University of Alberta

THMs and HAAs Formation, Modeling and Control in Small WTPs in Northern Alberta

by

Wahida Zaman ©

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This thesis is dedicated with love and respect to my dearest parents

and

to my beloved husband

Abstract

A proactive approach was taken by Alberta Environment to understand the behavior of and to develop control strategies for the high levels of Trihalomethanes (THMs) and Haloacetic acids (HAAs) in small waterworks before their regulatory limits are posted. This work demonstrates the condition of THMs and HAAs for eight small facilities, including an in-depth analysis of collected data from the monitoring program. Fort McKay, Westlock, Woking, and Tangent waterworks exceeded the regulatory values of THMs and HAAs during the monitoring period. Lack of consistent operation, chlorine dose and residual chlorine, raw water pH, and temperature seem to have been the major causes for formation of these by-products. Bonnyville, Fort Chipewyan, Vilna, and St. Michael waterworks had lower levels of THMs and HAAs. THMs and HAAs concentrations were higher in the summer months and consistently increased within the distribution system. Regression analysis and back propagation neural network analysis were performed to correlate THM levels for both raw and treated water quality parameters with the combined facility data. The developed models need to be recalibrated. Strong correlation between THMs and HAAs has been observed. Chlorine overdosing should be checked for minimizing high levels of THMs and HAAs. Jar test is also recommended for optimizing coagulation. Other cost effective control measures for small water treatment plants are also highlighted.

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List of Abbreviation

ANN	Artificial Neural Network
AOPs	Advance Oxidation Processes
AOX	Adsorbable Organic Halides
BAC	Biologically Activated Carbon
BAT	Best Available Technology
BDCM	Bromodichloromethane
BPNN	Back Propagation Neural Network
cm^{-1}	per centimeter, unit of length
°C	degree centigrade, unit of temperature
CDBP	Chlorinated Disinfection Byproducts
$CHCl_3$	chemical formula of Chloroform
ClO_2	chemical formula of Chlorine dioxide
COHC	2-chloro-5-oxo-3-hexene diacyl chloride
CT	mathematical product of disinfectant residual (C) and contact time (T)
DAF	Dissolved Air Floatation
DBP	Disinfection Byproduct
DBPFP	Disinfection Byproduct Formation Potential
DCAA	Dichloroacetic Acid
D/DBP	Disinfection/Disinfection Byproducts
DMA	Dimethyle Amine
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter

GAC	Granular Activated Carbon
GC	Gas Chromatography
GCDWQ	Guideline for Canadian Drinking Water Quality
FBT	Fluidized Bed Treatment
FP	Formation Potential
HAAs	Haloacetic acids
HAAFP	Haloacetic acids Formation Potential
H_2O_2/UV	Hydrogen Peroxide and Ultraviolet Oxidation
HOBr	chemical formula of Hypobromous Acid
HOCl	chemical formula of Hypochlorous Acid
ICR	Information Collection Rule
L/mg-m	liter per milligram-meter, unit of specific ultraviolet absorbance
m^3	cubic meter, unit of volume
MAC	Maximum Acceptable Concentration
MCL	Maximum Contaminant Level
MIEX	Magnetic Ion Exchange
MIEX (R)	Magnetic Ion Exchange Resin
mg/L	milligram per liter, mass per volume
μg/L	microgram per liter, mass per volume
MX	3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone
NDMA	*N*-Nitrosodimethylamine
NDEA	*N*-Nitrosodiethylamine
NF	Nanofiltration

ng/L	nanogram per leter, mass per volume
nm	nanometer, unit of length
NOM	Natural Organic Matter
O_3	chemical formula of Ozone
O_3/UV	Ozone and Ultraviolet Oxidation
OH^-	Chemical formula of Hydroxyl Ion
OCl^-	Chemical formula of Hypochloride Ion
PAC	Powdered Activated Carbon
RO	Reverse Osmosis
SGMWW	Standards and Guidelines for Municipal Waterworks Wastewater and Storm Drainage Systems
SOM	Self Organizing Map
SUVA	Specific Ultraviolet Adsorbance
TCAA	Trichloroacetic Acid
TCU	True Color Unit
TDS	Total Dissolved Solids
TDP	Total Dissolved Phosphorus
THM	Trihalomethane
THMFP	Trihalomethane Formation potential
TTHMs	Total Trihalomethanes
TOC	Total Organic Carbon
TOX	Total Organic Halide
TOXFP	Total Organic Halide Formation Potential

TP	Total Phosphorus
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
UV_{254}	UV absorbance at 254 nm
UV/TiO_2	UV radiation with TiO_2 as Catalyst
WHO	World Health Organization
WTPs	Water Treatment Plants

Chapter 1: Introduction

1.1 Background

Conventional drinking water treatment processes normally include coagulation, flocculation, sedimentation, filtration, and disinfection. Coagulation destabilizes colloidal particles, flocculation agglomerates neutralized particles by chemically joining or bridging them together, and sedimentation and filtration remove these flocs and other neutralized particles, including pathogens (disease-causing microorganisms). Disinfection is the final step, and it serves two main purposes which are to kill or inactivate remaining disease-causing microorganisms as well as to provide a disinfectant residual in finished water in order to prevent microbial re-growth in distribution systems. Disinfection by-products (DBPs) are a group of organic and inorganic compounds that are formed as undesired products during disinfection. Usually these DBPs are formed by the reactions between disinfectants and natural organic matter (NOM) or the inorganic substances present in water. Chlorine is an effective, easy to use and economical disinfectant which has been used in drinking water treatment for many years. Trihalomethanes (THMs) and haloacetic acids (HAAs) are a group of major DBPs that can form in drinking water during or after chlorine disinfection. Numerous epidemiological and toxicological studies of THMs and HAAs have confirmed the adverse health effects upon long term exposure and have classified these THMs and HAAs as probable and possible human carcinogens (Minear and Amy, 1996; Singer, 1999; Xie, 2004). Due to the potential health risks, regulatory values of THMs and HAAs have been set in the drinking water treatment guidelines of most countries. Health Canada (2008) has set the maximum acceptable concentration (MAC) value for THMs at 0.1 mg/L and for HAAs at 0.08 mg/L. Most drinking water treatment facilities in Canada use chlorine as a disinfectant and maintain minimum chlorine residual in the distribution system in order to prevent microbial growth. Hence, the issue of THMs and HAAs formation in chlorinated drinking water has raised concern in terms of both guideline requirements and public health. Alberta Environment has adopted the new THMs and HAAs limits and the existing water treatment facilities are now required to meet the new limits within five years from the dates that the limits were first posted. Inevitably, it should be noted, as tighter and increasingly numerous regulations to enhance public health protection take effect, the cost of providing safe drinking water in compliance with the updated regulations will increase.

1.2 Problem Statement

A number of drinking water facilities in the Northern Region of Alberta Environment's jurisdiction either have shown levels of THMs above the maximum acceptable concentration (MAC) of Guidelines for Canadian Drinking Water Quality (0.1 mg/L) or have a high potential for THMs formation. In order to meet the new THMs and HAAs restrictions and provide safe drinking water, some innovative and cost-effective control strategies of THMs for different types of water treatment facilities are in need of development in the province of Alberta before water treatment facilities can undertake intensive upgrades.

1.3 Objectives of the study

Monthly THM (chloroform, bromodichloromethane, dibromochloromethane and bromoform) & HAA (monochloro, dichloro and trichloroacetic acid, bromochloroacetic acid, monobromo and dibromoacetic acid) concentrations with pH, temperature, dissolved organic carbon (DOC), color, UV, chlorine (Cl_2) dose and chlorine residual data (free and total chlorine) have been collected at eight small waterworks (less than 10,000 service population, using different raw water and chlorine disinfection) in a short-term monitoring program developed by Alberta Environment as a proactive strategy. The present research is based on the collected database. The objectives of this work are:

- to understand the causes for the formation of THMs and HAAs at these eight small facilities in Northern Alberta;
- to develop correlations (if any) between the water quality parameters and THMs as well as HAAs formation at those eight facilities; and
- to suggest some cost-effective control strategies for these facilities, based on the analyzed results, in order to minimize THMs and HAAs.

1.4 Thesis Organization

The body of the thesis is organized into five chapters, with the contents of chapters 2-5 outlined below:

Chapter 2 (Literature Review) includes a summary of occurrences of chlorinated by-products, including their health effects, regulatory requirements, causes of formation and modeling, and the available control strategies for THMs and HAAs, all based on a review of published journal papers, conference papers, and books. Previous THMs and HAAs studies having been conducted in Canada are also described.

Chapter 3 (Materials and Methods) introduces the monitoring program, the obtained materials (data) for this research, and the methodology used to retrieve the data from the databases and input it for further analysis. The methods applied for analyzing the data are also presented in this chapter.

Chapter 4 (Results and Discussions) describes the water quality of the facilities, the overall picture of THMs and HAAs in treatment plants and within distribution systems, and the relationship between water quality and the treatment efficiency of individual facilities. Models describing the relationships of THMs and HAAs with water quality parameters have been developed and THMs and HAAs control strategies are proposed based on the formation factors from the analyzed results. This chapter also includes the average bromodichloromethane (BDCM) analysis and speciation analysis of THMs and HAAs for the eight facilities.

Chapter 5 (Conclusions and Recommendations) briefly summarizes this research work and outlines the research contributions and limitations of the study. The chapter also recommends several research directions which would merit further investigation to broaden the outcomes of this research.

Chapter 2: Literature Review

2.1 Disinfection By-Products

The sources of contaminants in ground and surface water are the natural substances leaching from soil, run-off from agricultural activities, discharges from sewage treatment/industrial plants and hazardous chemicals from landfill sites (Singer, 1999). The purpose of drinking water treatment is to remove pathogens, toxic chemicals, and aesthetic contaminants from raw water. A conventional water treatment system usually includes coagulation, flocculation, sedimentation, filtration, and disinfection. The final step, disinfection, serves two main purposes: the first is to kill or inactivate disease-causing microorganisms (bacteria, viruses, and protozoa) and the second is to provide a disinfectant residual in finished water in order to prevent microbial re-growth in distribution systems. Although the majority of pathogens are removed in the preceding steps, disinfection is a critical measure to avert the outbreak of waterborne diseases.

Disinfectant residual concentration (C) and contact time (T) are the two most important design criteria for chemical disinfection. The effectiveness of disinfection is related to the product of the disinfectant residual and the contact time, or CT (C times T) value, for a given disinfectant. For a given log-reduction objective, the required CT value is also affected by temperature and pH. To achieve the same disinfection efficiency, water plant operators could use a lower disinfectant residual and longer contact time, or a higher disinfectant residual and shorter contact time, as long as the product or CT value is maintained (Xie, 2004). Common disinfectants used in drinking water treatment are chlorine, chloramines, ozone, chlorine dioxide, and ultraviolet radiation. DBPs are the group of organic and inorganic compounds that are formed as undesired products during water disinfection. Based on the formation and chemical properties, these DBPs may be categorized into the following groups.

2.1.1 Trihalomethanes

In 1972, Rook first reported the occurrence of trichloromethane or chloroform from chlorinated water sample analysis (Singer, 1999). Following this discovery, numerous studies established the presence of chloroform in chlorinated drinking water all over the world (Trussell and Trussell, 1980). THMs were traced and usually found to have formed in chlorinated water due to a complex reaction between chlorine and natural organic matter (NOM) present in water (Rook, 1976; 1977). The total trihalomethane (TTHM) value is calculated as the arithmetic sum of the individual mass concentrations of the four most common THMs: trichloromethane (chloroform), bromodichloromethane, chlorodibromomethane and tribromomethane (bromoform). Chloroform is the principal DBP in chlorinated drinking water (Lebel and Williams, 1995). The formation of brominated THMs is caused by the presence of bromine in chlorinated water. The rate and degree of THM formation increase as a function of the chlorine and humic acid concentration, temperature, pH, and bromide ion concentration. These four THMs are liquids at room temperature and are relatively to extremely volatile, with vapour pressures at 25°C. THMs are only slightly soluble in water, with a solubility rate of less than 1 mg/mL at 25°C (Health Canada, 2006).

There are three approved analytical methods for THMs (Xie, 2004): EPA Methods 502.2, 524.2, and 551.1. Both EPA methods 502.2 and 524.2, use purge-and-trap method for sample concentration and gas-chromotography (GC) for sample analysis. For THM detection, EPA Method 502.2 uses photoionization and electrolytic conductivity detectors in series while EPA Method 524.2 uses a mass spectrometer. Both methods can be used for many other regulated and unregulated volatile organic chemicals. EPA Method 551.1 uses micro liquid-liquid extraction with methyl tert-butyl ether (MTBE), GC separation, and electron capture detection. Three analytical methods for THMs are listed in Standard Methods. These are Standard Methods 6232B, 6232C, and 6232D. Standard Method 6232B is a liquid-liquid extraction gas chromatographic method which specifies pentane as the extraction solvent and uses an electron capture detector for detection. This method is similar to EPA Method 551.1. Standard Method 6232C is a purge and trap GC/mass spectrometric method, which is almost identical to EPA Method 524.2. Standard Method 6232D is a purge and trap GC method, which is almost identical to EPA Method 502.2. GC/electron capture detection is commonly used for sample analysis (Singer, 1999; Xie, 2004).

2.1.2 Haloacetic Acids

Haloacetic acids, or HAAs, are another major group of DBPs found in chlorinated drinking water. There are three common groups of haloacetic acids. They are monohaloacetic acids (CH_2XCOOH) with one halogen (X), dihaloacetic acids (CHX_2COOH) with two halogens, and trihaloacetic acids (CX_3COOH) with three halogens. These three different types of HAAs are significantly different in their chemical and biological properties. HAAs are less volatile compared with THMs. The boiling points of HAAs are higher than THMs, and they are also acidic and dissociate in water (Health Canada, 2006). Method development for the detection of HAAs trails behind that of THMs. The relatively nonvolatile and hydrophilic properties of HAAs make purge trap, headspace, and liquid-liquid extraction methods less effective for HAA separation, especially at the natural pH level. In addition, these acids cannot be easily separated or detected by GC/electron capture detection. For GC/electron capture detection analysis, these acids need to be chemically converted into their methyl esters, or methylated HAAs (Xie, 2004).

The three approved methods by USEPA for HAAs detection are EPA Methods 552.1, 552.2, and Standard Method 6251B. All three methods include sample extraction, methylation, and GC/electron capture detection. EPA Method 552.2 and Standard Method 6251B use micro liquid-liquid extraction with MTBE at acidic conditions. Both sodium sulfate and sulfuric acid are added to samples to increase the extraction efficiency. EPA Method 552.1 uses solid phase extraction with ion exchange resins. Standard Method 6251B uses a common methylating reagent, diazomethane, for HAA methylation. Due to its hazardous nature, diazomethane is replaced with acidic methanol in EPA Methods 552.1 and 552.2. A capillary GC/electron capture detection is used in all three methods (Singer, 1999; Xie, 2004).

Three standardized tests are commonly used for evaluating THMs or HAAs. They are the formation potential test, simulated distribution system (SDS) test, and uniform formation conditions (UFC) test (Singer, 1999). These test methods have been optimized to yield specific information since the water quality parameters used in each procedure highly influence the yield and speciation of DBP formation (Xie, 2004).

2.1.3 Inorganic and Organic DBPs

Two inorganic DBPs are currently regulated under the Stage 2 D/DBP (Disinfectant/ Disinfection By-products) Rule in the United States (USEPA, 2006): chlorite (ClO_2^-) and bromate (BrO_3^-). Chlorite is a common DBP found in water treated with chlorine dioxide, which is an alternative oxidant and disinfectant for drinking water treatment. The formation of chlorite is due to the degradation of chlorine dioxide in the presence of NOM or other reducing agents. Bromate is a common DBP found in ozonated water containing bromide. The formation of bromate is due to the ozonation of the bromide ion in water. A study by Von Gunten and Oliveras (1998) has shown that bromate formation during ozonation of bromide-containing waters is due to three general pathways either involving only molecular ozone (direct pathway) or both molecular ozone and hydroxyl radicals produced from ozone decomposition (direct-indirect and indirect-direct pathways). In addition to bromate, ozone also reacts with NOM to form additional organic DBPs. Three common types of these organic DBPs are aldehydes, ketoacids, and carboxylic acids (Xie, 2004).

2.1.4 Other halogenated DBPs

In addition to the DBPs mentioned above, many other organic halogenated DBPs have been detected as a result of different disinfection techniques. These DBPs mainly include trihaloacetaldehydes, haloacetonitriles, haloacetones, trihalonitromethane, and cyanogens halides (Xie, 2004). These DBPs are not regulated in the Stage 1 D/DBP rule, and many of these DBPs could lead to the formation of THMs and HAAs through various reactions. MX is one such DBP. MX, or mutagen X, is a chlorination disinfection by-product that forms from the reaction of chlorine and humic acids in raw water. The chemical name of MX is 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone. MX has been measured in drinking water samples in several countries at levels that ranged from non-detectable to 310 ng/L (McDonald and Komulainen, 2005). A study also suggested a possible new disinfection by-product, 2-chloro-5-oxo-3-hexene diacyl chloride (COHC), formed during the formation of MX by chlorination (Zou et al., 2002).

2.1.5 *N*-Nitrosodimethylamine (NDMA)

N-Nitrosodimethylamine (NDMA) is a non-halogenated DBP associated with chloramination, and is an alternative disinfectant. NDMA has been found in a recent study to have a drinking water unit risk two to three orders of magnitude greater than currently regulated THMs and HAAs (Charrois and Hrudey, 2007). Another study has shown that NDMA can be directly formed by the reaction of monochloramine with di-methyl amine (Choi and Valentine, 2001). Andrzejewski et al. (2005) have suggested that the reaction in water between di-methyl amine and chlorine leads to the formation of NDMA as one of many by-products. The results have indicated that the usage of both chlorine and chlorine dioxide leads to the formation of NDMA but reactions with ozone do not lead to the formation of NDMA.

2.2 Health Effects of DBPs

Numerous epidemiological studies have been conducted to investigate the potential health risks of chlorinated or chloraminated waters. Many of these studies have indicated an association between water chlorination and bladder and rectal cancers. Long term human exposure to different types of chlorination disinfection by-products has been linked to an increased risk of adult leukemia (Kasim et al., 2006). Association between THMs and spontaneous abortion, low birth weight, and birth defects have also been reported (Singer, 1999; Xie, 2004). A series of toxicity studies on rabbits and rats have been conducted to confirm that HAAs, especially dichloro-, dibromo-, and bromochloroacetic acids, have a major impact on metabolism and reproductive functionalities of mammals (George et al., 2000; Klinefelter et al., 2000; Veeramachaneni et al., 2000; Bodensteiner et al., 2001). Some species of halogenated DBPs are considered as potentially carcinogenic in laboratory animals and are probably carcinogenic to humans (Bove et al., 1995; Cantor et al., 1998; Kallen and Robert, 2000). MX has been confirmed as carcinogenic (McDonald and Komulainen, 2005), and bromate has also been declared a potential carcinogen (Kurokawa et al., 1990). Nitrosoamines, mainly *N*-nitrosodimethylamine (NDMA) and *N*-nitrosodiethylamine (NDEA), are also suspected of carcinogenic activity in the human body (Andrzejewski et al., 2005). Under the classification of 1986 USEPA Weight-of-the-Evidence Categories, based on sufficient evidence in animals and inadequate evidence in humans, chloroform, bromodichloromethane, bromoform, dichloroacetic acid, and bromate have been placed in Group B2 as probable human carcinogens. Based on limited evidence in animals in the absence of human data, dibromochloromethane, trichloroacetic acid, and chloral hydrate (trichloroacetaldehyde) have been placed in Group C as possible human carcinogens (Singer, 1999; Xie, 2004).

2.3 Regulatory Requirement

A guideline value represents the concentration of an element that does not result in any significant risk to the health of the consumer over a lifetime of consumption. Considering the long term health effects of these DBPs, USEPA in 1979 promulgated regulatory limits on maximum contaminant levels (MCLs) of THMs as 100 μg/L in potable water and in 1998 further lowered the MCL to 80 μg/L (Pontius, 1999). The Stage 2 D/DBP rule has set the value for Total Trihalomethanes as 0.08 mg/L and for HAAs (5) as 0.06 mg/L. Regulatory guidelines for bromate as 0.01 mg/L, bromodichloromethane as 0.016 mg/L, and TTHMs as 0.100 mg/L have been set by Health Canada (2006). More recently, Health Canada has established the regulatory values of chlorite (1 mg/L), chlorate (1 mg/L) and HAAs (0.08 mg/L) (Health Canada, 2008). WHO (2006) guideline values of THMs are 0.3 mg/L for chloroform, 0.1 mg/L for bromoform, 0.06mg/L for bromodichloromethae, 0.1 mg/L for dibromochloromethane, and, among HAAs, 0.2 mg/L for trichloroacetic acids and 0.05 mg/L for dichloroacetic acids.

