges found in the historical water quality data records. The DOC reading is, however, above the mean historical value. The high SUVA calculated for the sample suggests that the water is amenable to coagulation and, indeed, the influent raw water passes through a conventional treatment system before being distributed to users.

The samples from communities B, E, and F had comparable DOC, UV254, and true colour results. The samples differed somewhat with regards to SUVA, indicating that some might be more amenable to coagulation than others. The difference between true and apparent colour in the Community E water supply likely indicates interference by particulate matter during analysis.

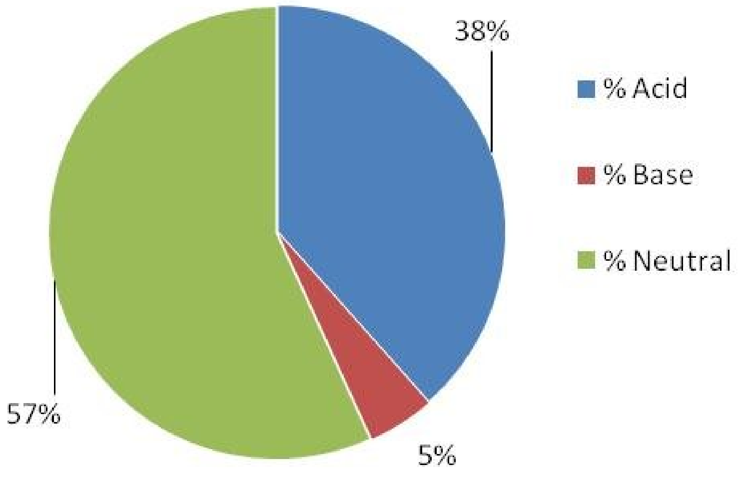
Finally, the sample from Community D had moderate levels of DOC, UV254, and true and apparent colour. The SUVA of the water was also moderate, indicating that it may be possible to remove some portion of the organic matter using coagulation. There was barely any difference between the true and apparent colour measurements, suggesting that there was little particulate matter present in the raw water sample.

As noted previously, though most of the variation observed among the samples was likely related to the individual characteristics of the water supplies, some of it may be explained by the sampling schedule. That is, some proportion of the organics measured in the water samples from Community B, Community C, and Community E may be related to the fact that these three samples were collected in early September. The Community F sample was collected in early December, likely before any major freezing or snowfall while the samples from Community D and Community A were collected in January and February of 2011, respectively. This may have contributed to the low colour, DOC, and UV254 of these samples compared to the rest.

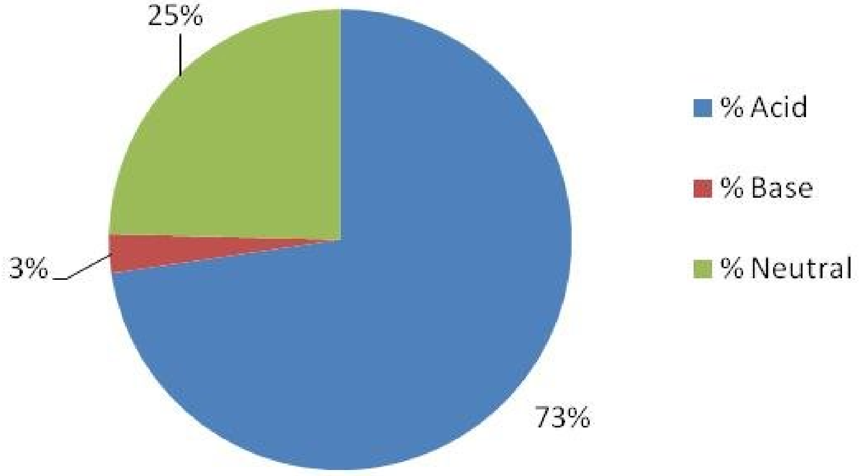
6.1.2 Fractionation

As described in the methodology section, the NOM in each raw water sample was separated into six fractions using a series of resins. The amount of material in each fraction was quantified by weight as DOC. The DOC of the bulk raw water samples from some communities was observed to be higher than the sum of the DOC readings of the individual fractions. This discrepancy results from the inefficiencies inherent in the resin fractionation method, in particular, the elution procedure used to remove the adsorbed NOM from each individual resin. Some researchers have noted that it is the amino acid and protein species (HIBs and HOBs) that tend to be lost during the resin fractionation process (Croué et al., 2000), so these species may be underrepresented in the laboratory results presented here as well.

Figure 6.1 consists of two pie charts that show the percentages of acid, base, and neutral NOM recovered (measured as DOC) from the samples from communities A and B. Both samples were found to contain only small percentages of basic species. Neutral species represented 57% of the NOM in the sample from Community A but only 25% of that in the sample from Community B. The low colour and UV254 measured in this sample may be related to the low proportion of acidic NOM as well as the total amount of NOM present. The low SUVA in the sample (UV254/DOC) is more likely to be related to the distribution of acidic, neutral, and basic NOM because it is a measure of reactivity. In any case, the different percentages of acidic NOM may indicate differences in the disinfection formation potential and treatability of the NOM in each sample. All of the remaining samples had distributions similar to that observed in the sample from Community B.



Community A



Community B

Figure 6.1 Percent acid, base, or neutral NOM in communities A and B

The percentages of hydrophilic and hydrophobic NOM in each sample (measured as DOC) were also calculated and are shown in Figure 6.2. The samples from Community A and Community B were found to contain higher percentages of hydrophilic NOM while those from the remaining communities were found to contain higher percentages of hydrophobic NOM. These differences may be related to the source of the NOM; high levels of hydrophobic NOM have been observed in water supplies with a large proportion of allochthonous vs. autochthonous NOM (Zumstein and Buffle, 1989; Croué, 2000).

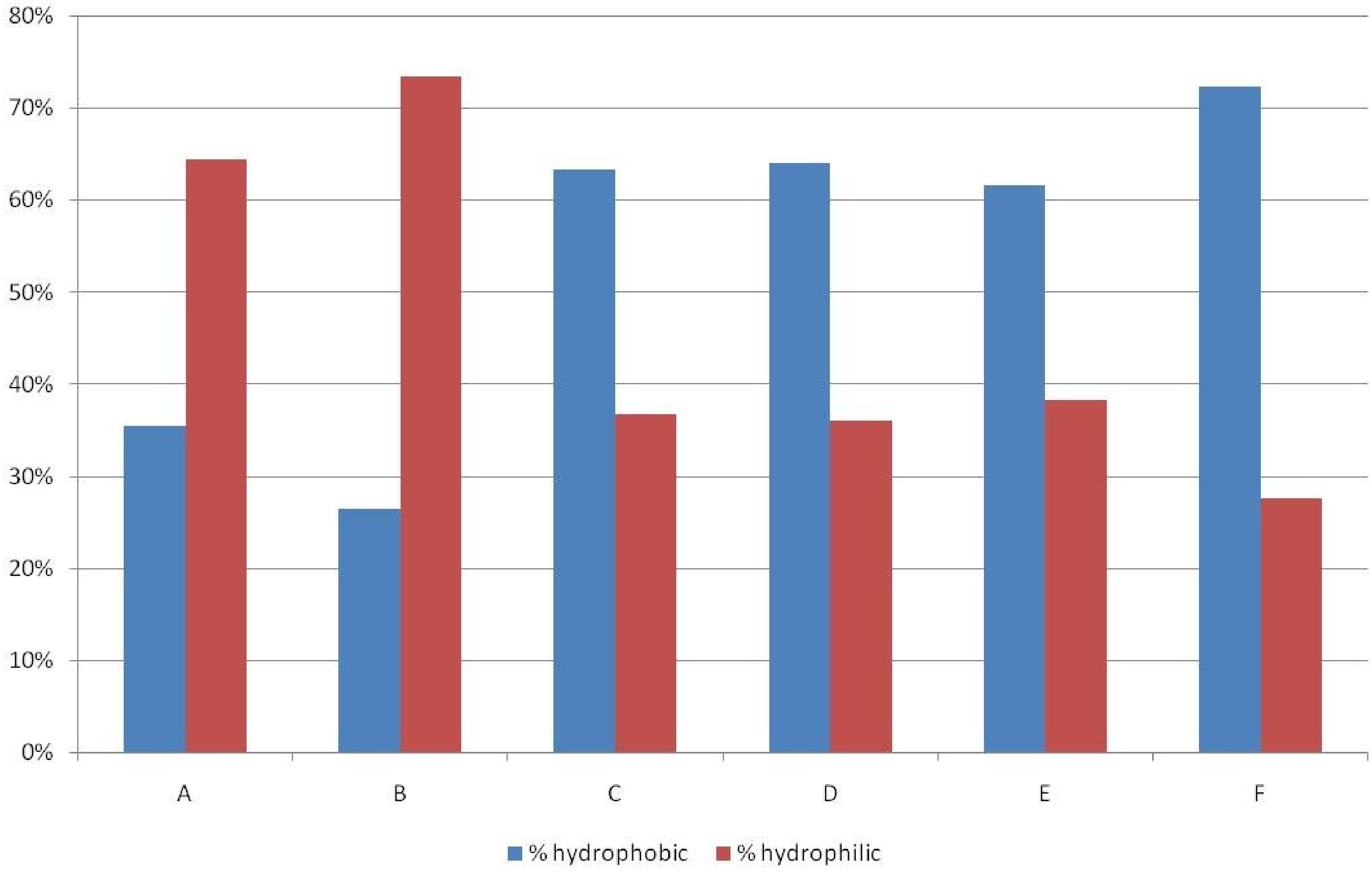


Figure 6.2 Percent hydrophobic vs. hydrophilic NOM in participating communities

UV254 is usually assumed to be a reliable measure of hydrophobicity. In this study, however, the percent hydrophobicity was not significantly related to the UV254 of the sample ($p > 0.05$). This may be because the amount of UV light absorbed is related to the total number of chromophores in a given water sample, which is obviously related to DOC, so the relationship between SUVA and the percent HO was also investigated. This relationship was also insignificant.

A summary of the total amount of each fraction obtained during the resin fractionation is provided in Figure 6.3. The hydrophobic acid (HOA) fraction represented most of the NOM in four of the six water samples. This is similar to results obtained by Bourbonniere (2005) during his study of lakes in eastern Canada. Communities C and E also showed moderate hydrophilic neutral (HIN) fractions. Communities C and F had small contributions from the hydrophilic acid fraction (HIA) and Community F also had a small but noticeable hydrophobic base (HOB) fraction. A large proportion of the NOM from Community A was made up of HIN compounds while HIA made up the largest proportion of NOM in the remaining sample (Community B).

Note that for all of the communities there was a discrepancy between the DOC of the bulk water and the sum of the six fractions. The differences, which ranged from 0.1 mg/L to 3.3 mg/L, were most pronounced for communities A and C, where the sum was more than the bulk water DOC, and Community B, where the sum was less than the bulk water DOC. The researcher who conducted the resin fractionation procedure suggested that these errors are often related to the reactions that take place between NOM compounds (HIBs and HIAs) and the resins in the final two columns.

The UV254 of the raw water and the filtrate from each column was also measured to illustrate the change in aromaticity as each individual fraction was removed from the NOM matrix. The results from all six communities are presented in Figure 6.4. As expected, the greatest change in UV absorbance occurred after the HOA fraction was removed. A substantial drop was observed in the UV254 of all six raw water samples after the column used to adsorb HOAs.

In some communities, the UV254 of the filtrate rose after the HON fraction was removed, while in others, it decreased. This suggests that the composition of the HON fractions from different communities were not uniform. The increase noted in the UV254 measured in the filtrate of the first column might indicate that some of the HON molecules had had an inhibitory effect on the absorbance of UV light at 254 nm by the bulk sample. Alternatively, given the known inefficiency of the elution process, the slight increase may also be a result of laboratory error.

As observed for the other samples, the UV254 of the water sample from Community E decreased after the removal of the HOA fraction. Some absorbance capacity remained, however, until the HIB fraction was removed from the matrix. This suggests that the particular HIB species found in this water sample contained more UV light absorbing structures than their counterparts from other communities. The presence of these chemical structures is thought to be related to the eventual formation of DBPs upon chlorination, so the UV absorbance exhibited by these fractions may be an indication that they will eventually make an important contribution to the overall load of THMs and/or HAAs in the finished water.

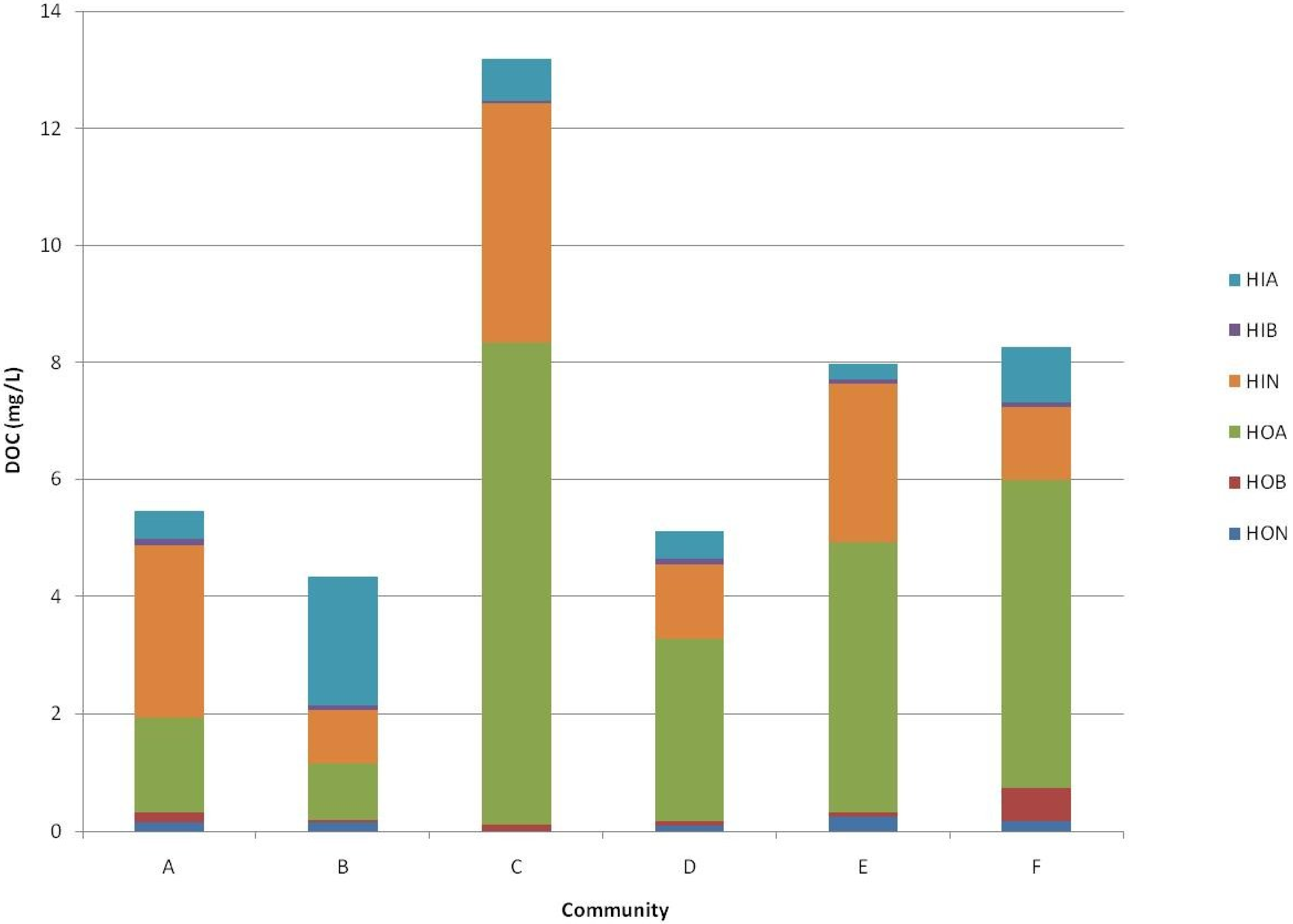


Figure 6.3 NOM fractions present in six source waters in Newfoundland and Labrador

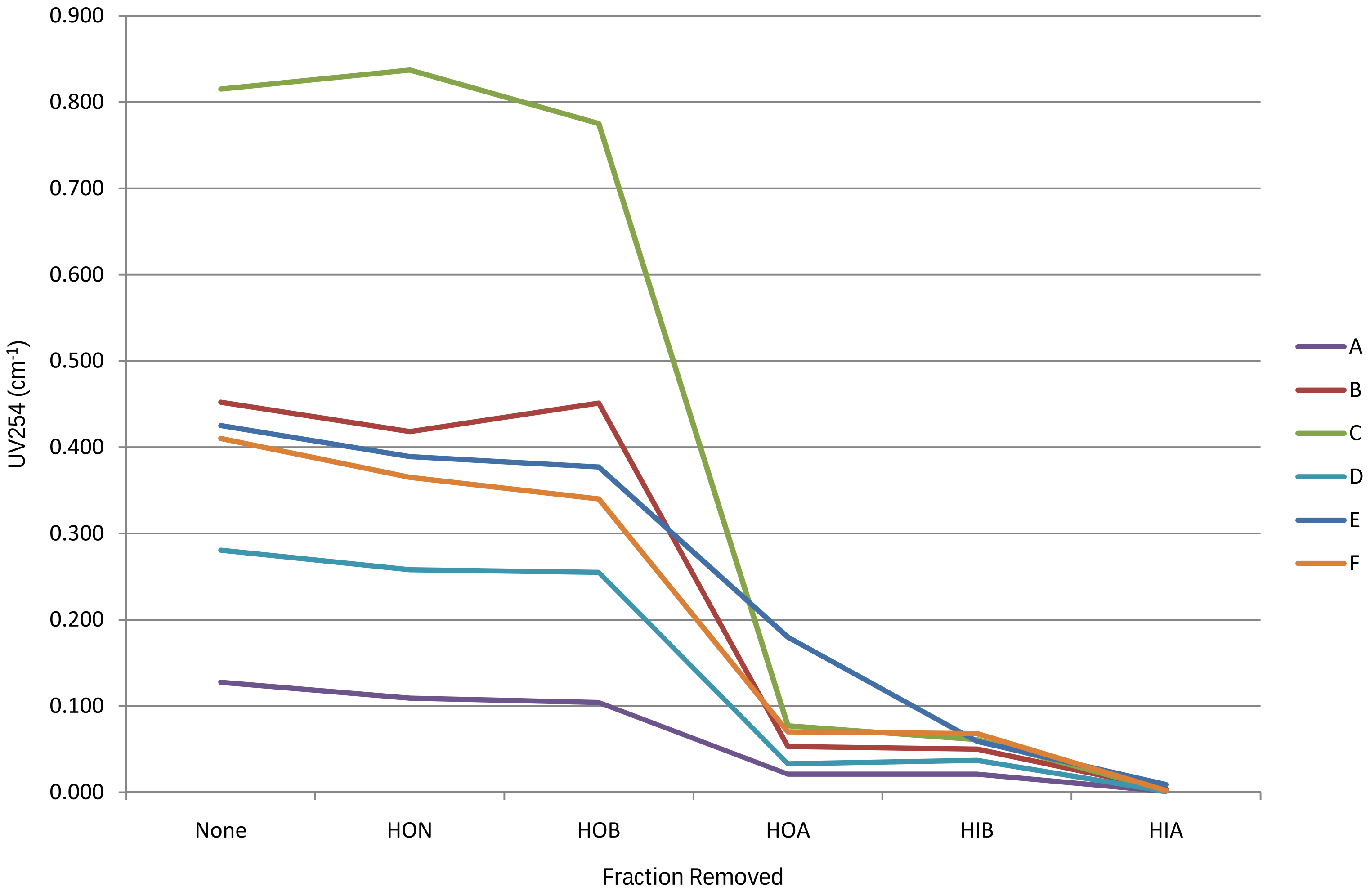


Figure 6.4 UV254 absorbance of bulk water after the removal of fractions in using resin fractionation columns

6.1.3 Molecular Weight

The MW profile of the NOM in the bulk water and each of the individual NOM fractions was measured using HPSEC and illustrated on chromatograms (Appendix C). The x-axis of the graph shows the amount of time that each NOM molecule took to pass through the size exclusion media. This can be related back to the MW of the molecules by comparing them to existing standards (size calibration). The y-axis shows the amount of UV light absorbed by the NOM as it passes through the media. The absorbance shown on the y-axis is related to both the concentration and the absorbance capacity of the NOM molecules being measured.

For example, Figure C.1 is one of the raw water chromatograms for Community A. The bulk water sample, labeled 'Raw', shows a number of peaks. The first occurred after approximately 9 minutes and represents large MW compounds. The small magnitude of this peak compared to later ones may indicate that the molecules it represents had low UV absorbance at 254 nm or that they were few in number (or a combination thereof). None of the individual fractions has a comparable peak, indicating that these fractions (in this case all hydrophilic) are not responsible for the peak in the raw water sample. A quick look at Figure C.2 shows that the first raw water peak is mirrored by a similar peak for the HOA fraction. Thus, the raw water sample contains large MW HOA compounds.

Note that the magnitudes of the UV absorbance peaks measured for individual fractions cannot be directly compared to one another because of the sample preparation method. Specifically, each fraction was concentrated to a level where it became possible to detect sufficient UV absorption to characterize the molecular weights of the molecules it contained. This resulted in each sample being concentrated to a different degree. The 'raw' datasets, that is, those obtained by running the bulk water samples through the fractionation process, can be compared because the samples were not concentrated and therefore are able to represent the actual behaviour of the NOM species present in the raw water.

The chromatograms for each of the six water sources profiled in this study and the related tables of molecular weights (MWs) can be found in Appendix C. Please note that the colour codes are not consistent among the different communities. For the purposes of interpretation, the MW of each species will be described as shown in Table 6.2.

Table 6.2 Description of molecular weight ranges

Molecular Weight Range	Description
> 10,000 Daltons	Large
1,000 to 10,000 Daltons	Moderate
< 1,000 Daltons	Small

As described previously, the raw water chromatograms for Community A show a number of distinct peaks. The first is located on the left side of the graph and represents large molecular weight (MW) compounds. The only other datasets with matching peaks are those describing the HOA, HON, and HIB (difficult to see) fractions. Peaks denoting moderate weight species were found to be related to all of the NOM fractions. The moderate MW species described by this portion of the graph were mostly HOAs, HOBs, and HONs, with some HIAs and HIBs. The lower MW portion of the graph was dominated by HINs.

The chromatogram for Community B also has peaks in the large, moderate, and small MW ranges. The large MW peak is related to the HOA and HON fractions. The smallest MW species were found in the HIA and HIB fractions. All fractions contributed to the moderate MW portion of the graph, with HOAs, HIBs, and HONs dominating at larger MWs and a more equal distribution of fractions at the lower end of the MW spectrum.

A similar distribution was apparent in the datasets from Community C with the exception that the smallest MW species are part of the HON fraction rather than the HIA and HIB fractions. These and the other fractions included species with MWs lower than those observed in the water samples from other communities.

All fractions were represented in the moderate MW range in Community D, but as seen in other communities, only HOAs, HIBs, and HONs were present in the high MW range. All fractions included some low molecular weight species. Communities E and F showed similar distributions of MWs.

Overall, the MW profiles of all six communities were remarkably similar. This makes it difficult to relate them to the characteristics of the water supplies and watersheds.

6.2 Disinfection By-products

6.2.1 Bulk Water Quality

All six communities had THMfps and HAAfps above the recommended guideline values of 100 µg/L and 80 µg/L, respectively. This result is not unexpected; the standard formation potential test is conducted at a pH of 8.0, a temperature of 20°C and while maintaining a chlorine residual of 1.0 mg/L over a time period of 24 hours. These represent ‘worst case’ conditions for THM formation that will rarely, if ever, be replicated in distribution systems in Newfoundland and Labrador. Indeed, the water quality datasets for the participating communities show that both THMs and HAAs have historically been well below the THMfp and HAAfp values measured using the standard formation potential tests. Nonetheless, the DBPfp values can be used to compare communities to one another based solely on raw water NOM content.

Figure 6.5 shows the absolute THMfp and HAAfp measured in the raw water samples from each community. The sample from Community F, which had a DOC of 9.0 mg/L and a UV254 of 0.410, had the highest THMfp (1,735 µg/L) among the six communities. Community A was found to have the smallest at 375 µg/L. The same pattern emerged for HAAfp, though the differences among communities were smaller in this case than for THMfp. All of the communities had higher THMfp than HAAfp, which may be due to the types of NOM present in the samples or due to the limits of the testing procedure, which uses the ideal THM formation conditions to evaluate both THMs and HAAs despite the fact that ideal conditions for HAAs are slightly different.

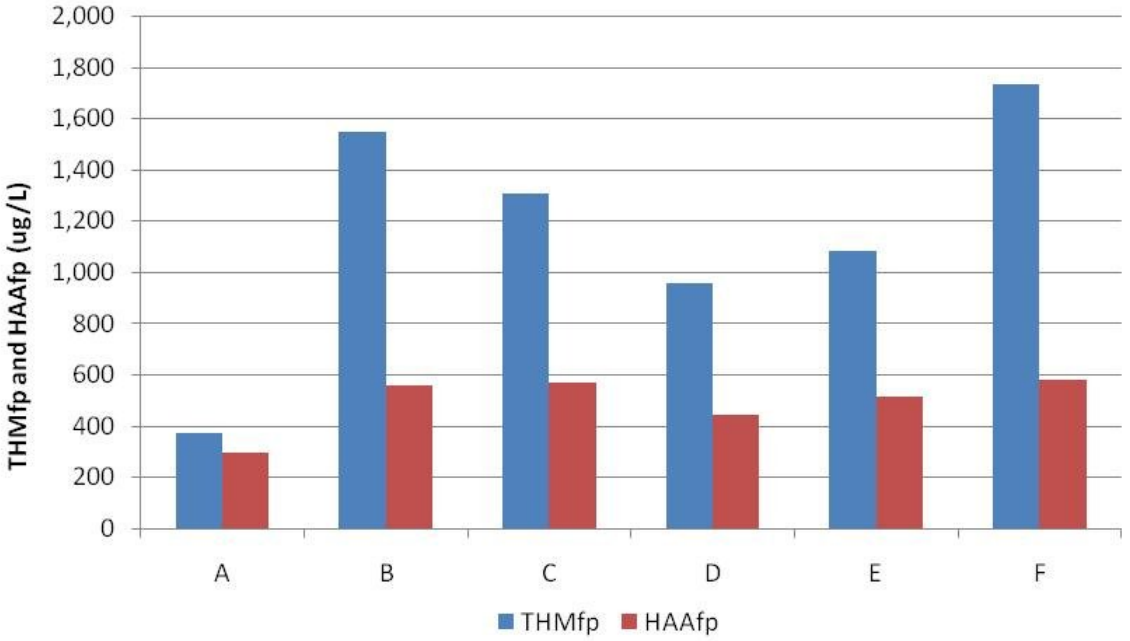


Figure 6.5 THMfp and HAAfp of bulk water samples from participating communities

Figure 6.6 shows the THMfp and HAAfp results divided by DOC ('normalized' to DOC) for the six participating communities. By dividing the THMfp and HAAfp by DOC the influence of concentration on the total amount of DBPs formed is removed, permitting a comparison of the relative reactivity of the bulk NOM from each community. In theory, it would then be possible to predict the amount of DBPs that would be formed as DOC increases or decreases in the surface water. In practice, however, DOC is not the only predictor of DBP formation; the distribution of NOM species (and resulting 'reactivity') is rarely constant, making any such predictions unreliable.

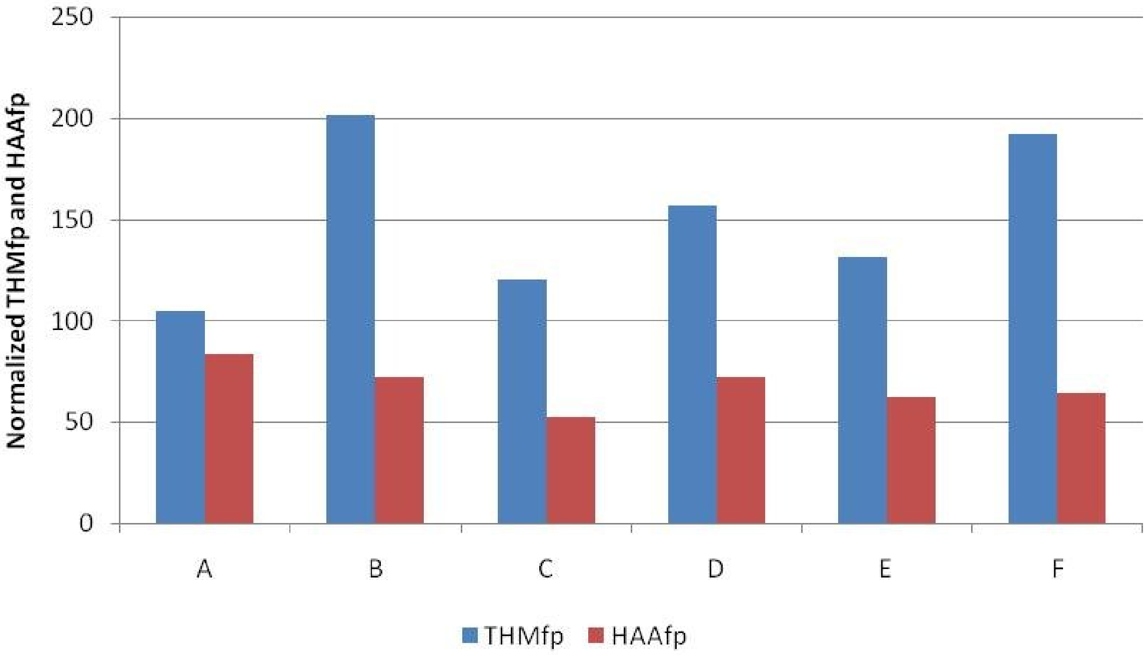


Figure 6.6 THMfp and HAAfp of bulk water samples from participating communities normalized to DOC

As was observed with the absolute THMfp, Community A had the lowest normalized THMfp. Community B had the highest normalized THMfp, followed closely by Community F. The three remaining communities fell between these two extremes. Overall, less variation was observed among communities for normalized THMfp than for absolute THMfp. Even less variation was observed in the normalized HAAfp results. Interestingly, the sample from Community A, which had the lowest HAAfp, had the highest normalized HAAfp. This suggests that the lack of absolute HAAfp observed in the water sample for this community was more a function of concentration (i.e., DOC) then reactivity.

It is also interesting to note that the raw water from Community D was more THM and HAA reactive than that from Community C despite having a smaller SUVA. This suggests that the DBP reactivity of a sample is not solely dependent on its degree of aromaticity, at least in the samples analyzed in this study.

Assuming a normal distribution, linear regressions were performed on the data points available from the laboratory analyses. As was observed in section 4.2.2, UV254 and DOC, colour and DOC, and UV254 and colour were significantly correlated.

The regressions failed to detect significant relationships between THMfp and DOC, THMfp and UV254, HAAfp and UV254, THMfp and colour, or HAAfp and colour. A significant relationship was found between HAAfp and DOC. A summary of the r^2 and significance values for the regression analyses is provided in Table 6.3.

Table 6.3 Results of linear regressions performed on bulk raw water quality data

Summary of Regressions	r^2	p	n
UV254 vs. DOC	0.86	< 0.05	6
Colour vs. DOC	0.70	< 0.05	6
UV254 vs. DOC	0.96	< 0.05	6
DOC vs. THMfp	0.61	> 0.05	6
DOC vs. HAAfp	0.85	0.01	6
UV254 vs. THMfp	0.34	> 0.05	6
UV254 vs. HAAfp	0.59	> 0.05	6
Colour vs. THMfp	0.18	> 0.05	6
Colour vs. HAAfp	0.40	> 0.05	6
UV254 vs. normalized THMfp	0	> 0.05	6
UV254 vs. normalized HAAfp	0	> 0.05	6

These results are similar to those obtained during the analysis of field data provided by the ENVC (Section 4.2.2). In that case, it was hypothesized that the weak or non-existent relationships between THMfp/HAAfp and common organic parameters such as DOC and UV254 were due to differences in chlorine dose and retention time from one community to another. The results presented in Table 6.3 were obtained from water samples that were analyzed in the lab under standardized conditions (1 mg/L chlorine residual, 24 hour retention time). Therefore, the lack of significant linear relationships among the variables is more likely to be due to the small number of measurements available for analysis.

6.2.2 Fractionation

6.2.2.1 THMFP

The absolute and normalized THMfp and HAAfp were measured for each of the individual NOM fractions isolated from each raw water sample. The results are provided in Figure 6.7 and Figure 6.8, respectively. It should be noted that the sum of the THMfps of each fraction did not always add up to that measured in the bulk raw water. This might have been due to losses in the resin fractionation process. In some cases, however, the sum was higher than that measured in the raw water. This may be because the fractions behaved differently once they were separated out from one another, as has been observed in other studies (Owen et al., 1993).