2.4 Formation Mechanism

Due to the complexity of the chemistry behind DBP formation and the uncertain chemical structure of aquatic humic substances, well-defined model precursors have been studied. Figure 2.1 shows the generalized conceptual model for the formation of the major organic halide products from fulvic acids. In this model, Reckhow and Singer (1985) considered fulvic acids as polyfunctional unsaturated organic molecules with both aliphatic and aromatic components (Singer, 1999). Highly activated compounds contain ß-diketone moieties (oxygenated functional group) which can be readily oxidized by chlorine. Hydrolysis then occurs rapidly and yields a monoketone group. Depending on the remaining 'R' group, the reaction will yield either dichloroacetic acid or trichloromethyle species. At a neutral pH, if the 'R' group is an oxidizable functional group capable of readily donating an electron pair to the rest of the molecule, trichloroacetic acid will form. In the absence of such oxidative cleavage, hydrolysis will prevail, yielding chloroform (Singer, 1999).

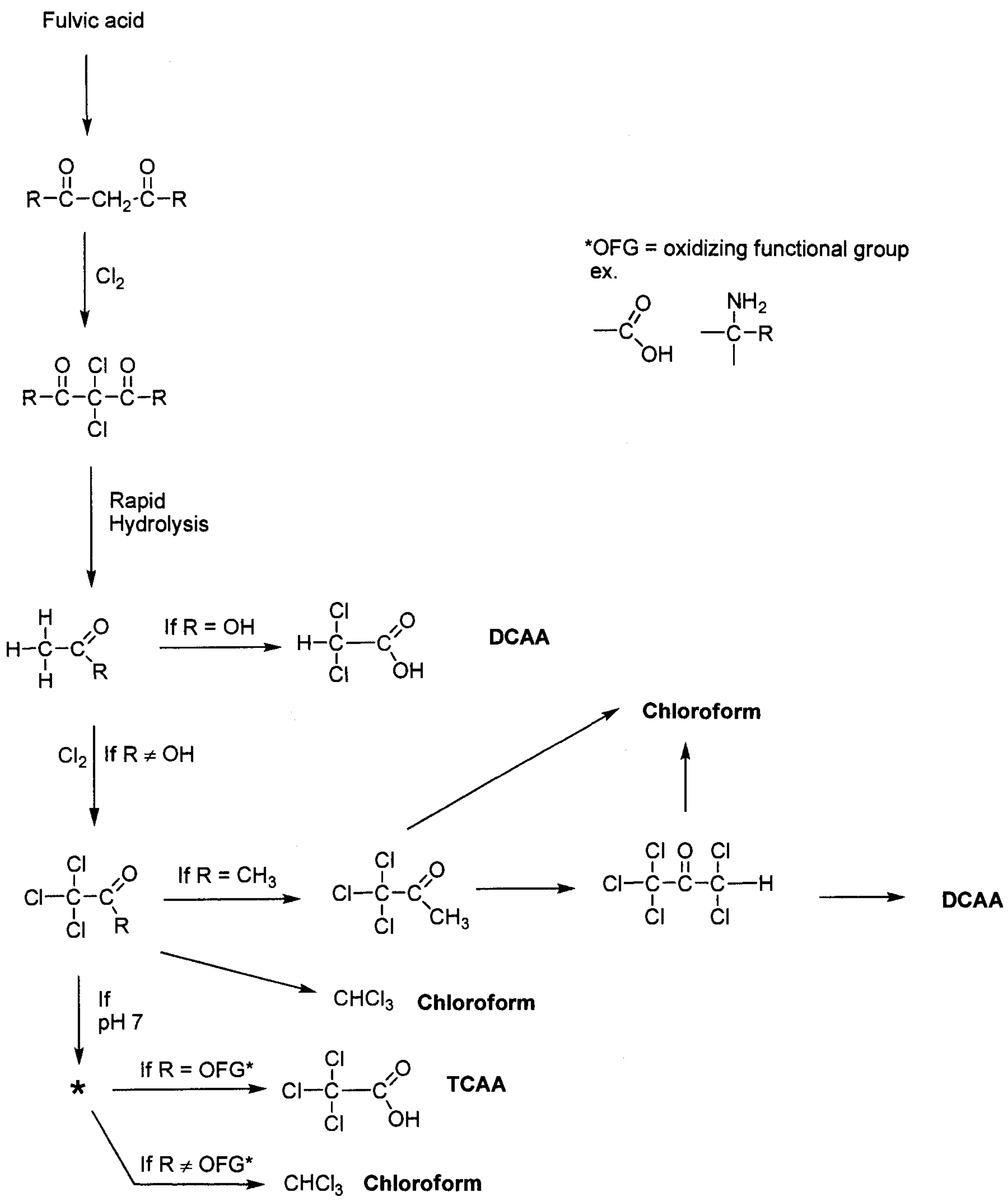


Figure 2.1: Generalized conceptual model for the formation of major organic halide products from fulvic acids

(Adapted from Reckhow and Singer, 1985)

DCAA- Dichloroacetic acid; TCAA- Trichloroacetic acid

2.5 Formation of DBPs

Formation of THMs dominates during the treatment stage at the drinking water treatment plant as a function of the raw water quality and the treatment technology used. Significant formation may then continue in the effluent water within the distribution system, an occurrence which is mainly a function of the effluent water quality, initial chlorine concentration, and reaction time. The formation of DBPs in drinking water is generally caused by the reaction between NOMs and chlorine or other disinfectants. The speciation and concentration of DBPs in water are affected by many water quality parameters and operating conditions, including natural organic matter, chlorine residual, reaction time, concentration of bromine, temperature, and pH.

2.5.1 Effect of Natural Organic Matter (NOM)

Natural organic matters are a mixture of chemicals found commonly in the environment. NOMs are composed of two main classes of compounds: humic and non-humic material (Owen et al., 1995). The humic portion represents the majority of the NOMs and is operationally defined as a combination of fulvic acid, humic acid, and humin. The non-humic material includes other organic substances such as proteins, carbohydrates, and small organic acids. NOMs can be separated into several fractions, including humic acids, fulvic acids, hydrophobic acids, hydrophobic neutrals, hydrophilic acids, hydrophilic neutrals, etc (Singer, 1999; Xie, 2004). NOM levels generally are measured as total organic carbon (TOC) or dissolved organic carbon (DOC). UV absorbance by NOM is due to the one or more functional groups containing unsaturated bonds. A strong correlation between UV absorbance and the aromatic content of NOMs has been reported for humic and fulvic acids extracted from various water sources (Chin et al., 1994). UV absorbance measured at 254 nm (UV_{254}) can be used as a surrogate parameter to monitor overall NOM concentration and trihalomethane formation potential (THMFP) (Chin et al., 1994; Owen et al., 1995). The specific ultraviolet absorbance (SUVA) of water—which is defined as the UV absorbance (measured in cm^{-1}), times 100, and divided by the DOC concentration (mg/L)—has been found to be a good surrogate for the water's humic content (Owen et al., 1995; Krasner et al., 1996; Singer, 1999). Water containing higher SUVA indicates higher humic contents and higher THMFP (Krasner et al., 1996; Singer, 1999). The higher the SUVA, the higher the content of humic substances and the easier will be the removal of NOM by coagulation (Liang and Singer, 2003; Xie, 2004). HAA precursors have a higher aromatic content than THM precursors (Lian and Singer, 2003). Wei et al. (2008), for instance, found that the more hydrophobic the chemical fraction, the higher the SUVA value, and larger molecular sizes were found to correspond to a higher SUVA. However, the researchers did not identify a strong correlation between specific THMFP and SUVA in their experiment.

In drinking water, NOM may be responsible for color, taste, and odor problems and can encourage microbial growth and increase chlorine demand in water. In particular, NOMs concentration and characteristics significantly affect the formation of DBPs. Reckhow and Singer (1990) hypothesized that higher molecular weight would preferably lead to the formation of TCAA over chloroform. A conjugate double-bond of aromatic origin will produce a higher fraction of THMs while a conjugate double-bond of aliphatic nature may produce a greater amount of TCAA. Owen et al. (1995)

showed that coagulants especially likely to remove higher-molecular-weight fractions of NOM; ozone, however, may convert humic to non-humic material within the NOM fraction, and this content may be difficult to remove by subsequent coagulation. According to Marhaba and Van (2000), the hydrophilic acid fraction is the most reactive precursor to THM formation while the hydrophobic neutral fraction has been found to be the major precursor to HAA formation.

Liang and Singer (2003) found that hydrophobic fractions rendered higher HAAs and THMs formation potentials than their corresponding hydrophilic fractions, but hydrophilic carbon played an important role in disinfection by-product formation for waters with low humic content. Hydrophilic neutral and hydrophobic acid are the main organic components in raw water and the most important contributors of THM formation potential (THMFP) (Panyapinyopol et al., 2005). Kim and Yu (2005) have shown that the formation potential of THMs is highly influenced by the hydrophobic fraction, whereas HAA formation potential (HAAFP) depends more on the hydrophilic fraction. Some recent studies have also shown that the hydrophilic fraction influences HAAs formation (Uyak et al., 2008). The molecular weight and size of the NOM fraction and the functional group play important roles in the overall reactivity with chlorine and thus with DBP formation.

Elemental analysis of NOM shows that it includes carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and ash content. These are reported as percent weight (%) and sometimes as ratios, i.e., O/C ratio (polarity of NOM), H/C ratio (saturation of NOM) and N/C ratio (origin of NOM) (Minear and Amy, 1996). In water containing bromine, in general, a low level of NOM results in a higher percentage of the brominated DBPs than that for a high level of NOM. This is due to the fact that a higher NOM level requires a higher chlorine dose, which results in a lower ratio between bromine and chlorine (Xie, 2004).

2.5.2 Effect of Chlorine Dose

For chlorination, chlorine dosage is the key factor in DBP formation. Some DBPs are intermediate products of chlorination reaction while others are end-products. If the DBP is an end-product, then increasing the chlorine dose will increase the formation of the DBP. However, if the DBP is an intermediate product, then increasing the chlorine dose may decrease the formation of the DBP. These intermediate products can be further oxidized by chlorine into end-products. In fact, increasing the chlorine dose increases the formation of THMs, HAAs, and many other chlorinated DBPs that are typical end-products (Symons et al., 1993; Singer, 1999; Xie, 2004). Many researchers have found chlorine dose to be the most important factor in the formation of THMs.

2.5.3 Effect of Chlorination Time

Many DBPs are formed by a series of reactions. If the DBP is an end-product, then increasing the reaction time will increase the formation of the DBP. However, if the DBP is an intermediate product, increasing the reaction time may decrease the formation of the DBP, especially for high chlorine doses. Some DBPs, including trihalopropanones, trihaloacetaldehydes, and trihalonitromethanes, undergo hydrolysis reactions. Increasing the reaction time, especially after chlorine and/or DBP precursors are exhausted, will benefit the hydrolysis reaction and reduce the concentration for these DBPs. Since THMs are typical hydrolysis products and chlorination end-products, the formation of THMs is generally increased by increasing the reaction time. Formation of DBPs often proceeds in two steps: an initial rapid stage within a few minutes to hour and a slower stage with nearly linear kinetics. Zou et al. (1997) found that about 55% to 75% of the one-day total organic halide formation potential (TOXFP) was produced within 30 minutes and 85% to 90% was produced within 2 hours.

2.5.4 Effect of pH

The addition of chlorine to water leads to the formation of hypochlorous acid (HOCl) and hypochloride ions ($OC1^-$), and the formation of these two species depends on the pH. The hypochloride ion is the dominant species of free chlorine for pH levels above 7.5 and is less reactive with NOM than with hypochlorous acid. The degree of protonation of NOM molecules also depends on the pH. As such, the formation of DBPs is expected to be influenced by pH. Generally, an increase in pH leads to an increase in chloroform formation and a decrease in HAA formation (Stevens et al., 1989; Reckhow and Singer, 1990; Nieminski et al., 1993; Rathbun, 1996). The oxidation potential is decreased when the pH is increased. Therefore, as a substitution product, chloroform dominates while TCAA (oxidation products) subordinates. Baum and Morris (1978) found that the chlorine demand was lower in alkaline solutions than in acidic or neutral solutions, and yet increased chloroform formation occurred in alkaline solutions. In fact, THMs increase as the pH is alkalized, due to the fact that both chloroform formation and the reaction rate increase as the concentration of hydroxyl ion (OH^-) in the solution increases; meanwhile, the solubility of humic acid increases and it has a broad molecule surface in a water solution. The effect of pH on the formation of HAAs is more complicated. According to Stevens et al. (1989) TCAA formation in chlorinated waters is higher at a lower pH, whereas DCAA formation is not as much affected by pH. The authors showed that at pH 5 and pH 7, TCAA formed in a similar manner whereas at pH 9.4 it was greatly reduced, and DCAA was formed mainly in alkaline conditions. In general, low pH water favors the formation of HAAs, trihaloacetaldehydes, trihalopropanones, and cyanogen halides. Kim et al. (2003) showed that DBPFP was the highest at pH 7.0 and increased with the reaction time of chlorination. Liang and Singer (2003) found that increasing the pH from 6 to 8 increased THM formation, decreased trihaloacetic acid formation, and had little effect on dihaloacetic acid formation. More THMs were formed than HAAs at pH 8, while the reverse was true at pH 6.

2.5.5 Effect of Temperature

Numerous researchers have found, while studying the effect on temperature within a low to high range, that increases in temperature are associated with increased THM formation. Oliver and Shindler (1980) found that increases in temperature from 2 to 20°C increased chloroform formation from fulvic acid. They also found that after free chlorine had been quenched, chloroform was still continuously increased as the temperature increased. This suggested that the intermediate products of THM are present following the reaction of chlorine with humic substances. Amy et al. (1987) observed that, at short reaction times, the temperature effects on THM formation are apparent. THM levels were found to be higher in summer than in winter and increased in the distribution system with increasing distance from the plant (Fayad et al., 1993; Rodriguez et al., 2004, 2007). While levels of HAAs and other DBPs were usually higher in summer than in winter, their levels did not increase consistently within the distribution system (LeBel et al., 1997). Another study demonstrated that DBP levels fluctuated as a function of water treatment practice and the age and temperature of the water. During summer, higher organic content in lakes and rivers leads to a higher rate of formation of DBPs, and the rate of formation of DBPs increases at higher temperatures.

2.5.6 Effect of Bromine Concentration

Concentrations of bromine can impact the speciation of chlorinated disinfection by-product (CDBP) species as well as the formation of DBPs (Pourmoghaddas et al., 1993; Symons et al., 1993; Huang and Yeh, 1997; Nokes et al., 1999). Bromine can be oxidized by chlorine or ozone to either hypobromous acid or hypobromite depending on the pH. Like hypochlorous acid and hypochlorite, both hypobromous acid and hypobromite react with NOM to form brominated DBPs. In general, bromine is much more reactive to NOM than is chlorine. Since bromine will occupy the site for chlorine substitution, the formation of chlorinated species will be reduced. The mass of bromine (with an atomic weight of 80) is much heavier than chlorine (with an atomic weight of 35.5); the mg/L concentration of the correlated bromoform will be twice that for chloroform. Therefore, at similar chlorination conditions, increasing bromide could significantly increase the mass concentration of THMs. An increase in bromine levels also reduces the formation of chlorinated HAAs and increases the formation of brominated HAAs (Xie, 2004). Moreover, water utilities need to monitor for bromine levels and must focus careful attention on evaluating their point of chlorination.

2.5.7 Effect of Other Factors

Chen and Weisel (1998) have demonstrated that THMs increase with increasing residence time in the distribution system, while HAAs concentrations decrease with increasing residence time in the distribution system. Concentrations have been found to change more rapidly in warm months than in cold months. The researchers found that chlorine residuals and temperature were the most important parameters affecting DBP formation. Biological degradation of HAAs might be the reason for its decreasing within the distribution system. Many studies have in fact confirmed this phenomenon (Singer and Bilyk, 2002; Rodriguez et al., 2004; 2007; Baribeau et al., 2005; Speight and Singer, 2005). Degradation of HAAs species occurs in full-scale distribution systems due to biodegradation by microorganisms present in the pipes. Chemical decomposition may also play an important role in trihaloacetic acid species degradation. Furthermore, temperature and chlorine residual loss may affect the conditions for chlorine decay and biological activity (Speight and Singer, 2005). This phenomenon, it should be noted, is site-specific.

The influence of heating or boiling on the formation and behavior of DBPs has also been investigated, and it has been found that thermal cleavage of larger halogenated species may lead to the formation of THMs and HAAs (Wu et al., 2001). The effect of indoor tap water handling has also been examined, and it has been found that THMs may be removed through boiling and storage while HAAs can be removed only by boiling (Leuesque et al., 2006). McQuarrie and Carlson (2003) investigated the potential for biological processes during aquifer storage to reduce DBP and DBP precursors under controlled conditions. They found that aquifer storage of chlorinated finished water resulted in a 44% reduction in TTHM formation in their experiments. They concluded that the sequencing of chlorination or ozonation with respect to aquifer storage and recovery operations can impact DBP formation. The influence of sunlight, pH, and time on DBPs in drinking water has also been studied (Lekkas and Nikolaou, 2004). The researchers found that most of the volatile DBPs decreased with increasing pH, both in sunlight and in darkness, while HAAs remained unaffected by pH. They also showed that HAAs were influenced by sunlight to a significantly greater extent than volatile DBPs. Another study suggested that the organic precursor material associated with the deposits in the pipe wall of the distribution system may increase the level of THMs in water (Rossman et al., 2001). Semerijan et al. (2007) observed that THMs concentrations were higher when the raw water sources were surface waters compared to groundwater sources.

2.5.8 Other DBPs Formation

For the formation of NDMA during chloramination, a study has indicated that the concentration of NDMA is closely related to the ratios of chlorine, ammonium ions, and dimethyle amine (DMA) present in the water and the maximum concentration of NDMA is formed at pH levels of 7 to 8 (Andrzejewski et al., 2005). Chang et al. (2000) investigated the formation of DBPs in water treated with chlorine dioxide with humic acid as the organic precursor in a natural aquatic environment. The results indicated that the primary DBPs formed were THMs and HAAs, with chlorite ions as the primary inorganic by-product. The distribution of the individual species was a function of the bromide content. With higher chlorine dioxide doses, the amount of DBPs produced was reduced while the amount of DBPs increased along with reaction time. A study showed that bromate formation during ozonation was favored at high pH levels, high initial bromide concentrations, high ozone dosages, but low DOC and ammonia levels (Huang et al., 2003). On the other hand, organic by-products, *e.g.*, aldehydes and carboxylic acids, were favored at low pH levels, high bromide levels, and high O_3/DOC ratios.

2.6 Modeling of THMs and HAAs

Due to the complex nature of DBP precursors and their corresponding reactions with disinfectants, models for quantification of DBPs have largely been developed using empirical approaches. These modeling approaches involve statistical analysis of data derived from controlled laboratory or field experiments to develop functional relationships in order to predict the concentration of DBPs based on water quality and reaction conditions. A series of studies have coalesced around the monitoring and modeling of the formation of two significant CDBPs, THMs, and HAAs. A number of different modeling approaches have been found to be used for the prediction of CDBP. Regression analysis and artificial neural network (ANN) modeling are the most frequently used approaches (GarciaVillanova et al., 1997; Vikesland et al., 2001). The correlation between different parameters (pH, chlorine dose, TOC, residence time) and the formation of CDBPs can be found using these modeling approaches.

Canale et al. (1997) developed a mathematical model to estimate THMFP in Lake Youngs, Washington. The model simulated both seasonal trends and spatial variations. The model kinetic framework included TOC, THMFP, chlorophyll a, zooplankton, Secchi disk depth, dissolved oxygen, total dissolved phosphorus (TDP), and total phosphorus (TP). In a similar study, GarciaVillanova et al. (1997) conducted a study to determine the THMs of drinking water in Spain. They observed that data were correlated statistically with the chlorination dosages in the treatment plants and the distribution system, the distances run by the water, free chlorine residual and total chlorine, TOC, pH, and temperature. They also observed a positive correlation between TOC with a consumption of chlorine residuals, and found that chlorine residual was inversely proportional to the content in THMs; meanwhile, temperature with pH showed the strongest influence on THMs formation. Gang et al. (2002) developed a simple mechanistic model to predict TTHMs and the sum of nine HAAs' formations based on chlorine demand. Their model was suggested to be readily calibrated to local conditions. Abdullah et al. (2003) developed some linear and non-linear models for predicting THMs in Malaysian drinking water. Positive correlations of THMs were found with TOC, chlorine dose, and distance from the treatment plant using a Pearson correlation method. The non-linear model was slightly better than the linear model in terms of percentage prediction errors. The models developed were site-specific and the predictive capabilities in the distribution systems varied according to the given environmental conditions.

Espigares et al. (2003) observed from their developed models that levels of THMs in water correlate directly with levels of combined residual chlorine and nitrates, and inversely with the level of free residual chlorine. Al-Omari et al. (2004) developed two mathematical models for expressing TTHM concentration in terms of initial chlorine concentration, total organic carbon, bromide ion concentration, contact time, and pH for the Zai water treatment plant in Jordan: one for a constant temperature of 20°C and another to express TTHM growth rate as a function of varying temperatures. Nikolaou et al. (2004) found a lower correlation coefficient in their developed models. They suggested that the different water quality characteristics of two sources of water (river) in their particular study were responsible for this phenomenon. They concluded that the formation of THMs and HAAs in water might be difficult to be described by means of conventional regression techniques.

ANN has been used widely to describe and model water treatment processes in the past few years. These networks do not require programming, logical inference schemes, statistical algorithms, or any detailed knowledge of the kinetics of the system to be modeled, as would be the case with most conventional computing systems. ANNs are capable of learning the pattern of examples from representative data that describe a physical phenomenon or a decision process, and can develop the ability to correctly classify new data. Application of ANN for predicting THMs has been studied extensively (Milot et al., 2002; Lewin et al., 2004, Rodriguez and Serodes, 2004). It can be useful for early detection of potentially high THM concentrations in finished water and gives plant operators enough advanced warning to reduce THM precursors. Lewin et al. (2004) demonstrated the application of artificial neural network techniques for predicting the concentration of THMs in finished water in the E.L. Smith water treatment plant, Canada. Three models were derived using raw water, post clarification water, and a combination of raw and post clarification water parameter inputs. The model that most successfully predicted the concentration of THMs in finished water is the model that uses clarifier effluent parameter inputs.

2.7 Treatment/Control

Removal of DBPs, once formed, is difficult to achieve. As such, control of DBP formation is the usual practice in drinking water disinfection. Three basic strategies are used to control DBPs in drinking water: removal of the DBP precursors prior to chlorination, use of alternate disinfectant, and removal of DBPs after formation. A number of studies are reviewed below in order to evaluate the available control technologies for THMs and HAAs.

2.7.1 DBP Precursor Removal

One of the most effective methods of minimizing DBP formation is to maximize its precursor removal. There are various ways to remove these precursors, such as enhanced coagulation, membrane separation, granular activated carbon adsorption, biological treatment, and advanced oxidation process.

2.7.1.1 Enhanced Coagulation

The enhanced coagulation process is defined as an optimized coagulation process for removing DBP precursors, or NOM. In general, this is practiced at a higher coagulant dose and a lower pH. Enhanced coagulation can significantly reduce the NOM level in water. A jar test is required to evaluate enhanced coagulation for removing TOC (Krasner and Amy, 1995). Crozes et al. (1995) conducted bench-scale studies with TOC values ranging from 2 to 11 mg/L and found that ferric chloride was more effective than alum in removing NOM. Pre-adjustment of pH at a value of 6.0 ±0.2

increased NOM overall removal to 65% and reduced the coagulant dose by as much as 60%. Enhanced coagulation led to higher overall operating costs, but pre-adjustment of pH with sulfuric acid reduced costs by lowering the coagulant dosage and sludge production. Jiang and Graham (1996) have discussed the effect of coagulant chemistry on the removal of color-causing NOM, and have suggested that pre-polymerised coagulants can improve NOM and THMFP removals at relatively lower dosages, lower costs, and with a reduction in sludge production.

Vrijenhoek et al. (1998) evaluated the effectiveness of enhanced coagulation for removing particles and THM precursors at various alum dosages and coagulation pH levels. They showed that a more significant amount of THM precursors were removed by enhanced coagulation at pH 5.5 than at the original pH. They suggested that higher doses of alum are needed to remove THM precursors than for particle removal. Pilot-scale experiments were performed by Childress et al. (1999) to investigate the effectiveness of enhanced coagulation in removing THM precursors from surface water. They found that the optimal removal of particles and THM precursors by enhanced coagulation with ferric chloride was obtained at high coagulant doses (>16 mg/L) and low pH conditions. They also suggested that enhanced coagulation was less effective for source water with the lower SUVA. Archer and Singer (2006) conducted an evaluation of the relationship between SUVA and NOM coagulation using the Information Collection Rule database. Their findings demonstrated the ability of SUVA to predict the reactivity of NOM and provide the basis for an alternative enhanced coagulation matrix. Amirtharajah et al. (1993) studied the ferric chloride coagulation of two types of natural dissolved organic matter. They suggested from their study that it is possible to maximize the removal of dissolved organic matter (DOM) and minimize THMs by coagulation only under very specific conditions of pH and ferric chloride doses. Marhaba and Pipada (2000) demonstrated the effectiveness of coagulation in removing DOM fractions.

Jiang and Wang (2003) conducted another study evaluating potassium ferrate as an enhanced coagulant for removing humic substances. They suggested that potassium ferrate can remove UV_{254}, DOC and THMFP better than ferric sulphates at lower doses. Uyak and Toroz (2005) conducted a study to apply enhanced coagulation of DBPs precursors in an Istanbul water supply. They measured DBP surrogate parameters of TOC, UV absorbance, and THMFP, and their jar test results showed an optimum coagulation condition that can increase the removal of DBP precursors using alum and iron salt coagulants with different pH levels.

A number of studies have been done to investigate the treatability of NOM using enhanced coagulation with ion-exchange resin. Bolto et al. (2002) found that alum was not as effective as ion exchange for the elimination of individual ionic NOM fractions, and a combination of coagulation with a cationic polymer and adsorption by an anion exchanger removed all of the NOM. They suggested that the preference of the coagulants was for the larger hydrophobic molecules, and of resins for smaller highly charged hydrophilic molecules. Singer and Bilyk (2002) investigated the effectiveness of a magnetic ion exchange resin (MIEX (R)) to enhance the coagulation of DBP precursors from nine surface waters. They concluded that enhanced coagulation with MIEX (R) removed more than 60% to 90% of THM and

HAA precursors and MIEX pretreatment also lowered the coagulant demand of water.

Boyer and Singer (2005) compared enhanced coagulation with MIEX (R) for removal of NOM and bromide. They found that MIEX treatment reduced the THMFP and HAAFP to a greater extent than coagulation, and that it was most effective in raw waters having a high SUVA and a low anionic strength. Tan et al. (2005) observed that ion exchange resin is more effective in removing higher SUVA-absorbing DOM with higher molecular weights carrying water. Singer et al. (2007) described their pilot plant findings regarding the effectiveness of MIEX removal of DBP precursors. Their result indicated that the resin is very effective in removing DOC and UV-absorbing material except in water that has a high concentration of TDS and a low SUVA.

Singer et al. (2003) evaluated the effectiveness of pre- and intermediate ozonation coupled with enhanced coagulation in reducing DBP precursors in drinking water. Their results showed that the removal of halogenated DBP precursors was more effective when using both pre- and intermediate ozonation coupled with enhanced coagulation than when using enhanced coagulation alone. Both THM and HAA formation were lower in water with pre-ozonation then coagulation than in water that had been coagulated first and then ozonated. Fearing et al. (2004) investigated the removal of NOM by conventional coagulation treatment using both bulk and fractioned NOM. They achieved over 70% removal of the hydrophobic and hydrophilic acid fractions but only 16% removal of the hydrophilic nonacid fraction; and then optimized conditions in their experiments increased removal of hydrophilic fractions. They suggested that staged coagulation could be of benefit in the removal of the recalcitrant fractions. Bob and Walker (2006) examined a number of process modifications to the lime-soda softening process for enhanced NOM removal. Their results provided new approaches for improving DBP precursor removal during lime-soda softening without significantly increasing lime and soda ash dosage or the generation of waste sludge.

2.7.1.2 Membrane Technologies

Numerous studies have been conducted on the use of membranes for DBP control in recent years. Membrane technologies are generally used for groundwater treatment and have been used for surface water treatment since the 1990s with special pre and post treatment (Xie, 2004). Taylor et al. (1987) studied the application of membrane process to groundwater sources for THM precursor control. A pilot study comparing microfiltration (MF), ultrafiltration (UF) and conventional treatment as pretreatment strategies for surface water nanofiltration (NF) has also been conducted (Chellam et al., 1997). The authors have suggested that NF may be capable of meeting THMs and HAAs regulations. Chang et al. (1998) conducted an experimental study including the addition of adsorbents to the feed water of an UF membrane system in order to remove DOC and THMFP. Visvanathan et al. (1998) investigated the effects of interference parameters (operating pressure, feed THMPs concentration, pH, presence of Ca^{2+} and Mg^{2+} and suspended solids) on the performance of NF for the removal of THMPs. Their results showed that pre-compacted membrane has a higher rejection capacity (90%) and higher pressure, feed THMP concentration, while suspended solids increase rejection and the presence of divalent ions serves to reduce the rejection capacity. Mulford et al. (1999) conducted a study of NF performance at three membrane pilot plants using groundwater. These pilot plants showed a good rate of removal of THMFP and HAAFP in finished water.

Chellam (2000) successfully conducted another study to determine THM and HAA precursor removal by NF and found that NF increased the concentrations of brominated THM and HAA species in the permeate because of the low bromide ion removal. Siddiqui et al. (2000) established rejection of disinfection DBP precursors from low-turbidity surface water using a range of NF modules. They observed rejections of DOC, THMFP, HAAFP, and chloral hydrate formation potential by 90%, 97%, 94%, and 86%, respectively. They also found DOC removal rates of less than 30% using UF alone. Removal of NOM from lake water in Croatia by UF and NF has been studied by Mijatovic et al. (2004). A study has suggested that the combined UF-NF membrane processes represent one of the best available methods for removing NOM (Kim and Yu, 2005). Karakulski et al. (2001) investigated the effect of chloroform content in various types of water on the performance of two types of reverse osmosis (RO) composite membranes and found that the presence of chloroform to some extent affects the transport and separation properties of the composite membranes used. Another study confirmed the effectiveness of NF treatment in rejection of DBP precursors from low turbidity surface waters (Siddiqui et al., 2000). Bodzek et al. (2002) investigated pressure-driven membrane (RO, NF and UF) treatment of THM containing water.

Jacangelo et al. (1995) conducted a pilot study to evaluate the efficacy of powdered activated carbon (PAC) as an UF pretreatment for removing DBP precursors. They observed that DBP precursor removal increased with increasing PAC doses. Lin et al. (1999) conducted a study to determine the effect of molecular weight fractions and PAC treatment on UF processes for removing humic substances. They concluded that UF systems were not effective in reducing DBPs because, although the UF system was able to remove a significant portion of THMFP in larger apparent molecular weight fractions, the permeate THM in terms of μg THMs/mg carbon was high in their case. Weber et al. (2005) suggested that molecular reconfiguration of the fulvic acid portion of NOM by catalyst-induced oxidative coupling reactions combined with UF can provide an effective scheme of removal of DBP precursors.

Karnik et al. (2005) conducted a study to evaluate the effects of combined ozonation and filtration on DBP formation. Their result showed a 50% reduction of DOC, an 80% reduction in simulated distribution system trihalomethanes (SDS THMs), and a 65% reduction in SDS HAAs using an ozonation/filtration process. They suggested that reducing the molecular weight cut-off of the membranes can reduce the concentration of both THMs and HAAs. Weng et al. (2006) conducted a study of the application of electro-microfiltration for increasing humic substances removal and decreasing flux decline. Their results showed that, at an applied voltage of 100V, their method was able to reduce UV_{254}, TOC, and THMFP by over 50%. In a recent study, Williams and Pirbazari (2007) investigated membrane bioreactor process for removing biodegradable organic matter and THM precursors from pre-ozonated water. They observed that addition of PAC increased the removal of THM precursors, DOC, and enhanced membrane permeate fluxes, and that pre-ozonation reduced membrane fouling.

2.7.1.3 Granular Activated Carbon (GAC) Adsorption processes

Granular carbon adsorption is also effective in removing NOM. In the early 1980s a number of studies were conducted on the applicability of GAC for removing DBP precursors and controlling DBP formation in drinking water treatment (Glaze et al., 1983; Glaze and Wallace, 1984). After that, Mcguire et al. (1991) evaluated GAC for THM control and concluded that GAC treatment can be expensive for THM control. Sakoda et al. (1991) conducted an experimental study of THM adsorption on activated carbon fibers. They found that the adsorption capacities of activated carbon fibers equal or slightly exceed those of GACs, which were presently being used for THM control in drinking water. Crittenden et al. (1993) conducted a study to determine the performance of GAC in reducing DBPs by removing DOC. Nakamura et al. (2001) examined THM removal by activated carbon fiber from single-component solutions. They found differences in the absorbed amount between THM with bromine and THM with chlorine and explained the differences by the polarity of THM molecules. They concluded that the strength of hydrophobicity of activated carbon fibers dominated the adsorbed amount of THM.

The effects of ozonation, GAC, and biological activated carbon (BAC) in the removal of NOM and DBP precursors from drinking water were studied by Kainulainen et al. (1995) on a pilot scale. Their results showed that ozonation was the best method to reduce concentrations of the precursors of adsorbable organic halides (AOX), chloroform, and mutagenicity; BAC was the most effective in removing organic matter, but chloroform formation potential always increased following GAC filtration. It should be noted that DBP precursors and low-molecular-weight fractions of NOM are poorly absorbable, a condition which can result in a non-proportionally poor removal of DBP precursors.

Collins et al. (1996) conducted a study to enhance NOM removal using filters amended with anionic resin and GAC. A pilot plant study has since been conducted by Vahala et al. (1999) to determine the effect of ozonation and two-step GAC filtration on the removal of DBP precursors. The authors have suggested that the performance of adsorptive GAC filtration is strongly dependent on the age of the GAC filter bed, which, in turn, is strongly correlated with NOM measurements and DBP formation potential. An upgrading of surface water treatment plants in Anglian Water with the installation of GAC and ozone has been demonstrated by Croll (1996). However, it is still necessary to conduct bench scale and/or pilot scale studies for GAC adsorption design and operation (Singer, 1999; Xie, 2004).

2.7.1.4 Biological Treatment (Ozone-BAC Treatment)

BAC can reduce biodegradable DBP precursors through biodegradation. Pre-ozonation converts non biodegradable NOM into biodegradable organics and improve the effectiveness of BAC for DBP precursor removal (Xie, 2004). Shukairy and Summers (1992) have investigated the application of ozonation and biological treatment for controlling DBPs through a bench scale study. They observed that pre-ozonation followed by biotreatment reduced organic halide formation with a reduction of 50% to 80% when chlorine was used, and greater than 90% with chloramines. Price et al. (1993) conducted a pilot plant and full scale study to evaluate the impacts of ozonation followed by biological filtration on the formation of

DBPs at two U.S. locations. Their results indicated that ozonation and biological filtration both can reduce THMFP.

Shukairy et al. (1995) evaluated the effect of bromide concentration, ozone dose and biotreatment on the control of DBPs. They suggested that THMPs were better controlled by ozonation, HAAPs were better controlled by biological treatment, but the combined processes were effective for the control of all halogenated DBP precursors. While evaluating the performance of an ozonation-biological activated carbon process for the removal of DOC and THMFP, Nishijima et al. (1998) showed a 36% rate of DOC removal and a 57% rate of THMFP removal. They did not find any seasonal changes with temperature ranges from 5 to 30°C in their ozonation-BAC process. Chiang et al. (2002) conducted a study to evaluate the effects of the characteristics of NOM on the treatability of ozonation, coagulation, filtration, and GAC. Using UV_{254} as a surrogate parameter, their results indicated that the DBP formation potential varied with the sources of water samples and treatment processes, but was closely related to the measurement of UV_{254}/DOC. They also suggested that pre- and post-ozonation processes could reduce some DBP precursors more effectively than the conventional treatment process and are thus more effective for reducing the overall DBPFP content.

Yavich and Masten (2003) conducted a study to evaluate ozonation in combination with biological fluidized-bed treatment (FBT) for control of THM precursors in drinking water. The study showed that a combined ozonation-FBT process was effective in removing THM precursors and might be a cost-effective and viable alternative to conventional coagulation process that requires O_3-BAC for controlling

DBPs in drinking water. Chen et al. (2007) conducted a two-year-long pilot test comparing water treatment processes (conventional process, conventional plus advanced treatment, pre-oxidation plus conventional process and pre-oxidation plus conventional plus advanced treatment) to enhance organic matter removal. Their results showed that the combination of the conventional process and O_3-BAC provides the best performing treatment for treating polluted source water in China.

2.7.1.5 Advanced Oxidation Processes

An alternative group of technologies that can potentially be used to minimize the formation of DBPs is advanced oxidation processes (AOPs) (Zhou and Smith, 2001). Several studies have been conducted to investigate the treatability of THMs and HAAs using various AOPs. Pilot plant studies looking at the effect of ozonation and UV with direct filtration on DBPs were conducted (Amirsardari et al., 2001)., The authors found that disinfection efficiency was strongly influenced by competition reactions of organic and inorganic compounds with ozone. These advanced pre-oxidation processes resulted in reductions of 90% and 98% of TTHM precursors and total organic halides, respectively. Collivignarelli and Sorlini (2004) conducted an experimental study of the removal of two odorous compounds (geosmin and 2-methylisoborneol) and a pesticide (metolachlor) by advanced oxidation with O_3/UV. Their results showed a medium removal of 20% to 40% for UV_{254} and 15% to 30% for THMFP. Murray and Parsons (2004) conducted a study of the removal of NOMs from drinking water by Fenton's and photo-Fenton's processes. They found that a 90% removal of DOC and UV_{254} could be achieved by both processes, and that both of these processes were dependent on pH.

Chin and Berube (2005) conducted an experimental study to compare the effect of O_3, UV_{254}, and a combined O_3/UV advanced oxidation process to remove THMs and HAAs from raw surface water, and concluded that O_3/UV AOP was more effective than applying O_3 or UV alone; they showed that the combined process can reduce THMFP by 80% and HAAFP by 70% at an ozone dose of 0.62 ±0.019 mg O_3/mL and a UV dose of 1.61 W/cm^2. For UV/TiO_2 treatment, it has been shown that titanium dioxide photocatalysis can achieve over a 96% reduction in hydrophobic NOM and over an 81% reduction in DOC (Murray and Parsons, 2006). Wang et al. (2006) conducted a study to evaluate the degradation characteristics of DOC in water using H_2O_2/UV treatment. They found that the treatment is effective in removing THM precursors with higher H_2O_2 doses for the photolysis of high concentrations of organic THM precursors. The effects of H_2O_2/UV based AOP and its integration with BAC treatment for DBP reduction from raw surface water have been studied recently by Toor and Mohseni (2007). They observed that H_2O_2/UV AOP combined with BAC showed significant reductions of 43%, 52%, and 59% relative to untreated raw water for THMs and HAAs, TOC, and UV_{254}, respectively. A recent study by Lee et al. (2007) investigated the use of adsorption and photodegradation of humic acids by nano-structured TiO_2. The results showed that high humic acid adsorption on the homemade nano-structured TiO_2 can be achieved at low pH condition and increased cation strength whereas high adsorption of humic acid on TiO_2 did not show a significant effect on the photo-degradation rate of humic acid. The combination of O_3/H_2O_2 for controlling THM in drinking water was also examined in multiple laboratory studies (Wallace et al., 1988, Tuhkanen et al., 1994).

2.7.1.6 Other Treatment Processes

The effect of dissolved air floatation (DAF) for removing DBP precursors was also studied. Gehr et al. (1993) conducted batch, pilot, and full-scale DAF tests on a eutrophic water source to determine suitable physical and chemical (coagulation) conditions for the removal of THM precursors. They found poor THM reductions in a full-scale DAF plant compared to pilot plants because of poorer chemical mixing conditions. They also found from their analysis that algae accounted for a major share of the precursor concentration whereas DOC was a minor indicator of THM precursor concentration. Johnson et al. (1995) conducted pilot plant testing of DAF for treating a low-turbidity surface water supply in Boston. They recommended a treatment process train consisting of dissolved air flotation, ozone, biological filtration, and chloramination. The effectiveness of coagulation, ozonation, and biofiltration in controlling DBPs was successfully evaluated by Chaiket et al. (2002). A series of studies indicated that coagulation/sedimentation coupled with either pre- or post-ozonation processes could reduce DBP precursors more effectively than the conventional treatment process, and were more reliable for reducing the overall DBPFP (Chiang et al., 2002; Singer et al., 2003; Chin and Berube, 2005). The effect of ozonation on the removal of TOC and THM precursors was examined by Chang and Singer (1991). Collins et al. (1992) evaluated the capacity of conventional slow sand filtration for removing NOM using two different filter cleaning techniques in their pilot-scale filter studies. Siddiqui et al. (1997) conducted a study to evaluate ozone enhanced removal of NOM from drinking water sources. They observed 40% to 60% removal rates of THMFP in their experiment. Page et al. (2002) described in their study that conventional alum treatment did not always reduce the THM levels under 250 µg/L.