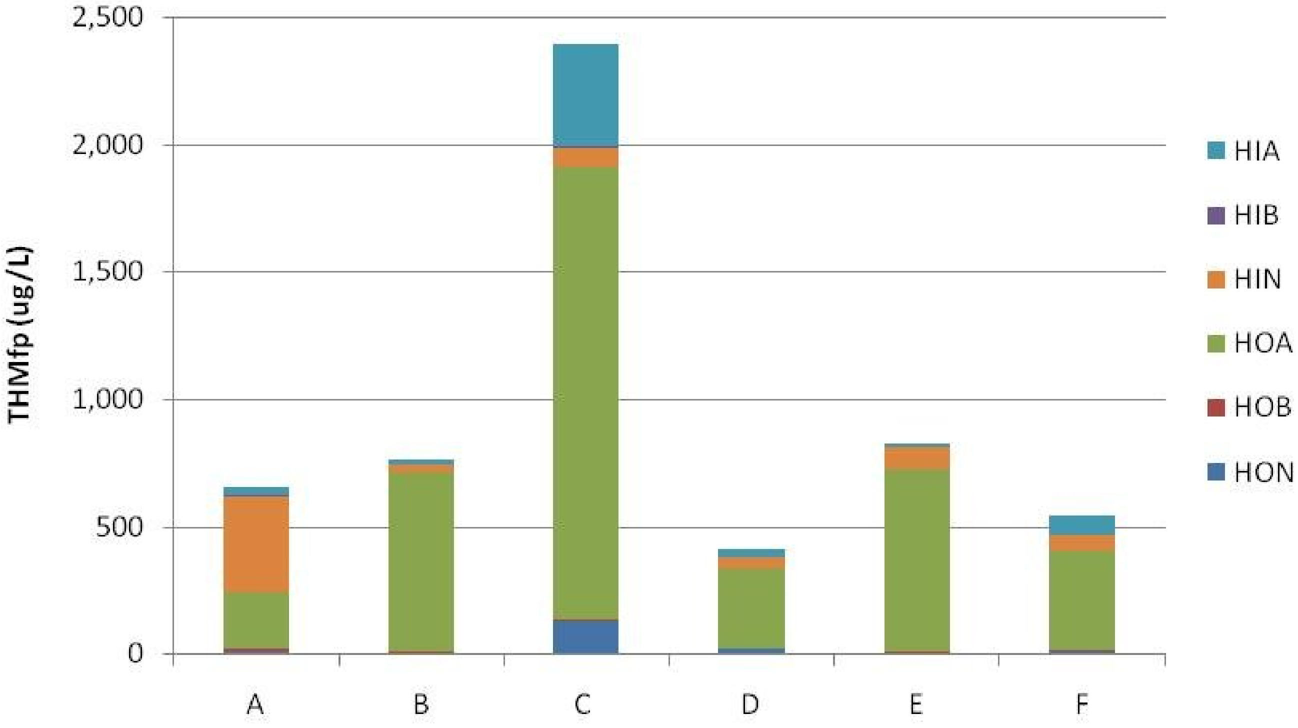


Figure 6.7 THMfp of NOM fractions recovered from water samples from participating communities

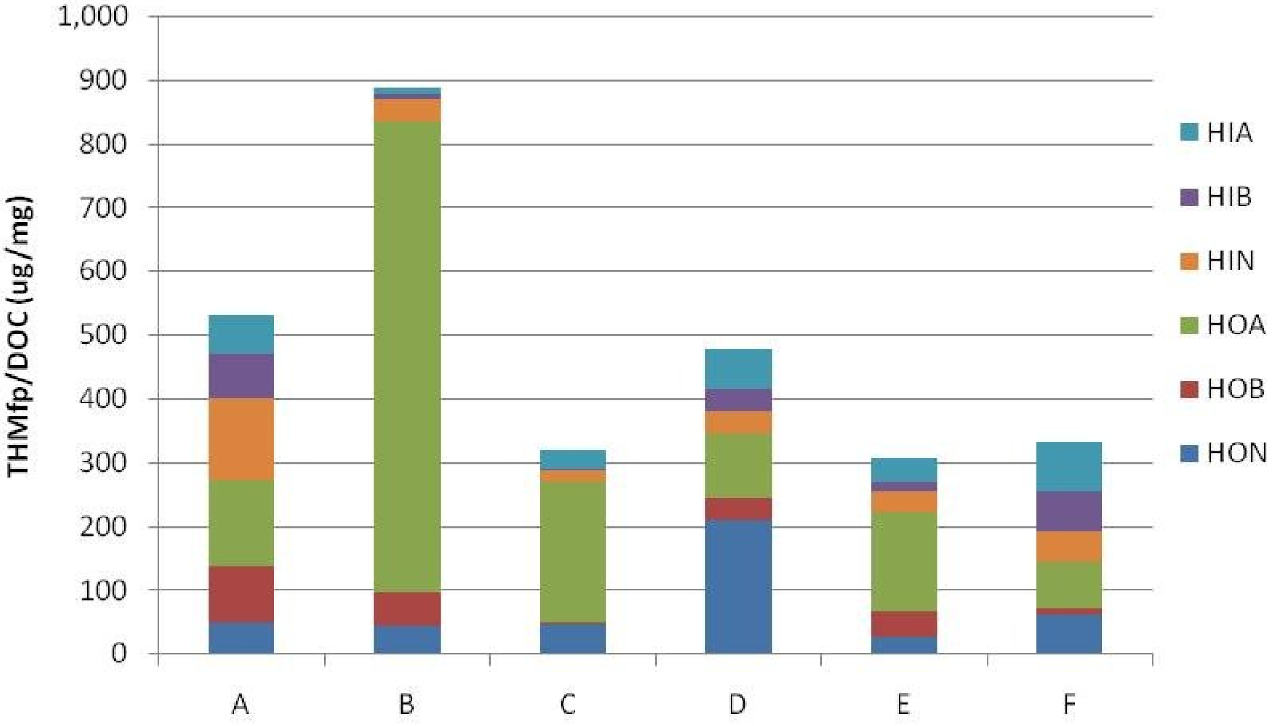


Figure 6.8 THMfp of NOM fractions recovered from water samples from participating communities normalized to DOC

The normalized THMfp results, shown in Figure 6.8, are noticeably different from the absolute THMfp results. Once the concentration of NOM (DOC) is taken out of the picture it is apparent that numerous NOM fractions acted as THM precursors in most of the communities. For example, all of the NOM fractions in the samples from Community A and Community F appeared to be nearly equally likely to react with chlorine to form THMs. Had the concentrations of these fractions been higher, the total THMfp for the sample may well have been higher as well.

The HOA fraction was the most reactive in the samples from three of the four remaining communities, particularly Community B. The HON fraction made a large contribution to the overall reactivity of the NOM from Community D. These findings are not unique (see Section 2.5.1.3) and challenge the widely held assumption that most THMs are formed from HOAs due to the intrinsic chemical characteristics of HOA species. Rather, it seems that in some cases the HOA fraction is responsible for the majority of the THMfp simply because it makes up a larger proportion of the total DOC in a given water sample. Alternatively it might be that the particular compounds contained in each fraction differ from source to source.

These results call into question the reliance by researchers and utilities on parameters used to quantify HOAs (i.e., UV254, SUVA) to predict THM formation. This might help to explain the lack of significant relationships found between these parameters in the historical datasets provided by ENVC. The findings should, however, be investigated in greater detail through repeated sampling (minimum monthly) before any definite conclusions are drawn with regards to the applicability (or lack thereof) of common organic water quality parameters used to predict the formation of THMs in any given water supply.

6.2.2.2 HAAFP

The absolute HAAfps of the NOM fractions isolated from each of the six raw water samples are shown in Figure 6.9. As with the absolute THMfp, the HOA fraction was responsible for the majority of the HAAfp in all but one of the communities. In this case, however, it is Community B that stands out from the rest with the HIN fraction making the largest contribution to the total HAAfp. Community C is also somewhat different from the rest because the HIA fraction made up a sizeable portion of the overall HAAfp.

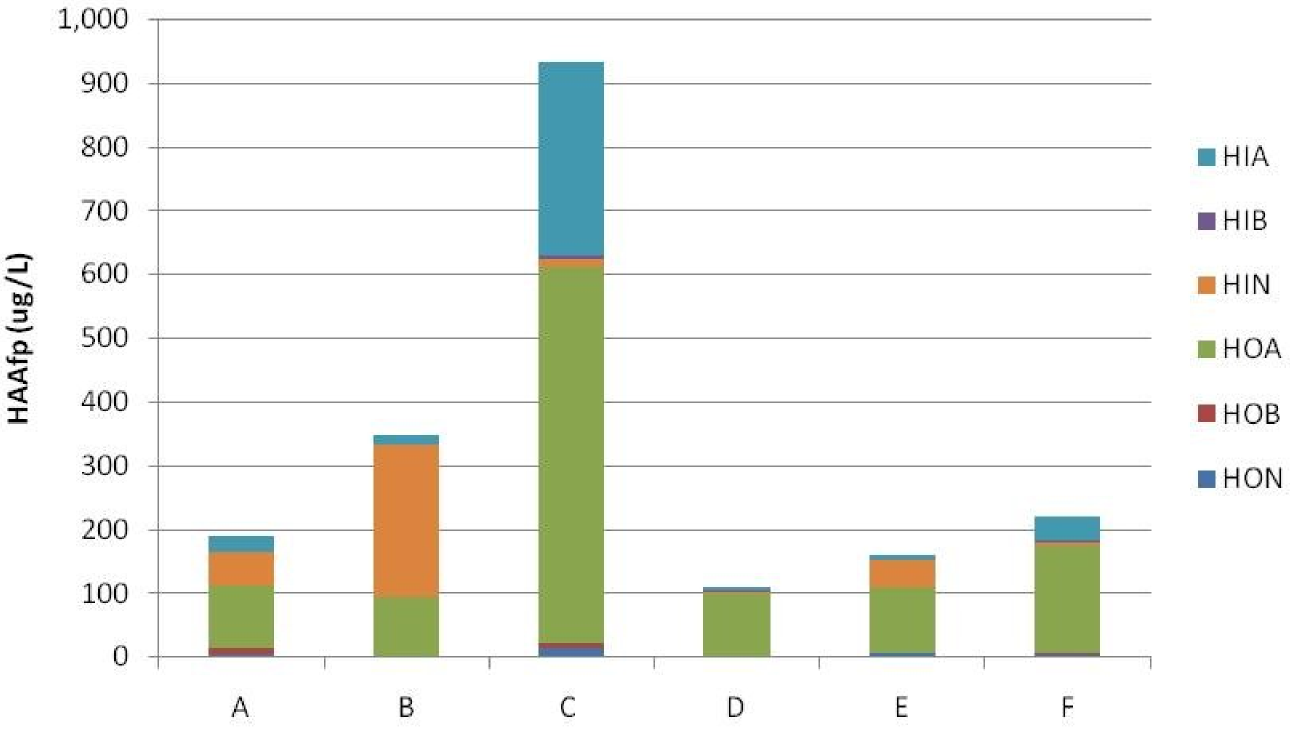


Figure 6.9 HAAfp of NOM fractions recovered from water samples from participating communities

The normalized HAAfp results (Figure 6.10) were similar to the normalized THMfp results; all six NOM fractions appear to have contributed to the overall reactivity of the NOM matrix in each sample. The contributions were roughly equal in Community A and Community E but much less so in communities B and C. In Community B the HIN fraction was dominant whereas in Community C the HOA fraction was the most likely to react to form HAAs. The HIB fraction, which is not usually linked to the formation of organic DBPs was one of the more reactive fractions in both Community D and Community F.

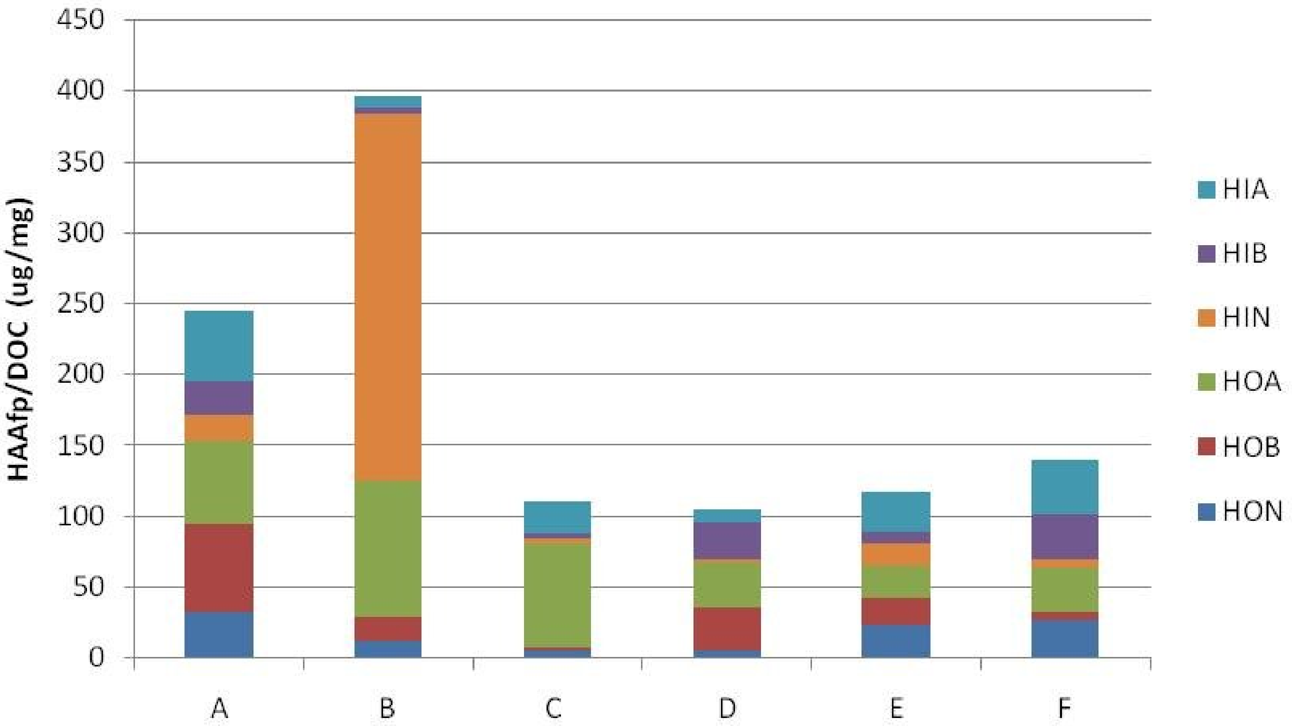


Figure 6.10 HAAfp of NOM fractions recovered from water samples from participating communities normalized to DOC

6.2.2.3 INFLUENCE OF HYDROPHOBICITY

Most commonly used organic parameters (UV254, SUVA) measure the amount of hydrophobic matter present in a sample because it is commonly assumed that most DBP precursors are hydrophobic. In this section, we compare the absolute and normalized THMfp and HAAfp of the hydrophobic and hydrophilic fractions from each community.

Figure 6.11 shows the percent absolute THMfp associated with the hydrophobic (HO) and hydrophilic (HI) fractions. The HO species contributed more to the overall THMfp than the HI species in the water samples from all but one of the participating communities. This follows the results of many other studies that have found that the HO fractions, in particular the HOAs, are the most important THMfp precursors. The water sample from Community A stands out because it is the only one where the HI fractions contributed more to the THMfp than did the HO fractions. This follows the findings of Kitis et al. (2002), who found that hydrophilic compounds contributed more to the formation of DBPs when the source water had a low SUVA. This is particularly interesting because the DOC results of the HO vs. HI fractions in the bulk water were more equal than their THMfps would suggest; indicating once again that DOC alone was not enough to predict THMfp. This is particularly true of Community B, which had more HI fractions by weight but whose THMfp was more closely associated with the HO fractions.

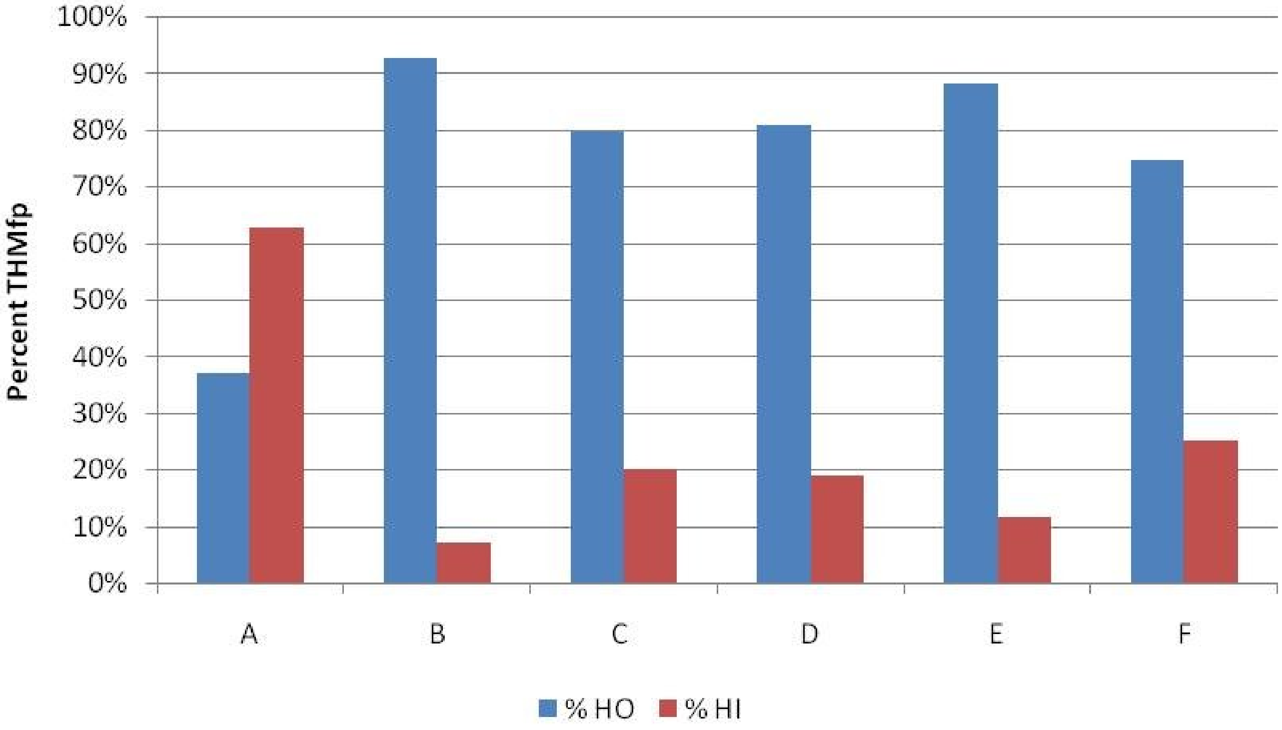


Figure 6.11 Percent THMfp represented by hydrophobic and hydrophilic NOM fractions recovered from water samples from participating communities

The percent normalized THMfps of the HO and HI fractions are presented in Figure 6.12. The HO fractions were more reactive in the samples taken from five of the six communities while the HI fractions were more reactive in one. This sample, which was taken from the water supply in Community F, had high bulk water DOC and UV254 compared to many of the communities where the HO fractions were more reactive than the HI fractions. The HO fraction dominated on a mass basis (Figure, however, and most of the THMs formed during the formation potential tests conducted on the sample were related to the HO fraction (Figure 6.11). Thus, though in this particular case the HI fraction was the most reactive, most of the THMs formed during the tests were related to HO NOM compounds because they were present in higher quantities than the HI NOM compounds.

The amount of absolute HAAfp caused by the HO and HI fractions in each water sample are compared in Figure 6.13. The percent contribution from the HO fractions ranged from 20% (Community B) to over 90% (Community D). The sample from Community B was the only one where the HI fractions contributed more than the HO fractions to the overall HAAfp. The opposite was true for all of the remaining water samples. The normalized HAAfp was more influenced by the HO fractions in four communities but by the HI fractions in the remaining two (Figure 6.14).

6.2.2.4 ACIDS, BASES, AND NEUTRALS

The contributions of acidic, basic, and neutral fractions to the quantity and behaviour of NOM in the water samples from Communities A and B is addressed in figures 6.15 to 6.18.

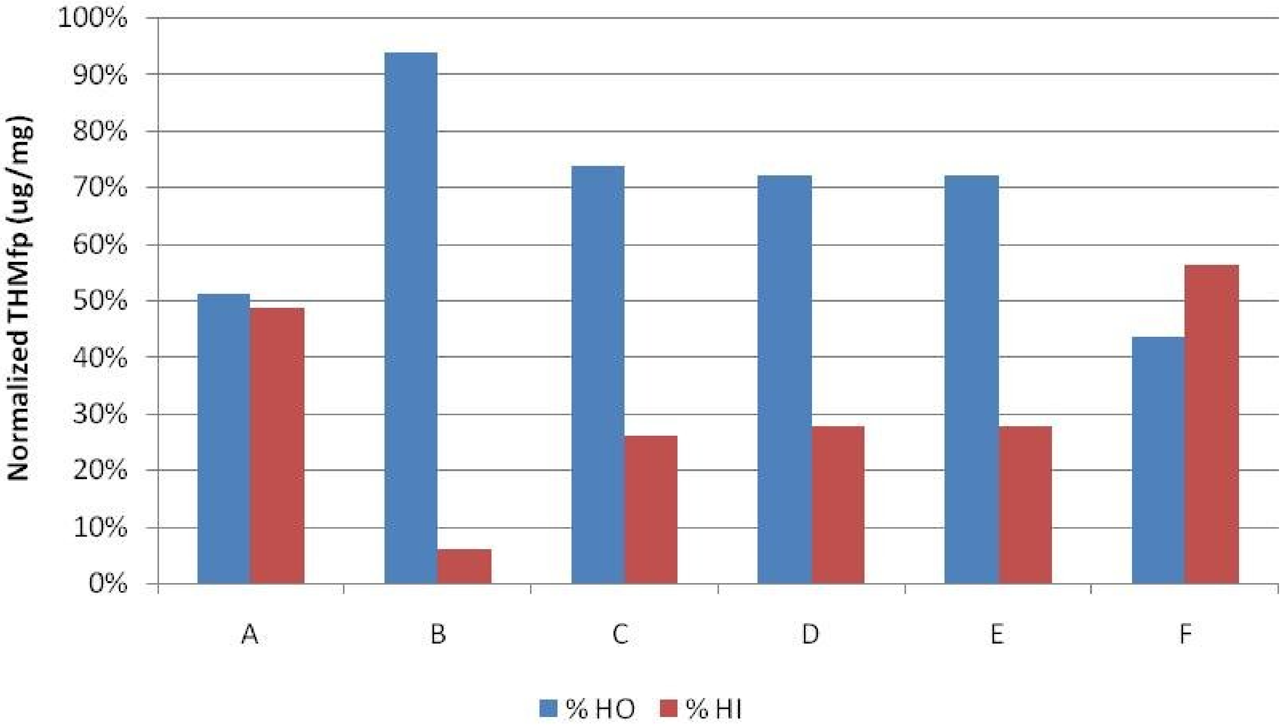


Figure 6.12 THMfp of hydrophobic and hydrophilic NOM fractions recovered from water samples from participating communities normalized to DOC

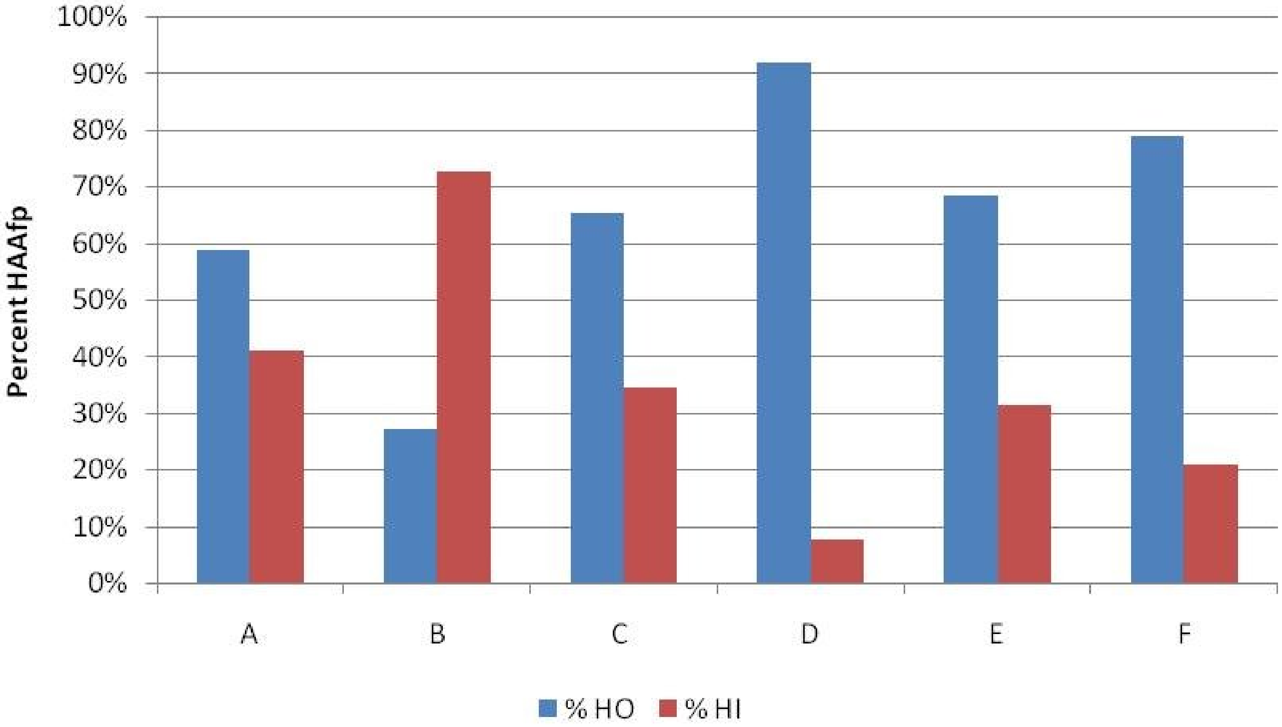


Figure 6.13 Percent HAAfp represented by hydrophobic and hydrophilic NOM fractions recovered from water samples from participating communities

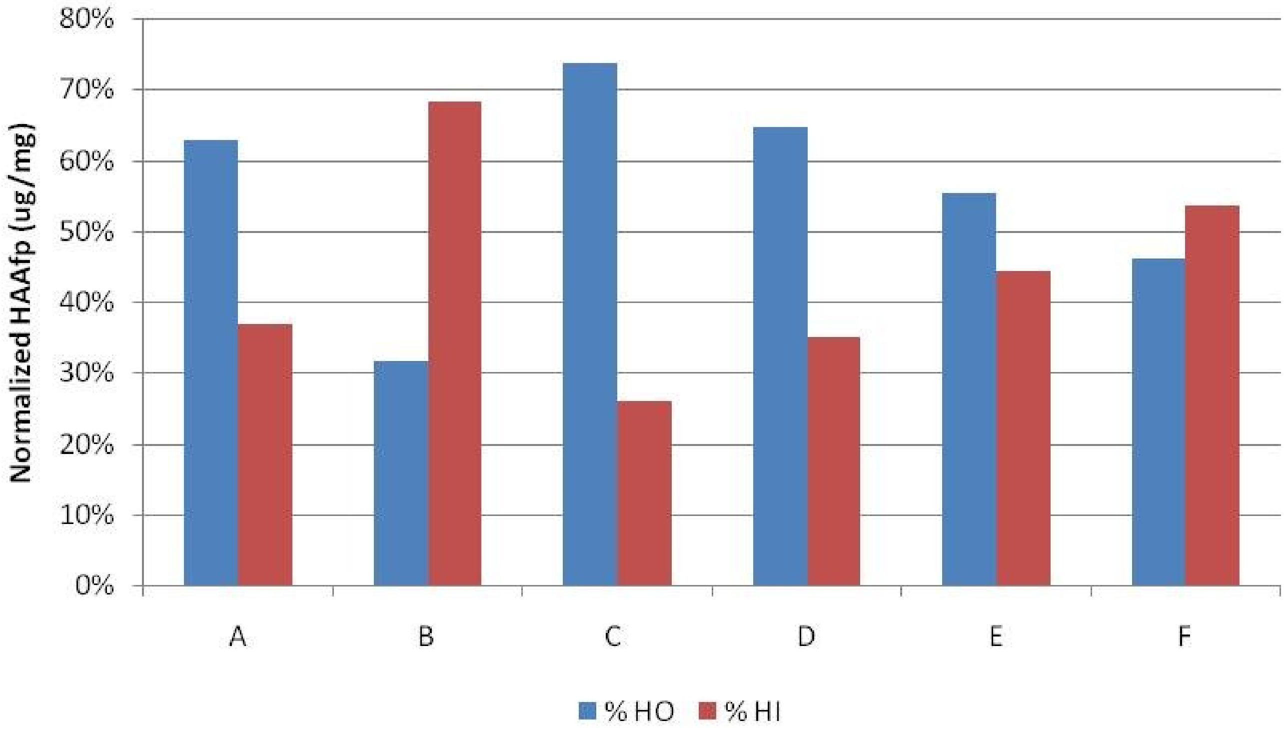


Figure 6.14 Normalized HAAfp of hydrophobic and hydrophilic NOM fractions recovered from water samples from participating communities

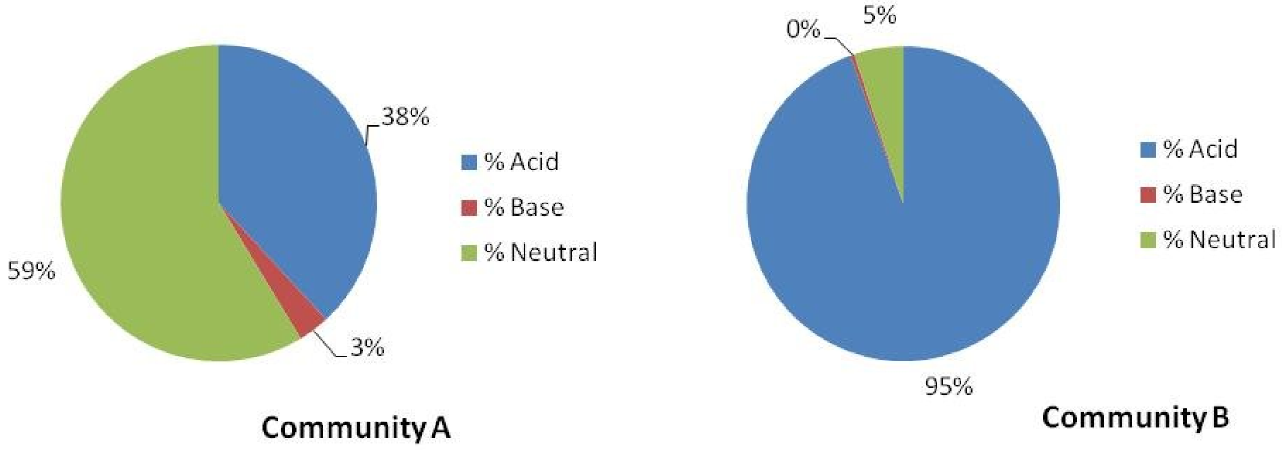
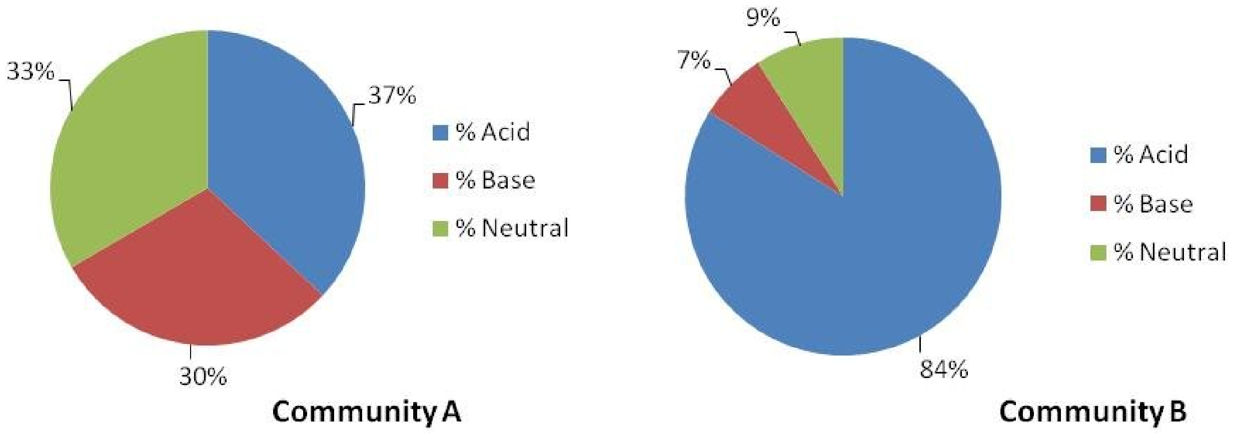


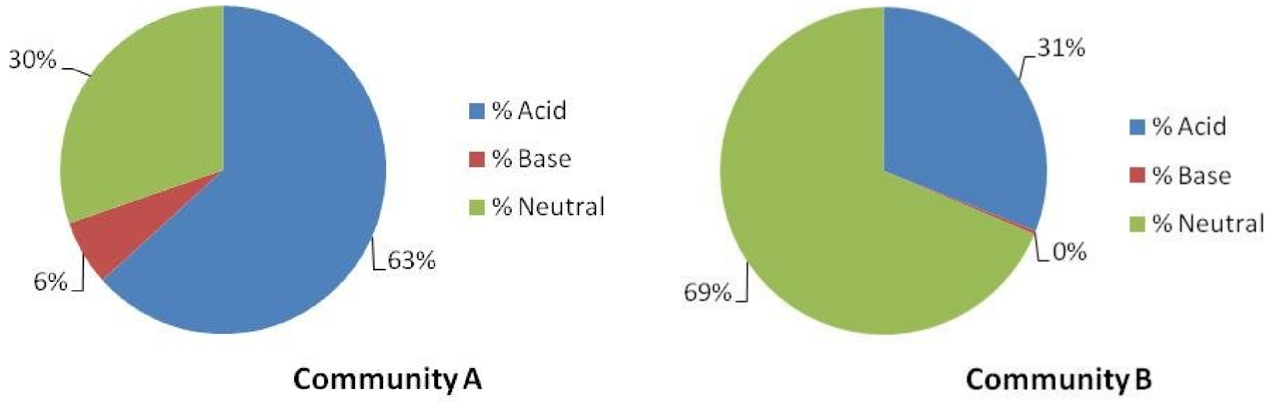
Figure 6.15 Percent THMfp represented by acidic, basic, and neutral NOM fractions recovered from water samples from participating communities



Community A

Community B

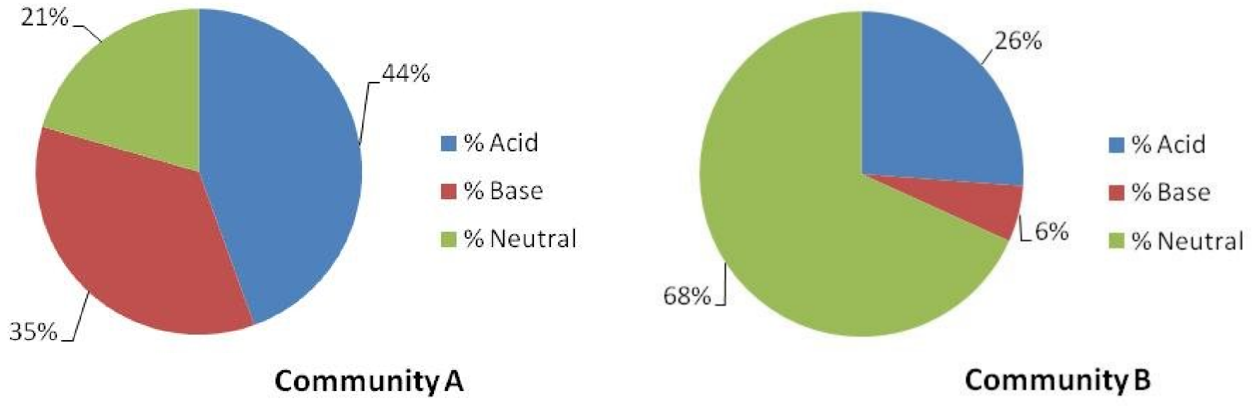
Figure 6.16 Normalized THMfp of acidic, basic, and neutral NOM fractions recovered from water samples from participating communities



Community A

Community B

Figure 6.17 Percent HAAfp represented by acidic, basic, and neutral NOM fractions recovered from water samples from participating communities



Community A

Community B

Figure 6.18 Normalized HAAfp of acidic, basic, and neutral NOM fractions recovered from water samples from participating communities

Figure 4.5 in Chapter 4 showed that most of the DOC in the sample from Community A was neutral while that in Community B was mostly acidic. Not surprisingly, the majority of the THMs in the sample from Community A were formed by the neutral species (59%) while those in the sample from Community B were mostly formed by the acidic ones (95%), as shown in Figure 6.15. Interestingly, the normalized THMfp from Community A (Figure 6.16) shows that acidic, basic, and neutral species were equally likely to form THMs. In contrast, the absolute and normalized THMfp pie charts for Community B show that the acidic fractions were more reactive and contributed more to the overall THMfp than the other fractions.