The effect of river bank filtration for removing TOC, DOC and DBP formation potential were investigated by Weiss et al. (2003). They observed 35% to 67% reductions of TOC and DOC and 50% to 80% rates of removal of THMFP and HAAFP following riverbank filtration in a number of Midwestern USA drinking water utilities. Nnadi et al. (2004) demonstrated the techniques for control of DBPs in a pilot study. They examined air-stripping, potassium permanganate ($KMnO_4$) addition, pH adjustment, evaluation of corrosion control inhibitors, final disinfection, and GAC filtration, and found that some HAAs increased at higher pH levels. Their results showed that the use of air stripping greatly reduced the required amount of chlorine disinfectant, and that air stripping, permanganate addition, and chloramination reduced DBPs to 20 mg/L. They suggested that using chloramine as a second disinfectant would be effective and that the addition of an inhibitor (Stiles-Kem 7840) could effectively control lead and copper concentrations in the distribution system.

Guo et al. (2007) studied the removal of organics and bromate in a pilot plant with pre-ozonation, coagulation-sedimentation, sand filtration, post-ozonation and BAC for a southern China water supply. They suggested that a combination of conventional treatment with pre-ozonation could be an effective alternative strategy to remove THMFP. Selcuk et al. (2007) investigated the effect on NOM removal of pre-ozonation alone as well as when combined with coagulation using different origin water. They observed that pre-ozonation enhanced the removal of TOC and reduction of TTHMFP when it was used in combination with alum and polyaluminium chloride coagulants, but that THAAFP increased after each coagulation, ozonation, and combined process.

2.7.2 Alternative Disinfectant

A non-chlorine-based disinfectant can also be used as the primary disinfectant while chlorine is added as the secondary disinfectant. In this approach the amount of chlorine needed is significantly reduced, and therefore the quantity of chlorinated DBPs formed is comparatively lower. Using alternative disinfectants like chloramines, chlorine dioxide, ozone and, UV radiation can significantly reduce chlorinated DBP formation. Case studies have been conducted using these alternative disinfectants. Chloramine can reduce the THM level but poses a risk of producing another non halogenated, highly carcinogenic DBP- NDMA. DBP formation during chloramination was studied by Diehl et al. (2000). The study demonstrated that HAA formation was more problematic during chloramination than was THM. The use of chloramines as a secondary disinfectant was recommended by another study to meet Stage 1 of the D/DBP rule (Nnadi et al., 2004). Hua and Reckhow (2007) compared DBP formation using chlorine and chloramine, both with and without pre-ozonation and chlorine dioxide. They observed that pre-ozonation decreased the formation of THMs, HAAs, and TOX during postchlorination and chloramines and chlorine dioxide produced a higher percentage of unknown TOX than did free chlorine. The use of chloramine as an alternative disinfectant was suggested by Norman et al. (1980).

A study was conducted to evaluate the effectiveness of chlorine dioxide in meeting the current and future enhanced surface water treatment and D/DBP rules (Arora et al., 2001). The results showed that water spiked with high bromide concentrations produced insignificant amounts of THMs or HAAs after reaction with chlorine dioxide. In contrast, higher chlorine dioxide residuals were proven to be a source of chlorite and chlorate formation (Schmidt et al., 2000). Ozone has been found to be a very effective disinfectant with the ability to reduce significantly the level of DBP in finished water. High levels of bromine in water pose a risk of producing bromate, another inorganic DBP by ozone. UV disinfection is another effective disinfectant; no DBP has been identified using UV so far. A study has shown that post-chlorination additions of a secondary disinfectant comprised of silver and hydrogen peroxide (Ag^+/H_2O_2) dramatically reduce the formation of halogenated DBPs (Batterman et al., 2000). Table 2.1 shows the properties of alternative disinfectants in drinking water.

Table 2.1: Alternative disinfectants

Disinfectant	**Efficacy as disinfectant**	**Disinfectant residual in Distribution system**	**Dominant precursors for DBP formation**	**Dominant DBPs of regulatory concern**
Ozone (O_3)	High	no	bromide and TOC	bromate (BrO^3), aldehydes
Chlorine (HOCl/OCl-)	intermediate	yes	bromide and TOC	THMs and HAAs
Monochloramine (NH_2Cl)	intermediate	yes	TOC and organic nitrogen	nitrosamines
Chlorine dioxide (ClO_2)	intermediate	no	decay of ClO_2	chlorite and chlorate
UV irradiation	high	no	none	none

2.7.3 Changing Chlorination Point

Many of the treatment plants use pre-chlorination of raw water, a point of practice which is responsible for a major portion of THM and HAA formation. By removing NOM, coagulation significantly reduces the chlorine demand and DBP formation potential. Therefore, moving the chlorine addition points from before coagulation (e.g., prechlorination) to after coagulation (e.g., intermediate or postchlorination) could significantly reduce the formation of DBPs in finished water. Changing the chlorination point or substituting pre-chlorination to pre-oxidation can significantly reduce the level of THM and HAA formation (Xie, 2004).

2.7.4 Treatment Cost and Applicability

Jar tests and bench scale column tests are necessary for cost effective usage of enhanced coagulation and GAC adsorption processes. Enhanced coagulation is one of the best available technologies (BAT) for controlling DBP formation. Due to high capital and operating costs, membrane technologies are not considered as BAT under USEPA regulation (Xie, 2004). According to Xie (2004), using chloramine as the secondary disinfectant poses the lowest cost for both small and large systems. Chlorine dioxide has the highest cost for small systems, while ozone has the highest cost for large systems. The practice of increasing coagulant dosage, or enhanced coagulation, poses the lowest cost for both small and large water systems. GAC adsorption has the highest cost for small water systems. NF, finally, has the highest cost for very large water systems (20 mgd) (Xie, 2004).

2.8 Trihalomethanes Study in Canada

Peterson et al. (1993) conducted a study to evaluate the relationship of THMs in finished drinking water with DOC and treatment processes for Alberta surface water. Their analysis suggested that THM levels in water exceeded 50 µg/L when the DOC level of filtered water exceeded 4 mg/L and when chlorination was used. Waller et al. (1996) conducted a study on the characterization of Nova Scotia surface water and treatment options for the removal of color and THM precursors. They found that TOC was strongly correlated with color and THMFP in project samples and settling-filtration was more effective than direct filtration of raw waters with high TOC from their laboratory batch tests. Charrois et al. (2004) conducted a survey of selected DBPs in 11 rural Alberta communities (Populations Range: 60 to 2300) to evaluate source water quality as TOC, THMs and HAAs concentrations within distribution systems and within water treatment plants. From their survey study, they observed high (>100 µg/L) THM3 (chloroform, bromodichloromethane, chlorodibromomethane) concentrations. They also found that the source waters with the highest TOC concentrations (15 mg/L) had the highest average THMs concentrations (200 µg/L). A series of THMs and HAAs studies have been conducted in Quebec (Rodriguez et al., 2000; 2001; 2003; 2004; 2005; 2007). Coulibaly and Rodriguez (2003) conducted a comparative study examining distributed water quality in ten small municipal drinking water utilities in Quebec. All of these utilities applied direct chlorination to surface water or groundwater under the direct influence of surface water without any previous treatment. Serodos and Rodriguez (2003) investigated the occurrence of THMs and HAAs in the waters of three utilities in

Quebec City (Canada) and developed regression models for the distribution systems. Although their models were statistically significant, the models all showed a low ability to predict full-scale halogenated DBPs. They suggested that special caution should be taken when using experimental halogenated DBPs data from full-scale distribution systems. Niquette et al. (2007) demonstrated an innovative process for the treatment of high loaded surface waters for small communities in Quebec. The specially designed process combines complementary treatments operated by a centralized computer and consists of ozonation, membrane filtration, and biological filtration, as well as reduced operation to basic tasks. The process has been shown to considerably lower TOC, DOC, color, turbidity, chlorine demand, and concentrations of THM precursors present in the raw water.

Chapter 3: Materials and Methods

3.1 Data Collection

A significant number of small drinking water facilities in Alberta have been found to be in need of consideration in terms of controlling THMs and HAAs, which were exceeding the guideline value or had the potential of high THMs and HAAs. Due to the upcoming MAC and GCDWQ, it was necessary to first establish a database summarizing the concentration of these DBPs as well as other important water quality factors which can influence their formation. The Municipal Approval Team of the Northern Region of Alberta Environment had taken the leading role in this task by creating the baseline database of THMs and HAAs. A successful small-scale short-term THM monitoring program was conducted for 20 months, beginning in August, 2005. The monitoring program included eight small drinking water facilities in the Northern Region of Alberta Environment having been selected from four different waters depending on the severity of the THM problem. The sources of these chosen facilities covered lake water, river water, impoundment water and groundwater, implying that the wide field of sources under study can provide a full understanding of THMs and HAAs formation according to the variability of source water.

All the monitored waterworks were comparatively small and served less than 10,000 people. Table 3.1 shows the list of the monitored facilities with their sources and service populations. Raw water and filtered water daily average flow of the facilities are also included.

Table 3.1: Sources, service population and daily average flow of the facilities

Waterworks	Raw Water Source	Service Population	[1]Raw Water Flow, cubic meter/day	[1]Filtered water Flow, cubic meter/day
Bonnyville	Moose Lake	7000	2966	2512
Fort Chipewyan	Lake Athabaska	1200	1804	1144
Fort McKay	Ells River	450	333	296
Westlock	Pembina River	5091	2145	2115
Woking	Surface Runoff	100	50	27
Tangent	Surface Runoff	50	11	8
Vilna	Groundwater	280	238	190
St. Michael	Groundwater	80	10	10

[1] Raw water and filtered water daily average flow in cubic meter data during 2005 to 2006 obtained from Alberta Environment.

Figure 3.1 shows the sample locations of water quality data of the facilities.

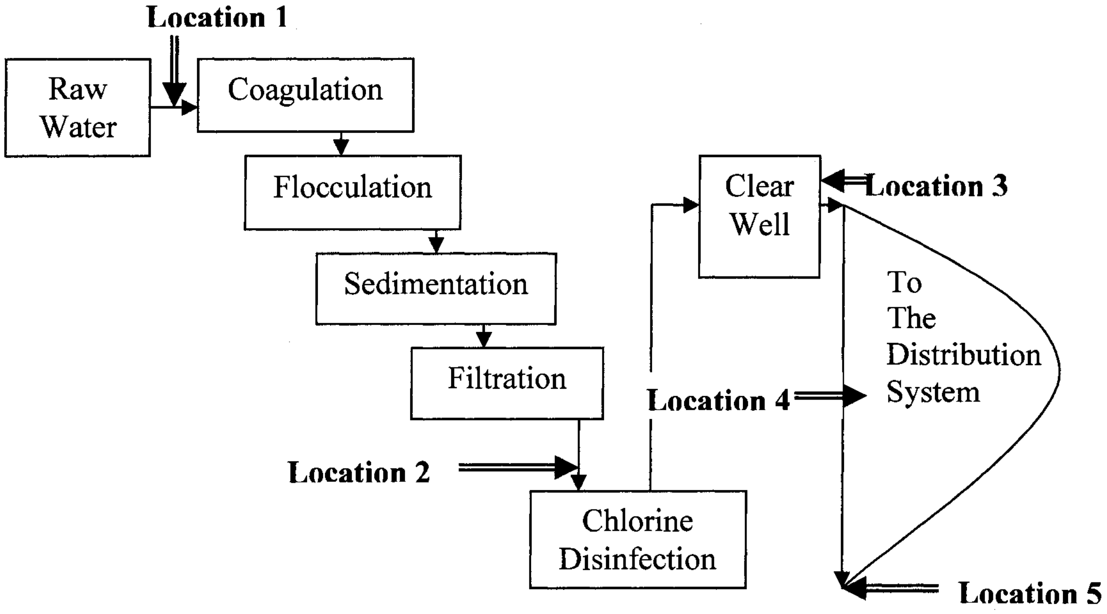


Figure 3.1: Sample locations and typical treatment scheme of the facilities

The parameters were tested from different locations as listed below.

- Location 1: Raw water entering the treatment plant; pH, temperature, DOC, color, UV_{254}

- Location 2: Filtered water after filtration and before chlorination; pH, temperature, DOC, color, UV_{254}
- Location 3: Finished water entering the distribution system; pH, temperature, four THMs (chloroform, bromodichloromethane, dibromochloromethane and bromoform), six HAAs (chloroacetic acid, dichloroacetic acid, trichloroacetic acid, bromoacetic acid, dibromoacetic acid and bromochloroacetic acid), free chlorine and total chlorine.
- Location 4: Finished water around the mid-point of the distribution system; pH, temperature, four THMs (chloroform, bromodichloromethane, dibromochloromethane and bromoform), six HAAs (chloroacetic acid, dichloroacetic acid, trichloroacetic acid, bromoacetic acid, dibromoacetic acid and bromochloroacetic acid), free chlorine and total chlorine.
- Location 5: Finished water at the farthest point of the distribution system; pH, temperature, four THMs (chloroform, bromodichloromethane, dibromochloromethane and bromoform), six HAAs (chloroacetic acid, dichloroacetic acid, trichloroacetic acid, bromoacetic acid, dibromoacetic acid and bromochloroacetic acid), free chlorine and total chlorine.
- Additional Parameter: Monthly average chlorine dose

Monthly samples were collected from these eight facilities in Northern Alberta and sent to laboratory for measuring of DOC, color, THM and UV absorbance. These parameters were tested by Norwest Labs in Edmonton (7217 Roper Road, Edmonton, Alberta, T6B 3J4 Canada). Information regarding the methods used in Norwest Lab were also collected. DOC was measured using a High-Temperature Combustion

Method, 5310B Standard Method for the Examination of Water and Wastewater (APHA); color was measured by Visual Comparison Method, 2120B Standard Method for the Examination of Water and Wastewater (APHA); UV_{254} was measured using Ultraviolet Absorption Method, 5910B Standard Method for the Examination of Water and Wastewater (APHA) and individual THM was measured using USEPA method, 524 US Environmental Protection Agency Test Methods. pH, temperature, and residual chlorine were measured using a pH meter, thermometer, and chlorine test kit, respectively, by the operator. The average chlorine dose, used in the last 24 hours prior to beginning the sampling, was provided in the field data sheet. These monthly field data and laboratory test results from each facility were sent to Alberta Environment and stored.

3.2 Access Database Created from Raw Data

Data obtained from the THM monitoring program was stored in the Municipal Approvals Team water abatement database using Microsoft Excel®. All of the facility data for the five locations was stored in one Excel file. Eight Excel files were provided from Alberta Environment for this research work in June, 2007. The raw data of the eight facilities is provided in Appendix C. It was necessary for the purpose of this research work to classify the acquired dataset in different groups for further analysis. First the dataset was organised using Microsoft Access® to create a complete database with all the monitored THM data. The created database was simple and thus it was easier to proceed with the analysis work. Provision was kept in the database for future additions in the case that the monitoring program was to be continued with additional facilities or parameters. Figure 3.2 shows the main form of the prepared DBP database. This can also be used in the future as a central database of THMs and HAAs from other treatment facilities with similar problems (if any) and can be very functional for future research in this area.

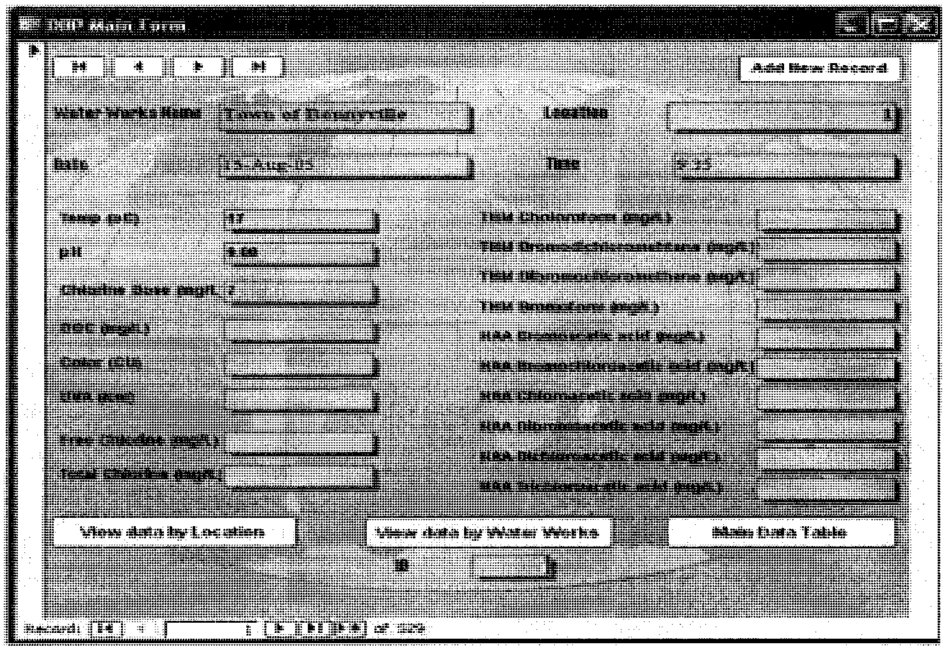


Figure 3.2: Main form of DBP database for future addition

3.3 Data Preprocessing

Data preprocessing is the first step towards modeling. The purpose of this step is to properly understand and analyze the data for modeling suitability and also to prepare a high quality dataset for further modeling steps. It is based on statistical analysis on the source dataset in order to find out and omit any erroneous data, possible outliers, or missing entries. Although the given data set was recorded over a period of 20 months (August, 2005 to March, 2007) at two locations each within eight small water treatment plants and three locations within each distribution system, the number of monthly data for each facility was not the same. Table 3.2 shows the data frequency of the monitored parameter for each facility.

Table 3.2: Number of data obtained from the facilities

Waterworks	THMs at 3 L	HAAs at 3 L	Monthly chlorine dose	DOC at 2 L	Color at 2 L	UV_{254} at 2 L	Free chlorine at 3 L	Total chlorine at 3 L
Bonnyville	12	1	12	11	11	11	11	11
Fort Chipewyan	10	4	6	10	10	10	7	no data
Fort McKay	11	2	11	11	11	11	11	11
Westlock	19	3	19	19	19	19	19	19
Woking	16	[a]2	16	15	15	15	16	16
Tangent	16	3	16	17	17	17	16	16
Vilna	15	4	12	12	12	12	12	12
St. Michael	5	no data	no data	[b]5	[b]5	[b]5	1	1

L- Location;

[a] Woking waterworks had 3 HAAs data at 2 locations (location 4 and location 5);

[b] St. Michael has no data at for DOC, color and UV at location 2.

Missing Months for THMs data are-

- Bonnyville waterworks- Apr, 06; May, 06; Jul, 06; Aug, 06; Oct, 06; Nov, 06; Feb, 07 and Mar, 07.
- Fort Chipewyan waterworks- Aug, 05; Sep, 05; Jan, 06; Feb, 06; May, 06-Sep, 06 and Dec, 06.
- Fort McKay waterworks - Aug, 05; Jan, 06; Apr, 06-Sep, 06 and Mar, 07.
- Westlock waterworks - May, 06 and Nov, 06.
- Woking waterworks - Apr, 06; May, 06; Jul, 06 and Mar, 07.
- Tangent waterworks - Aug, 05; Apr, 06 and May, 06;
- Vilna waterworks - Apr, 06; May, 06; Jul, 06; Dec, 06 and Mar, 07 and for St. Michael waterworks available data for five months (Aug, 05-Oct, 05; Dec, 05 and Feb, 06).

Initial visual examination of the data set demonstrated a total of 104 THMs data points at each location. Because of the fewer number of data for each facility, all facilities' data were considered together for further modeling steps. Data tables were prepared according to seasons, months, locations, sources, and facilities. Seasonal variation (according to typical seasons in Canada) was observed later by dividing the dataset according to Table 3.3.

Table 3.3: Seasonal division

Season	**Month**
Spring	March April May
Summer	June July August
Fall	Sep Oct Nov
Winter	Dec Jan Feb

For combined analysis, after the initial visual examination, statistical analysis was performed on the dataset to determine the mean, median, standard deviation, minimum, maximum, and percentile (1st, 5th, 25th, 75th, 95th and 99th) values on the average of the eight facilities' monthly data. These values are represented in Appendix A. From this analysis, the data set showed very good data points with almost no outliers. The minimum values of all parameters were all close to their corresponding 1st percentile. Similarly, the maximum values of all the parameters were close to their 99th percentile. After the statistical analysis, each parameter was plotted against time to determine the presence of any seasonal or daily trends and possible outliers in the dataset. Ten time-series plots were generated in total, as shown in Figures-A 6.1 to A 6.10 in Appendix A.

Graphical analysis of the average values of parameters of the combined facility data did not show any outliers. Individual facility data was also analyzed statistically and graphically, but no possible outlier was found to be discarded except for blank entries of some parameters among the limited individual data. Some datasets were missing entries of one or more parameters, and, for further modeling purposes, those datasets have been discarded. The data tables prepared with raw data are attached in Appendix C. All the calculations and analyses of the dataset have been completed using Microsoft Excel®.