In Community A, the acidic compounds were responsible for 63% of the absolute HAAfp but made up only 43% of the total HAA reactivity of the sample. The basic fractions also accounted for a large percentage (35%) of the total reactivity. This is interesting because the NOM in the sample from Community A was 57% neutral by weight. This large mass of less reactive material might explain why this sample had the lowest THMfp and HAAfp of the six participating communities.

In contrast, the neutral fractions made up the majority of the HAAfp and normalized HAAfp in the sample from Community B despite the fact that the NOM isolated from it was 73% acidic. A closer look at the graphs discussed in previous sections reveals that the majority of the acidic compounds in the Community B sample were HIAs, which, according to figures 6.9 and 6.10 in this chapter, are unlikely to react with chlorine to form THMs or HAAs.

6.2.2.5 SUMMARY

The absolute and normalized THMfp and HAAfp were determined for six NOM fractions isolated from six raw water samples. The contribution of each fraction to the overall THMfp and HAAfp varied from community to community. In most cases, the HOA fraction was responsible for the majority of organic DBPs formed during the tests. Some communities also had major contributions from the HIN and HIA fractions.

Oftentimes fractions were quite reactive (i.e., high normalized organic DBPfps) but represented less of the total THMfp and HAAfp than might be expected because there was very little of them in the sample by weight. In other cases, though the DOC of the bulk raw water sample was high, the DBPfps were smaller than expected because of the nature of the compounds in the sample. Each fraction is made up of numerous compounds, some of which behave differently than others during the chlorine disinfection process.

A number of source specific results were observed. For example, in the water sample from Community A, the acidic fractions were more likely to form HAAs whereas the neutral fractions were more likely to contribute to the formation of THMs. The opposite was true for Community B. This underlines the fact that most of the trends in the data were source specific and that care should be taken before generalizing the results of this study to other water sources.

6.2.3 HPSEC Results

Unfortunately, the HPSEC results did not provide much additional insight into the formation of DBPs, though some comparisons can be made to published data. Researchers have suggested that high molecular weight HOAs are important DBP precursors. All six of the water samples evaluated during this study contained high MW HOAs. Moderate MW compounds (1,000 to 10,000 Daltons) have also been observed to produce large amounts of organic DBPs, particularly in the presence of bromine (Kristiana et al., 2010). All of the samples in the study had numerous NOM fractions that fell into this category, which likely accounts for much of the THMfp and HAAfp not associated with the high molecular weight HOA fraction.

6.3 Water Treatment for NOM Removal

6.3.1 *Bulk Water Quality*

Of the sixteen WTPs in Newfoundland and Labrador seven include a coagulation-based treatment train while three use ozone and filtration in some form. Samples of raw and treated water were taken from a coagulation-based WTP (Community C) and an ozone and filtration WTP (Community D) and analyzed using resin fractionation and HPSEC. The bulk water quality was also assessed.

Please note that the results in this section are specific to the water samples used and the treatment systems sampled. To truly establish the effectiveness of coagulation-based treatment vs. ozone and filtration it would be necessary to conduct bench or pilot-scale testing of each process on water samples from the same water source that were collected at the same time of year. The results in this section should be interpreted with these caveats in mind.

6.3.1.1 COMMON WATER QUALITY PARAMETERS

A summary of bulk water quality before and after treatment at the two WTPs is provided in Table 6.4.

Table 6.4 Bulk raw and treated water quality in a coagulation-based treatment process and an ozone and filtration process

Community	TOC	DOC	UV254	Apparent Colour	True Colour	THMfp	HAAfp	SUVA
	mg/L	mg/L	cm^{-1}	CU	TCU	ug/L	ug/L	L/mg.m
Coagulation-based Treatment								
Raw	11.3	10.8	0.815	99	92	1,306	570	7.5
Treated	3.5	3.8	0.109	8	5	225	187	2.9
Ozone and Filtration								
Raw	7.0	5.2	0.281	23	22	958	442	5.4
Treated	6.1	5.1	0.110	9	9	229	36	2.1

Both the coagulation-based and ozone and filtration systems reduced TOC and DOC, but the coagulation-based treatment system did so far more effectively. Both systems also reduced UV254 and colour, though once again the coagulation-based treatment system proved more effective than the ozone and filtration system. SUVA was reduced from 7.5 L/mg.m to 2.9 L/mg.m by the coagulation-based system and from 5.4 L/mg.m to 2.1 L/mg.m in the ozone and filtration system. This suggests that both systems were able to reduce the amount of aromatic NOM in the water.

Figure 6.19, which shows the percentage removal of DOC and UV254, shows that the coagulation-based system removed approximately 65% of the raw water DOC while the ozone and filtration system removed only 1%. This result is not unexpected as it is well-established that coagulation processes remove NOM while ozone systems convert it to different species (Owen et al., 1993). If any DOC is removed in an ozone-based process it is usually because the converted species become adsorbed or biodegraded in the filters that follow the ozone contactor. The results of this study cannot be compared directly or generalized to other systems, however, because different raw water was used in each case.

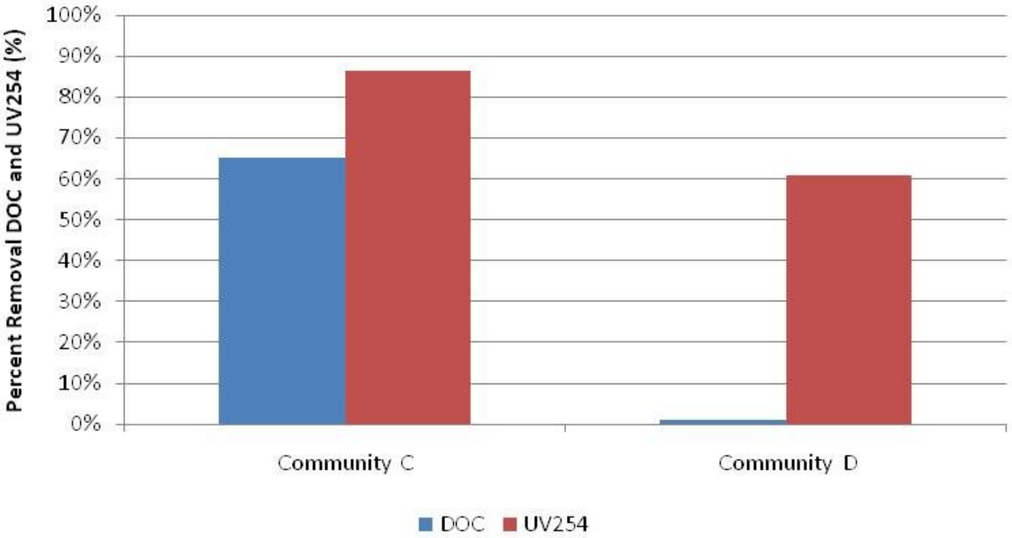


Figure 6.19 Percent reduction of bulk water DOC and UV254 observed in a coagulation-based treatment process (Community C) and an ozone and filtration treatment process (Community D)

The coagulation-based system in Community C removed 87% of the raw water UV254 and the ozone and filtration system in Community D removed 61%, showing that both systems target the aromatic NOM fractions that contain light-absorbing chemical structures. The more effective reduction observed in the coagulation-based process vs. the ozone and filtration process is opposite of what Owen et al. found in their 1993 study. This suggests that other factors such as system operation (chemical dosing, etc.) or initial raw water quality (total DOC, NOM fraction profile) may be responsible for the poorer UV254 reduction found in the ozone and filtration process. For example, the raw water collected from Community D Lake in January had lower DOC, UV254, and SUVA, than that from the ponds that are used in Community C. This indicates that there was less NOM, and in particular reactive NOM, available to react with the ozone being applied.

6.3.1.2 THMFP AND HAAFP

As shown in Figure 6.20 and Table 6.4, both WTPs were effective at reducing THMfp and HAAfp. The coagulation-based treatment in Community C system reduced THMfp by 83% and HAAfp by 67%. The resulting THMfp and HAAfp values were still well above the current provincial and federal guidelines, but this result is not unexpected given that the treated water still had a DOC of 3.8 mg/L and a UV254 of 0.109 cm-1. The result is also consistent with historical trends in the community, which has a history of high THMs and HAAs despite the existence of the WTP. Finally, the high THMfp and HAAfp might reflect the conditions of the standardized formation potential test.

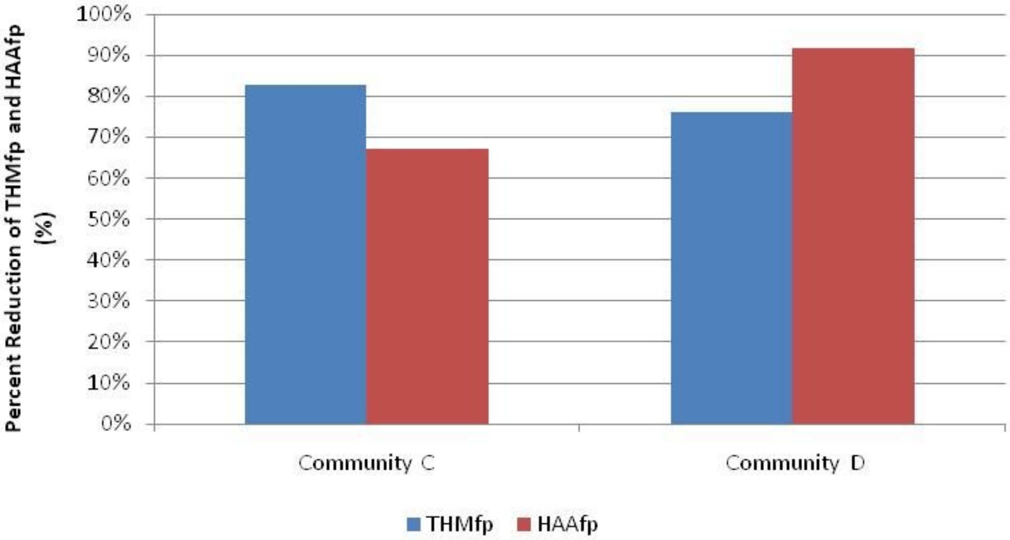


Figure 6.20 Percent reduction of bulk water THMfp and HAAfp observed in a coagulation-based treatment process (Community C) and an ozone and filtration treatment process (Community D)

THMfp and HAAfp were reduced by 76% and 92%, respectively, by the ozone and filtration system in Community D. These numbers are impressive given the poor DOC removal and moderate UV254 reduction observed for the system. The HAAfp of the treated water was much lower than that of the raw water, suggesting that the ozone and filtration system was particularly good at removing or transforming HAA precursors. The value measured in the laboratory is much lower than the usual HAA values measured within the distribution system in Community D. This discrepancy might be because of the raw water quality on the day of sampling, the conditions of the formation potential test, or because the majority of the HAAs measured during ENVC sampling events are forming within the distribution system.

The differences in DBPfp reduction between the two systems are likely related to differences in system operation and/or initial raw water quality in addition to the type of treatment system used. They do, however, highlight the fact that coagulation-based processes and ozone-based processes use different mechanisms to reduce THMfp and HAAfp.

6.3.1.3 REACTIVITY

The results in Figures 6.21 and 6.22 show how the coagulation-based and ozone treatment systems affected the THM and HAA reactivity of the water. Coagulation-based treatment reduced the THM reactivity of the water by 51% while ozone and filtration reduced it by 76%. The coagulation-based system had less of an effect on HAA reactivity, reducing it by only 6%, whereas the ozone and filtration system reduced HAA reactivity by 92%.

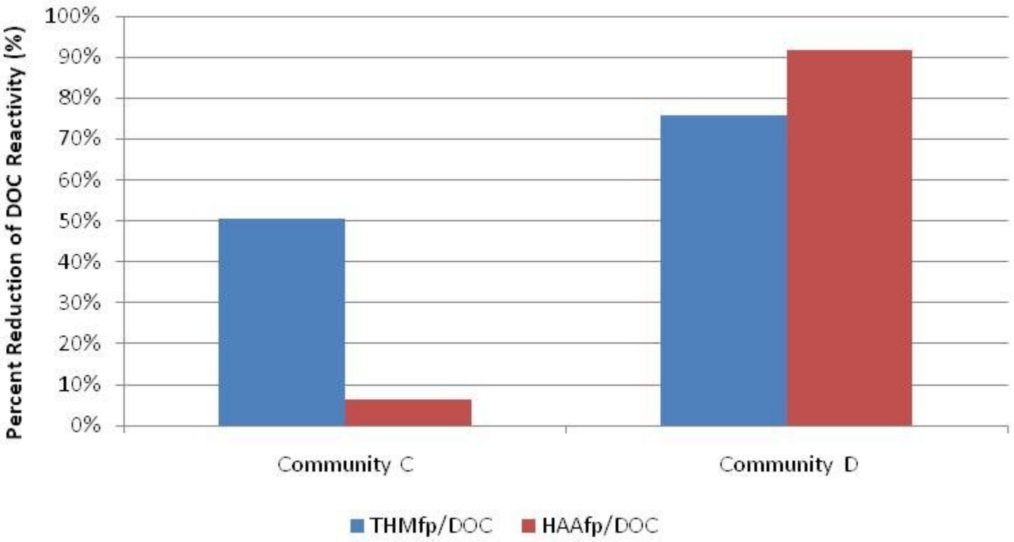


Figure 6.21 Raw and treated bulk water THM reactivity observed in a coagulation-based treatment process (Community C) and an ozone and filtration treatment process (Community D)

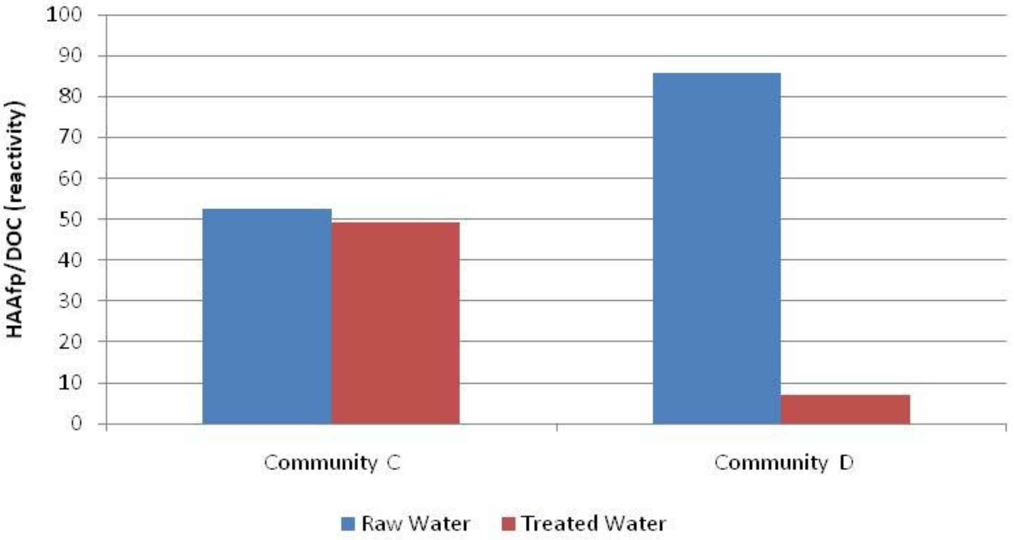


Figure 6.22 Raw and treated bulk water HAA reactivity observed in a coagulation-based treatment process (Community C) and an ozone and filtration treatment process (Community D)

The high level of reduction in the ozone and filtration system vs. the coagulation-based treatment system is not unexpected because reactivity is calculated by dividing the THMfp or HAAfp by DOC. Coagulation removes DOC, which increases the calculated reactivity unless the DBPfp is reduced as well. Ozone-based systems transform rather than remove DOC, keeping the bottom half of the equation constant. Any reduction in DBPfp will then reduce the calculated reactivity.

It is nonetheless interesting to note that the NOM that remained after the coagulation-based treatment system was still likely to react to form THMs and HAAs, whereas that remaining after ozone and filtration was less likely to do so. This could be due to differences in the NOM species remaining after each treatment process.

6.3.2 Fractionation

6.3.2.1 DOC

The mass of each NOM fraction in the raw and treated water from the two processes was measured as DOC and is shown in Figure 6.23. The majority of the DOC recovered from the raw water sample from Community C was present as HOAs and HINs, with a small contribution from the HIA fraction. The NOM in the treated water had a very similar distribution. The percentage of the total made up by HOAs was less in the treated water than in the raw water, indicating some preferential removal of these compounds.

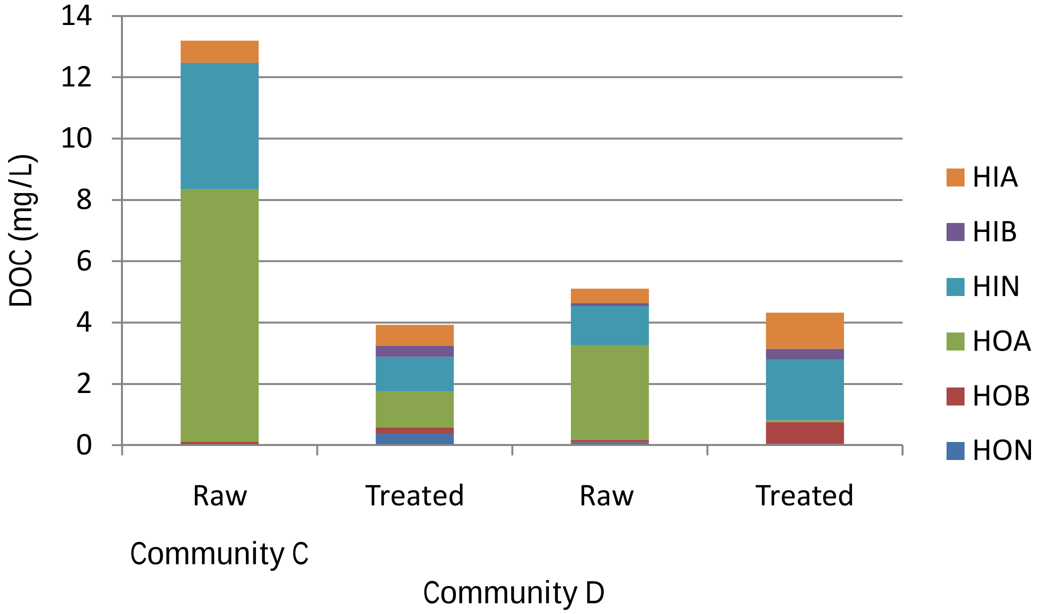


Figure 6.23 NOM fractions (as DOC) in raw and treated water from a coagulation-based treatment process (Community C) and an ozone and filtration treatment process (Community D)

In contrast, the distribution of NOM fractions in the raw and treated samples from the ozone WTP was noticeably different. The raw water sample contained primarily HOAs while the treated water sample was mostly made up of HINs, HIAs, and HIBs. These compounds are thought to be smaller and less reactive than HOAs, which might explain the reduced in THMfp and HAAfp in the treated water sample. The conversion of HOAs to smaller, less reactive, more hydrophilic, and/or more biodegradable species has been documented by numerous researchers (Owen et al., 1993; Sohn et al, 1997; Hesse et al., 1999) and was likely at work in this study as well.

6.3.2.2 DISINFECTION BY-PRODUCT FORMATION POTENTIAL

It is widely held that most THMs and HAAs are formed by large MW HOA compounds, though this has been challenged by some researchers (see Section 2.5.1.3). Figures 6.24 and 6.25 show the THMfp and

HAAfp of each fraction in the raw and treated samples collected from the coagulation-based and ozone and filtration WTPs.

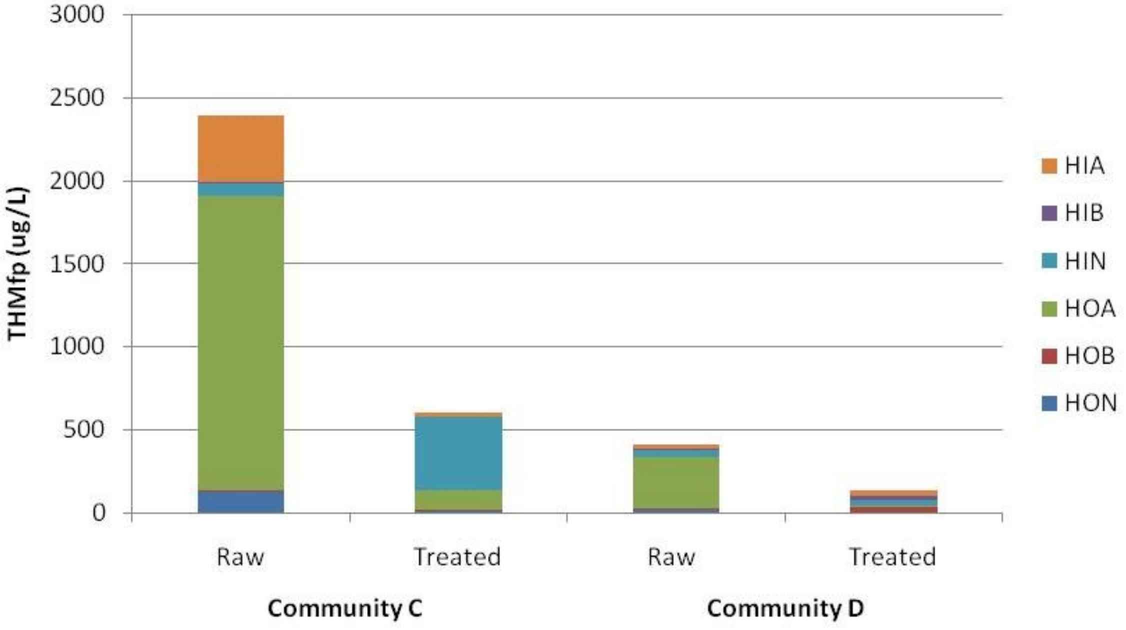


Figure 6.24 THMfp of raw and treated water samples obtained from a coagulation-based treatment process (Community C) and an ozone and filtration treatment process (Community D)

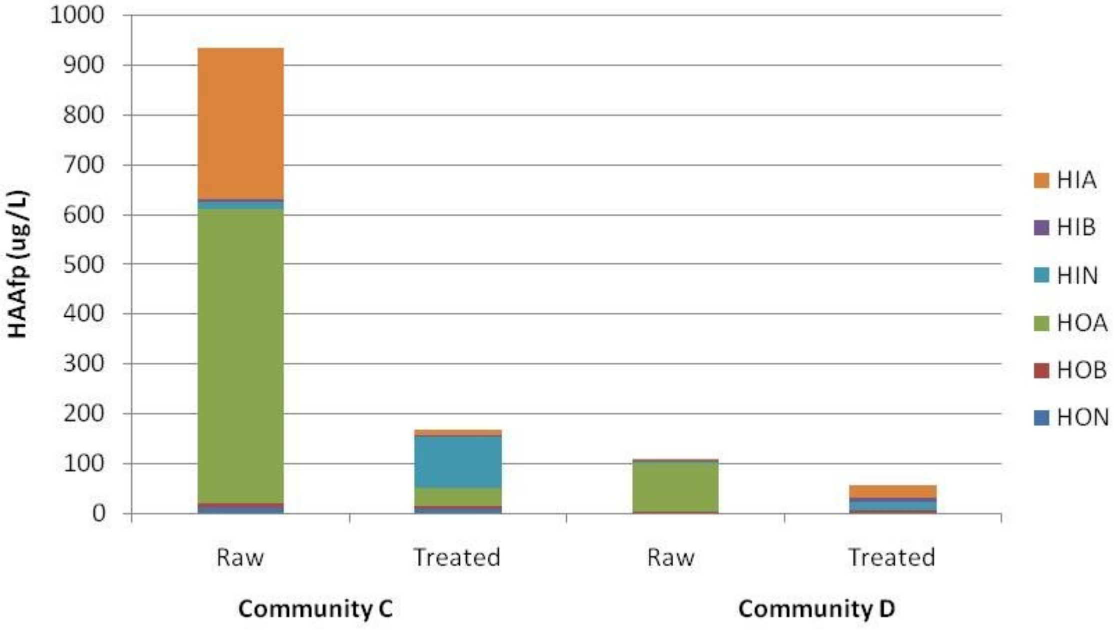


Figure 6.25 HAAfp of raw and treated water samples obtained from a coagulation-based treatment process (Community C) and an ozone and filtration treatment process (Community D)

In this study, the HOA fraction had the highest THMfp in both of the raw water samples. The THMfp in the treated water sample from the coagulation-based WTP was mostly related to the HIN fraction while that in the treated water sample from the ozone and filtration WTP was very small and evenly divided among the HIA, HIN, and HOB fractions, with small contributions from the HOA and HIB fractions.

The high THMfp of the HIN fraction may mean that these compounds were more likely to react with chlorine when there were fewer HOAs in the sample or be related to the fact that these compounds were the least likely to be removed through coagulation. The change in the quantity and source of THMfp in the water samples from the ozone and filtration WTP supports the hypothesis that the application of ozone converted some of the more reactive HOA species into less reactive ones.

Similar patterns are apparent in the HAAfp results shown in Figure 6.25. The HOA fraction contributed most of the HAAfp in both raw water samples, though the HIA fraction was also important in the sample from Community C. The HIN fraction once again dominated after the coagulation-based treatment process, while the HAAfp in the sample from the outlet of the ozone and filtration plant was evenly divided among the hydrophilic fractions.

These results are interesting and match up well with published trends, however, it is important to keep in mind that they are source water specific.

6.3.2.3 REACTIVITY

The THM reactivity of the NOM fractions obtained from the raw and treated water samples is presented in Table 6.5.

Table 6.5 THM reactivity of NOM fractions before and after treatment

	Coagulation-based Treatment			Ozone and Filtration		
	Raw	Treated	Change	Raw	Treated	Change
HON	47	32	-	210	45	-
HOB	2	27	+	35	45	+
HOA	220	99	-	101	124	+
HIN	18	399	+	35	20	-
HIB	3	1	-	33	53	+
HIA	29	40	+	65	34	-

The HOA fraction was highly reactive in both raw water samples, though it was more so in the sample from Community C. After coagulation-based treatment, the HIN fraction became the most reactive, followed by the HOA fraction. Overall, coagulation-based treatment increased the reactivity of the HOB, HIN, and HIA fractions while reducing that of the HON, HOA, and HIB fractions. The HOA and HON fractions represented the largest MW molecules in the raw sample from this community (Section 6.1) and are thought to be more likely to form THMs (Kristiana et al., 2010). These two fractions were preferentially removed by the coagulation-based treatment process, which likely explains the observed drop in reactivity.

The HON fraction was the most reactive one in the raw water sample from Community D, but after ozonation and filtration the HOA fraction became the most reactive. This is surprising given the lack of THMfp caused by this fraction. The HOB and HIB fractions, which are not usually linked with the formation of halogenated DBPs (Singer and Reckhow, 2011), also became more reactive after ozonation.

The HAA reactivity of each fraction is summarized in Table 6.6.

Table 6.6 HAA reactivity of NOM fractions before and after treatment

	Coagulation-based Treatment			Ozone and Filtration		
	Raw	Treated	Change	Raw	Treated	Change
HON	5	21	+	5	37	+
HOB	3	30	+	31	8	-
HOA	73	31	-	32	7	-
HIN	3	94	+	1	8	+
HIB	3	1	-	27	23	-
HIA	22	19	-	9	19	+

Both treatment processes reduced the HAA reactivity of the HOA fraction but increased that of the HON and HIN fractions. The last was of particular importance in the samples from the coagulation-based treatment process because these fractions were well represented in the bulk water samples (as measured by DOC) and contributed to their high HAAfps.

6.3.3 Molecular Weight

HPSEC was used to determine the MW distribution of the NOM present in the raw and treated water samples from the two WTPs investigated in this study. Both large and small MW NOM compounds have been implicated in the formation of DBPs but the larger MW fractions are thought to contribute more (Kristiana et al., 2010). An understanding of the MW distribution of NOM within a given water source could help system designers choose the most appropriate system. Chromatograms of the bulk raw and bulk treated NOM from the coagulation-based and ozone systems are shown in Figures 6.26 and 6.27 respectively. Chromatograms of the individual treated NOM fractions are provided in Appendix G.

A summary of the MWs of NOM fractions present in the samples is provided in Table 6.7.

Table 6.7 Molecular weight of NOM fractions in raw and treated water samples

	<1,000 Daltons	1,000 - 10,000 Daltons	>10,000 Daltons
C			
Raw	All	All	HON, HOA
Treated	All	All	None
D			
Raw	All	All	HOB, HON, HOA
Treated	All	All	HOB, HON, HOA

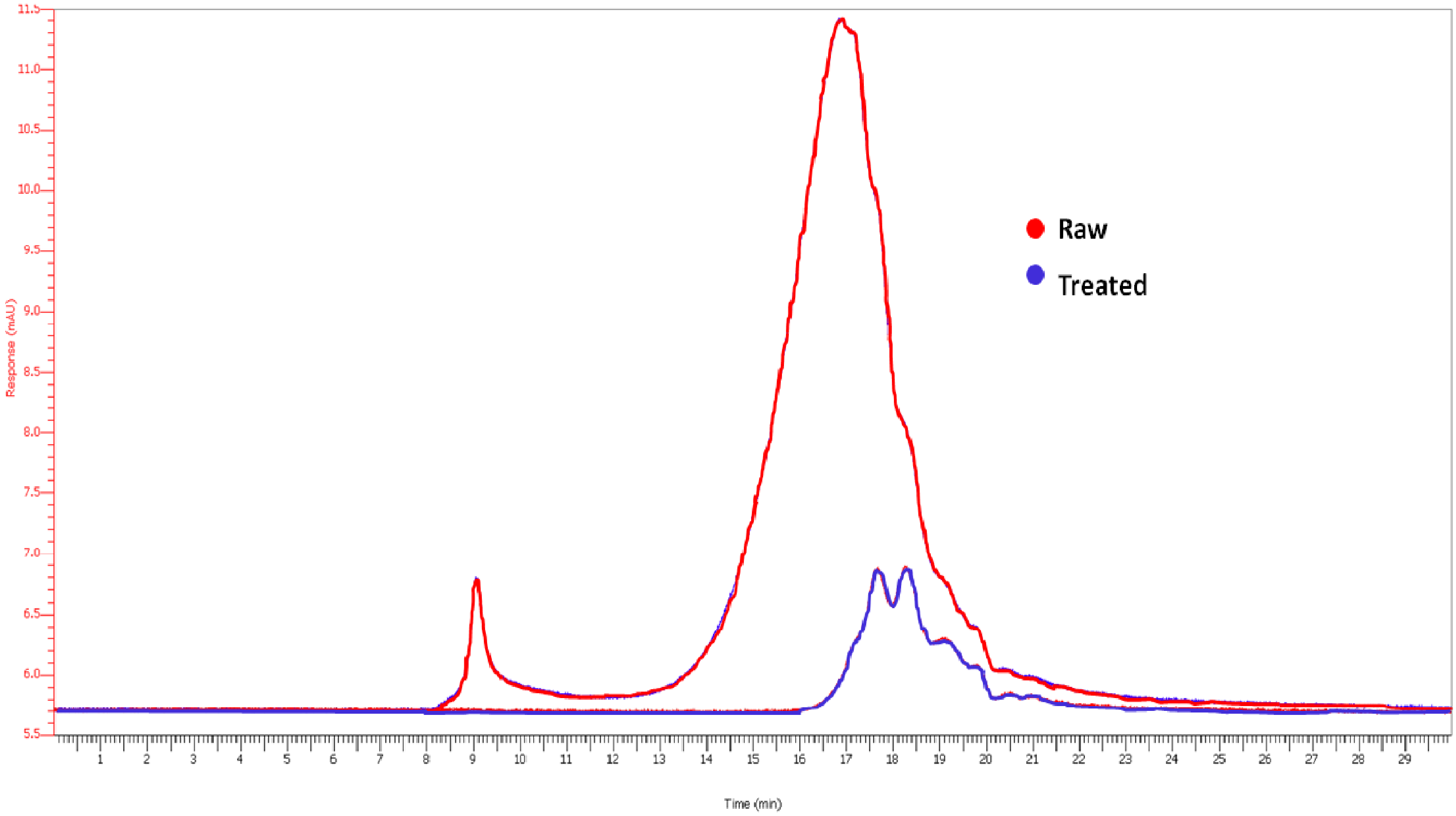


Figure 6.26 Community C raw vs. treated bulk water chromatogram

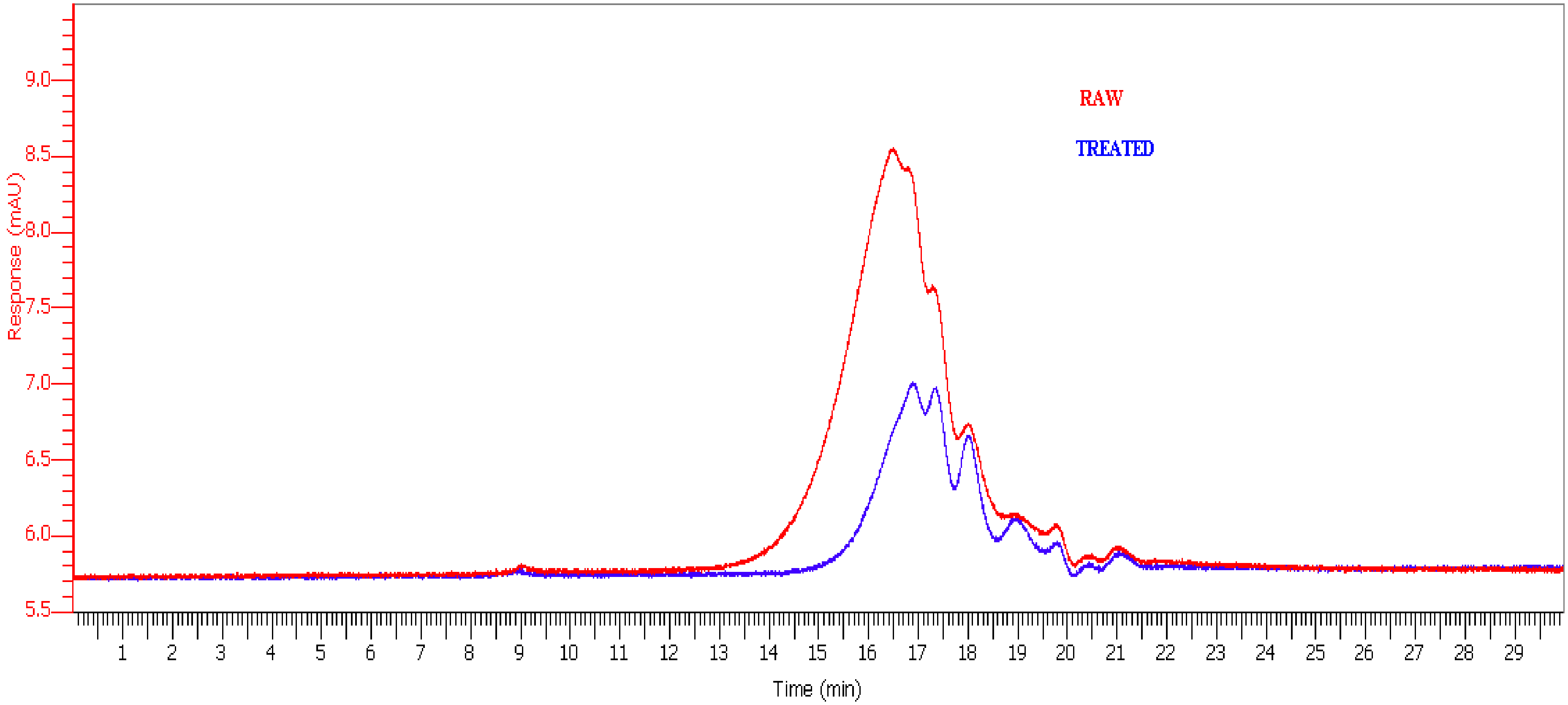


Figure 6.27 Community D raw vs. treated bulk water chromatogram

The coagulation-based treatment process effectively removed the large (>10,000 Daltons) HON and HOA molecules present in the raw water. It also removed some of the species in the moderate MW range (1,000 to 10,000 Daltons). The most obvious change was in MW of the HOA fraction. The small peak on the far left of the scale was removed completely while the large peak in the middle of the graph shifted noticeably to the right, showing a reduction in the overall MW of the NOM after coagulation-based treatment. These results are in line with those observed by other researchers (see Section 2.5.1).