3.4 Classification by Kohonen's Self Organizing Maps

A series of graphical analyses was conducted on the entire set of combined data for every location, season, month, and source. Another attempt was taken for classification of the data by Kohonen's self organizing maps using Neuroshell 2 ANN software. The Kohonen self organizing map is an unsupervised ANN. It can cluster a set of data from an historical database using the topological properties of the input space. The Kohonen self organizing map can be used to cluster the data based on raw water quality rather than seasonal classification. The seasonal temperature fluctuates significantly in Canada, especially in the province of Alberta. The winter season is long and sometimes includes spring and portions of the fall calendar months in Alberta. Applying self organizing maps on raw water quality may give a better classification as well as contributing to a better understanding of the formation of DBPs. The goal of this application is to discover some underlying structure of the data; this application significantly depends upon both the quality and quantity of data. However, for this research, the result was not feasible as the comparatively limited number of data could not give an acceptable result. Kohonen mapping with more available data can be used as a useful tool for future research in this area.

3.5 Modeling with Multiple Linear Regression Analysis

Multiple linear regression analysis was conducted using the regression tool of Microsoft Excel with the combined dataset for each season. Seasonal regression was conducted with raw and treated water quality parameter data in order to relate with THMs from the combined facilities data. It was expected that dividing the data into different seasons would more reliably characterize the relationship of THMs with the parameters. Serious limitations of the existing models include calibration with a limited dataset; lack of terms by which to simulate important parameters such as reaction time and inadequate validation. The model includes pH, temperature, color, DOC, UV_{254}, chlorine dose, and residual chlorine in the seasonal dataset. Additionally calculated SUVA was also applied in order to observe its effect on THMs concentration. However, the maximum observation was only 33 in winter analyses. The quality and quantity of data are also extensively considerable factors for modeling THMs with multiple linear regressions. Statistical approaches were maintained in order to develop the significant model. P-value and 95% confidence limits were considered in choosing the significant parameter to be included in the model. There was a limited dataset in spring and summer months and the developed models could not be validated due to the limited number of data. However these models need to be recalibrated and validated with additional data for use in specific facilities. One set of regression analyses used in this work is shown as an example in Appendix B.

3.6 Application of Artificial Neural Network

ANN application was conducted using Neuroshell 2 (Release 4.0, Ward System Group Inc.) software. The most established learning algorithm in ANN is called back-propagation. The knowledge acquired by ANN during the learning process is the final connection weight values representing the complex relationships between inputs and outputs. Three parameters are estimated by experimentation: the number of hidden elements; the learning rate; and the momentum. The learning prototype for BPNN is supervised learning. Supervised learning by back-propagation algorithm was employed here for the purpose of training the networks. In this learning procedure the network learns by comparing the model output with target outputs and then makes necessary adjustments to the hidden layers by back-propagating prediction errors. Learning continues until the learning epochs reach a specified value or events since minimum average error reach a specified value. A training data set is used in order for the network to be trained, a testing dataset is used in order for the network to stop training, and a validation dataset is used for checking the validity of the network. Network can also be run without testing the set. Here, random and rotational patterns were tested both with and without the testing set. For random pattern, momentum, and for rotational pattern, turboprop was chosen as a weight update. Stopping criteria were also varied for application in random-momentum and rotation-turboprop patterns. For random-momentum, the stopping criteria was chosen when the minimum average error was greater than 20,000 for best test set; for rotation-turboprop, the stopping criteria of the network for the best training set and the learning epochs was 600. The chosen functions were linear (open) for the input layer, logistic for the hidden layer, and linear for the output layer for the network. The best network was chosen based on the highest R^2 value of the production set. The batch processor tool of Neuroshell was used to obtain the best network from different combinations of pattern, architecture, function, and stopping criteria. However, the network did not show good R^2 for any combination. The best model was found using raw water quality parameters with R^2=0.36. Based on the quality and quantity of the dataset, this application can be used effectively for the modeling of THMs.

Chapter 4: Results and Discussions

4.1 Treatment Scheme

According to Alberta Environment, all the monitored eight facilities used chlorine for disinfection. The Bonnyville water treatment plant had a raw water supply from Moose lake, coagulant addition, flocculation, lime softening clarification, dual media rapid sand filtration, seasonal taste and odor control, fluoridation, gas chlorine disinfection, and algae control. Fort Chipewyan waterworks had raw water (Lake Athabasca) storage, coagulant addition, flocculation, clarification, pH adjustment (as required), dual media rapid sand filtration, and gas chlorine disinfection. Fort McKay had raw water supply from Ells River, raw water reservoir with algae control, enhanced coagulation, membrane filtration, and sodium hypochlorite disinfection. Westlock waterworks had raw water coming from the Pembina River, raw water reservoir, prechlorination, coagulation, flocculation, clarification, rapid sand filtration, fluoridation, and gas chlorine disinfection. Woking waterworks had a raw water supply from surface runoff, a raw water reservoir with aeration, coagulation, flocculation, dual media filtration, pH adjustment (as required), and sodium hypochlorite disinfection. Tangent waterworks had raw water from surface runoff, raw water reservoir with aeration, coagulant addition, flocculation, clarification, dual media filtration, pH adjustment and sodium hypochlorite disinfection. Vilna waterworks had raw water from a deep (300 ft.) groundwater well, raw water reservoir, aeration tower, coagulant addition, flocculation, adsorption clarification, dual media filtration and gas chlorine disinfection. St. Michael had a raw water supply from a shallow groundwater (40 to 50 ft.), filtration, and sodium hypochlorite disinfection.

4.2 Facilities Treatment Efficiency

Color, DOC and UV_{254} data from Location 1 (raw water) and Location 2 (before chlorination) were analyzed for each facility and the combined facilities. Location 2 data refer to treated water. To check the treatment efficiency of these WTPs, percent removals of color, DOC and UV_{254} were calculated from the raw water and treated water data for all the facilities. Table 4.1 shows the average percent removals for each facility. Woking, Fort McKay and Vilna waterworks have highly colored (30.7 to 44.7 TCU) raw water; after filtration, 83%, 80% and 30% of the color was removed, respectively. In the given period, Vilna waterworks was observed to have the least effective color removal by filtration. The high color, DOC and UV_{254} data for Vilna waterworks seemed unusual for a facility having groundwater as source water. DOC, which is the most important precursor of THMs formation, was highest (14.8 to 16.8 mg/L) in the raw water of Woking, Fort McKay, and Bonnyville whereas, after filtration, 52%, 46% and 41% of DOC was removed in these waterworks, respectively. Bonnyville and Westlock waterworks showed high pH levels with DOC as 16.4 and 9.5 mg/L and achieved 41% and 24% DOC removal by filtration. The maximum achievable removal of total organic carbon (TOC) is 50% for raw water with high alkalinity and high TOC (SGMWW, 2006). No alkalinity data was available to determine the treatment efficiency according to a maximum achievable rate of removal of DOC.

Table 4.1: Raw water quality and percent removal by treatment of the facilities

Facilities	Average Raw Water Quality					percent removal by treatment		
	pH	Temperature °C	Color TCU	DOC mg/L	UV_{254} /cm	Color %	DOC %	UV_{254} %
Bonnyville	9	7.8	12.8	16.4	0.22	50	41	55
Fort Chipewyan	7.2	3.96	5.3	3.96	0.06	5	42	57
Fort McKay	7.4	5.9	32.0	14.8	0.36	80	46	69
Westlock	8.2	8.7	21.2	9.5	0.25	54	24	43
Woking	7.5	10.3	44.7	16.9	0.45	83	52	72
Tangent	7.2	7.3	21.7	8.8	0.22	54	28	43
Vilna	7.4	6.2	30.7	11.1	0.34	30	12	24
St. Michael	n/a	n/a	5.0	3.98	0.03	n/a	n/a	n/a

However, THMs and HAAs formation might be affected by the remaining DOC, color, or UV_{254} still present after filtration. Table 4.2 shows the average value of parameters after treatment and before chlorination for these facilities. The average DOC of filtered water in Vilna and Bonnyville waterworks was high (about 10 mg/L) compared to that in other waterworks.

Table 4.2: Treated water quality of the facilities

Facilities	Average Treated water Quality				
	pH	Temperature °C	Color TCU	DOC mg/L	UV_{254} /cm
Bonnyville	8.4	8.7	6.5	9.7	0.10
Fort Chipewyean	6.6	4.7	5.0	2.3	0.02
Fort McKay	7.1	7.6	6.4	8.0	0.11
Westlock	7.9	8.6	9.7	7.2	0.14
Woking	7.3	13.4	7.8	8.2	0.13
Tangent	7.2	9.3	10.0	6.4	0.12
Vilna	7.9	6.6	21.4	9.8	0.26
St. Michael	n/a	n/a	n/a	n/a	n/a

Table 4.3 shows the calculated average value and the range of all the parameters tested for combined facilities over the monitoring period. During the monitoring period, the average concentration of THMs and HAAs for the combined data was above the guideline value of 0.100 mg/L and 0.080 mg/L as shown. The average value of free chlorine residuals and total chlorine residual within the distribution system was 0.71 mg/L and 1.19 mg/L (Table 4.3).

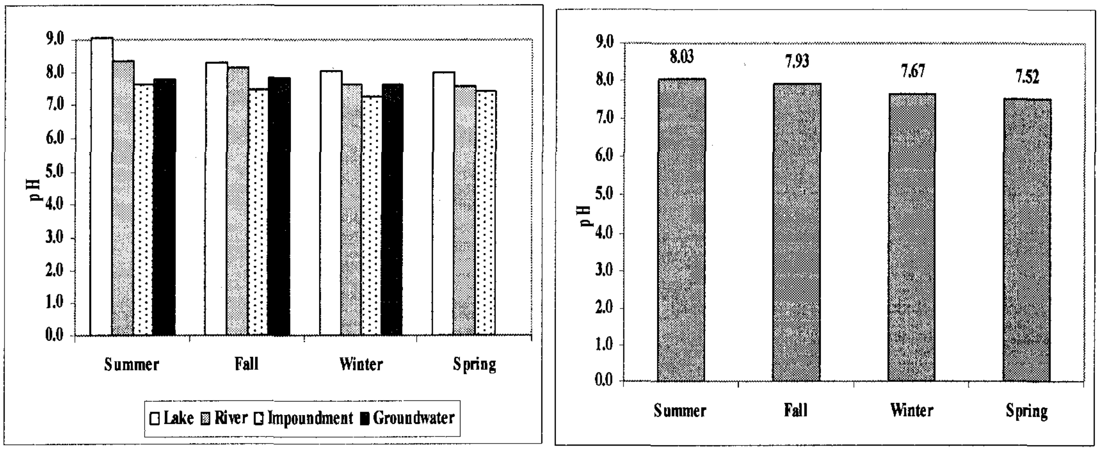
Table 4.3: Average water quality data over the monitoring period

Sample	**pH**	**Temperature °C**	**Color TCU**	**UV_{254} /cm**	**DOC mg/L**	**Cl_2 Dose mg/L**	**Free Cl_2 mg/L**	**Total Cl_2 mg/L**	**THMs mg/L**	**HAAs mg/L**
Location 1	7.8	8.1	23.0	0.259	10.9	5.85	n/a	n/a	n/a	n/a
Location 2	7.5	9.4	9.7	0.130	7.2		n/a	n/a	n/a	n/a
Location 3	7.45	10.4	n/a	n/a	n/a		1.01	1.56	0.08	0.07
Location 4	7.45	10.8	n/a	n/a	n/a		0.72	1.25	0.10	0.07
Location 5	7.44	9.6	n/a	n/a	n/a		0.41	0.78	0.11	0.07

4.3 Graphical analysis of the parameters

4.3.1 Observations in Raw Water Quality Parameter

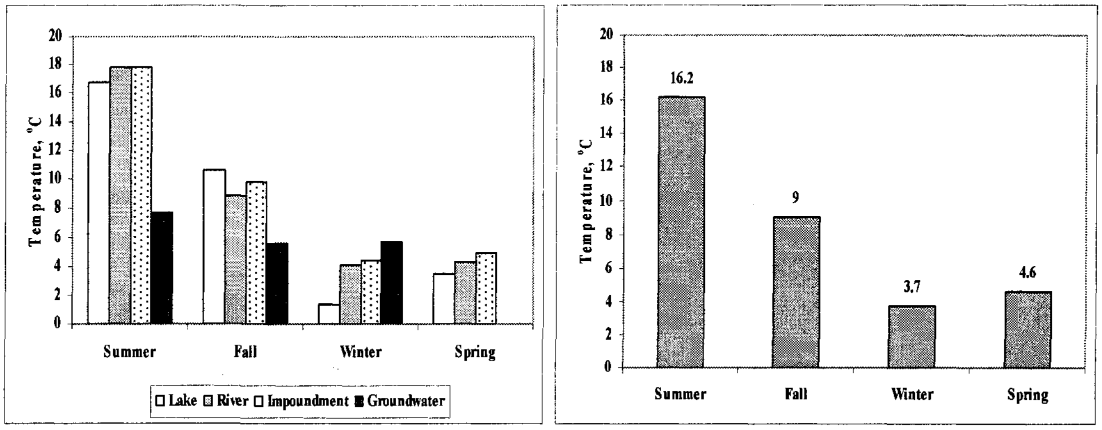
The combined dataset has been analyzed graphically in order to account for the pattern of the water quality parameter within different seasons and according to their raw water sources. Bonnyville and Fort Chipewyan data were combined for lake water, Fort McKay and Westlock waterworks data were combined for river water, and Woking and Tangent waterworks data were combined for runoff water analysis. Groundwater analysis was done with the combination of Vilna waterworks and St Michael waterworks. In many cases, there was no data from these waterworks. Figures 4.1 to 4.6 demonstrate the observed pattern in raw water parameters. The average pH of the raw water of eight facilities was highest in summer and decreased in fall, winter, and spring, respectively. Lake water pH was observed to be higher compared to river, impoundment, and groundwater pH levels (Figure 4.1). The pH of all the sources did not fluctuate significantly over the seasons.



* Groundwater had no pH data for spring at Location 1

Figure 4.1: Raw water pH

The raw water temperature of lake, river, and impoundment was comparatively higher than that of groundwater sources. There was no temperature data for spring months for groundwater sources, but the highest temperature of raw water in summer was around 16°C. The temperature gradually decreased in fall, spring, and winter, while groundwater temperature was relatively stable. The standard deviations were high because of the fluctuating temperature and the limited amount of data.



* Groundwater had no temperature data for spring at Location 1

Figure 4.2: Raw water temperature

The average raw water color in the combined dataset did not vary significantly in summer, fall, and winter. Raw water color was as low as 23.5 TCU in fall months, however. The color of raw water varied significantly when the data was analyzed for lake, river, impoundment, and groundwater sources. Surface runoff (impoundment) showed the high colored raw water in all seasons, as expected. River water color was highest in spring and lowest in summer. High color in groundwater (Vilna waterworks) was observed in spring. Low color was observed in lake water in all seasons.

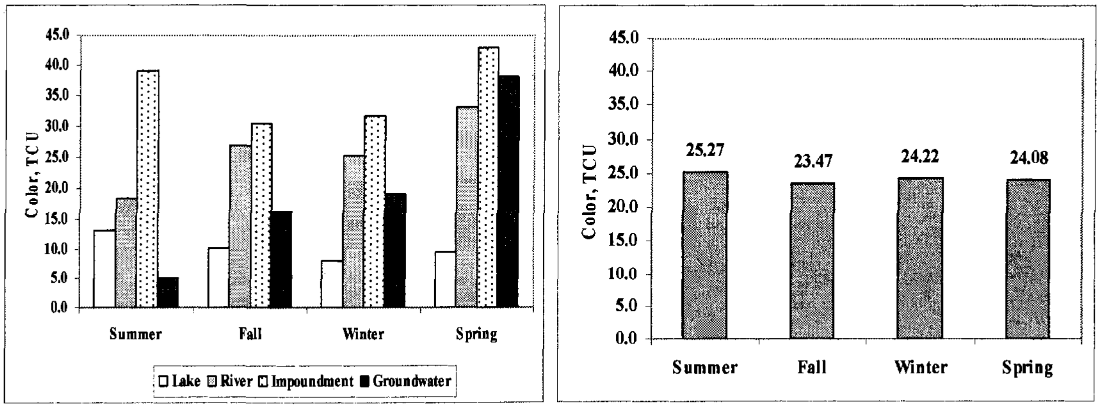


Figure 4.3: Raw water color

The raw water DOC, which is a measure of NOMs, did not show much variation among the seasons (Figure 4.4). Average DOC was higher in summer and spring than in fall and winter (12.4 to 11.8 mg/L). Source analysis showed average raw water DOC to be higher for lake, river, and impoundment than for groundwater, also as expected.

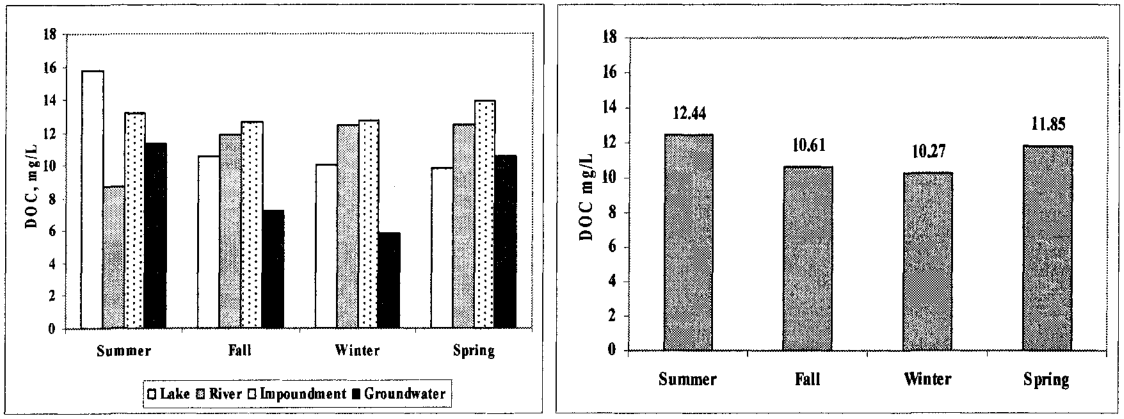


Figure 4.4: Raw water DOC

Average UV absorbance measured at 254 nm of raw water was plotted against the seasons in Figure 4.5 and was found to vary within a range of 0.259 to 0.268 per cm. UV_{254} for raw water was almost the same for impoundment in every season, whereas river water had the highest UV_{254} in winter, then decreasing in spring, fall, and summer, respectively. UV_{254} of groundwater was the highest in spring.

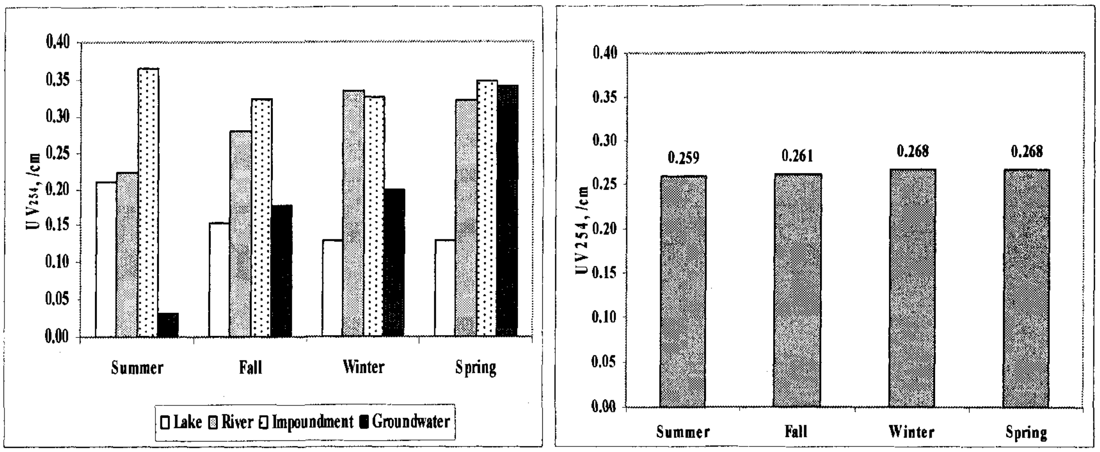


Figure 4.5: Raw water UV_{254}

From the DOC and UV_{254} of raw water data, the SUVA of raw water for these facilities was calculated. The calculated SUVA was found to be the highest in spring (2.45 L-mg/m) and was above 2 L/mg-m in fall and winter, also as shown in Figure 4.6.