The effect of ozone on the distribution of NOM fractions in the water from Community D is less obvious. The raw vs. treated water chromatogram for this WTP shows that the overall MW distribution shifted slightly to the right after ozonation and filtration, particularly the HOA fraction. This suggests that there was a higher proportion of low molecular weight compounds present in the treated water than the raw water. This change is subtle, however, and difficult to quantify using the chromatogram. If the change is considered in light of the results presented in Figure 6.23, however, it becomes apparent that although some larger HOAs remained after ozonation, there were fewer of them (by weight) in the treated water than in the raw water. The proportion of HIAs, HINs, and HOBs increased after ozonation. All of these are less than 10,000 Daltons in size, raising the possibility that some of the larger HOAs were converted into these smaller species. This would be similar to results presented by various researchers, as summarized in Section 2.6.3.1 of this report.

CHAPTER 7 APPLICATION OF FINDINGS

7.1 Predicting Disinfection By-product Formation and Treatability

7.1.1 Fractionation Results

For many years the water industry has assumed that HOAs are responsible for most or all THMs and HAAs. This assumption has been challenged by the results of some recent studies (Section 2.4.1), which have implicated other NOM fractions in the formation of these DBPs. Many researchers are now evaluating the reactivity of each fraction in addition to its absolute THMfp and HAAfp. Reactivity is calculated as the DBPfp divided by (or normalized to) the DOC of the fraction.

When reactivity is taken into account it becomes obvious that though HOAs may be responsible for most of the absolute THMfp and HAAfp in some cases this may only be because the HOA fraction makes up the largest proportion of DOC in the bulk water. Other NOM fractions may be just as reactive towards chlorine but not as well represented in the bulk water. In some cases, however, these other fractions may also be responsible for a large proportion of the absolute DOC, THMfp, and/or HAAfp.

HOAs made up the majority of the DOC found in the water samples from four of the six communities that participated in the study. This fraction was responsible for most of the absolute THMfp in all but one community and the majority of the absolute HAAfp in four out of six. In terms of reactivity, however, the reactivity of the HOA fraction towards chlorine (normalized THMfp and HAAfp) was similar to, and in some cases less than, the other fractions.

These results suggest that all NOM fractions should be considered when making decisions about water supply management and water treatment system design and operation. This may be more important in some communities than in others, based mostly on the distribution of NOM fractions in the water supply. Note that this distribution may change seasonally, as a result of severe weather events, and/or over time due to natural processes or human activities. Other water quality parameters, in particular bromide, can also impact the formation of THMs and HAAs.

7.1.2 Surrogate Parameters

The results of this study show that common surrogate parameters such as UV254 and SUVA can give a rough idea of the THMfp and HAAfp of a water sample but are not always able to predict either one accurately. This is because different fractions, some of which are not measured by UV254 and SUVA, can be responsible for DBP formation in some water supplies. Oftentimes, fractionation based on reactivity and/or MW is required to truly understand which NOM species are responsible for the formation of DBPs.

Resin fractionation is expensive, however, so it will continue to be necessary to predict DBP formation using surrogate parameters, which are easier and less expensive to measure. For example, in cases where the hydrophobic acid fraction is the most important DBP precursor, UV254 and/or SUVA could potentially be employed instead of resin fractionation and DBPfp tests. To investigate the feasibility of this, linear regressions were performed on some of the results of the laboratory work (raw and treated samples were pooled). The results are summarized in Table 7.2.

Table 7.2 Summary of linear regressions performed on laboratory results (raw and treated water samples)

Summary of Regressions	r^2	p	n
UV254 vs. DOC	0.90	< 0.05	8
Colour vs. DOC	0.77	< 0.05	8
UV254 vs. Colour	0.96	< 0.05	8
DOC vs. THMfp	0.75	< 0.05	8
DOC vs. HAAfp	0.71	< 0.05	8
UV254 vs. THMfp	0.57	< 0.05	8
UV254 vs. HAAfp	0.63	< 0.05	8
SUVA vs. THMfp	0.57	> 0.05	8
SUVA vs. HAAfp	0.73	> 0.05	8
Colour vs. THMfp	0.38	> 0.05	8
Colour vs. HAAfp	0.46	> 0.05	8
UV254 vs. normalized THMfp (THMfp/DOC)	0.24	> 0.05	8
UV254 vs. normalized HAAfp (HAAfp/DOC)	0.03	> 0.05	8
UV254 vs. %HO	0.26	> 0.05	8
UV254 vs. HOA	0.72	< 0.05	8
SUVA vs. %HO	0.21	> 0.05	8
SUVA vs. HOA	0.58	< 0.05	8
UV254 vs.THMfp of HOA	0.92	< 0.05	8
UV254 vs.HAAfp of HOA	0.77	< 0.05	8
UV254 vs. % THM attributable to HOA	0.52	< 0.05	8
UV254 vs. % HAA attributable to HOA	0.19	> 0.05	8
SUVA vs. % THM attributable to HOA	0.66	< 0.05	8
SUVA vs. % HAA attributable to HOA	0.23	> 0.05	8

Perfect linear relationships between parameters were not expected because of the small sample size and the variable character of NOM, which is not even fully captured by the fractionation methods used in this study. Thus, one would only expect a strong relationship between DOC and THMfp if one unit of DOC reacted predictably with one unit of chlorine to form a constant amount of DBPs.

Section 4.3.2 of this report presented the results of a linear regression performed on the paired DOC and UV254 results obtained during a sampling program conducted by the ENVC in 2010. A strong significant relationship was found between the two parameters, suggesting that many of the water supplies sampled during the program had similar (high) proportions of UV254 absorbing NOM (i.e., HOAs).

A similar relationship was apparent in the laboratory data ($r^2 = 0.9$, $p < 0.05$). The results shown in Figure 6.3 and Figure 6.23 call the original hypothesis into question, however, as the proportion of the total DOC represented by the HOA fraction (by weight) was unequal. Nonetheless, moderate significant relationships were found between UV254 and the DOC of the HOA fraction and SUVA and the DOC of the HOA fraction.

The results of linear regressions conducted on the THM and HAA results from the 2010 ENVC sampling program and their paired DOC and UV254 measurements were also provided in Section 4.3.2. A weak but significant positive linear relationship was found between UV254 and THMs in the 2010 dataset, but no such relationship was apparent between UV254 and HAAs. This lack of relationship is likely due to differences in water age and chlorine dosing practices in different communities.

The laboratory results provide some support for this hypothesis. The relationships between both DBPs and DOC and UV254 in the laboratory data were moderately positive and significant at a 95% confidence level, likely reflecting the controlled circumstances under which the tests were conducted (same chlorine dose, temperature, holding time, etc.).

UV254 was most strongly correlated to the THMfp of the HOA fraction ($r^2 = 0.92$, $p < 0.05$), though it was also moderately correlated to the HAAfp of the HOA fraction ($r^2 = 0.77$, $p < 0.05$). This indicates that UV254 can be used to provide a rough estimate of the amount of THMs and/or HAAs that will be formed by the HOAs in a water sample, though this will not account for the organic DBPs formed during reactions between chlorine and other NOM fractions. The relationships established in this study are not strong enough to develop predictive linear equations or to establish definite cut-off values that would indicate ‘high’ or ‘low’ DBP risk.

Attempts to correlate UV254 and SUVA to the normalized THMfp or HAAfp or the percent THMfp or HAAfp related to the HOA fraction were less successful. Moderate relationships were found between the percent THMfp represented by the HOA fraction and both UV254 and SUVA, but these relationships were not strong enough to be used in a predictive fashion.

7.2 Application of NOM Fractionation to the Design and Management of Water Systems

7.2.1 Implications for Water Supply Management

The results of this study show that, depending on the individual water supply, most or all NOM fractions contribute to the formation of THMs and HAAs.

As discussed in Section 2.2.1 of this report, some researchers have suggested that allochthonous NOM, or that originating from outside the water supply, is more hydrophobic/high MW/aromatic than autochthonous NOM, which forms within the water supply due to microbiological activities. This relationship is hardly definite, however, as many factors can influence the quantity and speciation of NOM in the water supply.

Communities where the HOA fraction is responsible for the formation of THMs and HAAs could focus on reducing the transport of NOM from the watershed to the water supply. This can be done by limiting human and agricultural activities in the watershed that increase soil erosion and/or minimizing wastewater inputs to the water supply.

If all NOM fractions are contributing to the formation of DBPs autochthonous inputs should also be controlled. As autochthonous NOM often results from the activity and decay of microorganisms, in particular algae, the main control measure would be to avoid the transport of nutrients into the water supply.

Note that though these actions can help mitigate NOM levels in the water supply they should not be relied upon exclusively as numerous factors, most of which cannot be controlled, contribute to NOM transport from the watershed to the water supply. Water treatment to remove organic DBP precursors is considered to be the most effective way to reduce THM and HAA to within acceptable levels in tap water.

7.2.2 Implications for Treatment System Design

The NOM fractionation process is onerous and expensive and will be beyond the needs of most communities in Newfoundland and Labrador. Nonetheless, should a community opt to conduct NOM fractionation during the initial design process, the results of the testing can be used to inform the design and operation of the resulting water treatment system.

For example, coagulation is known to preferentially remove large MW HOAs. This fraction accounted for much of the THMfp and HAAfp in most of the water samples analyzed during the study. It may therefore be possible to reduce the formation of DBPs in these communities using a coagulation-based process. However, the results of this study and of other studies suggest that DBPs can be formed by all NOM fractions. Coagulation processes are less effective at removing fractions other than HOAs, so if a source water that contains large proportions of fractions other than HOA is treated using a coagulation-based process it may still contain sufficient NOM to react with chlorine to form DBPs.

In such cases, an additional polishing step could be used to remove the remaining fractions. For example, biological filtration is an option for the removal of smaller, biodegradable NOM compounds and is often used as a polishing step in ozone-based processes. Some resin-based systems have also been shown to preferentially remove the smaller, less hydrophobic compounds (Section 2.5.4.2) when operated over a long period of time. The addition of a biological or resin-based polishing step after the main NOM removal process may help to reduce the THMfp and HAAfp associated with these fractions.

For example, the NOM in the sample from Community B was made up mostly of HIAs and HINs by weight, which are not targeted by coagulation and are less likely to absorb UV light (lower UV254). Further analysis showed, however, that the HOA fraction was responsible for most of the THMfp in this community and that it was by far the most reactive fraction towards chlorine. However, the HIN fraction was responsible for most of the HAAfp. This means that the community might be able to reduce the amount of THMs in the water using coagulation, but that this process is less likely to be able to reduce the formation of HAAs to within recommended guidelines unless some additional treatment optimized for HIN removal is also included.

Ozone and filtration is less specific to any one fraction but its tendency to transform, rather than remove NOM can make its application for organic DBP reduction more complex. The one ozone-based WTP evaluated during this study was able to reduce THMfp and HAAfp by transforming the HOA fraction into HIAs, HIBs, and HINs. These smaller compounds were less reactive toward chlorine than the HOAs in the raw water and therefore less likely to form DBPs. This may not be the case in every community and bench or pilot scale testing should be conducted in individual cases to confirm the effectiveness of ozone and filtration for DBP reduction.

A less selective treatment process could be used in communities where most of the DBPfp is caused by fractions other than the HOA fraction. Nanofiltration, which works through size exclusion, is able to remove all NOM fractions. It may be a particularly good option for Community A where the THMfp is mostly related to the HIN fraction. Communities where DBP formation is related to non-HOA fractions may consider using UV disinfection after the main organic removal process or substituting an alternative chemical for secondary disinfection instead of relying exclusively on chlorine. This will allow them to reduce the chlorine dose without compromising disinfection effectiveness. This option will only be available for communities where the treated water has a transmittance above 75%.

It should also be kept in mind that the NOM profile of a given water supply can change, sometimes dramatically, seasonally and over the course of time. Consequently, it would be unwise to develop a treatment strategy based exclusively on a one time grab sample of the raw water.

7.2.3 Disinfection

Most communities in Newfoundland and Labrador rely on chlorine to disinfect their drinking water. As few water systems in the province include treatment equipment for NOM removal, the water being chlorinated often has a high chlorine demand. This leads to large quantities of chlorine being added to the water in order to comply with the provincial requirement for a detectable chlorine residual throughout the distribution system. Naturally, this leads to the formation of THMs and HAAs as the NOM in the raw water reacts with chlorine. This report has mostly focused on the control or removal of NOM from water before disinfection but some DBP reduction can also be accomplished by minimizing chlorine addition.

Newfoundland and Labrador's disinfection requirements for drinking water are currently less rigorous than those in most other parts of Canada. They are based on the use of chlorine for disinfection, which reflects common practices in the province but makes it difficult to quantify disinfection achieved using filtration or alternative disinfection methods. If the province opts to change this such that these alternative methods can easily be applied to comply with provincial disinfection requirements many communities may be able to reduce the amount of chlorine added to the water. This will, in turn, reduce the formation of THMs and HAAs.

7.2.4 General Impacts on Water System Operation

A good understanding of the distribution of NOM fractions and MWs could potentially help operators manage their water treatment systems more effectively. For example, if the HOA fraction is known to be the greatest contributor to DBP formation it might be possible to increase the coagulant or ozone dose at times when this fraction is particularly well-represented.

For example, Community C uses a coagulation-based water treatment system to remove NOM and reduce the formation of DBPs. This process is periodically unable to remove enough of the DBP precursors in the water. The results of this study show that the HOA fraction is the largest contributor to THMfp and HAAfp, so the community might look into adding a UV254 analyzer to the raw or treated stream to assess when additional coagulant should be added.

The results also show that the HIA fraction in the raw water from Community C makes a contribution to the formation of HAAs and that the HIN fraction in the treated water contributes to the formation of THMs and HAAs. This suggests that an additional polishing step capable of removing these fractions may also help reduce the formation of DBPs. Depending on seasonal effects this polishing step may only be required periodically.

Note that in cases where the treatment process is optimized to remove all NOM fractions operators will not be possible to rely on UV254 to assess the effectiveness of the treatment system. Instead, the performance of the system will have to be monitored by periodically measuring DOC, which is less specific to any one individual NOM fraction.

7.2.5 Summary

A summary of the information provided in the previous sections is summarized in Table 7.1.

Table 7.1 Summary of design considerations

Definition	Most THMfp and HAAfp related to HOA fraction	Most THMfp and HAAfp related to non-HOA fractions
Water Supply Management	Minimize allochthonous inputs	Manage both autochthonous and allochthonous inputs
Recommended Treatment	Coagulation-based, ozone and filtration, NF/RO	NF/RO, ozone and biological filtration, resin-based treatments
Operational Considerations	UV254 analyzer can be used to optimize treatment in real time	Additional polishing step(s) may be required for conventional treatment systems
Notes	Additional treatment may be required if other NOM fractions contribute to DBP formation	If DOC is low, DBPs may be related to water age or excessive chlorine dosing

7.3 ENVC and DMA Requirements

7.3.1 Definitions of NOM and Organic Contamination in ENVC Guidelines

The existing design guidelines refer to ‘organics contamination’, a term that is not defined within the text. The language used in the guidelines makes it difficult to differentiate between naturally occurring organic matter and synthetic organic chemicals from, for example, industrial or agricultural run-off. These two concepts should be clearly separated and defined. Recommended mitigation strategies and pre-design requirements should be tailored to each.

NOM occurs naturally in the watershed and water supply and, as discussed in previous sections, is not easily controlled through watershed management. Therefore, it should not be described as a ‘contamination’. Unlike some synthetic organics, the health risk posed by NOM compounds is related to their role as organic DBP precursors, rather than any direct impacts on human health. Organic DBP formation can be minimized by choosing a water supply low in DOC/UV254, removing NOM through treatment (coagulation, ozone, membranes, etc.), minimizing chlorine use, using alternative disinfectants, and minimizing water age in the distribution system.

Synthetic organics are most likely to originate from run-off or waste discharges from industrial or agricultural users, though they can also enter water systems from municipal sources. They are not usually implicated in the formation of organic DBPs but can pose human health risks. In Newfoundland and Labrador, wastewater is most often disposed of in the ocean, making point-source contamination of drinking water sources less likely than in many other provinces. Chemicals may still seep in from non-point sources due to runoff or groundwater contamination.

Potential sources of synthetic organic chemicals should be identified during the pre-design process. Communities at risk should conduct a thorough water characterization study to determine the extent of contamination. This will help to determine what (if any) water treatment process can be employed to reduce levels of the contaminant to within federal and/or provincial recommended values.

If a drinking water source is known to contain synthetic organic chemicals, watershed and/or wellhead protection measures should be instituted to prevent further contamination. If contamination is determined to be extensive or difficult to manage, a new water source may be required. This should be chosen only after a thorough review of the potential for contamination and overall water quality of the proposed source.

7.3.2 Pre-design and Piloting Requirements – Existing Design Guidelines (ENVC)

Initial and/or pre-design studies are also referred to throughout the existing design guidelines. The end product of the study is referred to alternately as a:

- Technical report;
- Pre-design report;
- Conceptual report;
- Feasibility report; and
- Preliminary engineering report.

These are not separately defined in the guideline document, which could lead to confusion about the expected content of each. One term should be chosen and explained in a clear and concise manner within the guideline document. Specific reference should be made to water disinfection/treatment systems (as opposed to wastewater systems). A section tailored to systems designed for organic removal may also be useful as this is a primary objective for many communities in the province. The department may choose to refer to the format used in the *Atlantic Canada Guidelines for the Supply, Treatment, Storage, Distribution, and Operation of Drinking Water Supply Systems* (ACWWA, 2004). If more than one type of report is to be described, definitions and required content should be provided for both.

The guidelines also include instructions for pilot studies conducted using individual treatment processes (i.e., direct filtration, membrane filtration, etc.). These should be brought in line with the expectations of the DMA and summarized in a single section of the document.

7.3.3 Pre-design and Piloting Requirements – Proposed Generic Terms of Reference (DMA)

The Department of Municipal Affairs (DMA) is in the midst of developing standardized terms of reference (*Generic Terms of Reference*) to be used by municipalities and their consultants during the selection of treatment equipment and design of water treatment systems. This document will essentially act as a guide to the pre-design and preliminary engineering phases of a design project.

The proposed standardized TOR document specifically outlines the following:

- Consultant selection;
- Administration;
- Water usage and design flows;
- Selection of best available technology; and
- The anticipated impact(s) on the municipal budget.

The section that describes the selection of the best available technology is the only one that is directly applicable to the current study. It requires that at least six separate water treatment technologies be evaluated for each community during the initial stages of the project. Three of these are to be chosen for bench or pilot scale testing. This approach is likely to yield much data and result in the installation of the best available technology for the application. It may, however, prove onerous for smaller communities in the province, which often lack access to the human and monetary capital required to successfully complete such a process.

In cases where organic removal is the primary goal of the treatment process, it may be possible to quickly eliminate numerous potential processes by thoroughly reviewing existing ENVC water quality records and/or conducting a raw water characterization study. Where required, these could be followed by bench scale testing of the processes most likely to reduce the formation of THMs and HAAs. Finally, equipment from one or more suppliers could be piloted to confirm flow rates, determine chemical requirements, and develop cost estimates.

A review of the existing water quality records for the community will indicate whether the community has had trouble with THMs and/or HAAs in the past and whether the raw water source is high in DOC. Communities who have not experienced DBP exceedances in the past are unlikely to need to install organic removal unless NOM reduction is desired for aesthetic reasons (colour) or their lack of DBPs is related to improper disinfection practices (i.e., not chlorinating). Communities with a history of DBPs but low or moderate DOC (< 4 mg/L) should assess whether water age and/or excessive chlorine dosing are responsible for the formation of DBPs before they move to install water treatment processes optimized to remove NOM. Finally, communities with both DBP exceedances and high DOC (> 4 mg/L) should be encouraged to proceed with a raw water quality characterization study, bench scale testing, and piloting (if feasible) in order to select the best treatment option.

A raw water characterization study could be used to establish average NOM levels, seasonal NOM patterns, and the link between DOC and UV254 measurements and DBP formation. A raw water sample would be collected once a month for a year and tested for DOC, UV254/UVT (at minimum) as well as THMfp, and HAAfp (preferred). The results could then be used to establish:

- Ranges of water quality conditions for the water supply;
- Optimum timing for bench and pilot scale tests;
- The relationship between UV254 and THMfp and HAAfp; and
- SUVA values.

The most useful outcome of the raw water characterization study will be determining whether it will be possible to reduce DBPfp using treatment methods that target HOA (measured as UV254). If changes in THMfp and HAAfp match changes in UV254 absorption levels, then DBP formation is likely to be connected to the HOA fraction. These indicators will dictate the category of treatment processes that should be tested at the bench scale (i.e., coagulation-based, resin-based, etc.).

Bench scale testing should be conducted on water collected during the time of the year when NOM levels in the water supply are at their maximum. This can be established by analyzing the existing water quality records for the community, but can be established more accurately through a raw water characterization study. Water from supplies with high UV254 levels (or SUVA above 4 L/mg.m) should be tested using treatment methods known to reduce or remove the HOA fraction. This includes coagulation-based processes, ozone-based processes, and high pressure membranes (NF/RO). If the community has high THMfp and HAAfp but low UV254 (or SUVA between 2 and 4 L/mg.m), testing should include high pressure membranes and/or other treatment processes known to remove all or more NOM fractions, such as ozone and biological filtration or resin-based processes.

Finally, pilot testing of the most effective bench scale technologies may be conducted to confirm flow rates, establish operating parameters, and assess operating costs. The pilot program could be conducted with multiple suppliers comparing similar systems or with one or more suppliers comparing variations on a similar process. It should be noted, however, that the costs associated with pilot testing may not be feasible for small communities. If pilot testing is not conducted, the design of the treatment process should include conservative design allowances to account for any uncertainty with regards to system operation.

7.4 Proposed Decision-making Framework

ENVC and DMA should consider developing a comprehensive pre-design and piloting framework to help municipalities and their consultants choose the most appropriate water treatment process for organic removal/DBP prevention and establish effective operating strategies. Figure 7.1 presents a potential framework that includes: a review of existing water quality records; raw water characterization; bench scale testing; and pilot testing.

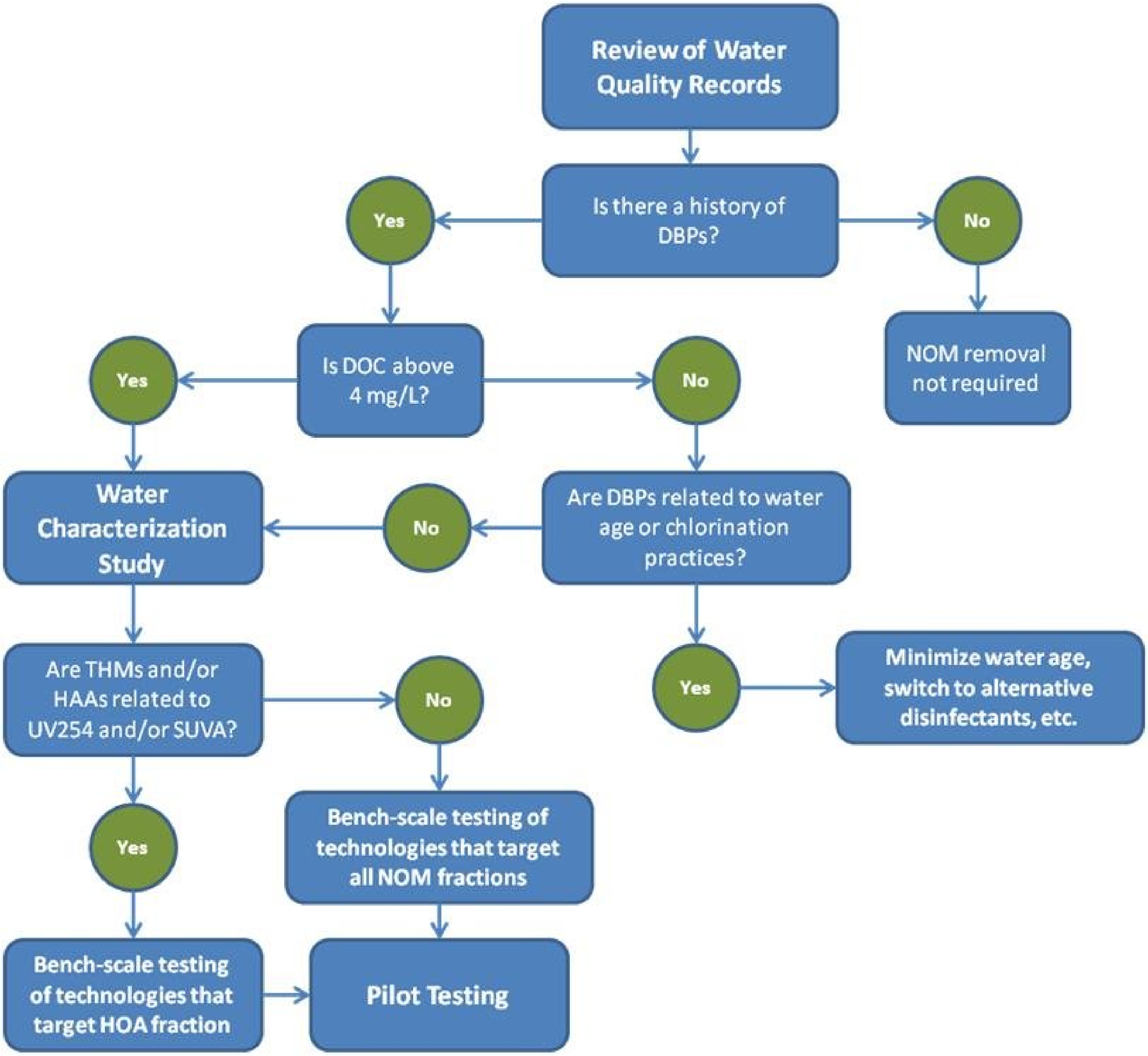


Figure 7.1 Proposed decision-making framework for the selection of water treatment processes and equipment to minimize DBP formation

This framework could be used as a guide for the pre-design (as defined in design guidelines) and/or preliminary engineering (equipment selection as defined by DMA) phases of a design project.

It is understood that some of the components of the framework may be too onerous for smaller communities. The ENVC and DMA may allow some communities to omit some portion(s) of it depending on their individual circumstances. Omission of an initial assessment of the existing water quality records or of bench scale tests is not recommended. Piloting requirements can be assessed only after raw water quality and overall treatment objectives have been clearly established. In some cases the departments may also consider referring to past piloting experience from projects conducted in other communities to minimize the need for additional raw water characterization, bench scale testing, and/or piloting.

7.4.1 Surrogate Parameters

As described previously, surrogate parameters such as DOC, UV254, and SUVA are commonly used to predict THMfp and HAAfp. Overall, the results of the study show that UV254 acted as a rough indicator not only of total DOC but also of the THMfp and HAAfp of the HOA fraction. Additional data points may provide a more definite relationship that could be used to develop predictive equations and definite cut-off values. For the purposes of this project, however, cut-off values will by necessity be based on accepted DOC and SUVA limits and empirical observations of UV254, as summarized in the following short sections and in Table 7.3.

7.4.1.1 DOC

The results of this study confirm that DOC is not, on its own, adequate for accurately predicting THMfp and HAAfp and that equivalent DOC values in different water supplies can lead to the formation of different levels of THMs and HAAs, even under controlled laboratory conditions. It is undeniable, however, that increasing DOC is associated with increased formation of both classes of organic DBPs. As a result, the Stage 1 Disinfectants and Disinfection Byproducts rule developed by the US EPA includes a bin system designed to help utilities determine the level of DOC removal required to comply with THM and HAA limits (80 ug/L and 60 ug/L, respectively). The highest DOC permitted in treated water with alkalinity below 60 mg/L as $CaCO_3$ (characteristic of NL surface water) is 4 mg/L while the lowest mentioned in the table is 2 mg/L. Though these cut-off values are hardly definite, they do provide useful operating ranges that could be applied to differentiate between communities where the formation of DBPs is driven mostly by DOC concentration rather than water age or chlorine dosing practices. For example, if a community is experiencing THM exceedances when the water has a DOC of 2 mg/L it is likely that excessive chlorine and water age are contributing factors.

7.4.1.2 SUVA

As discussed in Section 2.5.1 of this report, SUVA can be used to predict the treatability of NOM by giving some indication of its aromaticity. The updated version of this work is provided in Chapter 3 of the most recent version of Water Quality and Treatment published by the AWWA (Edzwald and Tobiason, 2011). Here, it is suggested that a SUVA value below 2 L/mg.m represents a water sample that is characterized by non-humic, non-hydrophobic NOM with low UV absorbance and MW. SUVA between 2 L/mg.m and 4 L/mg.m is thought to have medium UV absorbance an MW and contain a mixture of humic and non-humic matter. Finally, if SUVA is above 4 L/mg.m, the NOM in the water sample is predicted to be aromatic, hydrophobic, and humic in nature (i.e., high proportion of HOAs). Higher SUVA is associated with greater treatability using coagulation and other treatment processes that excel at removing HOAs.

It is proposed that these values be adopted as indicators of NOM treatability for the province of Newfoundland and Labrador. For example, the NOM from water supplies that are continuously characterized by high (> 4 L/mg.m) SUVA levels is more likely to respond to coagulation-based treatment processes, while those from supplies with moderate SUVA values that still experience DBP exceedances may need to employ less selective treatment processes (ex. NF or RO membranes).

7.4.1.3 UV254

If the formation of THMs and HAAs is connected to the UV254 absorbing NOM fraction (mostly made up of HOAs), it would be expected that increases in the latter would lead to increases in the former. To establish whether this was the case in a water supply, one could take regular samples from a water supply and analyze them for both UV254 and THMfp/HAAfp. If all three rise and fall together, it will likely be possible to minimize DBP formation using a treatment process known to remove or transform UV254-absorbing compounds, such as coagulation or ozone and filtration.

7.4.1.4 SUMMARY TABLE

Table 7.3 Summary of proposed DOC, SUVA, and UV254 cut-off values

	DOC	SUVA	UV254
Low	< 2 mg/L	< 2 L/mg.m	n/a*
Moderate	2 mg/L to 4 mg/L	2 L/mg.m to 4 L/mg.m	n/a*
High	> 4 mg/L	> 4 L/mg.m	n/a*

*If UV254 is correlated to THMfp and HAAfp, some portion of the organic DBPfp can be removed by targeting UV254 absorbing compounds such as HOAs

7.4.2 Special Note – Cost

The decision-making framework is a tool that can help communities establish which strategies are most likely to reduce the formation of THMs and HAAs. It should be emphasized that local conditions will also impact the choice of treatment process. For example, a community with high UV254 and DOC that is choosing between low pressure membranes preceded by coagulation or low pressure membranes followed by nanofiltration must take into consideration:

- System footprint;
- Chemical usage;
- Pressure requirements;
- Raw water NOM quantity and characteristics;
- Effects of raw water quality on membrane fouling and scaling;
- Finished water quality requirements;
- Downstream disinfection processes;
- Characteristics of the distribution system; and
- Residuals treatment and/or disposal options.

Project costs can also be influenced by local site conditions. For example:

- Where is the community located?
- How far is the site from the raw water source?
- Does an intake have to be built?
- Are intake pumps required?
- Does a transmission main have to be installed?
- Does a building have to be constructed? Renovated?
- Is there sufficient land owned by the municipality to accommodate the plant?
- What improvements must be made to the site before construction?
- Is a packaged system available or will the process need to be designed from the ground up?
- Who will build the plant?
- Who will operate the plant?
- What kind of monitoring plan is required?
- What are the current and projected costs for media/coagulant/chlorine/power?

These and other questions often drive the decision making process during the pre-design, detailed design, and construction phases of a project and will dictate which NOM removal process is most appropriate for a given community. As a result, it is impossible to predict the cost of a treatment plant with any degree of accuracy without carefully evaluating local conditions.

7.4.3 Application of Proposed Decision-making Framework

The proposed decision-making framework has been applied to communities A, B, and F from this study. The results are presented in Table 7.4.

Table 7.4 Application of proposed framework for the selection of DBP mitigation strategies

	Community A	Community B
History of DBPs	Yes	Yes
DOC	3.6 mg/L - moderate	7.7 mg/L – high
Response	*Assess contribution of water age, chlorination practices, etc. and/or water characterization study*	*Water characterization study*
UV254 / SUVA*	0.13 cm^{-1} / 3.6 L/mg.m	0.45 cm^{-1} / 5.9 L/mg.m
Response	*Investigate alternative disinfection and/or bench scale testing*	*Bench scale and/or pilot testing*
Solution(s)	• Minimize allochthonous and autochthonous NOM inputs; • Add UV disinfection and/or treatment with NF/RO membranes, ozone and biological filtration, or resin-based systems • Monitor DOC of treated water.	• Minimize allochthonous NOM inputs; • Add coagulation, ozone with biological filtration, or NF/RO treatment; and • Monitor UV254 of treated water.

*Based on single sample – no action should be taken without further sampling

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The formation of large amounts of THMs and HAAs upon chlorination is a challenge faced by many operators in Newfoundland and Labrador. The problem is related to a number of factors, many of which are related to high levels of NOM in the raw water.

The six water supplies sampled for this study had very different NOM quantities and characteristics. They varied in bulk raw water quality (DOC, UV254) and by the proportions of different NOM fractions and molecular weights. The hydrophobic acid (HOA fraction) dominated in most of the communities, although some also had large HIA and HIN fractions. The HOA fraction was responsible for much of the THMfp and HAAfp in most of the communities, but not all of it. When the THMfp and HAAfp of each fraction were normalized to the DOC, it became apparent that all of the NOM fractions were contributing to DBP formation. The degree to which this occurred was different in each community, emphasizing the fact that most of the findings were source water specific.

Some researchers have observed that the characteristics of the water supply and its surrounding watershed can impact NOM quantity and characteristics. In particular, the size of the water supply can impact its retention time and consequently, the amount of NOM degradation that occurs over time. The one lake supply evaluated in this study has historically had lower, less variable DOC than the small raw water reservoirs used by some of the other communities. The particularly low DOC and colour in the lake sample used in the study may, however, have been related to the fact that it was collected in the winter when DOC levels are known to be lowest. No one watershed characteristic was found to be solely responsible for the amount or distribution of NOM fractions in each watershed. More likely, numerous factors were responsible for the type and amount of NOM entering each individual water supply from its watershed.

Treated water samples were gathered from the two communities with full-scale WTPs. The coagulation-based process removed DOC and reduced UV254 while the ozone-based treatment system reduced UV254 without reducing DOC. Both WTPs reduced THMfp and HAAfp. The coagulation-based treatment system preferentially removed large MW HOA compounds while the ozone-based treatment system transformed large HOAs into smaller, less reactive fractions.

Another important finding of the study was that UV254 and DOC were not able to predict the formation of THMs or HAAs consistently based on the historical dataset, where THM and HAA formation could be affected by chlorine dose and/or residence time. Nonetheless, DOC, UV254, and SUVA were all found to be significantly correlated to THM and HAA formation during the laboratory portion of the study, where temperature, chlorine dose, and residence time were carefully controlled. These relationships were not strong enough to justify the development of predictive equations but they were used to develop a proposed framework for pre-design/process selection for communities attempting to reduce THM and HAA formation in their drinking water systems.

8.2 Summary of Recommendations

DOC, colour, UV254, and SUVA should not be relied upon exclusively to predict total THMfp or total HAAfp.

Though UV254 and SUVA are well correlated to the THMfp of the HOA fraction they are not always accurate predictors of total THMfp or HAAfp because other NOM fractions also contribute the formation of THMs and HAAs. The THMfp and HAAfp of the raw water should be determined before selecting a treatment process.

ENVC and DMA should develop a comprehensive pre-design and piloting framework to help municipalities and their consultants choose the most appropriate water treatment process for organic removal/DBP prevention and establish effective operating strategies.

The framework should include a review of existing water quality records; raw water characterization; bench scale testing; and pilot testing. The framework should be summarized in the proposed *Generic Terms of Reference* (DMA) and the *Guidelines for the Design, Construction, and Operation of Water and Sewerage Systems* (ENVC). The latter should also include an updated section on natural organic matter.

Designers should not rely on a single grab sample to characterize the NOM content of a water supply.

The total concentration and distribution of NOM fractions changes over time and can be affected by weather events (ex. high precipitation). Seasonal changes are of particular concern.

Long-term monitoring of the water supply should be required before proceeding to the detailed design stage.

Water treatment processes should be designed to operate at the worst-case NOM conditions. Ideally, the water supply should be monitored once a month for a minimum of one year.

Watershed management can reduce (but not eliminate) internal and external NOM inputs to the water supply.

The total amount of NOM in a water supply is based on both external (allochthonous) and internal (autochthonous) inputs. Allochthonous NOM inputs, which are more likely to be hydrophobic/large MW/aromatic, can be minimized (but not eliminated) by limiting human activities in the watershed that might lead to soil erosion and increased NOM transport. This is particularly important for utilities that rely on a water source where HOAs are the dominant THM and HAA precursors. Autochthonous inputs are usually related to microbiological growth within the water supply itself. They can be minimized (but not eliminated) by limiting wastewater and nutrient inputs into the water supply.

Though water quality deterioration is related to many different factors, it can be reduced by ensuring that raw water reservoirs are properly designed and constructed.
Raw water reservoirs are commonly used in Newfoundland and Labrador to ensure a steady supply of water for a community. In some cases, however, the construction of a raw water reservoir has led to a deterioration in water quality. For example, the land that is to be flooded to create the reservoir must be cleared of plants and debris as these will contribute to the formation of dissolved NOM. Continuous management of plant growth and human activity near the reservoir can also help to minimize

Intakes should be installed at a location and depth that will minimize NOM levels in the raw feed water while avoiding common intake problems such as sediment deposition and ice formation.
The ideal intake location will be dependent on the characteristics of the water source and should be determined based on the results of water quality sampling at different depths over the course of at least one year. Multi-level intakes, while more expensive, allow utilities to draw water from different depths at different times of the year to maximize water quality. These should be considered for larger communities that have the financial capital to invest in them and the operational capacity to monitor and manage these.

The design and operation of the water treatment process should be tailored to the removal of the NOM fraction of greatest concern.
For example, water supplies that are determined to have a high proportion of HOAs or where the HOA fraction makes a significant contribution to the THMfp and HAAfp of the water should be treated using coagulation- or oxidation-based processes. If it is determined that THMfp and HAAfp are primarily related to other fractions treatment processes that are not specific to the HOA fraction should be employed instead (ex. NF membrane filtration).

It is understood that the laboratory procedures associated with NOM fractionation are complex and onerous and will only be cost-effective for large water utilities.

Chlorine application (and DBP formation) can be minimized by including pathogen-reducing steps in the treatment process.
These might include:

- Coagulation and filtration;
- DAF;
- Membrane filtration; and/or
- UV disinfection.

The effectiveness of a treatment process should be evaluated based on an appropriate surrogate parameter.
Systems optimized for HOA removal (ex. coagulation) will benefit from online UV254 monitoring while those designed to remove all NOM fractions (ex. nanofiltration) should evaluate performance based on regular DOC measurements. If an online TOC/DOC monitoring system is used for this purpose it should be carefully maintained and supplemented by regular grab samples.

8.3 Opportunities for Future Study

The results of the study were interesting but site-specific, making it impossible to generalize the results to other water supplies. Further study of other water supplies is expected to yield similarly site-specific information. It is expected, therefore, that the results of this and similar studies will be of greatest interest to individual communities seeking to mitigate DBPs, chlorine demand, and colour in their own water systems. It will be particularly helpful should the communities opt to conduct bench or pilot-scale studies to compare different treatment processes.

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APPENDIX A

Information Collection Sheet

Operator Questionnaire

This section to be filled out by the technician with input from the system operator.

* 1. Community Name

2. Operator Contact Information

Name:

Email:

Phone number:

Other:

3. Have you been certified as a water treatment or distribution operator?

○ Yes

○ No, but I am currently preparing to write the exam

○ No, but I have taken a number of courses

○ No

Courses taken:

4. Have you ever been visited by a Mobile Training Unit (MTU)?

○ Yes

○ No

Notes

5. Are as-built drawings available for the water system?

☐ Water supply system

☐ Water treatment system

☐ Water storage system

☐ Water distribution system

☐ No as-built drawings available

Notes

6. Please describe the major characteristics of the watershed.

Size

Borders

Industrial activity

Land cover

Influent water bodies (streams, etc.)

Effluent water bodies (streams, etc.)

7. Where is the raw water intake located?

8. Describe the transmission main from the raw water intake to the main treatment system:

Length

Width

Material

Maximum flow

9. Describe the raw water pumps:

Type

Make

Model

Size

Max pressure

10. Have you noticed any seasonal variation in the colour of the raw water?

○ Yes

○ No

○ Unknown

Notes

11. Describe any water treatment equipment used by the community.

Type

Make

Model

Date of installation

Operational status

Other

12. What type(s) of disinfection is (are) used in this community?

☐ Chlorine (gas)

☐ Chlorine (liquid)

☐ Chloramines

☐ Ozone

☐ UV

☐ Chlorine dioxide

Other (please specify)

13. If you add a chemical for disinfection (chlorine, ozone, etc), how much do you add?

Volume
Concentration
Weight
Other (please specify)

14. How do you measure the amount of chemical added to the water?

15. Describe the disinfection equipment.

Type
Make
Model
Date of installation
Operational status

16. Does your disinfection system include a clearwell or reaction tank?

○ Yes

○ No

Notes

17. If yes, what are its dimensions?

18. Is total water flow (use) monitored in this community?

○ Yes

○ No

○ Unknown

Notes

19. If yes, describe the following:

Flow measurement equipment

Flow measurement practices

Record-keeping practices

Record format

20. What is the distance between the point of chlorine (or other chemical) application and the first user in the distribution system?

21. What is(are) the diameter(s) of the pipe(s) between the point of chlorine (or other chemical) application and the first user in the distribution system?

22. Do you monitor the chlorine (or other chemical) residual at a specific location after the point of application?

☐ Yes, at the outflow of the clearwell

☐ Yes, at a designated location along the transmission main before the first customer

☐ Yes, at the first user's tap

☐ No

Other (please specify)

23. Does your distribution system include any type of water storage facility? (ex. water tower, underground storage tank, reservoir, etc.)

○ Yes

○ No

Notes

24. If yes, what are its dimensions?

25. Which of the following (if any) are monitored in your water treatment system?

☐ Influent pH

☐ Effluent pH

☐ Influent Temperature

☐ Effluent Temperature

☐ Influent Turbidity

☐ Effluent Turbidity

Other (please specify)

26. Are records maintained for any of the following?

☐ Maintenance activities

☐ Instantaneous flow rate (L/min, GPM, etc)

☐ Colour

☐ DOC

☐ TOC

☐ THMs

☐ HAAs

☐ pH

☐ Temperature

☐ Turbidity

☐ Biological testing results

☐ Chlorine (or other chemical) added

☐ Chlorine (or other chemical) residual

Other (please specify)

27. Is there anything else you would like to share about the water treatment and disinfection system in your community?

Site Conditions

This section to be filled out by the technician during the site visit.

1. Feed Water

pH

Temperature

Apparent colour

2. Point of Chlorine Application

pH

Temperature

Apparent colour

Free chlorine

Total chlorine

3. Clearwell Effluent

pH

Temperature

Apparent colour

Free chlorine

Total chlorine

4. First User's Tap

pH

Temperature

Apparent colour

Free chlorine

Total chlorine

5. Storage Tank Effluent

pH

Temperature

Apparent colour

Free chlorine

Total chlorine

Photos

A list of photographs that technicians should try to obtain during the site visit.

1. Did you manage to get photos of the following items?
(check all that apply - some items may only be present at a small number of sites)

☐ Watershed

☐ Source water

☐ Intake

☐ Intake pump

☐ Treatment equipment

☐ Flow meter

☐ Flow totalizer

☐ Turbidimeter

☐ Disinfection system

☐ Disinfectant dispensing equipment

☐ Disinfectant monitoring equipment (chlorine monitor, etc)

☐ Clearwell

☐ Storage tank

☐ Tap at first user

Other pictures taken at this site include:

APPENDIX B

Source Water Quality in Participating Communities

Table B.1 Alkalinity (mg/L as $CaCO_3$)

	Mean	Median	St. Dev.	Max	Min
Community A	4.1	3.5	3.1	17.0	0.0
Community B	1.3	0.0	3.6	12.0	0.0
Community C	1.1	0.3	1.9	7.0	0.0
Community D	4.5	4.0	3.1	13.0	0.0
Community E	2.1	1.6	2.2	10.0	0.0
Community F	28.0	27.8	3.4	34.0	20.9

Table B.2 Colour (TCU)

	Mean	Median	St. Dev.	Max	Min
Community A	11	11	4	21	3
Community B	98	97	31	170	46
Community C	99	92	52	250	35
Community D	44	44	6	58	29
Community E	60	59	16	106	34
Community F	49	50	11	70	25

Table B.3 pH

	Mean	Median	St. Dev.	Max	Min
Community A	6.5	6.5	0.2	6.9	6.1
Community B	5.5	5.5	0.4	6.2	4.6
Community C	5.3	5.2	0.5	6.5	4.6
Community D	6.4	6.4	0.2	6.9	5.9
Community E	5.9	6.0	0.4	6.7	5.1
Community F	7.2	7.3	0.2	7.5	6.6

Table B.4 TDS (mg/L)

	Mean	Median	St. Dev.	Max	Min
Community A	21.0	21.0	4.9	30.0	11.0
Community B	15.5	16.0	3.4	21.0	11.0
Community C	24.2	23.5	9.4	40.0	11.0
Community D	20.1	18.0	6.1	40.0	12.0
Community E	18.8	18.0	7.2	30.0	8.0
Community F	73.1	70.0	9.4	95.0	63.0

Table B.5 Dissolved Organic Carbon (mg/L)

	Mean	Median	St. Dev.	Max	Min
Community A	2.9	2.9	0.7	5.1	1.8
Community B	10.0	9.8	2.3	14.0	7.2
Community C	7.3	7.0	2.8	13.0	3.6
Community D	5.4	5.5	1.3	7.5	1.1
Community E	6.8	5.7	2.6	13.8	4.2
Community F	6.5	7.4	2.6	10.6	1.0

Table B.6 Turbidity (NTU)

	Mean	Median	St. Dev.	Max	Min
Community A	0.3	0.3	0.2	0.7	0.0
Community B	0.9	0.9	0.4	1.4	0.4
Community C	0.8	0.7	0.6	3.6	0.1
Community D	0.5	0.4	0.4	1.8	0.0
Community E	0.5	0.4	0.3	1.7	0.1
Community F	0.5	0.3	0.4	1.5	0.1

Table B.7 Bromide (mg/L)

	Mean	Median	St. Dev.	Max	Min
Community A	0.02	0.02	0.01	0.03	0.00
Community B	0.01	0.00	0.01	0.03	0.00
Community C	0.01	0.00	0.01	0.03	0.00
Community D	0.02	0.01	0.02	0.12	0.00
Community E	0.02	0.03	0.01	0.03	0.00
Community F	0.01	0.03	0.01	0.03	0.00

Table B.8 Iron (mg/L)

	Mean	Median	St. Dev.	Max	Min
Community A	0.02	0.02	0.02	0.05	0.00
Community B	0.49	0.44	0.17	0.82	0.26
Community C	0.25	0.22	0.11	0.58	0.11
Community D	0.05	0.06	0.03	0.12	0.00
Community E	0.24	0.21	0.15	0.8	0.09
Community F	0.08	0.07	0.08	0.42	0.00

Table B.9 Manganese (mg/L)

	Mean	Median	St. Dev.	Max	Min
Community A	0.01	0.01	0.00	0.02	0.00
Community B	0.01	0.01	0.00	0.017	0.00
Community C	0.01	0.01	0.01	0.03	0.00
Community D	0.01	0.01	0.01	0.023	0.00
Community E	0.03	0.02	0.05	0.211	0.00
Community F	0.01	0.01	0.01	0.05	0.00