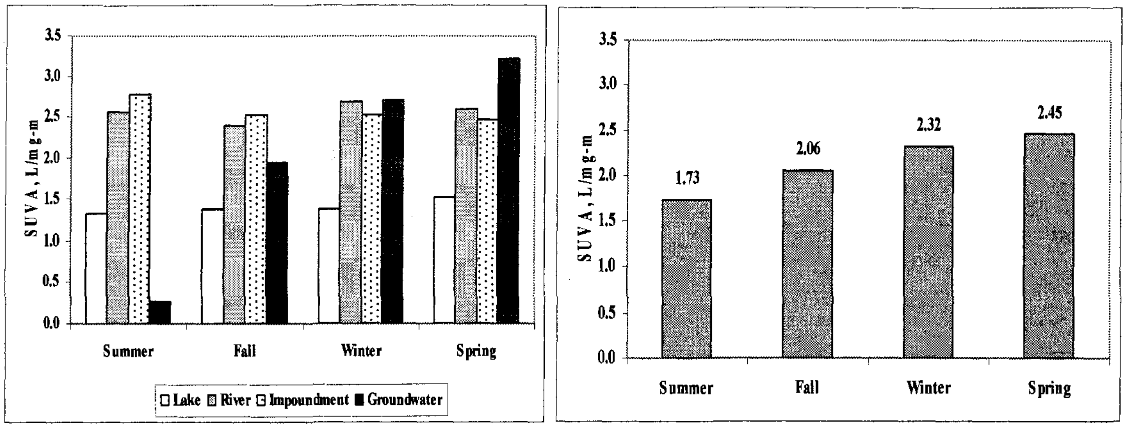
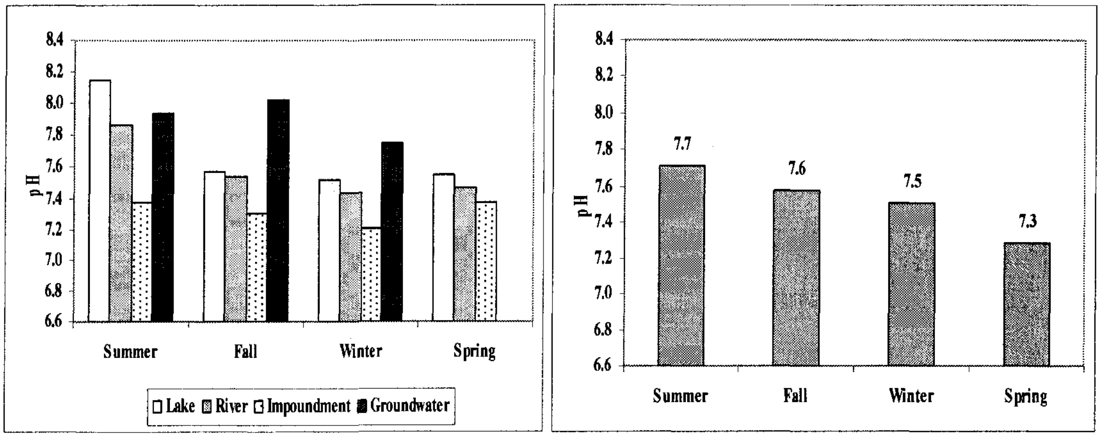


Figure 4.6: Raw water SUVA

Groundwater in Alberta is often naturally high in salts, iron and manganese. As well, shallow aquifers in Alberta are highly susceptible to contamination in areas with intensive agriculture (i.e. nitrate, fecal bacteria, phosphorus and salts from fertilizers and manure can also leach into groundwater). Land use type and groundwater depth influence the pH and DOC concentrations in groundwater. The high DOC, color, and UV_{254} are unusual for groundwater (Vilna waterworks) quality and may be due to the fact that the groundwater source is under direct influence of surface water, and that the quality and treatment procedures of groundwater sources are usually similar to those of surface water. Also, erroneous data may be the reason for this unexpected pattern in groundwater quality.

4.3.2 Observations in Treated Water Quality Parameters

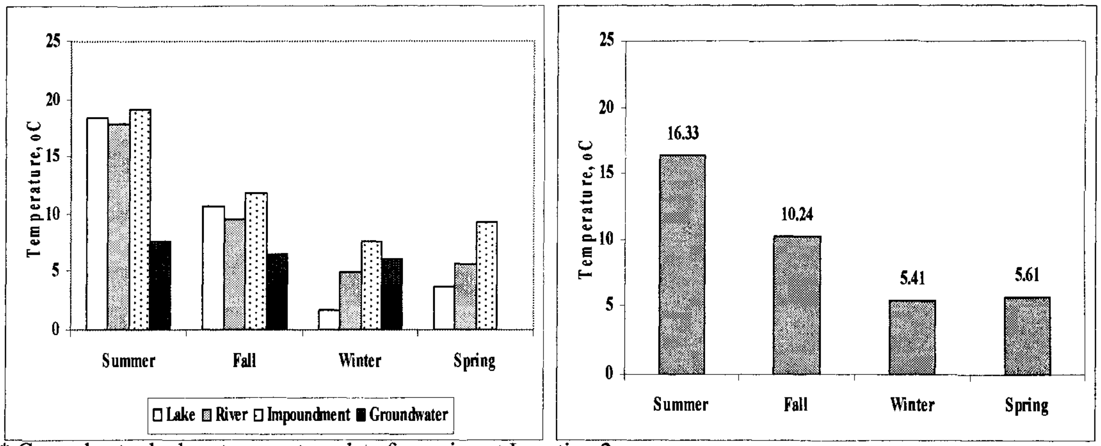
The treated water pH (Figure 4.7) was found to be the highest in the summer season and lowest in spring. The treated river water showed a higher value of pH in summer and lowest in winter. Treated groundwater showed the highest pH value in fall, then decreasing in summer and winter. The smaller amount of data for groundwater might be a reason for this.



* Groundwater had no pH data for spring at Location 2

Figure 4.7: Treated water pH

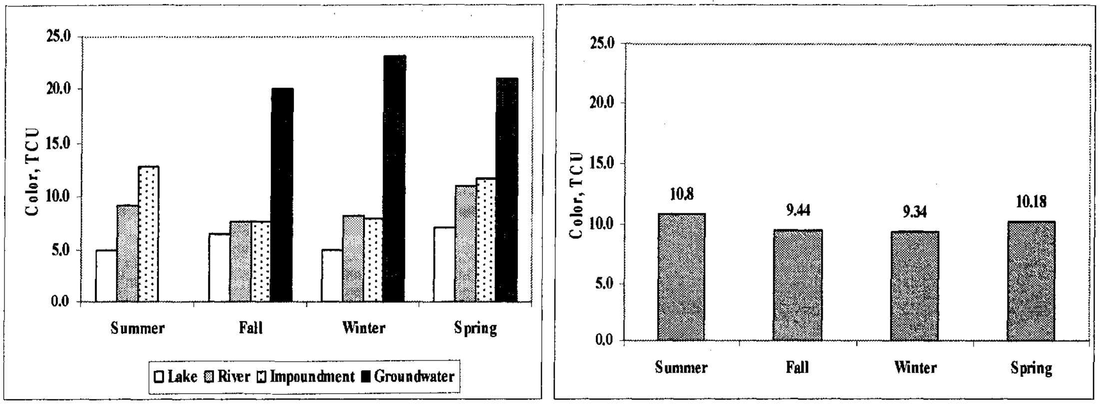
The average temperature of treated water (Figure 4.8) varied from a range to 5.6°C to 16.3°C in winter and summer seasons. The temperature was also low in spring. A source-wise analysis showed that the temperature was comparatively high for treated impoundment water in every season.



* Groundwater had no temperature data for spring at Location 2

Figure 4.8: Treated water temperature

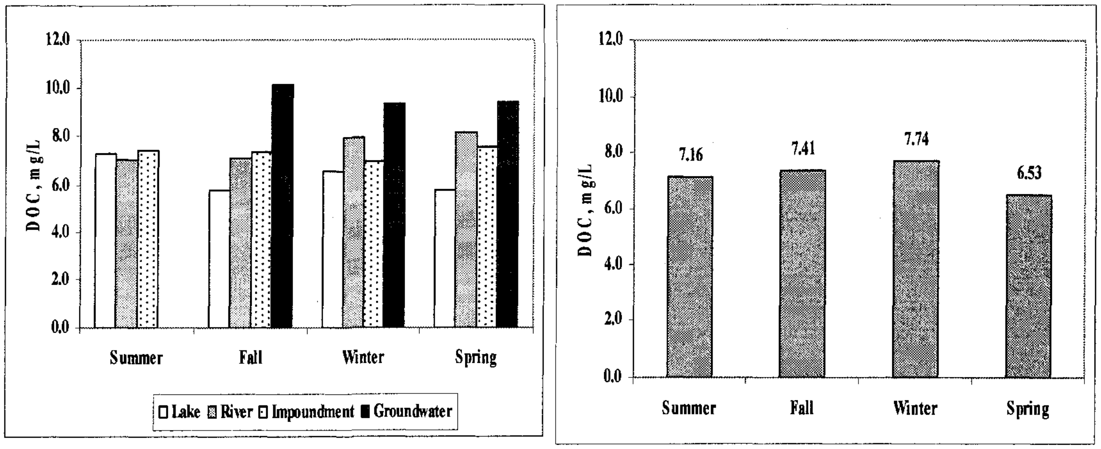
Groundwater (Vilna waterworks) color (Figure 4.9), unusually, increased significantly after treatment in winter, spring, and fall (20 to 23 TCU). These unexpected patterns again point to the possibility of faulty or insufficient data. There was no data for groundwater color in summer. River and Impoundment water color showed a similar value of color in fall and winter and higher in summer and spring. The average color of treated water was the highest in summer and lowest in winter.



* Groundwater had no color data for summer at Location 2

Figure 4.9: Treated water color

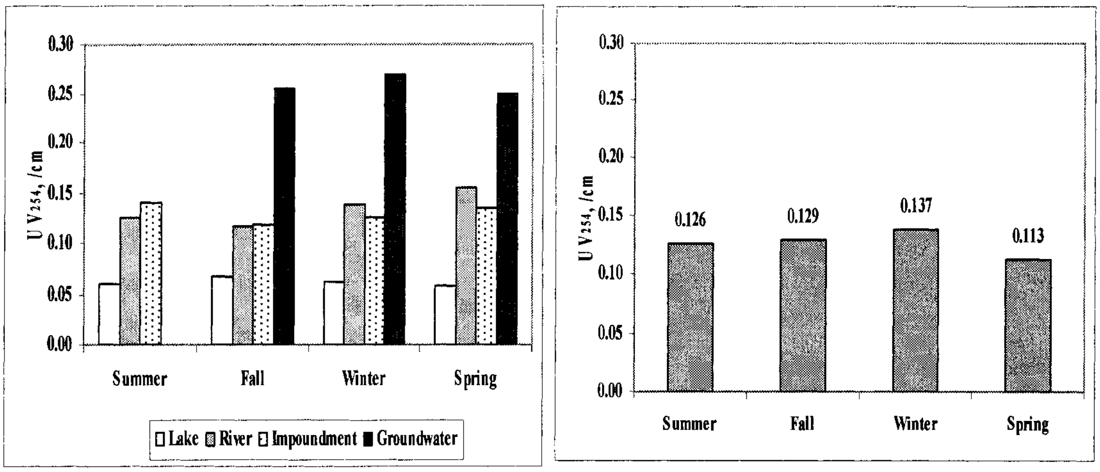
The average DOC of treated water data was observed to be lowest in spring and highest in winter, with a small fluctuation range of 6.6 to 7.7 mg/L (Figure 4.10). Highly colored treated groundwater (Vilna waterworks) showed a higher DOC content in fall, winter, and spring. The DOC of treated river and impoundment water did not vary significantly, and was around 7.5 mg/L in all seasons.



* Groundwater had no DOC data for summer at Location 2

Figure 4.10: Treated water DOC

The UV_{254} (Figure 4.11) of groundwater (Vilna waterworks) was also unusually high compared with lake, river, and impoundment water, as was the case with DOC and color. The UV_{254} of lake water was comparatively lower than river and impoundment water. Average UV_{254} of treated water was the lowest (0.115 /cm) in spring and the highest in winter (0.137 /cm) with a small increase.



* Groundwater had no UV data for summer at Location 2

Figure 4.11: Treated water UV_{254}

4.4 THMs and HAAs in Finished Water and within the Distribution System

The actual conditions of these eight small water treatment plants in terms of THMs and HAAs concentration were analyzed with the obtained data over the monitoring period. Table 4.4 shows the level of THMs and HAAs at finished water of the facilities under study (location-3; after chlorination before entering the distribution system).

Table 4.4: THMs and HAAs concentrations in finished water

Water Works Name	Source	THMs, mg/L	HAAs, mg/L
Bonnyville	Lake	0.073	0.095
Fort Chipewyan	Lake	0.013	0.039
Fort McKay	River	0.122	0.137
Westlock	River	0.104	0.119
Woking	Impoundment	0.126	0.120
Tangent	Impoundment	0.114	0.144
Vilna	Groundwater	0.022	0.019
St. Michael	Groundwater	0.013	n/a

HAAs exceeded the MAC of 0.080 mg/L in Fort McKay, Westlock, Woking, and Tangent waterworks, where the level of THMs was also above the guideline value of 0.100 mg/L. Figures 4.12 and 4.13 show the calculated mean and median values of THMs and HAAs concentration at different locations. Both mean and median values of THMs were above 0.100 mg/L for these waterworks. Median value can be a better representative when the data fluctuation is high and expresses the common run, where mean is affected by an excessively high or low figure. Only Fort Chipewyan, Vilna, and St. Michael waterworks showed lower mean and median values of THMs (below MAC) within the distribution system (Figure 4.12). As shown above, Vilna waterworks used to have high DOC, color, and UV_{254} in both raw and treated water, but still lower THMs and HAAs levels. This might be due to the presence of ammonia in the water. Applied chlorine reacts with ammonia to form chloramines, while the free residual chlorine concentration remains at lower levels in water to form higher THMs and HAAs concentrations. However, more data will be required in order to confirm the situation of these waterworks, as they may have high THMs and HAAs formation potential.

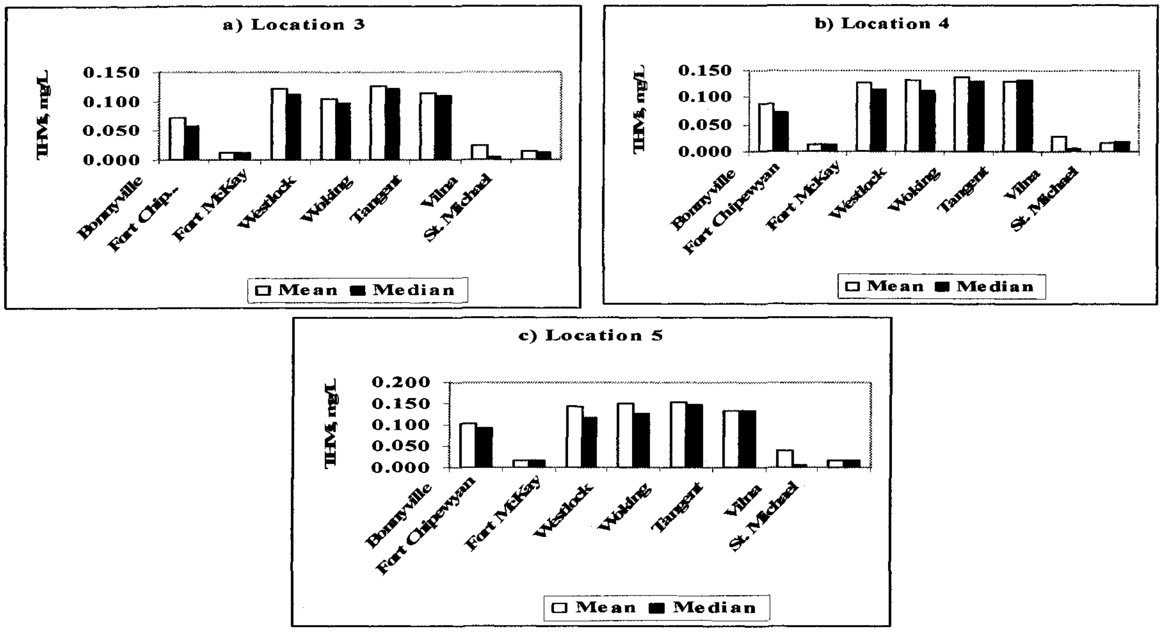


Figure 4.12: Mean and median value of THMs during the monitoring period

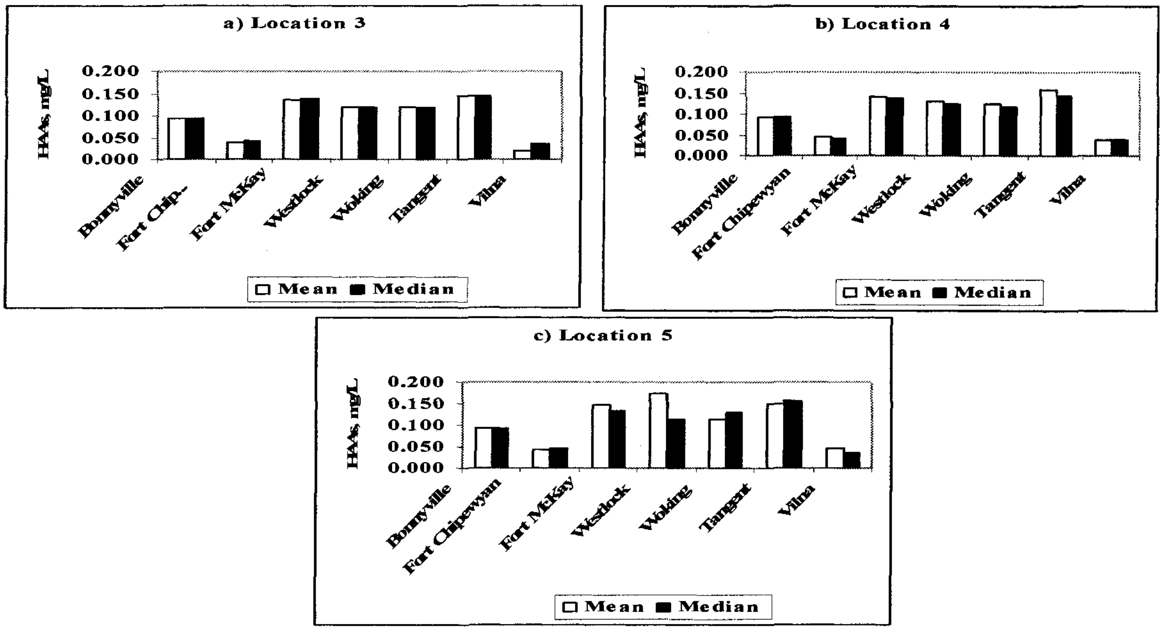


Figure 4.13: Mean and median value of HAAs during the monitoring period

Both THMs and HAAs formation increased within the distribution system over the monitoring period (Figures 4.14 to 4.17).

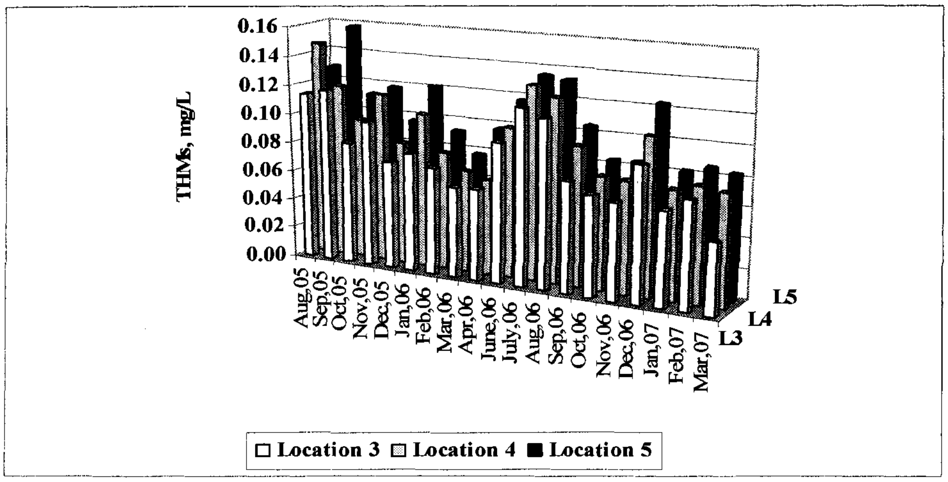


Figure 4.14: Monthly variation of THMs within the distribution system

The rate of increase of THMs within the distribution system was higher in summer than in winter, as anticipated in numerous studies (Rodriguez et al., 2004; Toroz and Uyak, 2005; Semerijan et al., 2007) which established the influence of temperature on the formation of these DBPs within the distribution system. Longer residence time within the distribution might increase the formation of THMs and HAAs as well.