APPENDIX C

Source Water NOM Chromatograms

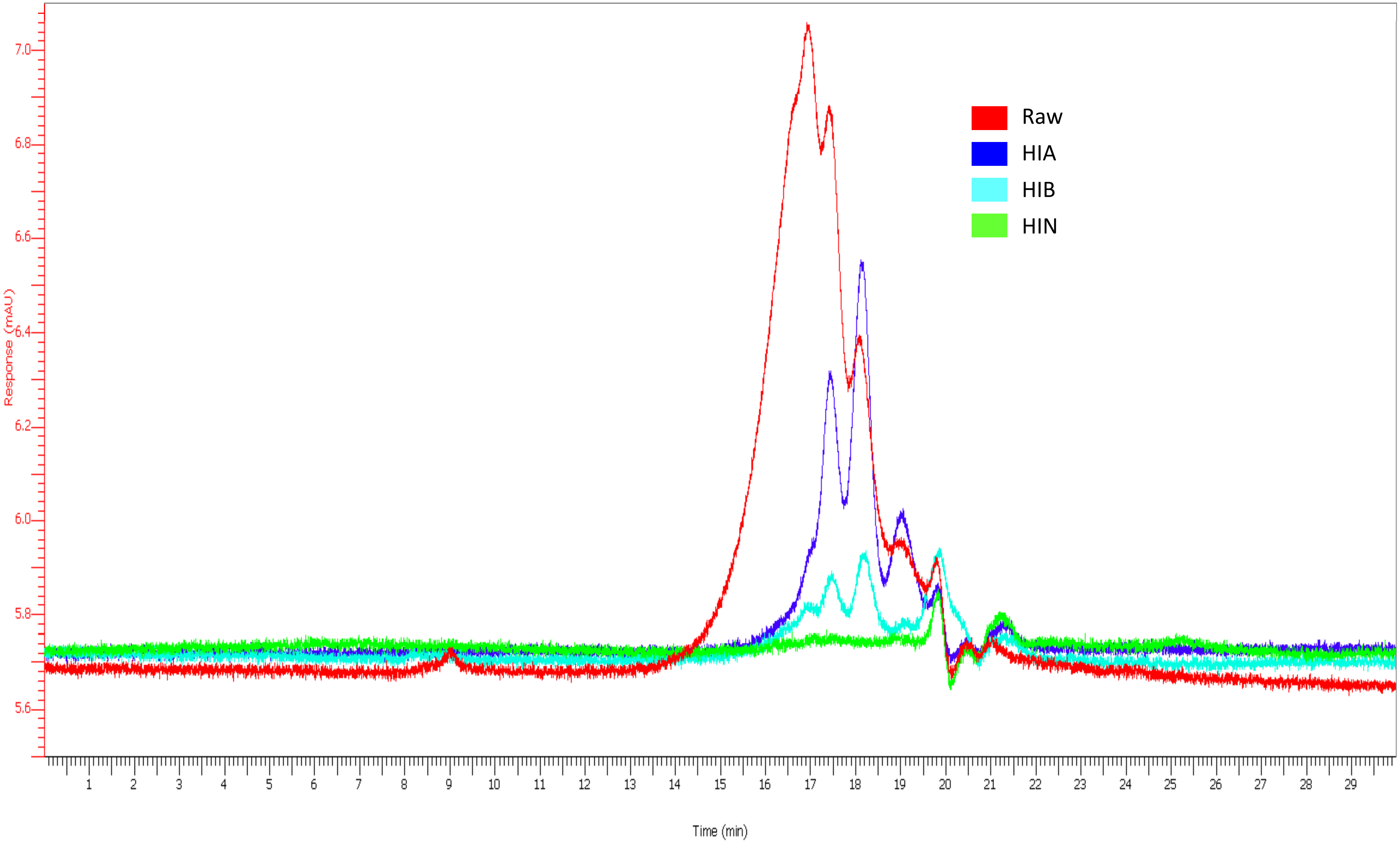

Figure C.1 **Community A Raw Water**

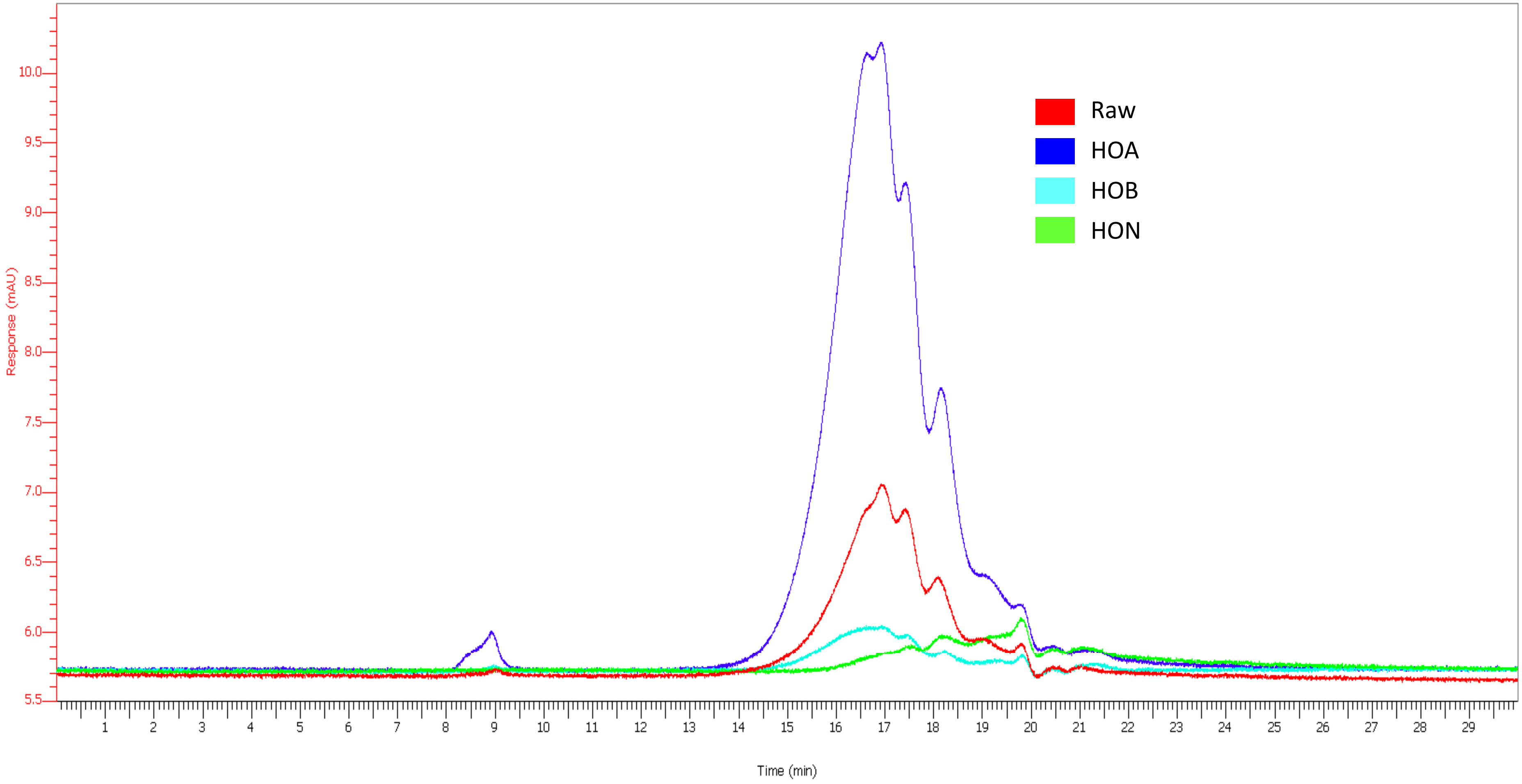

Figure C.2 **Community A Raw Water**

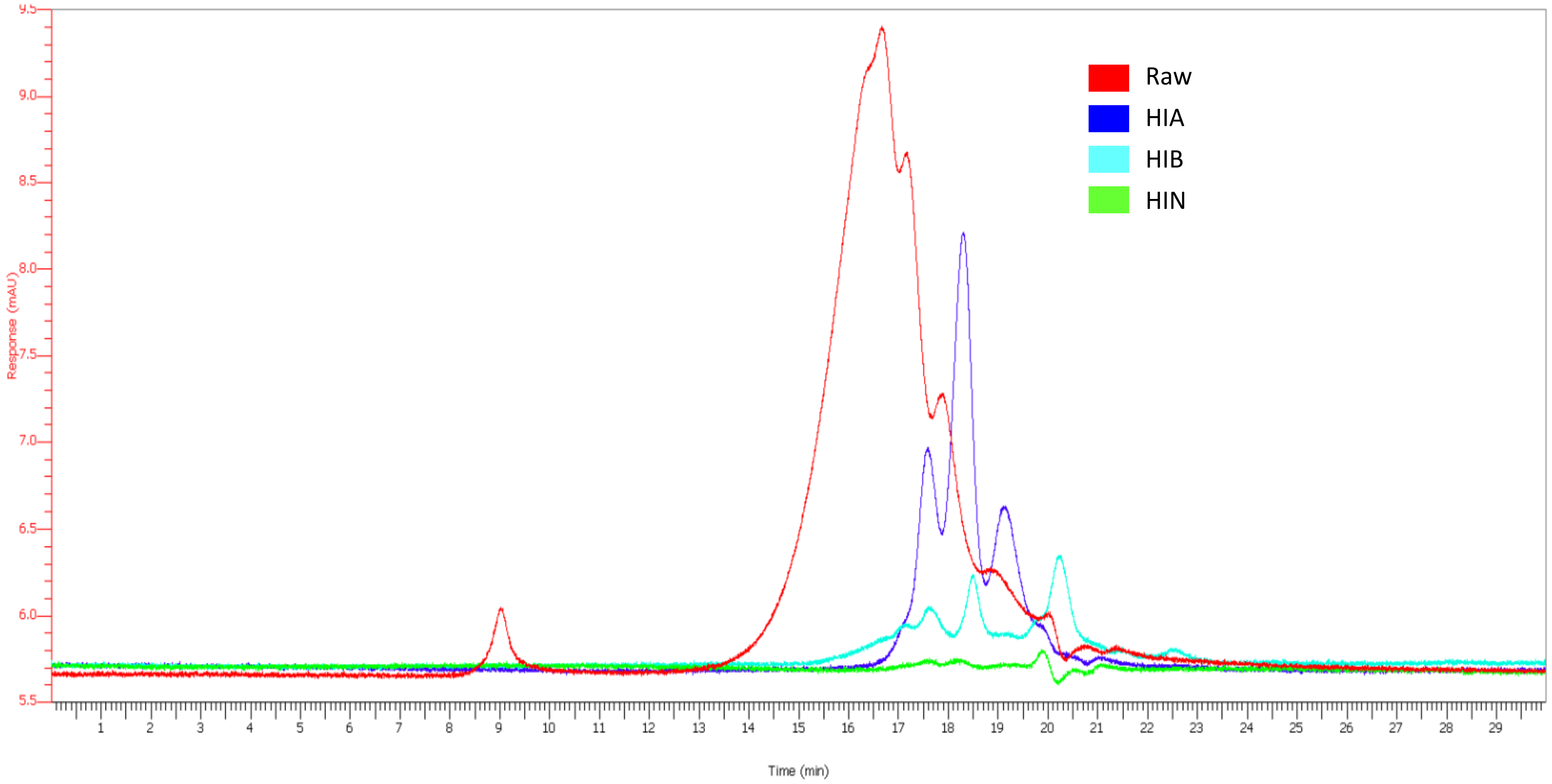

Figure C.3 **Community B Raw Water**

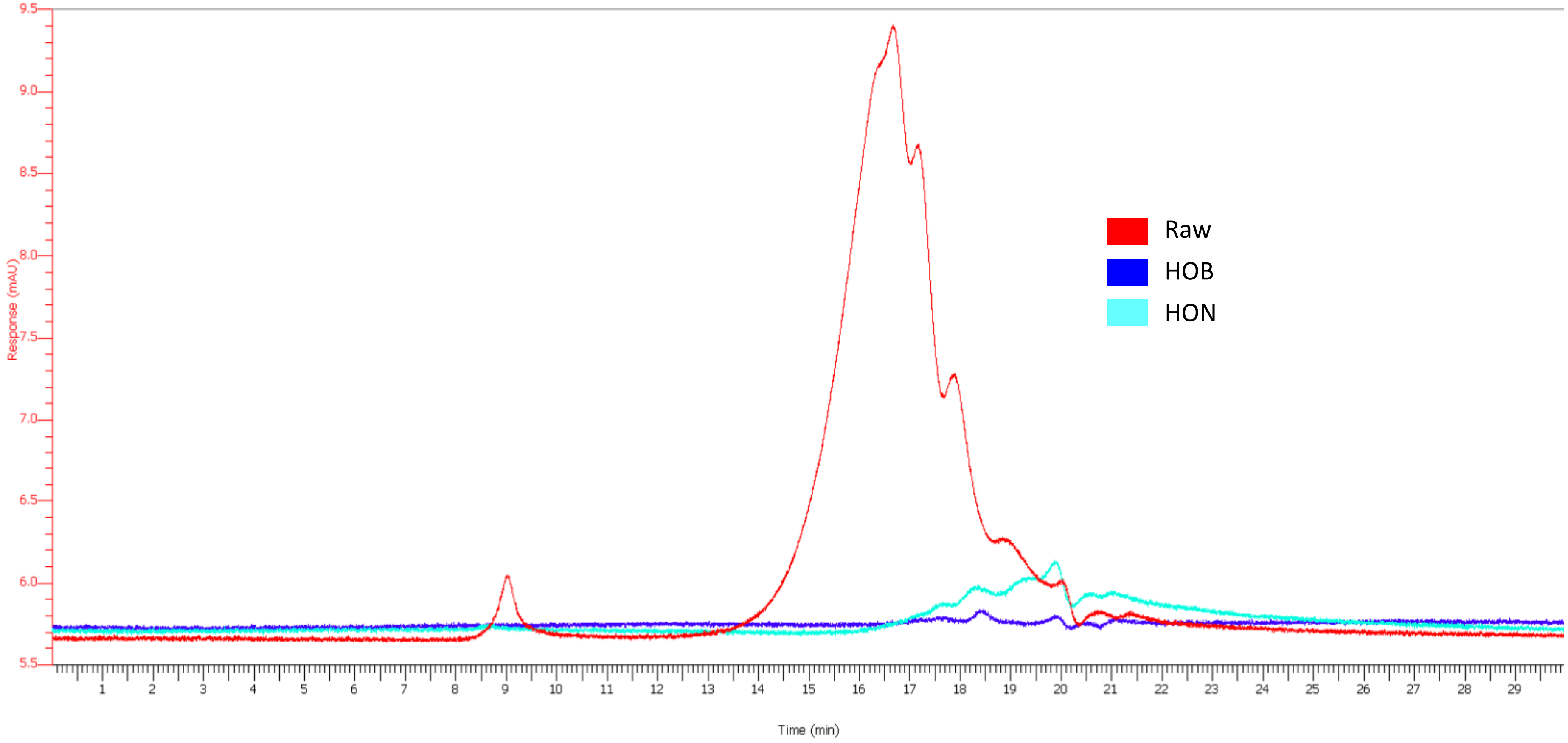

Figure C.4 Community B Raw Water

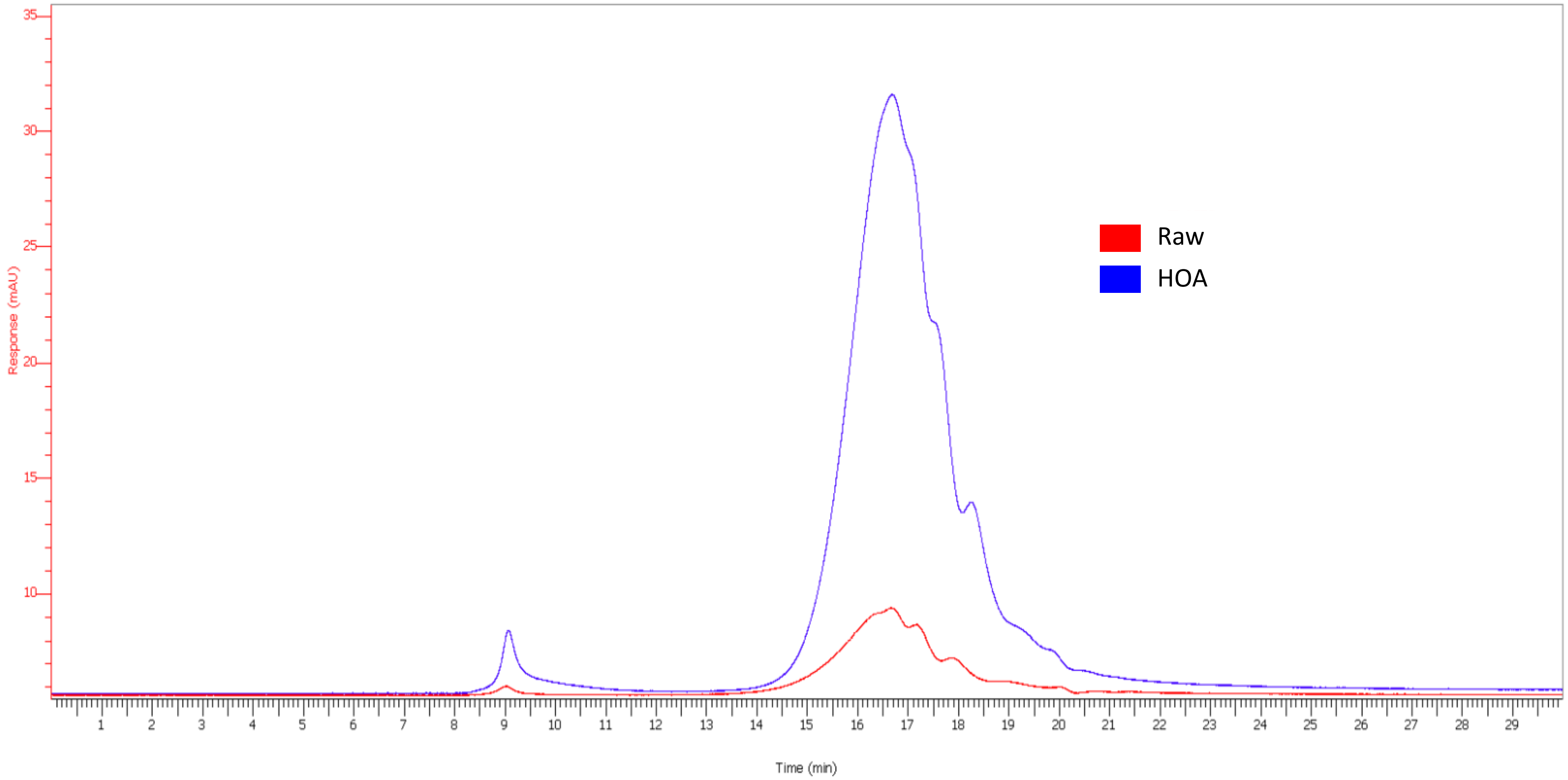

Figure C.5 **Community B Raw Water**

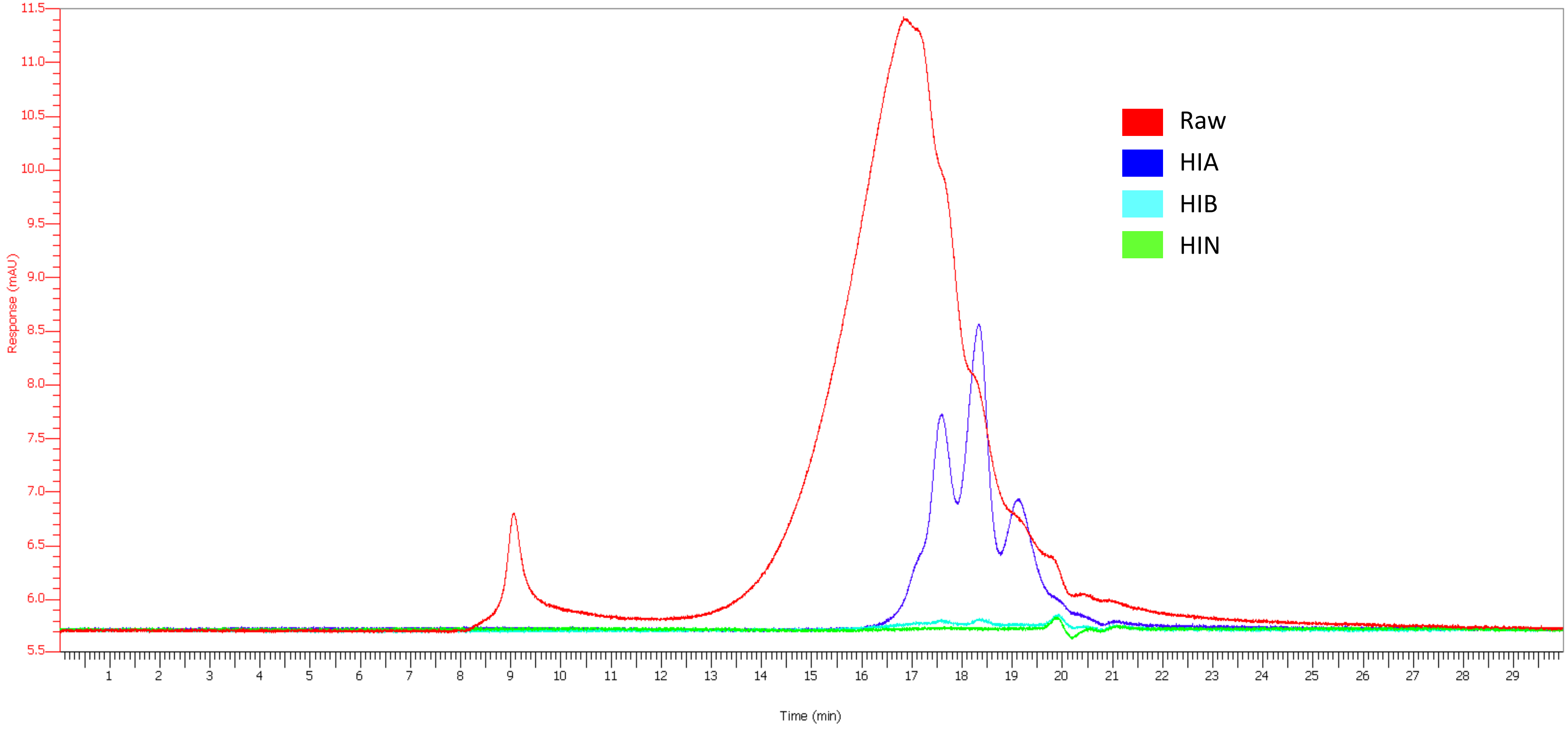

Figure C.6 **Community C Raw Water**

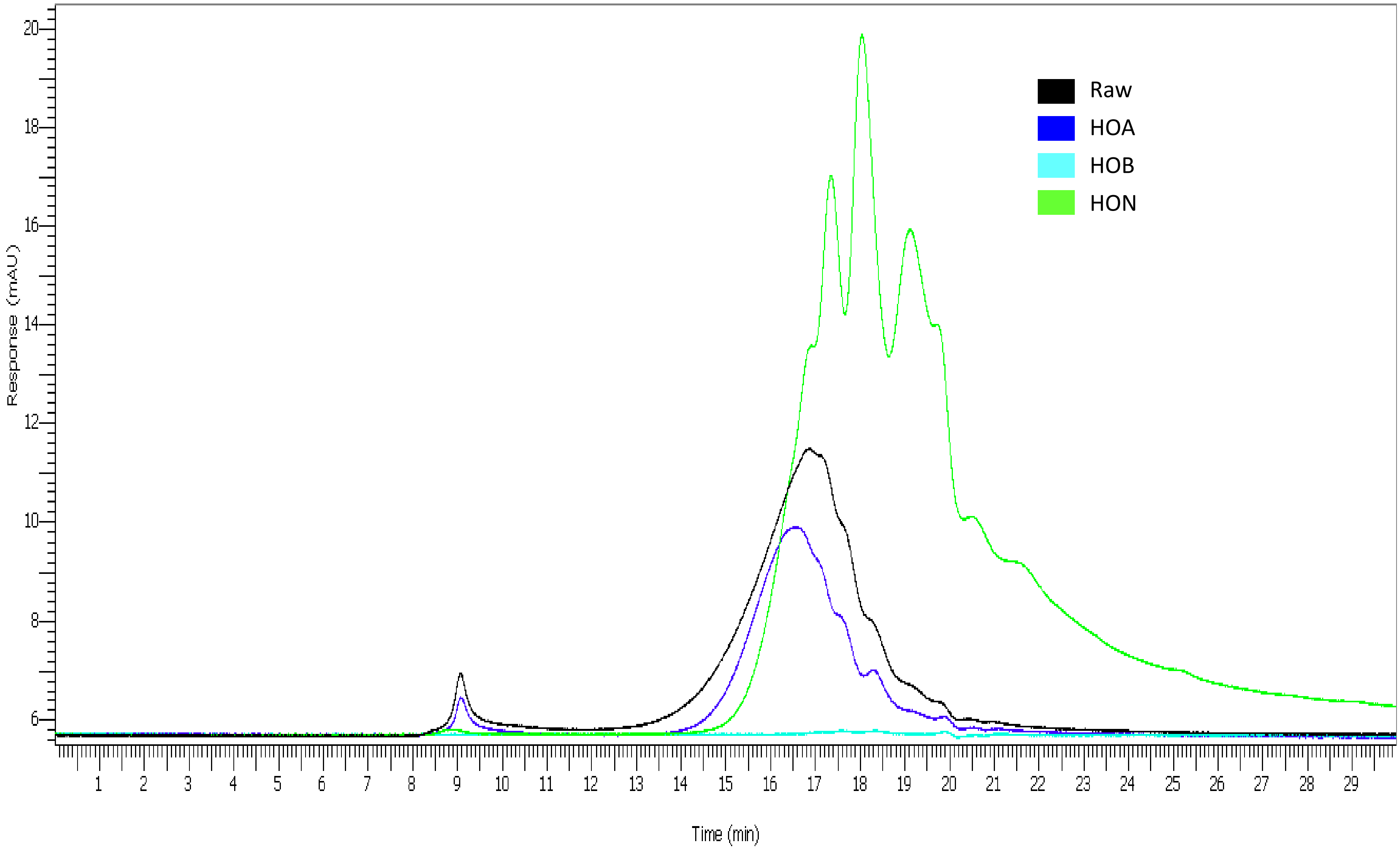

Figure C.7 **Community C Raw Water**

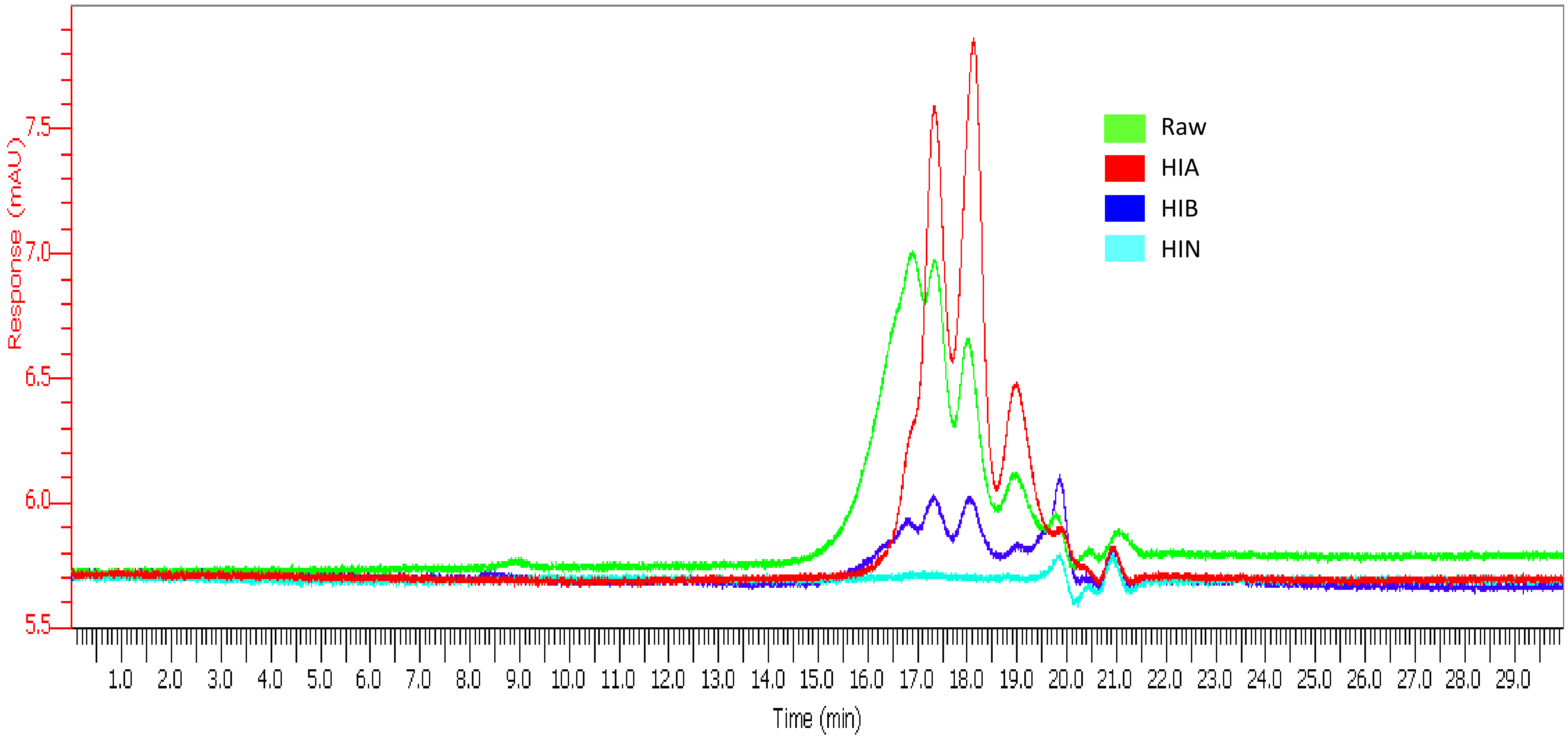

Figure C.8 **Community D Raw Water**

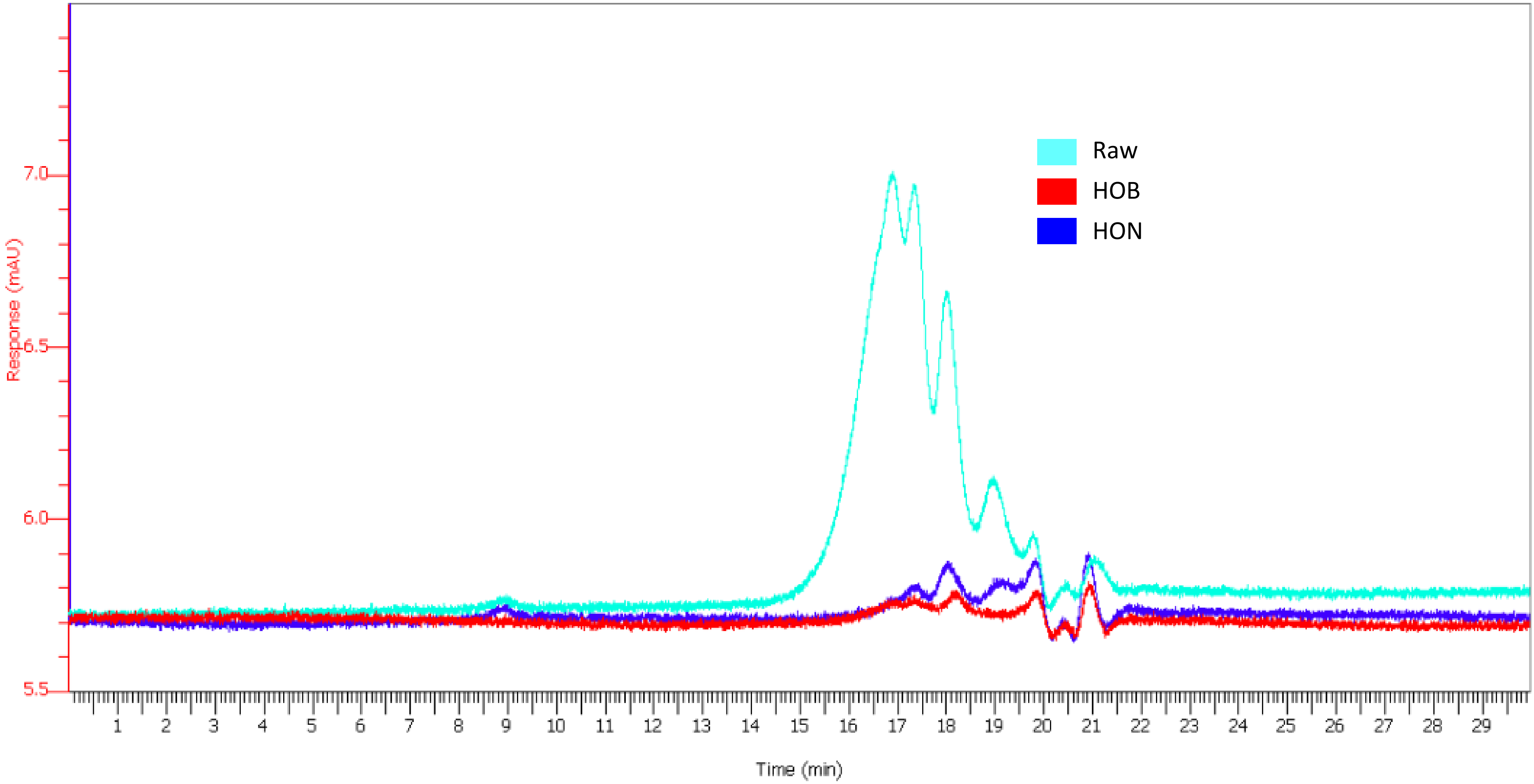

Figure C.9 **Community D Raw Water**

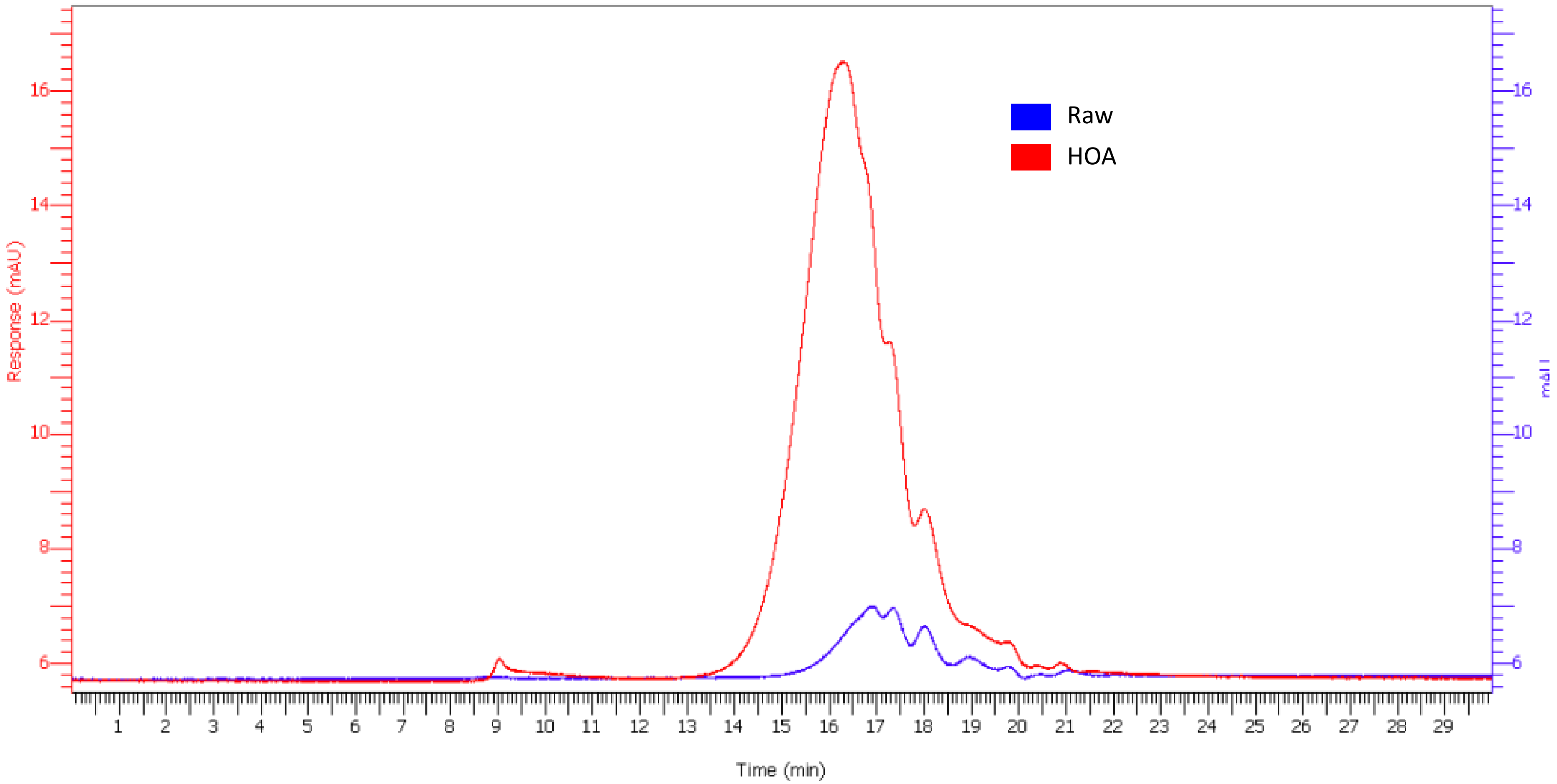

Figure C.10 **Community D Raw Water**

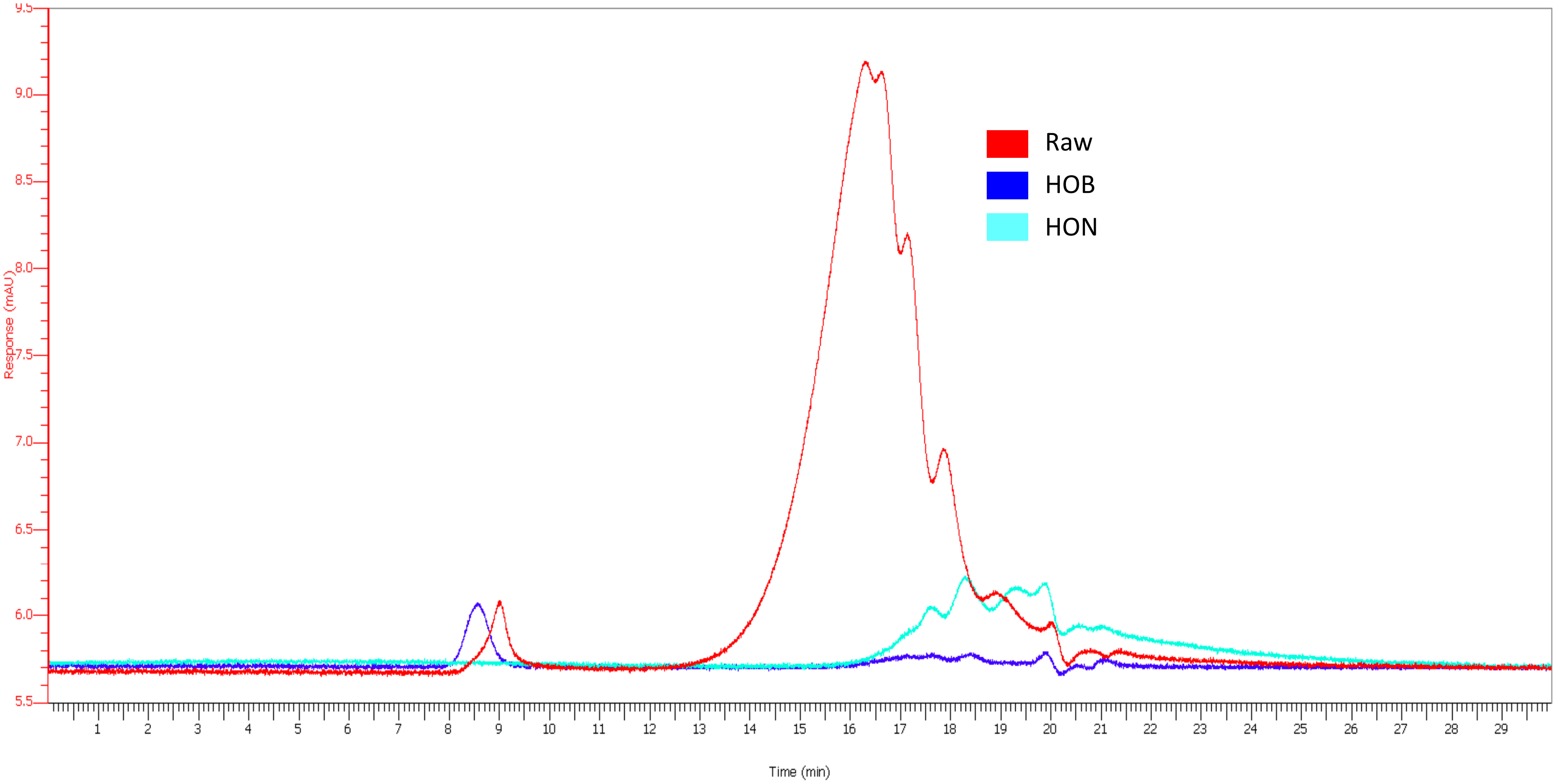

Figure C.11 Community E Raw Water

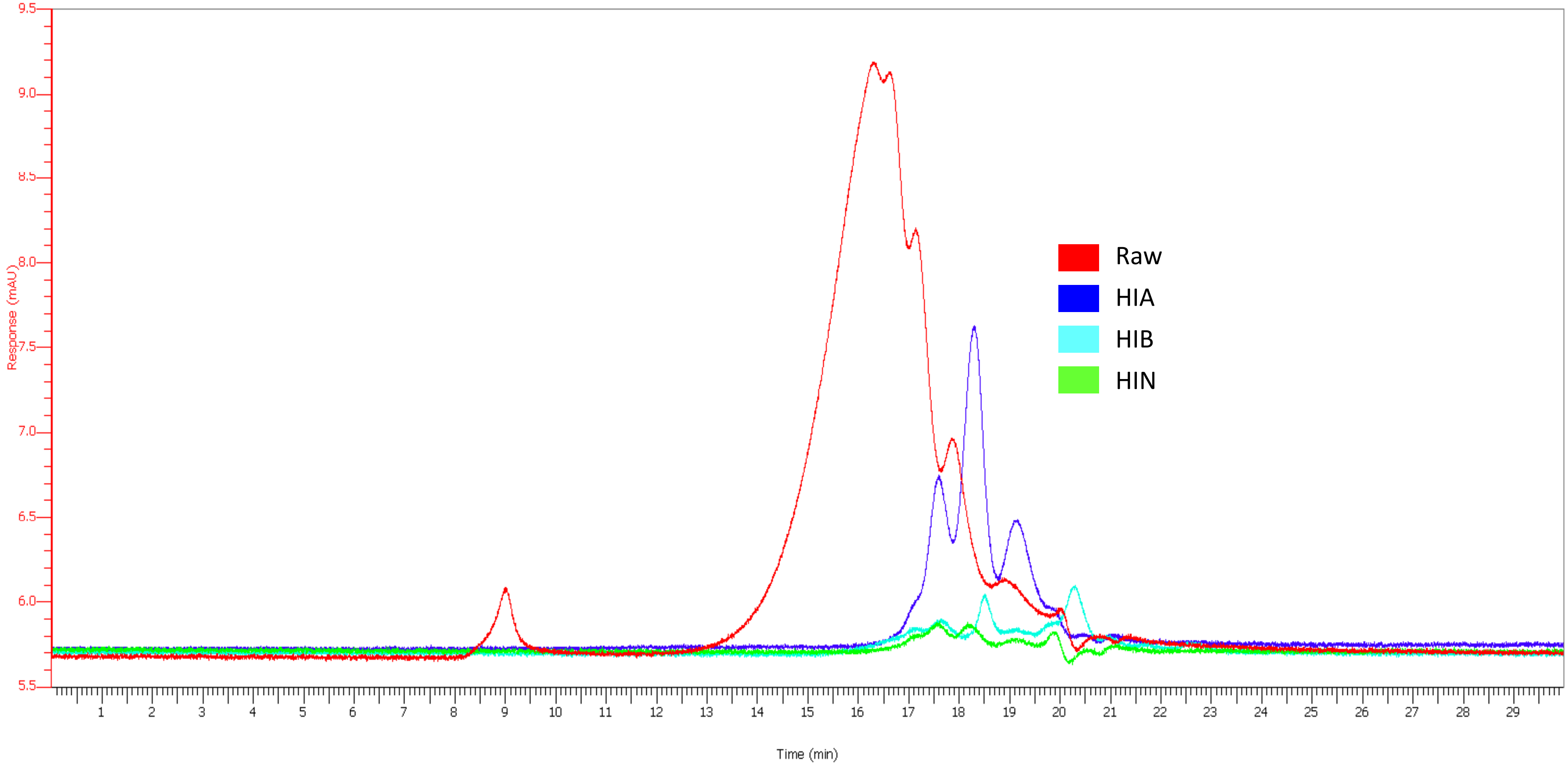

Figure C.12 **Community E Raw Water**

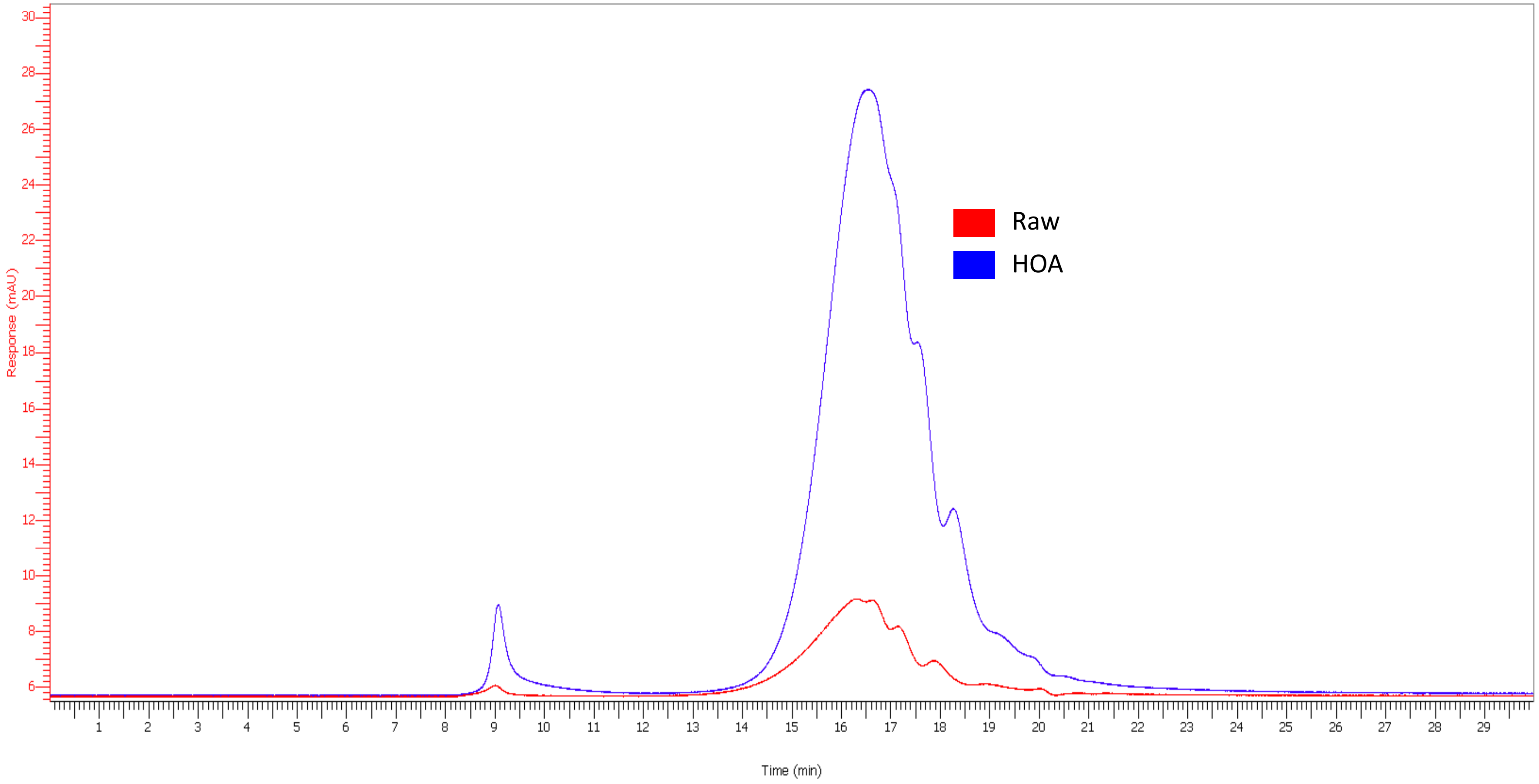

Figure C.13 Community E Raw Water

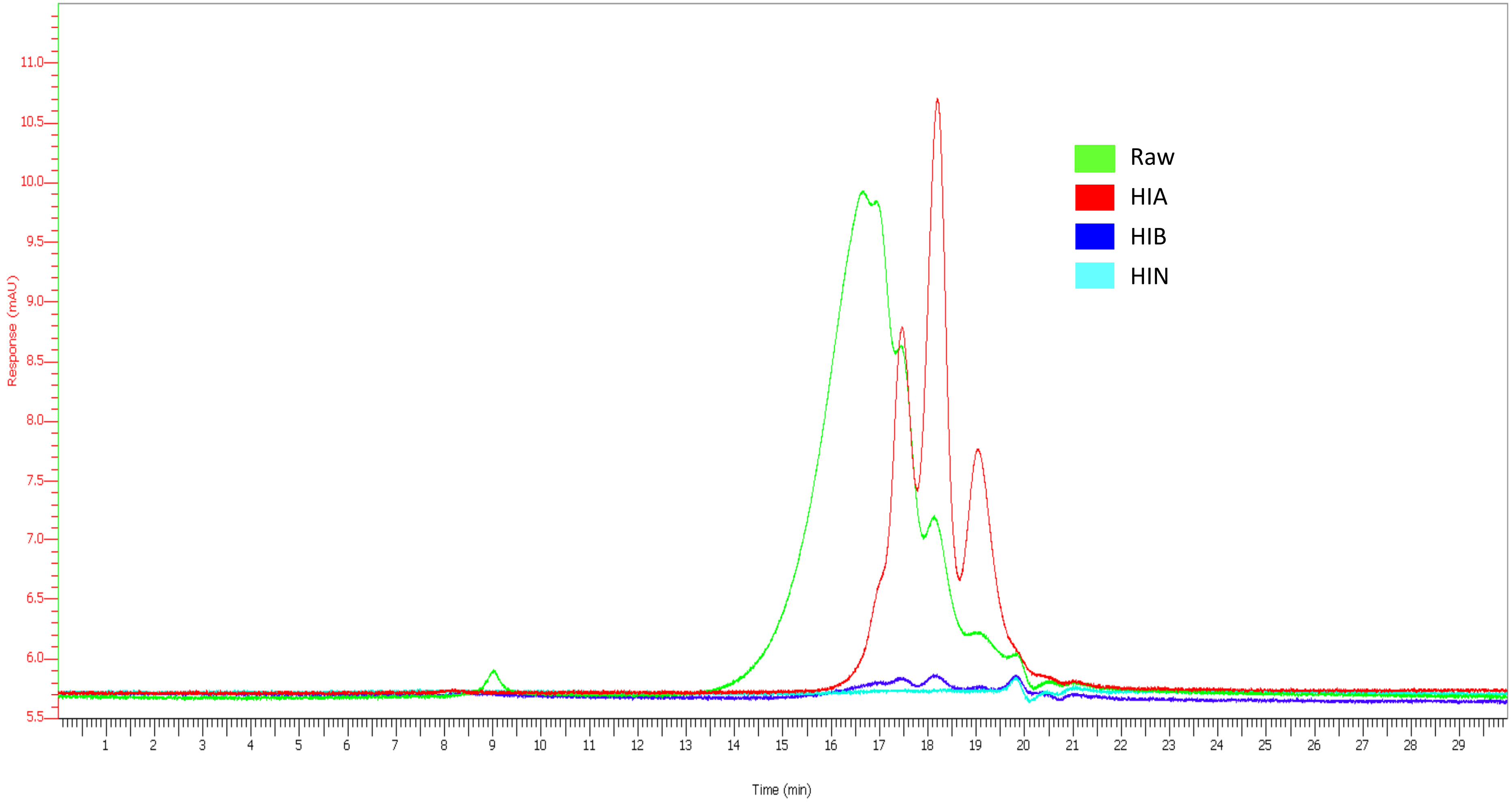

Figure C.14 Community F Raw Water

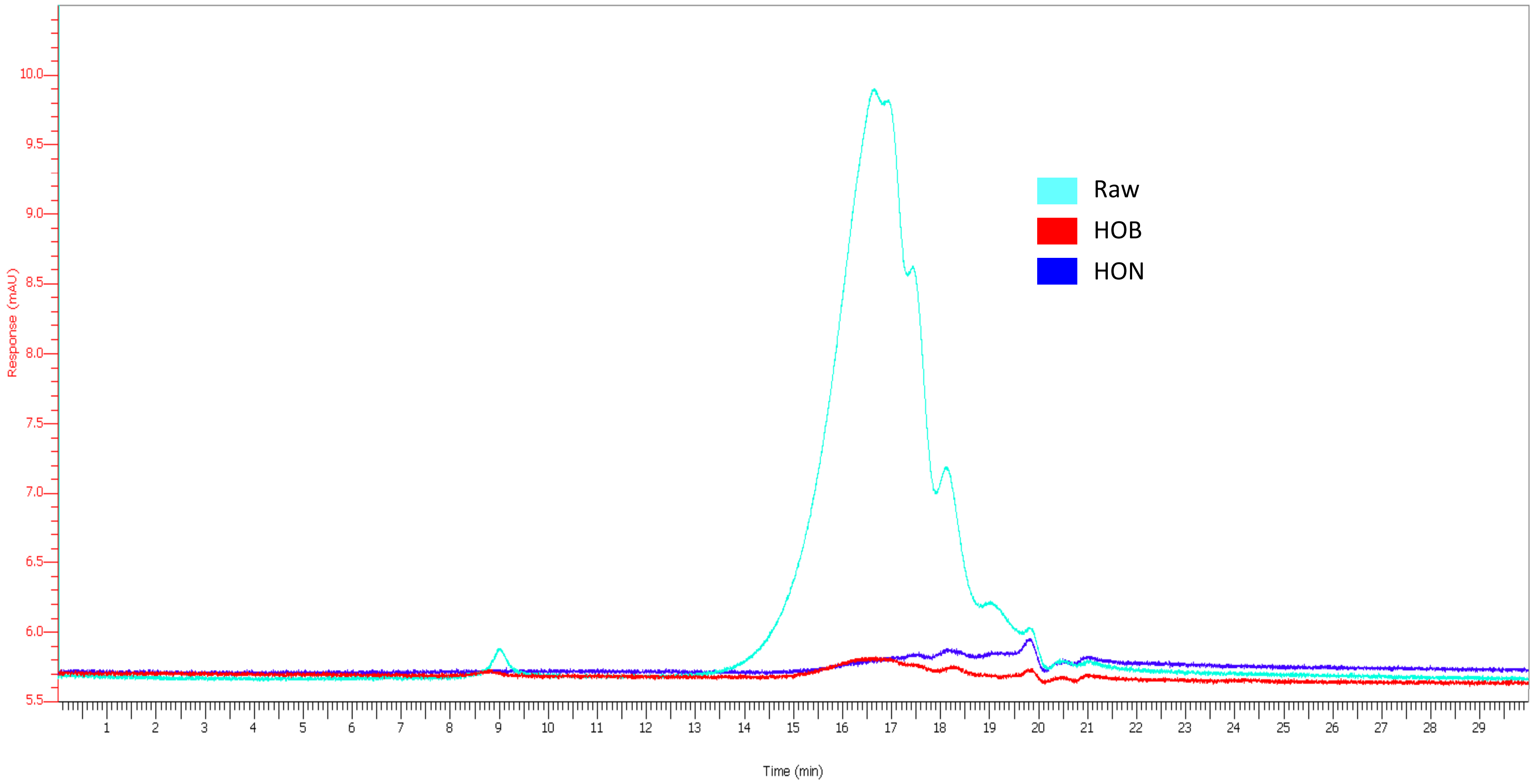

Figure C.15 Community F Raw Water

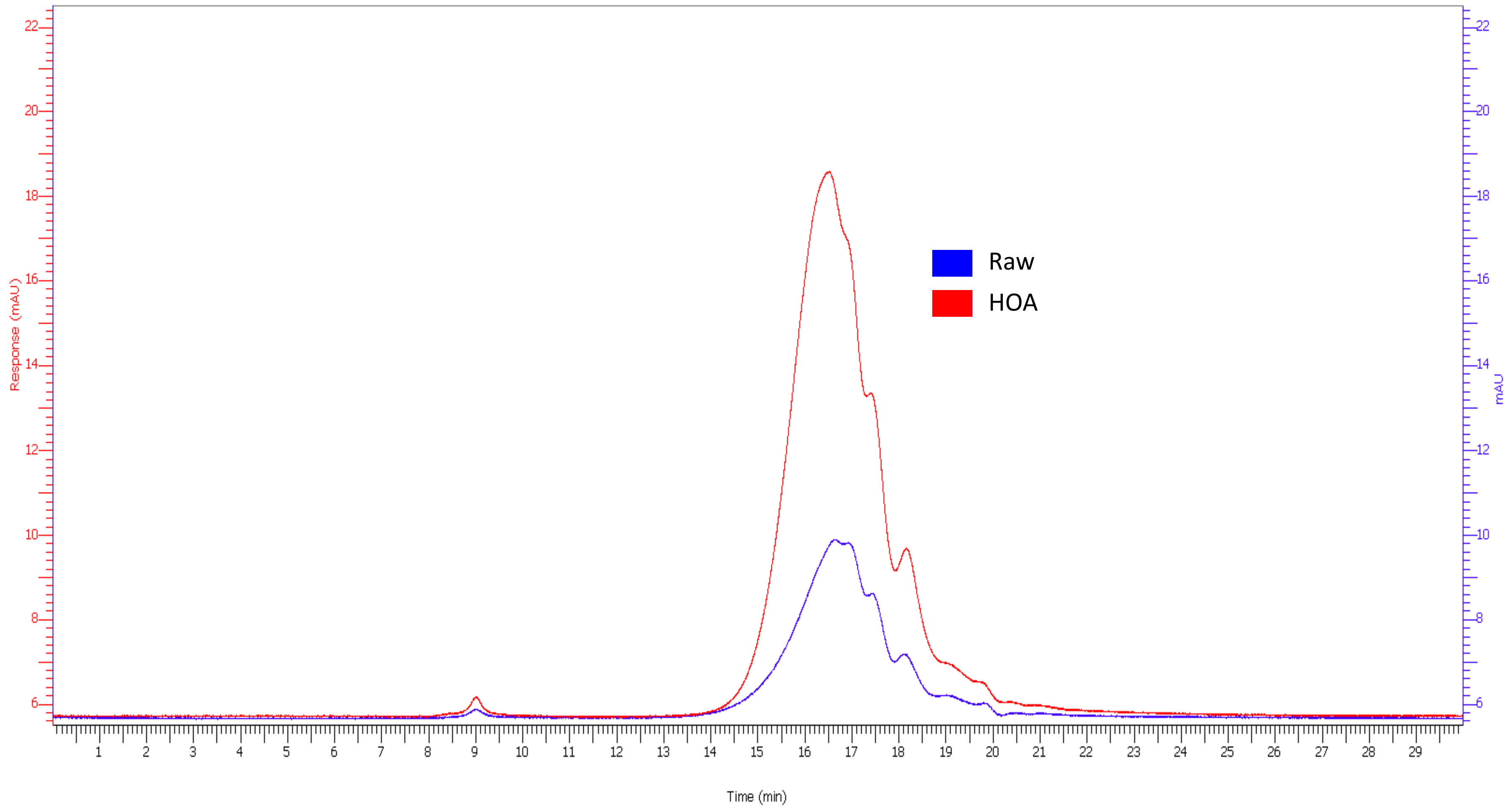

Figure C.16 Community F Raw Water

Table C.1 Community A Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10	Peak 11	Peak 12
Raw	35,221	3,348	3,008		1,441	1,101	762	622	513	466	412	
HON				1,678		1,082	708			481		367
HOB	34,975		2,645	1,636	1,348	1,085		622		485		353
HOA	36,904		2,591	1,690	1,409	1,044	715	596	507	464		334
HIB	33,571			1,820	1,398	1,029	770		554			344
HIA					1,579	1,140	786	598		480		361
HIN								628		489		366

Table C.2 Community B Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw	33,208	2,939	1,937	1,519	1,153	743	556	435	326	
HON	35,839		1,599	1,332	1,052	793	606	466	373	
HOB				1,273	1,026		616	460	369	
HOA	29,019	2,347	1,589	1,324	1,003	689		541	357	
HIN				1,321	1,127	701	603	473	379	
HIB			1,861	1,337	984		506		346	217
HIA				1,462	1,088	774	567	467	379	

Table C.3 Community C Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw	30,273	2,597	1,530	1,258	975	723	573	451	316	
HON	35,059	2,274	1,587	1,154	783	562	392	204	59	
HOB				1,334	997	620		473	371	
HOA	30,785	2,330		1,305	947	603		448	401	355
HIN				1,310		622		471	376	
HIB				1,441	1,026	739	599	465	384	
HIA				1,486	1,078	773	558	500	374	

Table C.4 Community D Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw		2,662	1,709	1,435	1,020	621	486	385		
HON	37,217		1,847	1,153	819	614	260			
HOB	41,080	3,039	1,404	495	397					
HOA	33,525	2,575	1,848	1,520	1,149	774	596	471	402	
HIN					630	487	404			
HIB		1,937	1,531	1,150	833	632	395			
HIA		1,601	1,167	810	553	494	399			

Table C.5 Community E Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw	34,243	2,868	1,872	1,575	1,193	819	542	435	336	
HON				1,574	1,055	754	594	455	357	
HOB	39,059		1,606	1,307	1,023		603	470	376	
HOA	29,362	2,466	1,593	1,319	1,017	704	546	447		
HIN				1,514	1,106	705	604	475	384	
HIB			1,861	1,337	984			506	344	217
HIA				1,468	1,082	767	556	463	374	

Table C.6 Community F Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw	33,568	2,317	1,635	1,384	1,122	703	608	482		
HON				1,463	1,106	785	623	484	391	
HOB	33,721	2,201			1,056		635	486	370	
HOA	24,414	2,462	1,659	1,389	1,054	710	578	464	361	
HIN							629	483	376	
HIB			1,537	1,124			619		392	
HIA			1,566	1,130		799	578	475	390	

APPENDIX D

Treatability Results from 2010 UTV/UVA Sampling Study

WO#	Location	SAMPLE DATE	UVA	DOC	SUVA	Coagulation	UVT	UV Disinfection
1027420	Aquaforte - Davies Pond	2010-11-05	0.36	8.6	4.2	yes	43.2	no
1027247	Arnold's Cove - Steve's Pond (2 Intakes)	2010-11-03	0.23	7.7	3.0	no	58.8	no
1028298	Bartletts Harbour - Long Pond (same as Castors River North)	2010-11-10	0.27	7.9	3.4	no	54	no
1028551	Bay de Verde - Island Pond	2010-11-16	0.13	4.7	2.8	no	73.9	no
1029118	Bay L'Argent - Sugarloaf Hill Pond	2010-11-22	0.32	7.9	4.1	yes	47.4	no
1027406	Bay Roberts, Spaniard's Bay - Rocky Pond	2010-11-01	0.11	3.3	3.5	no	76.8	yes
1029307	Beaches - Grassey Pond Brook	2010-11-24	0.38	9.2	4.2	yes	41.3	no
1029139	Beachside - Long Pond	2010-11-23	0.19	5.4	3.6	yes	64.1	no
1028299	Bellburns - Bound Brook Tributary	2010-11-11	0.23	7.2	3.2	no	58.6	no
1028551	Bellevue Beach - Unnamed Brook	2010-11-15	0.59	12.9	4.5	yes	25.9	no
1027900	Birchy Bay - Jumper's Pond	2010-11-08	0.26	9.8	2.7	no	54.7	no
1028298	Bird Cove (+Brig Bay) - Inner Gilmour Pond	2010-11-10	0.34	10.4	3.3	no	45.2	no
1027419	Biscay Bay - Unnamed Pond	2010-11-03	0.40	7.9	5.0	yes	40.2	no
1028297	Black Duck Cove - Long Pond - Black Duck Cove Intake	2010-11-10	0.34	9.1	3.7	yes	46.1	no
1027237	Bonavista - Long Pond	2010-11-02	0.22	7.8	2.8	no	60.5	no
1027803	Branch - Valley Pond	2010-11-08	0.34	7.5	4.6	yes	45.2	no
1028298	Brig Bay - Inner Gilmour Pond	2010-11-10	0.35	10.4	3.3	no	45.1	no
1028685	Brighton - Hynes Cove Pond	2010-11-18	0.23	10.2	2.3	no	58.7	no
1027405	Brigus (+Cupids, +South River) - Brigus Long Pond (to Brigus)	2010-11-01	0.28	7.7	3.6	yes	52.9	no
1027633	Buchans Junction - Lapland Pond	2010-11-04	0.25	8.2	3.1	no	56	no
1028604	Campbellton - Indian Arm Brook	2010-11-17	0.20	6.7	3.1	no	62.4	no
1029114	Cape Freels North - Long Pond	2010-11-23	0.78	9.2	8.4	yes	16.6	no
1027406	Carbonear - Island Pond / Flings Long Pond	2010-11-01	0.12	4.8	2.6	no	75	yes
1025811	Cartwright - Burdett's Pond	2010-10-13	0.61	11.8	5.2	yes	24.50	no
1028298	Castor River North - Long Pond (same as Bartletts Harbour)	2010-11-10	0.27	7.9	3.4	no	53.8	no
1028298	Castor River South - Unnamed	2010-11-10	0.13	4.6	2.8	no	74.2	no
1027441	Cavendish - Long Pond	2010-11-04	0.15	5.6	2.7	no	70.6	no
1029116	Centreville-Wareham-Trinity - Southwest Feeder Pond	2010-11-23	0.31	7.7	4.1	yes	48.5	no
1029913	Channel-Port Aux Basques - Gull Pond & Wilcox Pond	2010-12-03	0.04	2.7	1.4	no	91.4	yes
1027405	Clarkes Beach - Clarkes Pond	2010-11-01	0.07	3.9	1.9	no	84.6	yes
1023727	Colliers, Harbour Drive - #5 Well - Whalen's Well	2010-09-28	0.01	0.9	0.8	no	98.4	yes
1023727	Colliers, Harbour Drive & Main Road - #3 Well - Griffin's Well	2010-09-28	0.01	1.6	0.8	no	97.2	yes
1023727	Colliers, Main Road - #1 Well - Mahoney's Well	2010-09-28	0.00	0.8	0.5	no	99	yes
1023727	Colliers, Merrigan's Lane + Main Rd - #2 Well - Merrigan's Well	2010-09-28	0.00	0.8	0.1	no	99.9	yes
1027900	Comfort Cove-Newstead - Steady Cove Pond	2010-11-08	0.22	8.6	2.6	no	60.3	no

WO#	Location	SAMPLE DATE	UVA	DOC	SUVA	Coagulation	UVT	UV Disinfection
1028289	Conche - Martin's Brook	2010-11-08	0.82	17.6	4.7	yes	15	no
1028291	Cook's Harbour - Unnamed Pond	2010-11-09	0.15	6	2.6	no	70.1	no
1028604	Cottlesville - Rushy Cove Pond	2010-11-17	0.27	10.2	2.7	no	53.3	no
1028300	Cow Head - Short Cat Path Pond	2010-11-11	0.23	9.4	2.4	no	59	no
1027901	Crow Head - Oars Pond	2010-11-09	0.41	10.9	3.7	yes	39.1	no
1028299	Daniel's Harbour - Unnamed Spring & Brook	2010-11-11	0.06	3.8	1.6	no	87.1	yes
1027441	Dildo, Broad Cove (+South Dildo) - Broad Cove Pond	2010-11-04	0.24	7.4	3.2	no	57.8	no
1027237	Elliston - Big Pond	2010-11-02	0.13	4.9	2.6	no	74.8	no
1027900	Embree (+Little Burnt Bay) - Troke's Cove Pond	2010-11-08	0.18	7	2.5	no	66.5	no
1027901	Fairbanks-Hillgrade - Saltine's Pond	2010-11-09	0.25	9.6	2.6	no	55.8	no
1027420	Ferryland - Deep Cove Pond	2010-11-05	0.26	9	2.9	no	54.9	no
1030162	Fogo Island- Tilting - Sandy Cove Pond	2010-12-07	0.21	7.9	2.6	no	62.3	no
1030162	Fogo Island-Seldom-Little Seldom - Bullock Cove Pond	2010-12-07	0.36	10.8	3.3	no	43.6	no
1029124	Fortune (+Grand Bank) - Horsebrook	2010-11-22	0.11	4.1	2.7	no	77.4	yes
1027253	Francois - Our Pond	2010-11-01	0.27	5.5	4.9	yes	53.5	no
1029114	Gander - Gander Lake	2010-11-24	0.08	6.3	1.2	no	83.6	yes
1029124	Garnish - Witchazel Pond	2010-11-22	0.31	11	2.9	no	48.5	no
1027419	Gaskiers-Point La Haye - Big Hare Hill Pond	2010-11-03	0.59	14.2	4.2	yes	25.7	no
1030154	Gillams - Jackie Tapp's Brook	2010-12-07	0.22	7.2	3.1	no	60	no
1029151	Glenburnie-Birchy Head-Shoal Brook - Croucher's Brook	2010-11-22	0.20	5.3	3.8	yes	62.6	no
1029117	Glenwood - Gander Lake (The Outflow)	2010-11-22	0.29	7.9	3.6	yes	51.8	no
1027405	Glovertown - Northwest Pond	2010-11-02	0.29	7.8	3.7	yes	51.5	no
1029130	Goobies - Water Pond	2010-11-24	0.27	6.6	4.1	yes	53.5	no
1029124	Grand Bank - Horsebrook	2010-11-23	0.11	4.1	2.7	no	77.4	yes
1029118	Grand Le Pierre - Nip Nose Pond	2010-11-22	0.21	5.1	4.2	yes	61.3	no
1027253	Grey River - Big Charlie's Pond	2010-11-01	0.56	10.5	5.4	yes	27.3	no
1027405	Happy Adventure - Goose Neck Pond	2010-11-02	0.41	10.9	3.8	yes	38.8	no
1027406	Harbour Grace, Harbour Grace South (+Riverhead) - Bannerman Lake	2010-11-01	0.11	5.1	2.2	no	77.3	yes
1028298	Hawke's Bay - Torrent River	2010-11-10	0.32	9	3.5	yes	48.2	no
1029916	Hermitage-Sandyville - Granfer's Pond	2010-12-02	0.48	12.3	3.9	yes	32.8	no
1027901	Herring Neck, Hatchet Harbour, Salt Harbour, Shoal Cove, Sunnyside - Gut Pond	2010-11-09	0.18	8.2	2.2	no	65.6	no
1030154	Irishtown - Irishtown Brook	2010-12-07	0.29	8.7	3.4	no	51	no
1029913	Isle aux Morts - Burnt Ground Pond	2010-12-03	0.33	7.4	4.4	yes	46.9	no
1030162	Joe Batt's Arm-Barr'd Islands-Shoal Bay - Long Pond	2010-12-07	0.10	6.6	1.5	no	79.8	yes
1027242	Keels - Boland's Pond	2010-11-02	0.39	11.9	3.3	no	40.7	no
1027253	La Poile - Black Duck Pond	2010-11-01	0.88	16.7	5.3	yes	13.1	no

WO#	Location	SAMPLE DATE	UVA	DOC	SUVA	Coagulation	UVT	UV Disinfection
1027965	L'Anse au Loup - L'anse Au Loup River	2010-11-09	0.21	4.4	4.7	yes	62.3	no
1027632	Leading Tickles - Cook's Pond	2010-11-03	0.45	13.2	3.4	no	35.2	no
1029129	Little St. Lawrence - Butler's Brook (2 Intakes)	2010-11-23	0.11	2.9	3.9	yes	77	yes
1028604	Loon Bay - Southeast Pond	2010-11-17	0.20	7.2	2.8	no	63.2	no
1030618	Lushes Bight, Beaumont - Milkboy's Pond/Gull Pond	2010-12-13	0.27	9	2.9	no	54.3	no
1028289	Main Brook - Joe Burt's Pond	2010-11-08	0.16	6.8	2.4	no	69	no
1025811	Makkovik - Ranger Bight Pond	2010-10-12	0.21	5.1	4.1	yes	61.5	no
1027964	Mary's Harbour - St. Mary's River	2010-11-05	0.39	9.4	4.2	yes	40.7	no
1029130	Marystown - Fox Hill Reservoir / Clam Pond	2010-11-23	0.28	7.4	3.8	yes	52.4	no
1029150	McCallum - Drilled	2010-11-22	0.82				15	no
1027901	Merritt's Harbour - Jimmy's Pond	2010-11-09	0.24	9.3	2.6	no	57.3	no
1027633	Millertown - Water Pond	2010-11-04	0.21	8.6	2.4	no	61.8	no
1029916	Milltown, Head of Bay D'Espoir - Jersey Pond	2010-12-02	0.26	6.6	3.9	yes	55	no
1029916	Morrisville - Morrisville Pond	2010-12-02	0.34	7.8	4.3	yes	46.1	no
1028297	Nameless Cove / Flower Cove - French Island Pond	2010-11-09	0.25	8.1	3.0	no	56.8	no
1028552	New Perlican - New Perlican River	2010-11-16	0.15	5.4	2.9	no	70.1	no
1029114	Newtown-Templeton - Carter's Pond	2010-11-23	0.68	15	4.5	yes	21.1	no