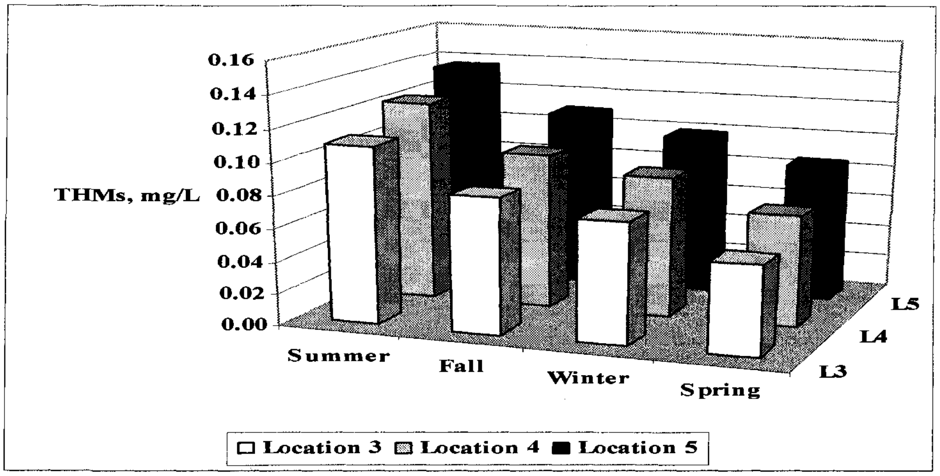


Figure 4.15: Seasonal variation of THMs within the distribution system

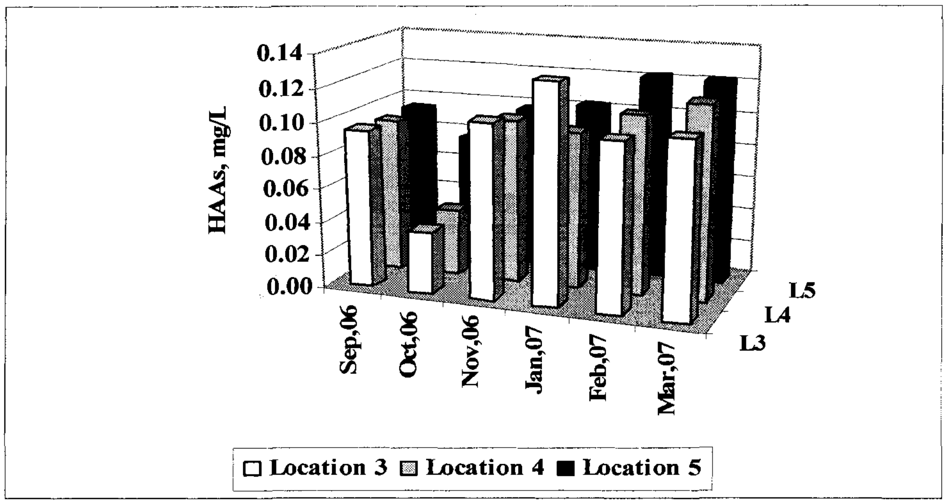


Figure 4.16: Monthly variation of HAAs within the distribution system

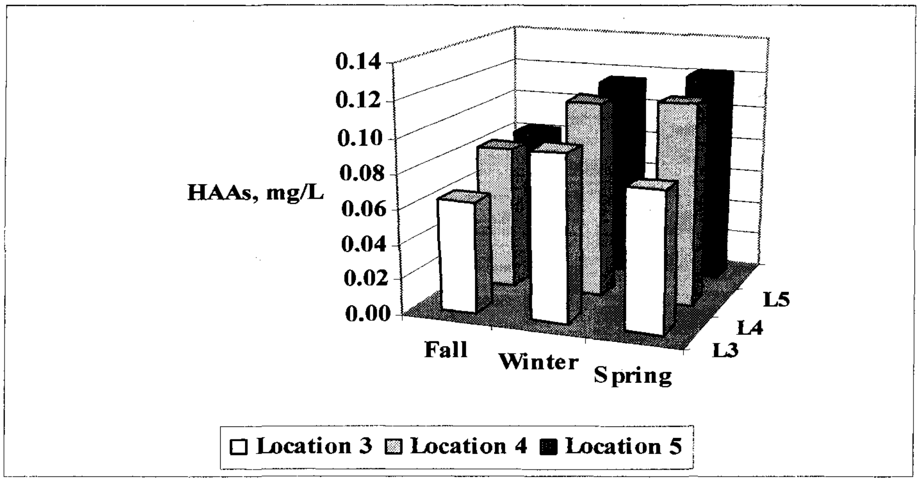


Figure 4.17: Seasonal variation of HAAs within the distribution system

The data at the midpoint of the distribution system (Location 4) and the furthest point of the distribution system (Location 5) of all these facilities were carefully analyzed and a definite increasing pattern was observed. The percent increase or decrease of THMs, HAAs, free chlorine, and total chlorine from Location 3 to Location 4 and Location 3 to Location 5 were calculated, and are presented in Table 4.5.

Table 4.5: Percent increase or decrease within distribution system

Season	**THMs, %**		**HAAs, %**		**Free Chlorine, %**		**Total Chlorine, %**	
	L3 to L4	**L3 to L5**	**L3 to L4**	**L3 to L5**	**L3 to L4**	**L3 to L5**	**L3 to L4**	**L3 to L5**
Summer	13	24	n/a	n/a	-39	-58	-28	-48
Fall	14	31	30	28	-30	-65	-23	-57
Winter	16	32	18	20	-27	-59	-8	-43
Spring	23	52	45	51	-21	-51	-25	-46

L-Location
L3- Entering distribution system
L4- Midpoint of distribution system
L5-Furthest point of distribution system
No summer data for HAAs
'-' denotes decrease

The average percent decreases of free and total chlorine from the entering point to the midpoint were 29% and 20%, and to the farthest point of the distribution system were 59.8% and 50%. THMs concentration increased consistently from the entering point to the farthest point of the distribution system at an average of 34% all through the monitoring period. This increase might have been due to the more organic precursor material associated with deposits on the pipe wall of the distribution system (Rossman et al., 2001). A similar increase of HAAs (average 0.096 mg/L to 0.109 mg/L above MAC value of 0.08 mg/L) was observed at the furthest point of the distribution system. HAAs increased at the midpoint of the distribution system by 31% and then also increased by an average of 33% from Location 3 to Location 5. The rate of increase of HAAs concentration was not higher from the midpoint to the furthest point of the distribution system. Previous studies have also shown an inconsistent increase of HAAs within the distribution system. A small decrease of HAAs within the distribution system, however, has been effectively explained by the biological degradation of HAAs (Chen and Weisel, 1998; Rodriguez et al., 2004;

2007; Speight and Singer, 2005). On the other hand, the behavior of HAAs within the distribution system could not be confirmed with the small amount of data available in this case.

The reaction between these chlorine residuals and the organic matters present in the distribution system resulted in more THMs and HAAs with an increase in residence time. Graphical analysis of monthly chlorine dose and free chlorine residuals (at Location 3) with average data of individual facilities was also carried out (Figures 4.18 to 4.21). It was observed that chlorine dose might be a significant factor for THMs and HAAs formation for these facilities. Within the month-long period spanning July-August, when the chlorine dose was as high as 8.65 mg/L, the corresponding THM concentration was 100 to 120 µg/L. THMs formation was high when the chlorine dose exceeded 4 mg/L in Fort McKay, Woking, and Westlock waterworks. Although Vilna waterworks used a 5.2 mg/L chlorine dose, the THMs were low because of either high groundwater quality or presence of ammonia. Tangent waterworks used very high chlorine doses and THMs formation was high over the monitoring period.

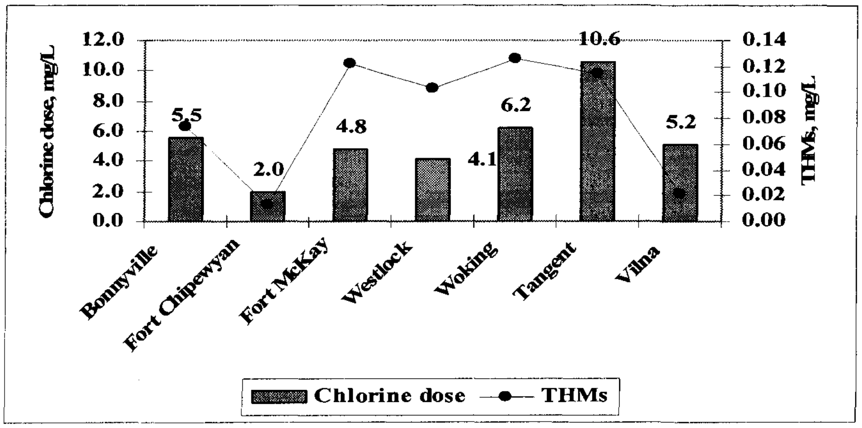


Figure 4.18: Chlorine dose vs. THMs at finished water

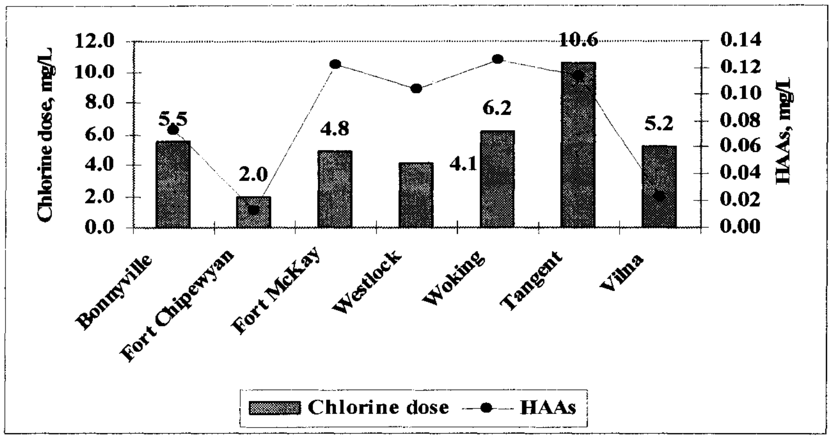


Figure 4.19: Chlorine dose vs. HAAs at finished water

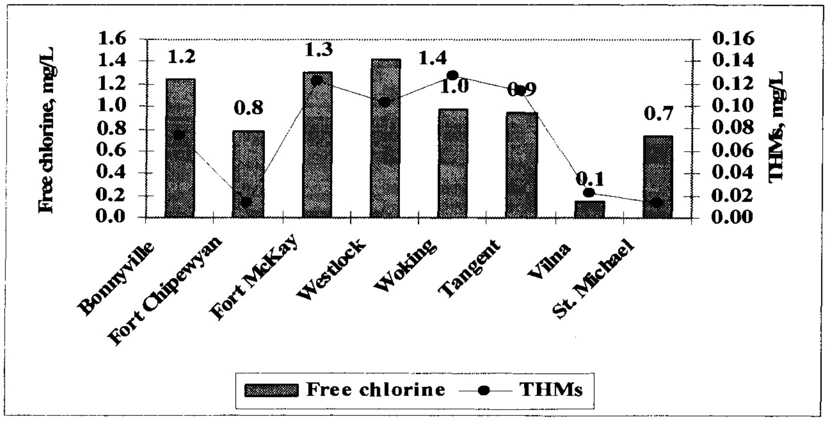


Figure 4.20: Free residual chlorine vs. THMs at finished water

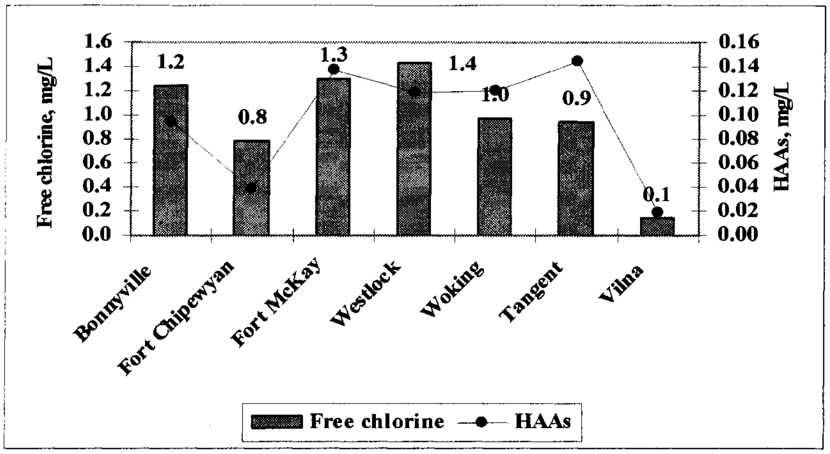


Figure 4.21: Free residual chlorine vs HAAs at finished water

Fort McKay, Woking, Westlock, and Tangent waterworks had about 1 mg/L free residual chlorine in finished water and high THMs and HAAs levels in finished water. The low velocity and large volume of reservoirs can increase the residence time and correspondingly provide an environment conducive to additional chlorine decay and accordingly an increase in THM formation (Abd El-Shafy and Grunwald, 2000). Minimum residual chlorine (free, combined or total chlorine) was greater than 0.1 mg/L in all locations of the water distribution system (SGMWW, 2006). Table 4.6 show the free and total residual chlorine levels for these facilities from combined data analysis.

Table 4.6: Seasonal variation of free and total residual chlorine

Season	**Free Chlorine, mg/L**			**Total Chlorine, mg/L**		
	L3	**L4**	**L5**	**L3**	**L4**	**L5**
Summer	1.01	0.62	0.42	1.52	1.09	0.79
Fall	0.93	0.65	0.33	1.55	1.19	0.67
Winter	1.02	0.74	0.42	1.55	1.43	0.88
Spring	1.09	0.86	0.53	1.67	1.25	0.91

L3 -Location 3 L4 - Location 4 L5 - Location 5

THMs and HAAs were shown to have a direct relationship with chlorine residual. It can thus be concluded that the THMs and HAAs increased in the distribution systems of the facilities in conjunction with an increase in residence time and a decrease in chlorine residuals within the distribution system.

4.5 THMs and HAAs Formation with the Treatment Efficiency of the Facilities

Seasonal variations in raw water quality, including water temperature, alkalinity, and TOC, subsequently lead to a high variation of chemical dose (i.e. coagulant,

coagulant aid, chlorine dose etc.) during conventional water treatment processes in order to maintain the residual chlorine level in the distribution system; this practice, in turn, can significantly influence the formation of THMs and HAAs in filtered water. The treatment efficiency of the facilities in terms of the percent removal of DOC, percent removal of color, and percent removal of UV_{254} have been calculated in the preceding section. THMs formation has been linked to the calculated treatment efficiency in order to understand its effect on individual facilities with regard to THMs and HAAs formation. Figures 4.22 to 4.27 illustrate the result. THMs formation was above the guideline value though the percent removal of DOC was about 50% by filtration in Fort McKay and Woking waterworks. The treatment efficiency of Tangent waterworks was comparatively low (28%) and THMs formation was high.

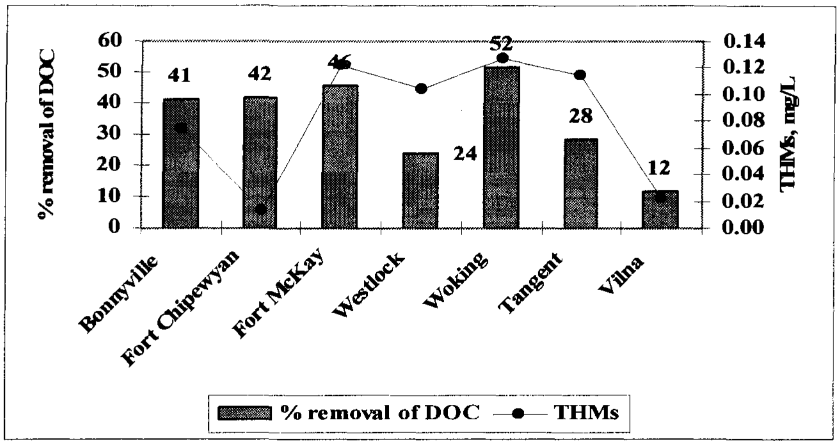


Figure 4.22: THMs formation with percent removal of DOC

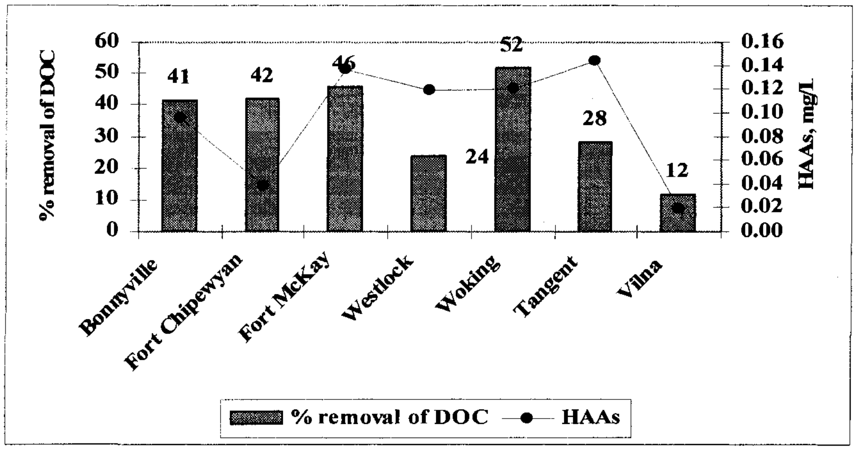


Figure 4.23: HAAs formation with percent removal of DOC

The percent removal of color showed a high efficiency in Fort McKay and Woking waterworks, but high THMs formation was also observed. With 54% removal of color, Westlock and Tangent waterworks showed high THMs formation as well.

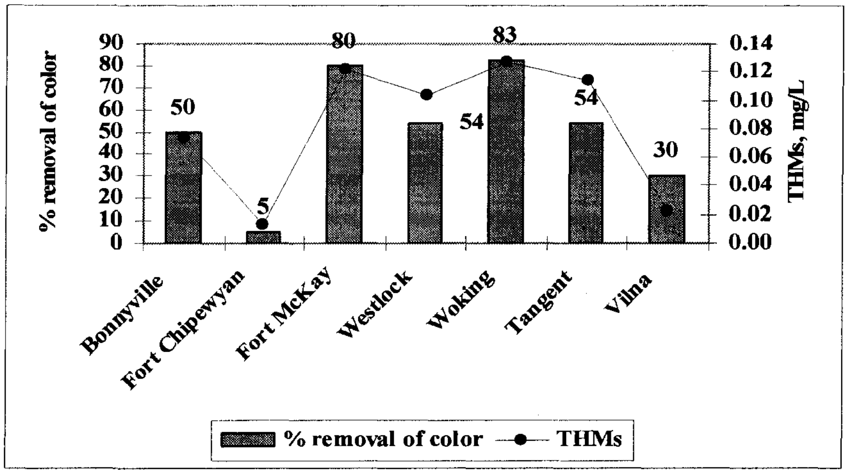


Figure 4.24: THMs formation with percent removal of color

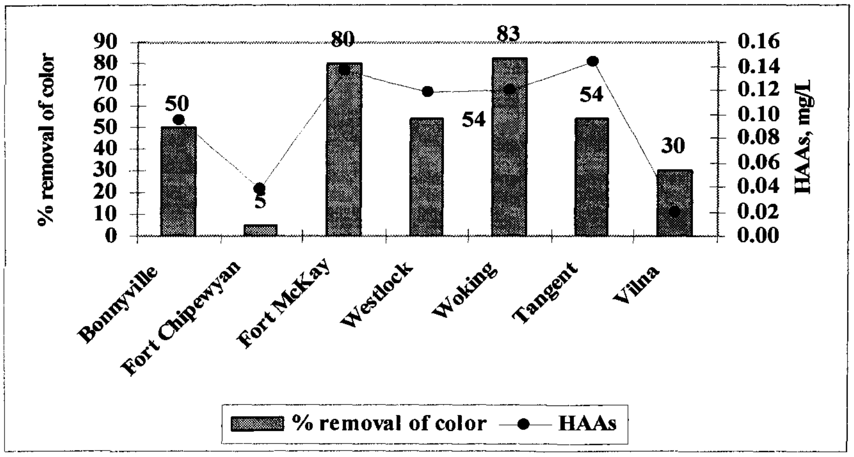


Figure 4.25: HAAs formation with percent removal of color

Among the eight waterworks under study, Fort McKay and Woking waterworks showed a good percent removal (69% and 72%) of UV_{254}; however, THMs formation was still high in these water treatment plants.