1029114	New-Wes-Valley- Wesleyville-Badger's Quay-Pool's Island, Brookfield-Poundcove - Little Northwest Pond	2010-11-23	0.32	8.9	3.6	yes	47.4	no
1028551	Norman's Cove-Long Cove - John Newhooks Pond	2010-11-15	0.15	5.3	2.8	no	71	no
1028301	Norris Point - Neddy Harbour Pond	2010-11-11	0.11	5.6	2.0	no	76.9	yes
1029130	North Harbour - Grandfather's Pond	2010-11-24	0.52	9.2	5.6	yes	30.5	no
1028551	Old Perlican - Bell Pond	2010-11-16	0.19	4.7	4.1	yes	64.4	no
1029118	Parkers Cove - Unnamed brook	2010-11-22	0.48	12.1	3.9	yes	33.3	no
1028300	Parson's Pond - Cold Brook	2010-11-11	0.03	2.4	1.4	no	92.6	yes
1029118	Petit Forte - Reddy's Pond	2010-11-22	0.39	8.7	4.5	yes	41	no
1030046	Piccadilly Head (+West Bay) - Unnamed Brook	2010-12-08	0.29	7.2	4.1	yes	50.7	no
1028297	Pigeon Cove - Long Pond (Intake #1)	2010-11-10	0.35	9.3	3.7	yes	44.9	no
1027632	Pleasantview - Little Arm Pond	2010-11-03	0.27	10.6	2.6	no	53.5	no
1027632	Point Leamington - Little Pond	2010-11-03	0.27	8.6	3.1	no	54.2	no
1029124	Point May - Short's Pond	2010-11-22	0.29	7.9	3.7	yes	51.2	no
1028283	Point of Bay - Indian Cove Pond	2010-11-12	0.20	8.5	2.3	no	63.4	no
1029917	Pool's Cove - Widgeon Pond	2010-12-03	0.20	6.8	2.9	no	63.8	no
1028299	Port au Choix - Winterhouse Pond	2010-11-11	0.18	7.4	2.4	no	66.1	no
1027965	Port Hope Simpson - Arnold's Brook and Pond	2010-11-10	0.48	12	4.0	yes	33.4	no
1028299	Port Saunders - Tom Taylor's Pond	2010-11-10	0.24	8.8	2.8	no	57	no
1028300	Portland Creek - Unnamed Streams	2010-11-11	0.11	4.2	2.5	no	78.4	yes
1027419	Portugal Cove South - Wrights Brook	2010-11-03	0.29	5.9	4.9	yes	51.4	no

WO#	Location	SAMPLE DATE	UVA	DOC	SUVA	Coagulation	UVT	UV Disinfection
1027803	Pouch Cove - North Three Island Pond	2010-11-09	0.17	7.5	2.3	no	67.6	no
1027901	Purcell's Harbour - Purcell's Harbour Pond	2010-11-09	0.64	15.5	4.1	yes	23	no
1027247	Queen's Cove - Reservoir	2010-11-03	0.28	6.9	4.0	yes	53	no
1027964	Red Bay - Northern Brook	2010-11-05	0.30	6.2	4.8	yes	50.4	no
1025811	Rigolet - Rigolet Pond	2010-10-12	0.51	13.8	3.7	yes	31	no
1028300	Rocky Harbour - Gull Pond	2010-11-11	0.25	8.1	3.1	no	55.6	no
1027405	Salvage - Wild Cove Pond	2010-11-02	0.46	13.7	3.4	no	34.4	no
1028686	South Brook - Next to Brook	2010-11-18	0.01				97.6	yes
1028297	St. Barbe - Long Pond (Intake #2)	2010-11-10	0.34	9.3	3.7	yes	45.2	no
1029118	St. Bernard's-Jacques Fontaine - Rattle Brook	2010-11-22	0.29	7	4.1	yes	51.3	no
1027803	St. Bride's - North Side Brook	2010-11-08	0.11	4.4	2.6	no	77	yes
1027803	St. Bride's - South Side Brook	2010-11-08	0.41	8.7	4.7	yes	38.7	no
1029147	St. John's - Windsor Lake	2010-11-25	0.03	2.7	1.3	no	92.3	yes
1029129	St. Lawrence - PWDU - St. Lawrence River	2010-11-23	0.00				99.7	yes
1027964	St. Lewis - Tub Harbour Pond	2010-11-05	0.50	11.6	4.3	yes	31.4	no
1028289	St. Lunaire-Griquet - Joe's Pond	2010-11-08	0.66	17.5	3.8	yes	21.7	no
1028300	St. Pauls - Two Mile Pond	2010-11-11	0.29	11	2.6	no	51.8	no
1030156	Steady Brook - Steady Brook	2010-12-08	0.31	8.6	3.6	yes	48.7	no
1028289	Straitsview - Saddle Hill Pond	2010-11-08	0.69	14.4	4.8	yes	20.4	no
1028604	Summerford (+Cottlesville) - Rushy Cove Pond	2010-11-17	0.28	9.9	2.8	no	52.9	no
1029118	Terrenceville - Big Brook	2010-11-22	0.18	6.1	2.9	no	66.4	no
1028604	Tizzard's Harbour - Rocky Pond	2010-11-17	0.49	12.3	4.0	yes	32.3	no
1028685	Triton, Jim's Cove, Card's Harbour - Triton Pond	2010-11-18	0.35	11.1	3.1	no	45	no
1030046	West Bay - Unnamed Brook	2010-12-08	0.30	7.3	4.1	yes	50.5	no
1029796	West Bay - Victor's Brook	2010-12-01	0.19	7	2.8	no	63.9	no
1027965	West St. Modeste - Well Field	2010-11-09	0.26	4.8	5.5	yes	54.4	no

APPENDIX E

Source Water Quality

Table E.1 Minimum and maximum DOC measured in source water, mg/L (ENVC, 2000-2009)

Community Name	Source Type	Minimum	Maximum
Channel - Port aux Basques	Pond	3.6	13.0
Clarenville	River	3.1	14.9
Conne River	Brook	2.5	7.7
Deer Lake	Lake and canal	0.8	4.2
Gander	Lake	1.1	7.5
Grand Falls	Lake	0.5	8.3
Happy Valley-Goose Bay	Groundwater	0.0	6.4
Heart's Delight	Pond	2.2	15.4
Lourdes	Brook	1.7	13.7
Lumsden	Pond	3.7	15.9
Musgrave Harbour	Pond	4.4	22.1
Pasadena	Pond	1.1	10.6
Placentia	Pond	2.9	12.0
Ramea	Pond	2.3	20.9
St. John's BBB	Pond	1.6	0.7
St. John's	Lake	0.6	3.5

Table E.2 Minimum and maximum colour measured in source water, TCU (ENVC, 2000-2009)

Community Name	Source Type	Minimum	Maximum
Channel - Port aux Basques	Pond	35	250
Clarenville	River	24	49
Conne River	Brook	30	44
Deer Lake	Lake and canal	5	24
Gander	Lake	29	58
Grand Falls	Lake	0	35
Happy Valley-Goose Bay	Groundwater	0	18
Heart's Delight	Pond	18	40
Lourdes	Brook	13	49
Lumsden	Pond	70	129
Musgrave Harbour	Pond	62	133
Pasadena	Pond	11	25
Placentia	Pond	5	39
Ramea	Pond	50	167
St. John's BBB	Pond	5	22
St. John's	Lake	0	6

Table E.3 Minimum and maximum pH measured in source water (ENVC, 2000-2009)

Community Name	Source Type	Minimum	Maximum
Channel - Port aux Basques	Pond	4.6	6.5
Clarenville	River	5.6	6.9
Conne River	Brook	4.7	5.8
Deer Lake	Lake and canal	6.2	7.5
Gander	Lake	5.9	6.9
Grand Falls	Lake	5.9	7.4
Happy Valley-Goose Bay	Groundwater	6.4	7.7
Heart's Delight	Pond	5.1	7.3
Lourdes	Brook	6.6	8.3
Lumsden	Pond	4.8	6.6
Musgrave Harbour	Pond	5.4	6.8
Pasadena	Pond	6.1	7.5
Placentia	Pond	5.3	6.7
Ramea	Pond	4.8	7.5
St. John's BBB	Pond	5.4	7.0
St. John's	Lake	5.7	6.4

Table E.4 Minimum and maximum bromide measured in source water, mg/L (ENVC, 2000 2009)

Community Name	Source Type	Minimum	Maximum
Channel - Port aux Basques	Pond	0.00	0.03
Clarenville	River	0.00	0.03
Conne River	Brook	0.00	0.37
Deer Lake	Lake and canal	0.00	0.03
Gander	Lake	0.00	0.12
Grand Falls	Lake	0.00	0.03
Happy Valley-Goose Bay	Groundwater	0.00	2.78
Heart's Delight	Pond	0.00	0.03
Lourdes	Brook	0.00	0.03
Lumsden	Pond	0.00	0.03
Musgrave Harbour	Pond	0.00	0.03
Pasadena	Pond	0.00	0.03
Placentia	Pond	0.00	0.03
Ramea	Pond	0.00	0.43
St. John's BBB	Pond	0.00	0.01
St. John's	Lake	0.00	0.03

Table E.5 Minimum and Maximum Turbidity Measured in Source Water, NTU (ENVC, 2000-2009)

Community Name	Source Type	Minimum	Maximum
Channel - Port aux Basques	Pond	0.1	3.6
Clarenville	River	0.1	2.2
Conne River	Brook	0.1	0.9
Deer Lake	Lake and canal	0.0	2.4
Gander	Lake	0.0	1.8
Grand Falls	Lake	0.0	2.1
Happy Valley-Goose Bay	Groundwater	0.2	120.0
Heart's Delight	Pond	0.2	1.3
Lourdes	Brook	0.1	6.2
Lumsden	Pond	0.3	3.6
Musgrave Harbour	Pond	0.3	47.4
Pasadena	Pond	0.0	2.3
Placentia	Pond	0.2	2.0
Ramea	Pond	0.2	5.7
St. John's BBB	Pond	0.2	0.3
St. John's	Lake	0.1	1.2

APPENDIX F

Water Quality Before and After the Construction of a WTP

*comparison of tap water quality before commissioning and during shutdown to periods when the plant was working

**coagulation + oxidation followed by greensand filtration

***cyclone filters, periodic coagulation, and multimedia filtration

Table F.1 Average DOC (mg/L) before and after the commissioning of WTP shown with p value from student's t test

Community	Treatment	Commissioned	Average DOC (mg/L)		
			No WTP	WTP	p
Channel – Port aux Basques	Coagulation-based packaged system	1988	-	2.3	-
Clarenville	Conventional	2007	-	1.8	-
Conne River*	Membrane (NF)	2006	5.3	1.5	0.267
Deer Lake	Thread filtration (3 µm)	2001	2.9	3.6	0.011
Gander	Ozone and filtration	2006	6.3	5.5	0.088
Grand Falls	Conventional	1996	-	2.5	-
Happy Valley-Goose Bay	Semi-conventional**	2002	-	0.6	-
Heart's Delight	Conventional with mixed oxidants	2001	7.4	3.5	0.074
Lourdes	Semi-conventional***	2004	6.4	6.3	0.915
Lumsden	Conventional	1972	-	3.6	-
Musgrave Harbour	Conventional	1996	-	4.2	-
Pasadena	Thread filtration (3 µm)	2002	4.4	5.4	0.210
Placentia	Ozone and dual-media filtration	1991	-	8.2	-
Ramea	Conventional	2002	1.8	2.2	0.306
St. John's BBB	Ozone and dual-media filtration	1978	-	3.3	-
St. John's	Membrane (MF)	2007	2.1	1.9	0.509

Table F.2 Average colour (TCU) before and after the commissioning of WTP shown with p value from student's t test

Community	Treatment	Commissioned	Average Colour (NTU)		
			No WTP	WTP	p
Channel – Port aux Basques	Coagulation-based packaged system	1988	-	1.3	-
Clarenville	Conventional	2007	-	0	-
Conne River*	Membrane (NF)	2006	27.6	1.2	8.66E-05
Deer Lake	Thread filtration (3 µm)	2001	23.0	16.8	0.016
Gander	Ozone and filtration	2006	25.8	17.0	0.000
Grand Falls	Conventional	1996	-	2.2	-
Happy Valley-Goose Bay	Semi-conventional**	2002	-	0.6	-
Heart's Delight	Conventional with mixed oxidants	2001	34.0	5.9	0.006
Lourdes	Semi-conventional***	2004	18.1	19.2	0.884
Lumsden	Conventional	1972	-	8.5	-
Musgrave Harbour	Conventional	1996	-	4.7	-
Pasadena	Thread filtration (3 µm)	2002	12.8	13.0	0.948
Placentia	Ozone and dual-media filtration	1991	-	29.1	-
Ramea	Conventional	2002	8	1.7	0.002
St. John's BBB	Ozone and dual-media filtration	1978	-	7.7	-
St. John's	Membrane (MF)	2007	3.4	0.8	0.039

Table F.3 Average TTHM (µg/L) before and after the commissioning of WTP shown with p value from student's t test

Community	Treatment	Commissioned	Average THMs (µg/L)		
			No WTP	WTP	p
Channel – Port aux Basques	Coagulation-based packaged system	1988	-	55.6	-
Clarenville	Conventional	2007	-	60.8	-
Conne River*	Membrane (NF)	2006	154.3	57.4	1.99E-04
Deer Lake	Thread filtration (3 µm)	2001	37.8	57.7	1.81E-04
Gander	Ozone and filtration	2006	197.7	77.4	7.43E-12
Grand Falls	Conventional	1996	78.5	83.0	0.834
Happy Valley-Goose Bay	Semi-conventional**	2002	-	62.7	-
Heart's Delight	Conventional with mixed oxidants	2001	141.2	89.5	0.001
Lourdes	Semi-conventional***	2004	155.1	179.6	0.488
Lumsden	Conventional	1972	-	61.6	-
Musgrave Harbour	Conventional	1996	-	100.7	-
Pasadena	Thread filtration (3 µm)	2002	78.5	141.9	3.90E-08
Placentia	Ozone and dual-media filtration	1991	-	93.8	-
Ramea	Conventional	2002	349.1	161.6	1.09E-05
St. John's BBB	Ozone and dual-media filtration	1978	-	20.3	-
St. John's	Membrane (MF)	2007	36.2	56.0	0.006

Table F.4 Average HAA5 (µg/L) before and after the commissioning of WTP shown with p value from student's t test

Community	Treatment	Commissioned	Average HAAs (µg/L)		
			No WTP	WTP	p
Channel – Port aux Basques	Coagulation-based packaged system	1988	-	124.7	-
Clarenville	Conventional	2007	-	63.3	-
Conne River*	Membrane (NF)	2006	265.9	64.7	0.002
Deer Lake	Thread filtration (3 µm)	2001	1	73.8	0.004
Gander	Ozone and filtration	2006	120.4	92.8	0.446
Grand Falls	Conventional	1996	-	100.4	-
Happy Valley-Goose Bay	Semi-conventional**	2002	-	41.6	-
Heart's Delight	Conventional with mixed oxidants	2001	166.0	81.1	0.025
Lourdes	Semi-conventional***	2004	42.8	222.3	0.091
Lumsden	Conventional	1972	-	86.8	-
Musgrave Harbour	Conventional	1996	-	181.8	-
Pasadena	Thread filtration (3 µm)	2002	-	189	-
Placentia	Ozone and dual-media filtration	1991	-	96.4	-
Ramea	Conventional	2002	-	61.6	-
St. John's BBB	Ozone and dual-media filtration	1978	-	53.4	-
St. John's	Membrane (MF)	2007	41.2	50.0	0.344

APPENDIX G

Treated Water NOM Chromatograms

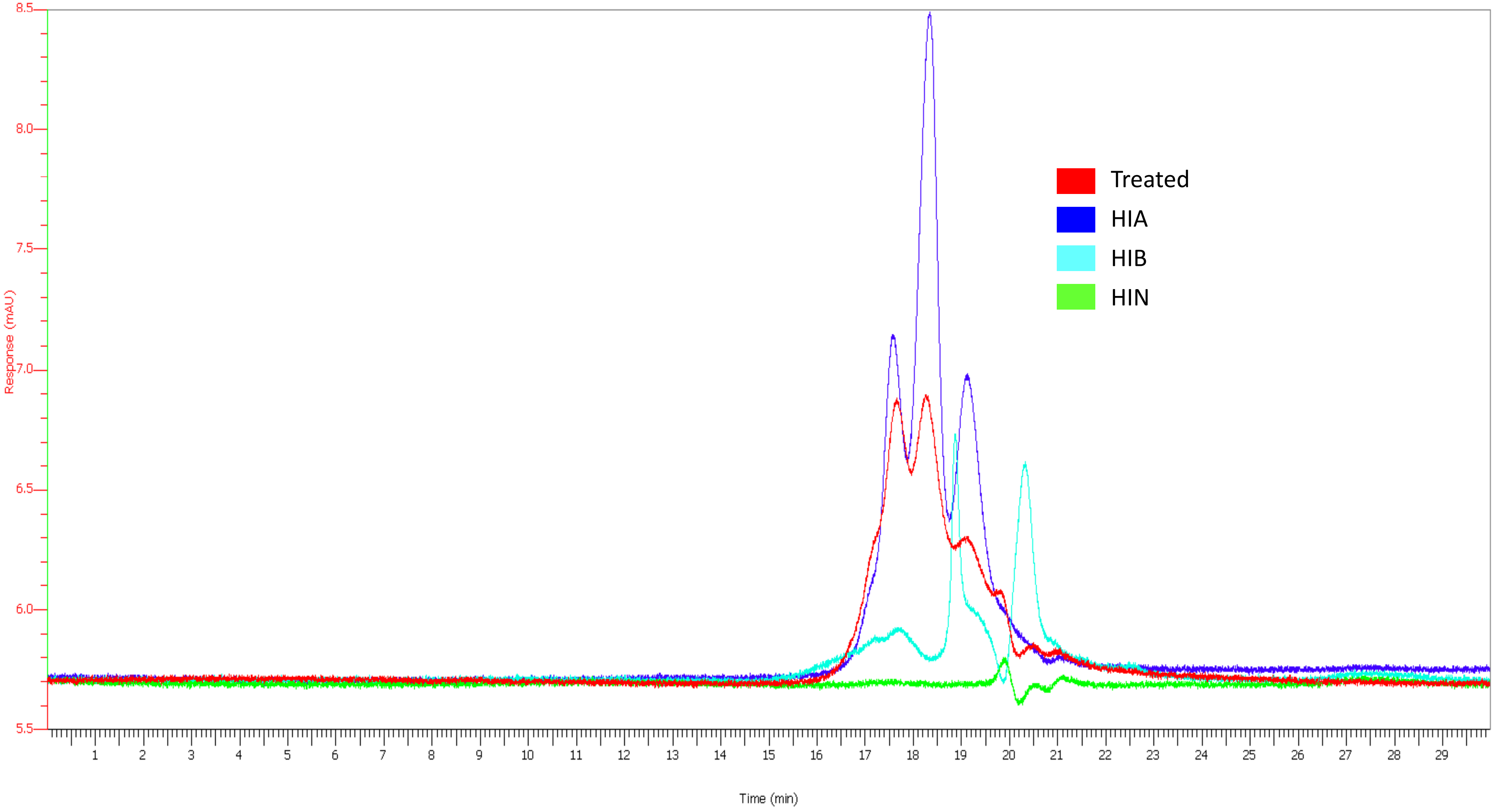

Figure G.1 **Community C Treated**

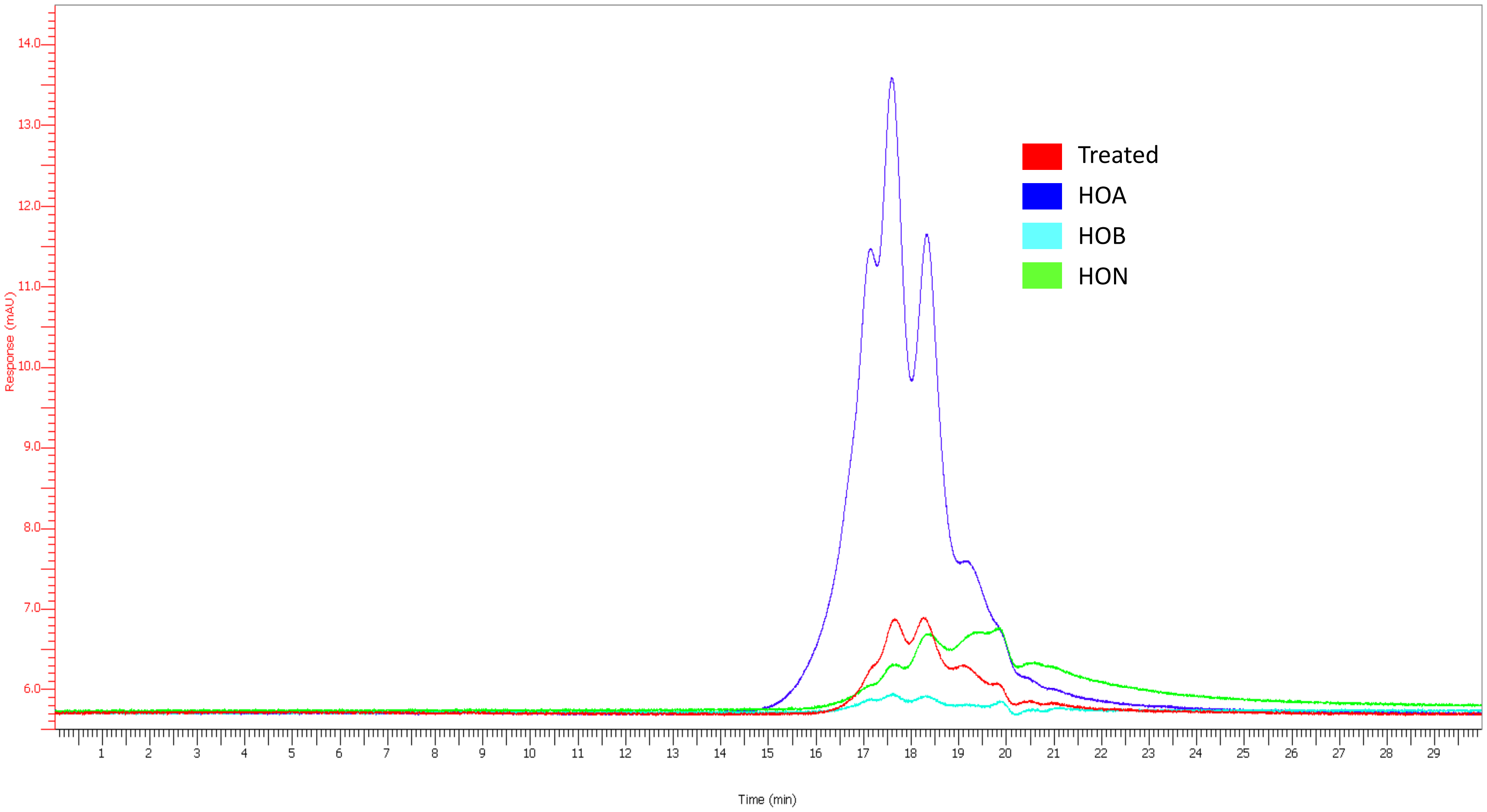

Figure G.2 Community C Treated

Table G.1 Community C Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw	30,273	2,597	1,530	1,258	975	723	573	451	316	
HON	35,059	2,274	1,587	1,154	783	562	392	204	59	
HOB				1,334	997	620		473	371	
HOA	30,785	2,330		1,305	947	603		448	401	355
HIN				1,310		622		471	376	
HIB				1,441	1,026	739	599	465	384	
HIA				1,486	1,078	773	558	500	374	

Table G.2 Community C Treated Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw			1,491	1,046	832	726	599	429	372	
HON			1,557	1,045	804	700	598		353	
HOB			1,619	1,379	1,003	723	607	474	383	
HOA		1,946	1,391	1,023		705	555		368	
HIN							596	418	358	
HIB			1,568	1,286	820			500	212	34
HIA			1,476	1,079		740			384	

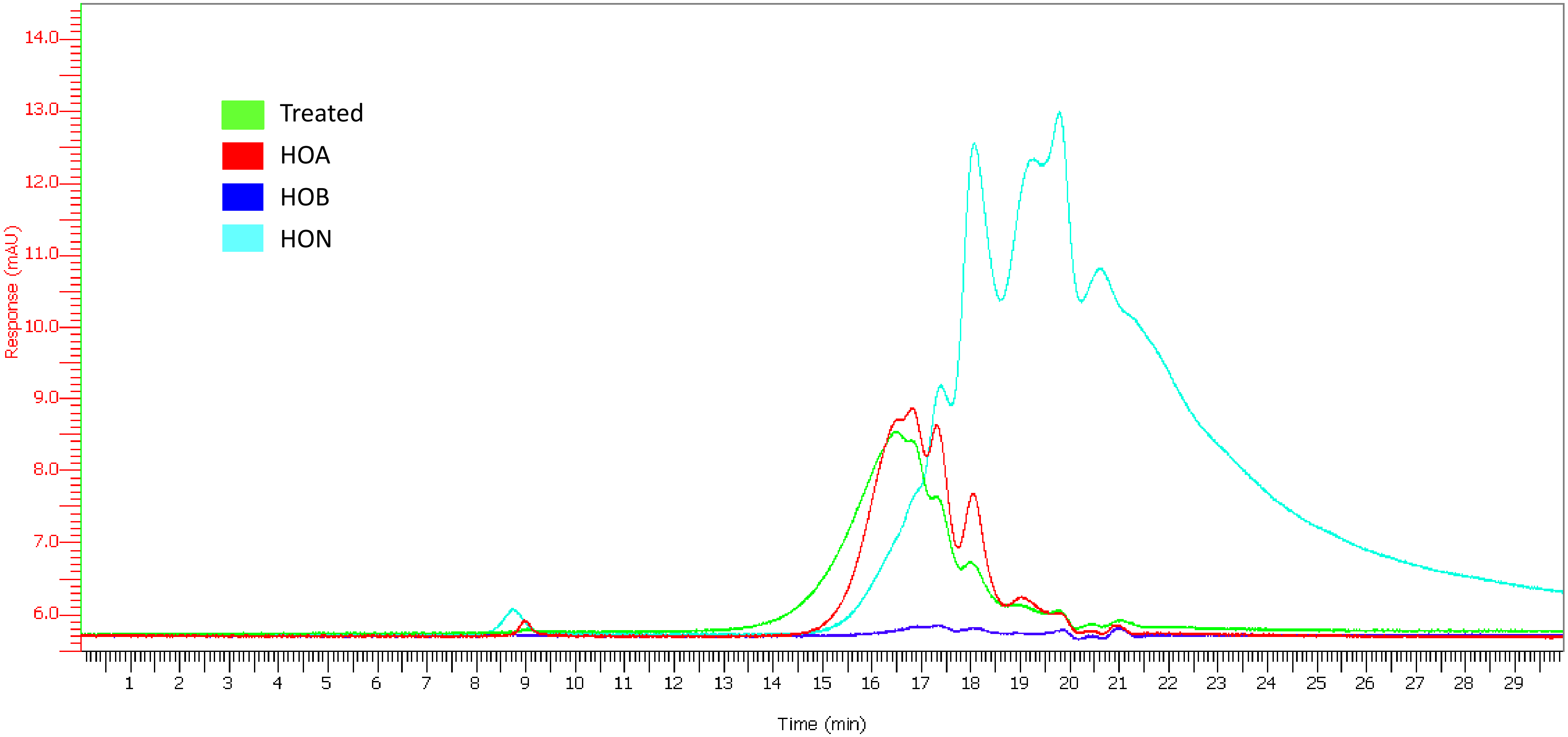

Figure G.3 **Community D Treated**

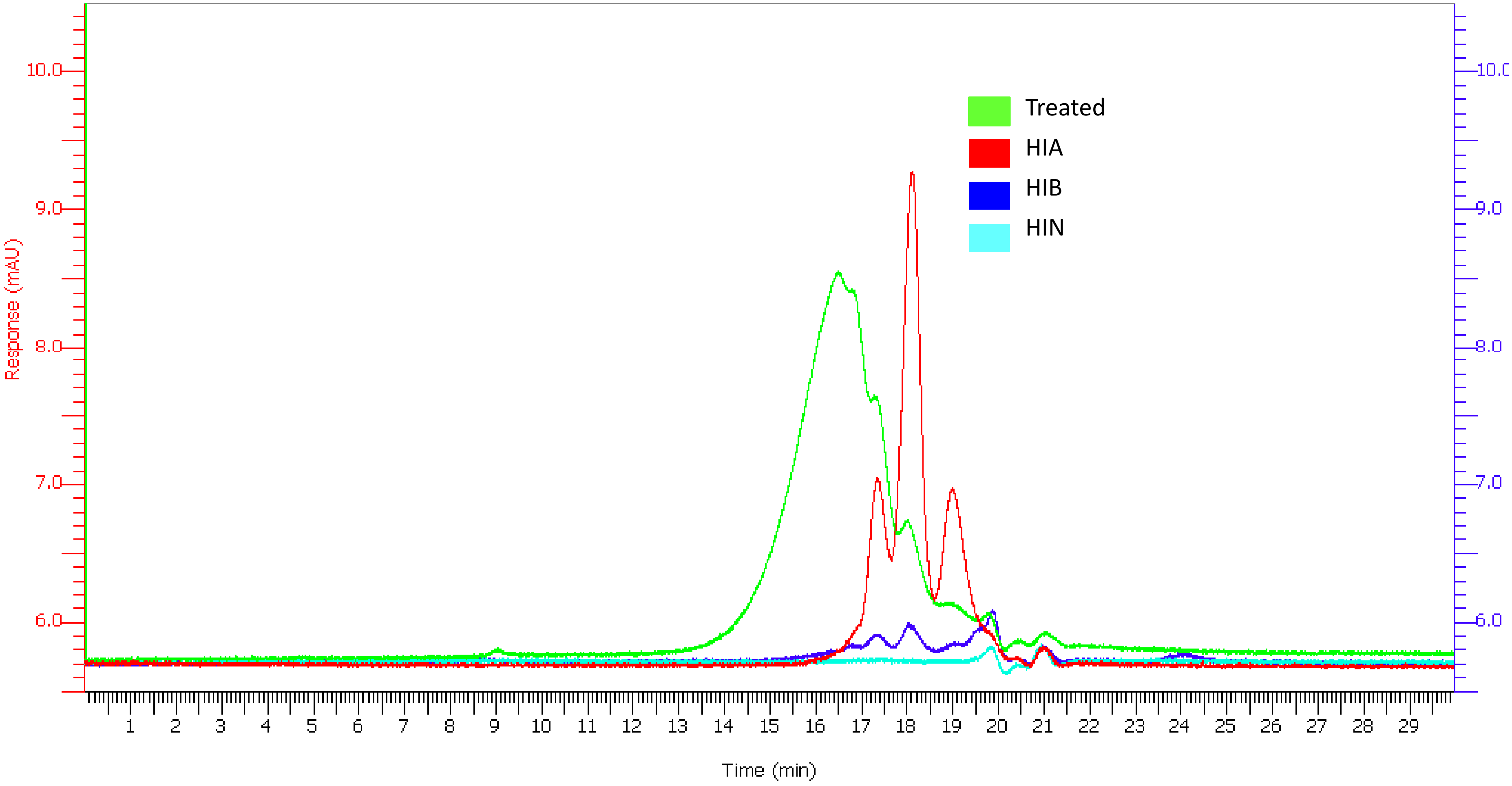

Figure G.4 Community D Treated

Table G.3 Community D Raw Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw	34,024	1,817	1,538	1,211	849	625	491	394		
HON	33,755	1,556	1,142	782	616	409	302			
HOB		1,844	1,483	1,092	628	407				
HOA	32,598	2,539	1,457	1,090	718	563	470	411		
HIN		1,569	636	486	409					
HIB		40,625	1,877	1,557	1,201	828	611	410		
HIA		1,626	1,153	841	600	487	407	292		

Table G.4 Community D Treated Water

	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5	Peak 6	Peak 7	Peak 8	Peak 9	Peak 10
Raw		2,662	1,709	1,435	1,020	621	486	385		
HON	37,217		1,847	1,153	819	614	260			
HOB	41,080	3,039	1,404	495	397					
HOA	33,525	2,575	1,848	1,520	1,149	774	596	471	402	
HIN					630	487	404			
HIB		1,937	1,531	1,150	833	632	395			
HIA		1,601	1,167	810	553	494	399			

APPENDIX H

Community Key

Code	Community
Community A	Carbonear
Community B	Cartwright
Community C	Channel – Port aux Basques
Community D	Gander
Community E	Steady Brook
Community F	Triton

APPENDIX I

Process Schematics

FIGURE I.1
CONVENTIONAL TREATMENT

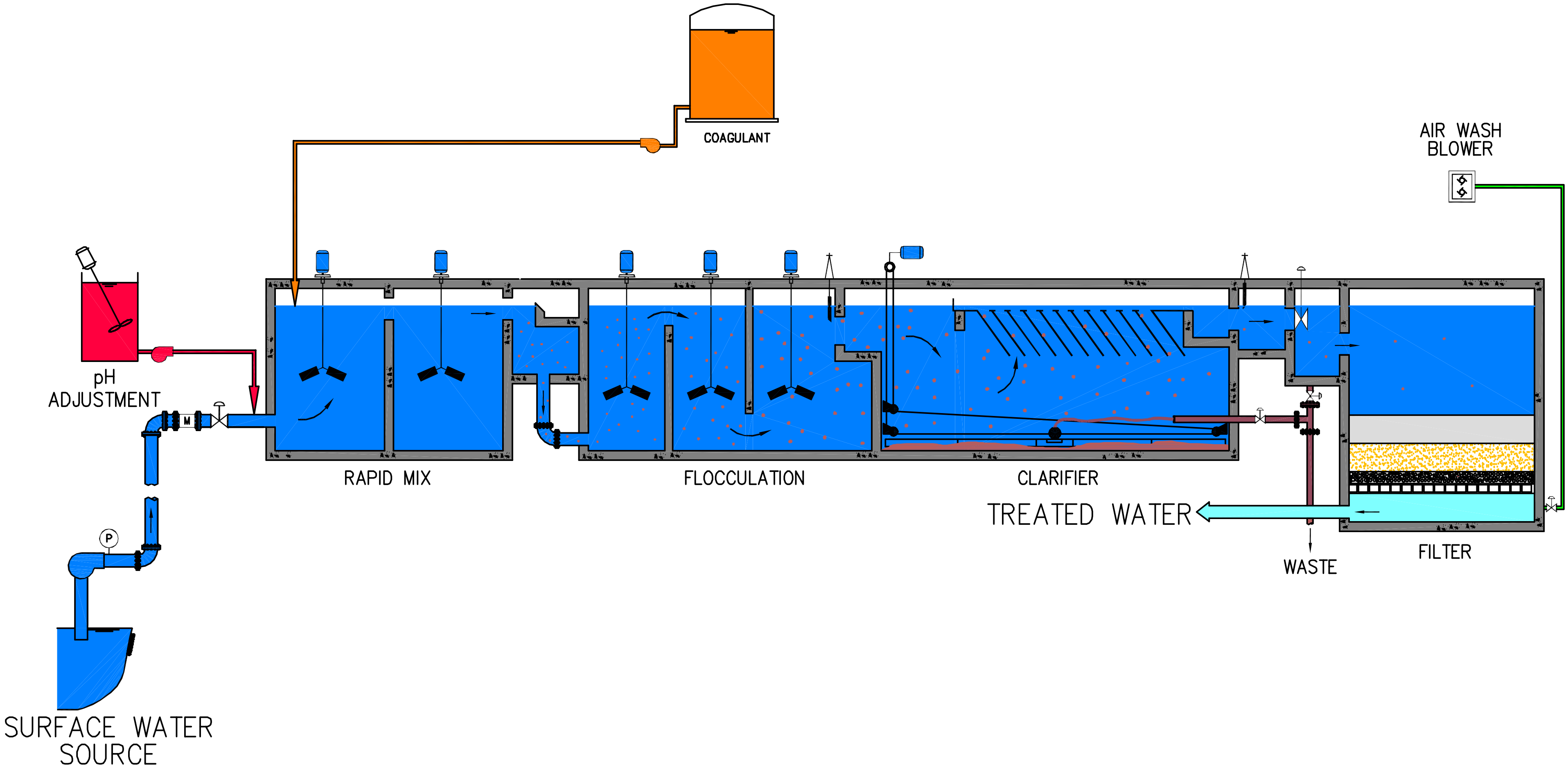

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FIGURE I.2
DISSOLVED AIR FLOTATION

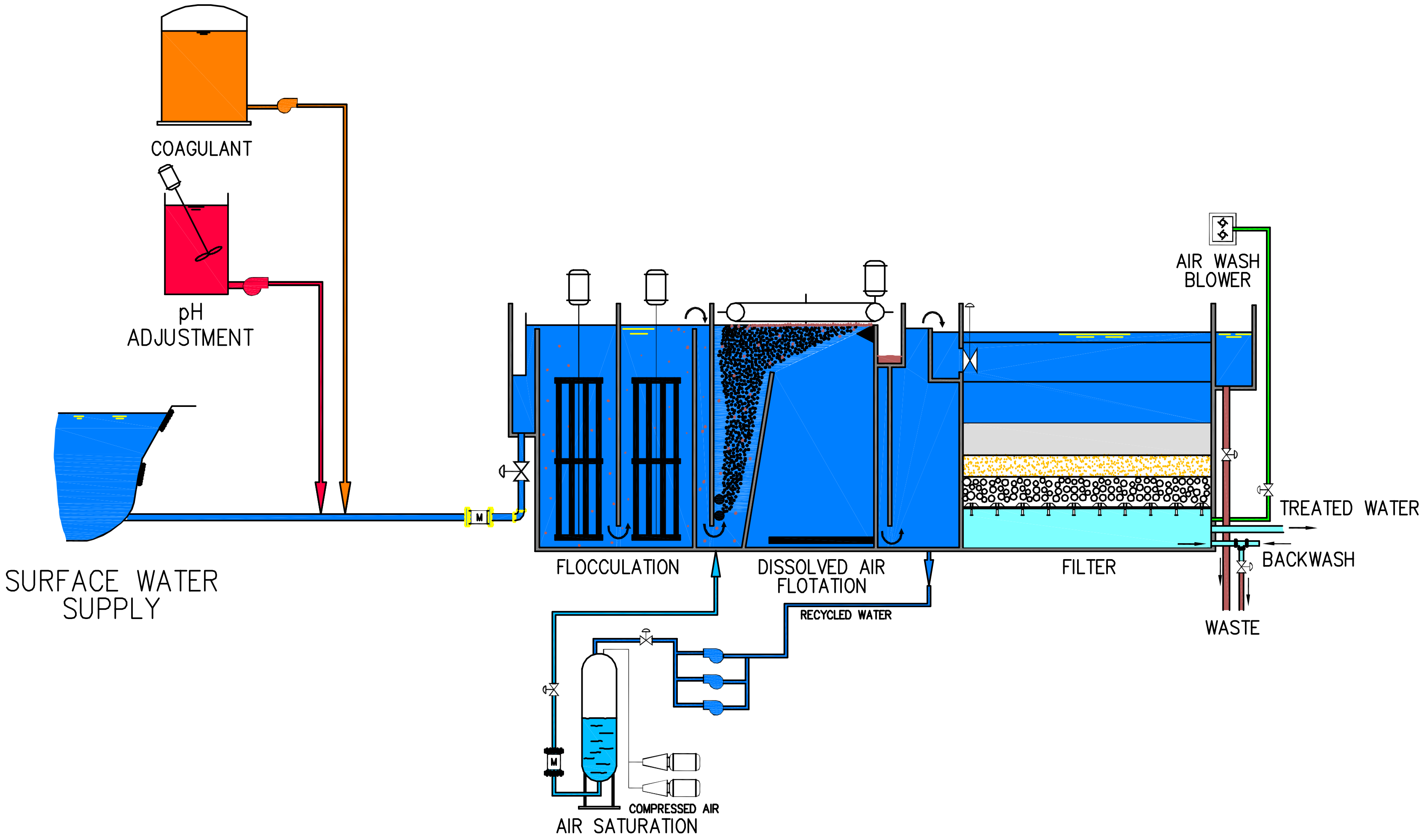

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FIGURE I.3
DIRECT FILTRATION

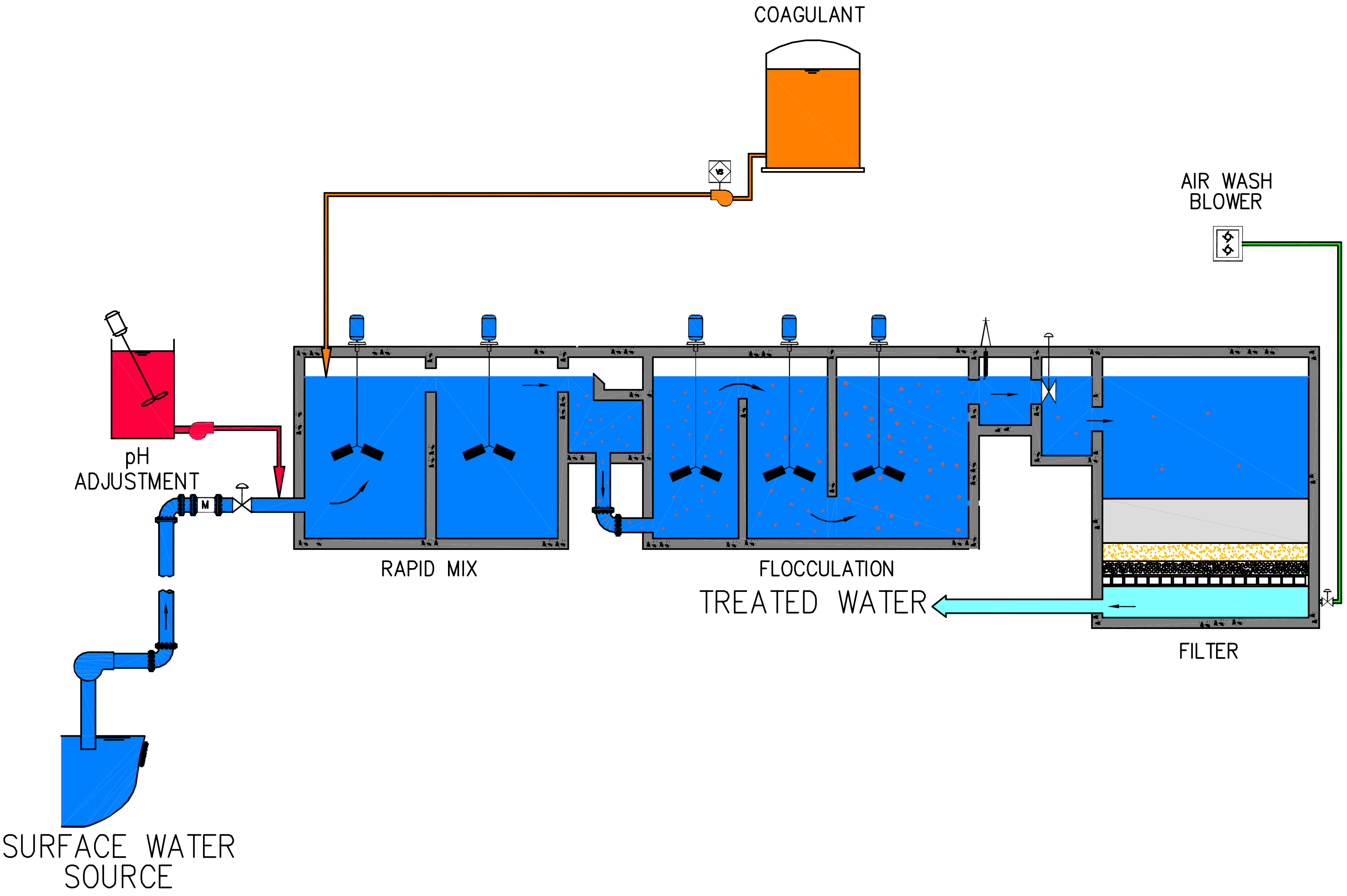

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FIGURE I.4
MEMBRANE FILTRATION

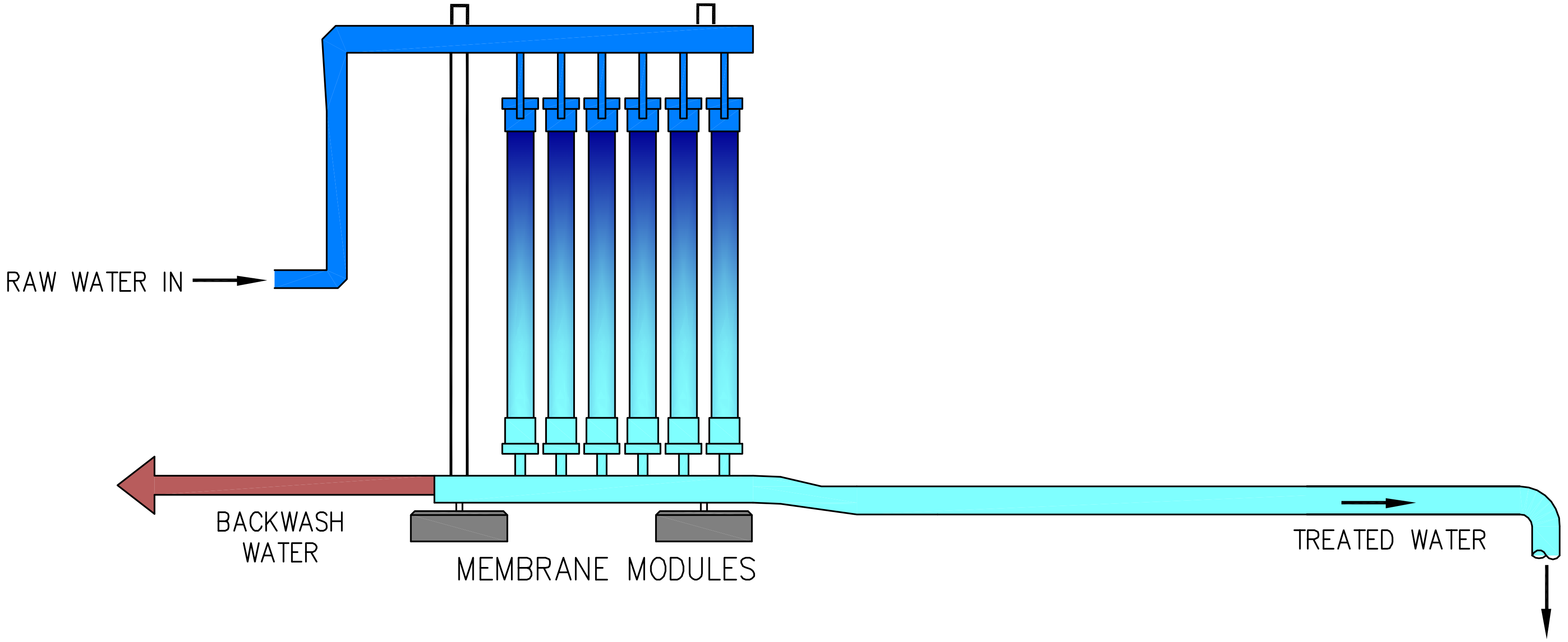
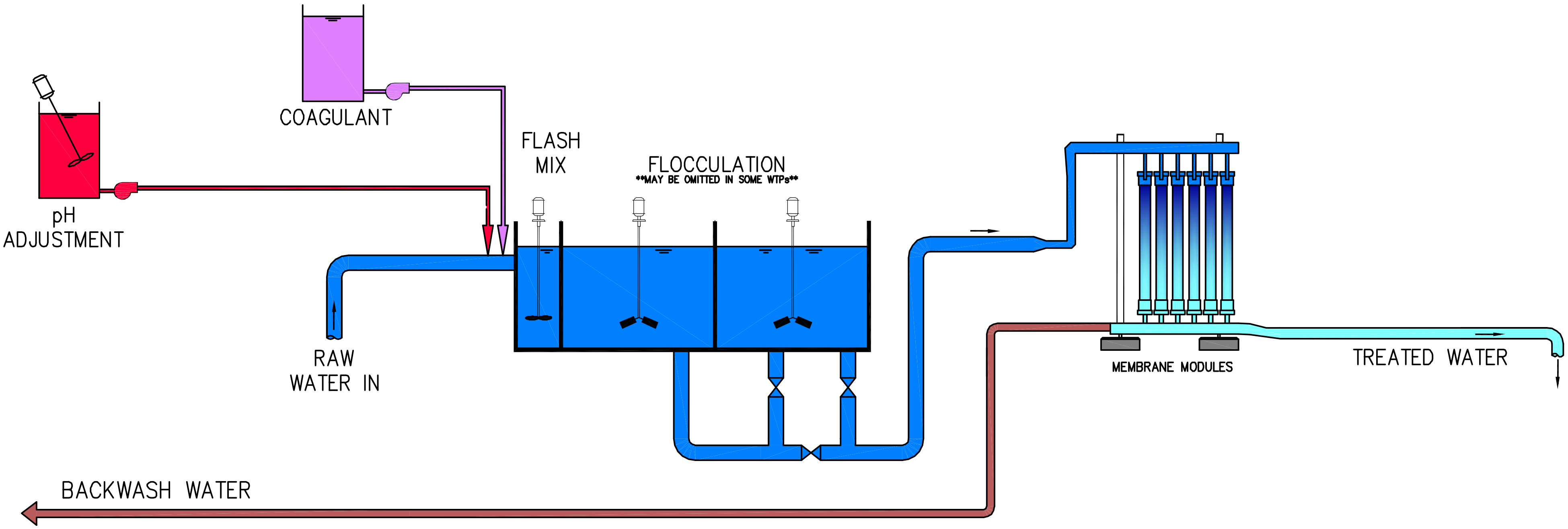


FIGURE I.5
MEMBRANE FILTRATION WITH COAGULATION PRETREATMENT



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