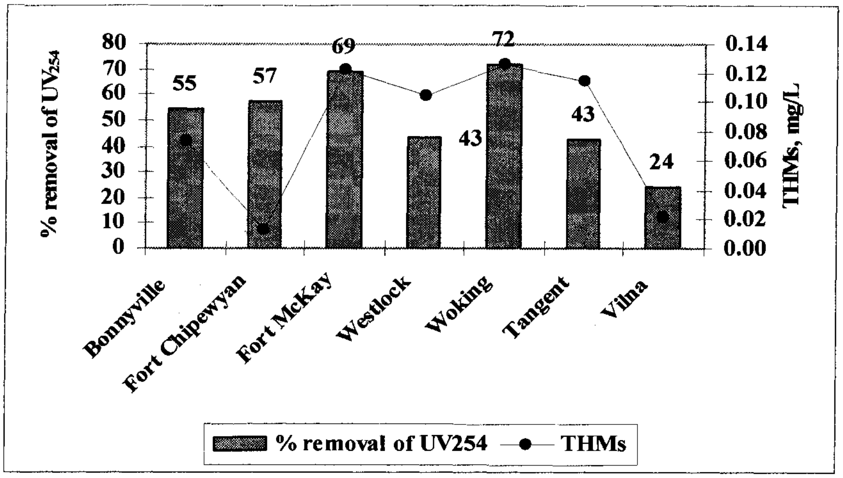


Figure 4.26: THMs formation with percent removal of UV_{254}

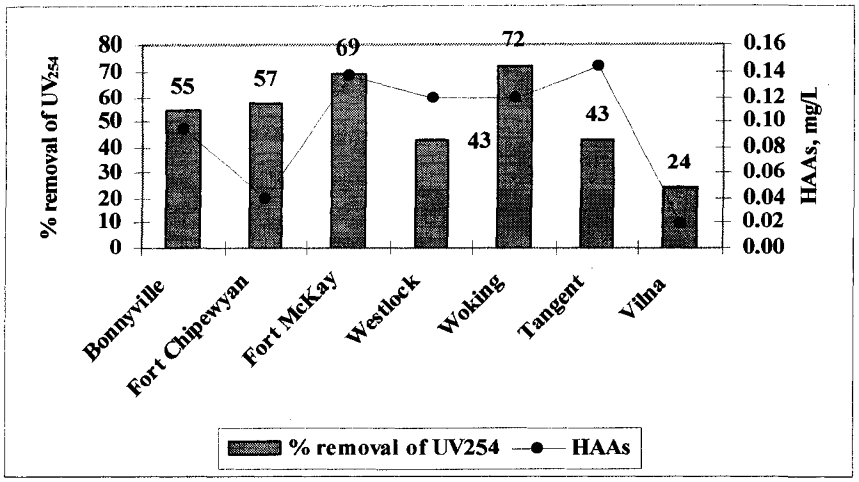


Figure 4.27: HAAs formation with percent removal of UV_{254}

Hence, THMs and HAAs formation were influenced here by the remaining DOC, color, and UV_{254} in these facilities. Although good percent removals of these parameters were observed from the analysis, the DOC, color, and UV_{254} of treated water were still high, as shown in Table 4.7.

Table 4.7: DOC, color, UV_{254} of treated water in the facilities

Facilities	Treated water DOC, mg/L	Treated water color, TCU	Treated water UV254 /cm
Bonnyville	9.7	6.5	0.10
Fort Chipewyean	2.3	5.0	0.02
Fort McKay	8.0	6.4	0.11
Westlock	7.2	9.7	0.14
Woking	8.2	7.8	0.13
Tangent	6.4	10.0	0.12
Vilna	9.8	21.4	0.26
St. Michael	n/a	n/a	n/a

4.6 Relationship of THMs with Water Quality Parameters

4.6.1 Relationship of THMs with Raw Water Quality Parameters

Most research in this area has sought to characterize the correlation of THMs formation with raw water quality parameters. Table 4.8 shows the individual correlation coefficient of finished water THMs with raw water quality data. Every first row of the table shows the average value of the parameters on the column while the second row shows the correlation coefficient of the parameter with THMs. Although the number data was the highest in fall and winter months (n=31 and 33), the correlation coefficients with THMs were very poor with all the parameters in these seasons. Summer and spring months have a limited number of data with which to confirm the moderate to good correlation coefficients among the parameters.

Table 4.8: Relationship of THMs with raw water quality parameters

Location 1	THMs-3 mg/L	Temp-1 °C	pH-1	DOC-1 mg/L	Color-1 TCU	UV-1 /cm	SUVA-1 L-mg/m
Summer	0.133	17.7	8.1	7.4	11.3	0.13	2.5
R^2 (n=10)	-	0.00	0.56	0.06	0.63	0.48	0.47
Fall	0.093	8.8	7.9	12.0	24.8	0.29	2.5
R^2 (n=31)	-	0.03	0.00	0.16	0.03	0.04	0.07
Winter	0.081	3.9	7.7	12.2	25.4	0.29	2.5
R^2 (n=33)	-	0.03	0.04	0.09	0.09	0.09	0.00
Spring	0.076	4.1	7.8	11.5	27.4	0.26	2.3
R^2 (n=8)	-	0.31	0.01	0.30	0.40	0.59	0.32

'*Temp-Temperature '3' and '1' denote location 3 and location 1 data

Two plots (Figure 4.28) of THMs vs. DOC (fall) and THMs vs. color (summer) are shown here. In general a seasonal classification of the data should give some pattern in each season. Although seasonal classification was performed here, however, all figures showed a scattered pattern of the parameters with THMs in every season, which might be an indication of inefficient operation in these facilities. All graphs for individual correlations are listed in Appendix B.

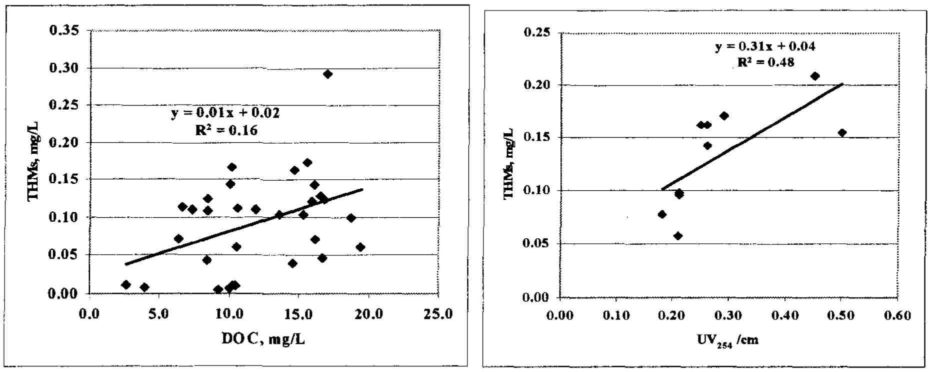
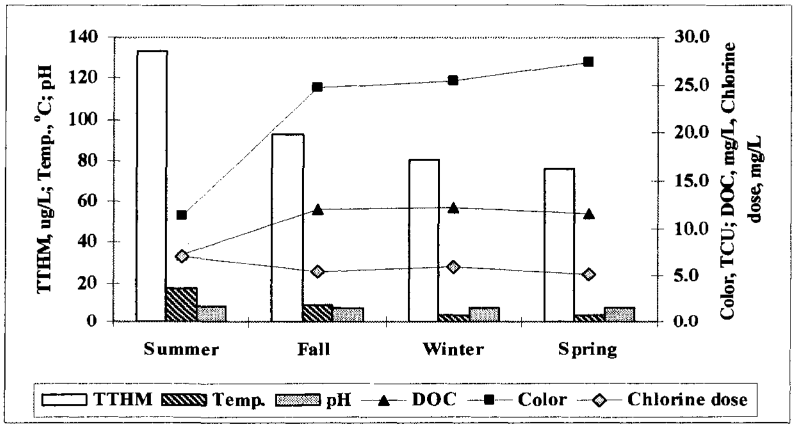


Figure 4.28: Individual correlation of THMs with raw water DOC (fall) and raw water UV (summer)

Figure 4.29 shows a plot representing THMs of finished water with the average raw water quality parameters. From Figure 4.29, no clear pattern was observed influencing THMs formation. The DOC of raw water and chlorine dose were found to be almost the same throughout the season. Additionally, the raw water pH was high, a condition which should favor THMs formation.



*Temp-Temperature

Figure 4.29: Average THMs with raw water quality parameters

Another set of graphical analyses was conducted for individual facility data with raw water quality parameters. Although the amount of data was limited, the relationship of raw water quality parameters with THMs concentration levels can be observed from these figures. The limited numbers of analyzed data are also attached with their corresponding figures. The figures are attached in Appendix B (B14 to B20).

Multiple regression analyses of the THMs in finished water with raw water temperature, DOC, UV_{254}, color, pH, monthly chlorine dose, and calculated SUVA were conducted and provided seasonal models to predict THMs levels. Seasonal models did not show a similar result in the positive or negative influence of the factors on THMs formation. With the limited amount of data available for the summer months, the multiple R^2 was found to be 0.92; however, no factor was found to be significant at a 95% confidence level. The only significant factor was found to be chlorine dose in winter data analysis, with a P-value of 0.031 at a 95% confidence level. The models developed from regression analysis are listed below.

Summer

$\text{THMs}= (-0.28).(\text{Temperature})^{(+0.02)}.(\text{DOC})^{(-0.04)}.(\text{color})^{(-0.002)}. (UV_{254})^{(+2.08)}$

$.(\text{pH})^{(+0.05)} .(Cl_2\ \text{dose})^{(+0.01)} .(\text{SUVA})^{(-0.16)}$ *$[R^2=0.92]$*----------------------------------(1)

Fall

$\text{THMs}= (-0.04).(\text{Temperature})^{(+0.001)} (\text{DOC})^{(-0.01)} .(\text{color})^{(+0.002)}$

$.(UV_{254})^{(+0.45)}.(\text{pH})^{(+0.03)}.(Cl_2\ \text{dose})^{(+0.01)}.(\text{SUVA})^{(-0.09)}$ *$[R^2=0.58]$*--------------------(2)

Winter

$\text{THMs}= (+0.12).(\text{Temperature})^{(-0.002)}.(\text{DOC})^{(+0.01)}.(\text{color})^{(+0.0003)}$

$.(UV_{254})^{(+0.64)}.(\text{pH})^{(-0.01)}.\mathbf{(Cl_2\ dose)}^{(+0.01)}.(\text{SUVA})^{(-0.07)}$

[R^2=0.62]--(3)

These models need to be recalibrated and validated with more data. Figures 4.30 to 4.32 show the relationship of predicted THMs from the models with the actual THMs for summer, fall, and winter.

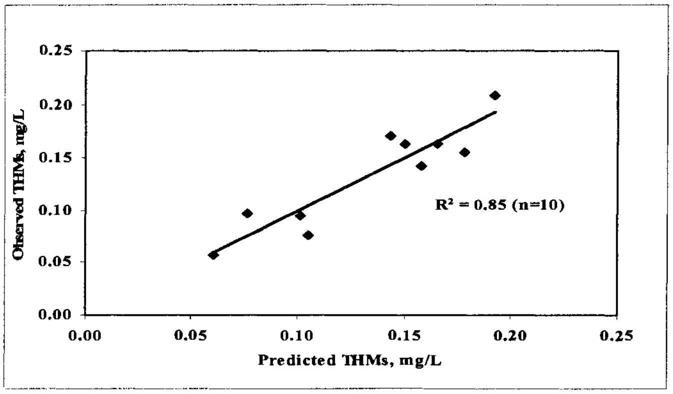


Figure 4.30: Regression analysis of THMs with raw water quality (summer)

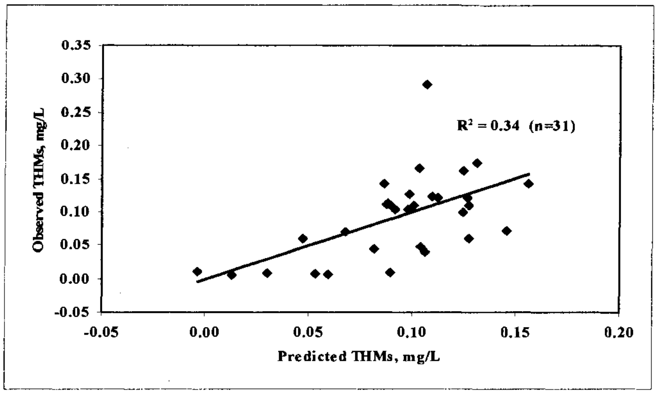


Figure 4.31: Regression analysis of THMs with raw water quality (fall)

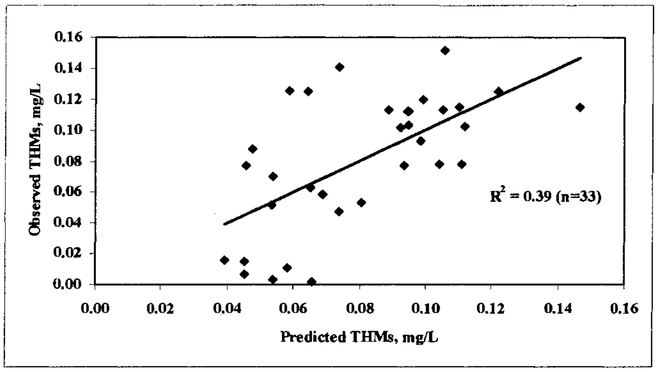


Figure 4.32: Regression analysis of THMs with raw water quality (winter)

Another set of regression analyses was conducted excluding the calculated SUVA (combined effect of collected parameters, DOC and UV_{254}) from the model parameters. No significant difference was observed in these analyses. These models are listed below:

Summer

$$\text{THMs} = (-0.45).(\text{Temperature})^{(+0.01)}.(\text{DOC})^{(-0.01)}.(\text{color})^{(+0.001)}.(UV_{254})^{(+0.61)}.(\text{pH})^{(+0.03)}.(Cl_2\ \text{dose})^{(+0.001)}$$

$[R^2=0.90]$-- (4)

Fall

$$\text{THMs} = (-0.13).(\text{Temperature})^{(-0.00002)}.(\text{DOC})^{(+0.01)}.(\text{color})^{(+0.003)}.(UV_{254})^{(-0.28)}.(\text{pH})^{(+0.02)}.(Cl_2\ \text{dose})^{(+0.01)}$$

$[R^2=0.53]$-- (5)

Winter

$$\text{THMs} = (+0.14).(\text{Temperature})^{(-0.0003)}.(\text{DOC})^{(+0.01)}.(\text{color})^{(+0.001)}.(UV_{254})^{(-0.11)}.(\text{pH})^{(-0.02)}.(Cl_2\ \text{dose})^{(+0.004)}$$

$[R^2=0.56]$-- (6)

In these analyses, no parameters were observed as significant within 95% confidence levels, coefficients of some parameters were very low and the P-values of all parameters were high. Positive and negative influences of these parameters on THMs formation also were not comparable in the seasonal models.

4.6.2 Relationship of THMs with Treated Water Quality Parameters

At Location 2 (before chlorination), the measured parameters for the facilities were pH, temperature, treated water DOC, color, and UV absorbance. THMs data from

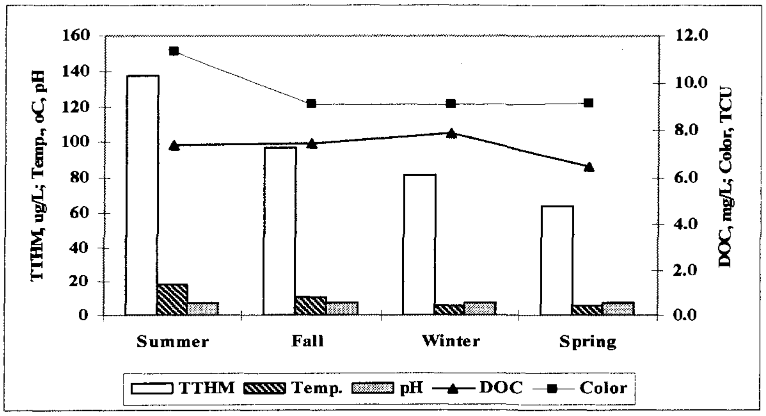
Location 3 was linked to these parameters for calculating individual correlation coefficient and modeling with multiple regressions. Table 4.9 shows the individual correlation coefficient and the average value of the parameters.

Table 4.9: Relationship of THMs with treated water quality parameters

Location 2	**THMs-3 mg/L**	**Temp-2 °C**	**pH-2**	**DOC-2 mg/L**	**Color-2 mg/L**	**UV_{254}-2 /cm**	**SUVA-2 L/mg-m**
Summer	0.137	18.5	7.6	7.4	11.3	0.13	1.8
R^2 (n=9)	-	0.04	0.57	0.05	0.47	0.63	0.26
Fall	0.097	10.2	7.6	7.5	9.1	0.13	1.7
R^2 (n-32)	-	0.10	0.06	0.01	0.15	0.09	0.10
Winter	0.082	5.4	7.5	7.9	9.1	0.14	1.7
R^2 (n=34)	-	0.06	0.05	0.00	0.12	0.04	0.02
Spring	0.064	5.7	7.4	6.5	9.1	0.10	1.6
R^2 (n=7)	-	0.22	0.44	0.69	0.66	0.77	0.01

'2' and '1' denote location 2 and location 1 data ; n= number of data; *Temp-Temperature

UV_{254}, DOC, and treated water color showed comparatively strong correlation with THMs formation in spring. The limited number of data in spring and summer months could not possibly confirm the relationship. All the data were again unusually scattered throughout the season. Figure 4.33 shows the average THMs for finished water with treated water temperature, DOC, pH, and color. The high temperature and color of treated water in summer might affect the high THM levels in summer.



*Temp-Temperature

Figure 4.33: Average THMs with treated water quality parameters

Multiple linear regression analysis for the treated water quality parameter with THMs was conducted for summer, fall, and winter. The analyzed result for summer showed a R^2 of 0.95. However, no parameter was significant at a 95% confidence level for the summer analysis. Some parameters showed very low coefficients with high P-values. UV_{254} and temperature showed a positive influence on THMs formation, but the data was too limited to reach any definite conclusion. The regression analysis of the fall and winter data showed a lower value of R^2 than the summer data. The DOC of filtered water was found to be significant at a 95% confidence level with the lowest P-value in fall and had a positive influence on the predicted THMs. Winter data analysis provided four significant factors for THMs formation; DOC, UV_{254}, SUVA, and pH, at a 95% confidence level. UV_{254} and pH showed an unusual negative impact on THMs formation whereas DOC showed a positive influence in the fall and winter model. The developed model equations for predicting seasonal THMs at finished water are listed below.

Summer

$$\text{THMs} = (0.4).(\text{Temperature})^{(+0.03)}.(\text{DOC})^{(-0.04)}.(\text{color})^{(+0.001)}.(UV_{254})^{(+4.14)}.(\text{pH})^{(-0.08)}.(\text{SUVA})^{(-0.25)}.(Cl_2\ \text{dose})^{(-0.01)} \quad [R^2=0.98]\text{------------}(7)$$

Fall

$$\text{THMs} = (0.06).(\text{Temperature})^{(+0.001)}.\mathbf{(DOC)}^{(+0.05)}.(\text{color})^{(+0.003)}.(UV_{254})^{(-2.4)}.(\text{pH})^{(-0.04)}.(\text{SUVA})^{(+0.16)}.(Cl_2\ \text{dose})^{(+0.0002)}$$

$$[R^2=0.68]\text{------------}(8)$$

Winter

$$\text{THMs} = (0.1).(\text{Temperature})^{(+0.003)}.\mathbf{(DOC)}^{(+0.04)}.(\text{color})^{(+0.002)}\ \mathbf{(UV_{254})}^{(-2.78)}.\mathbf{(pH)}^{(-0.05)}.\mathbf{(SUVA)}^{(+0.21)}.(Cl_2\ \text{dose})^{(-0.002)}$$

$$[R^2=0.67]\text{------------}(9)$$

The dissimilarity of the seasonal models needs to be affirmed by recalibrating and validating these models with more data in future work. Figures 4.34 to 4.36 show the relationship of predicted THMs from the models with the actual THMs for summer, fall, and winter.

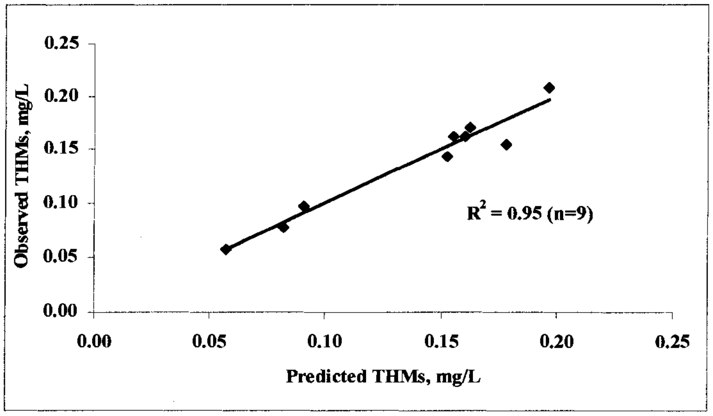


Figure 4.34: Regression analysis of THMs with treated water quality (summer)

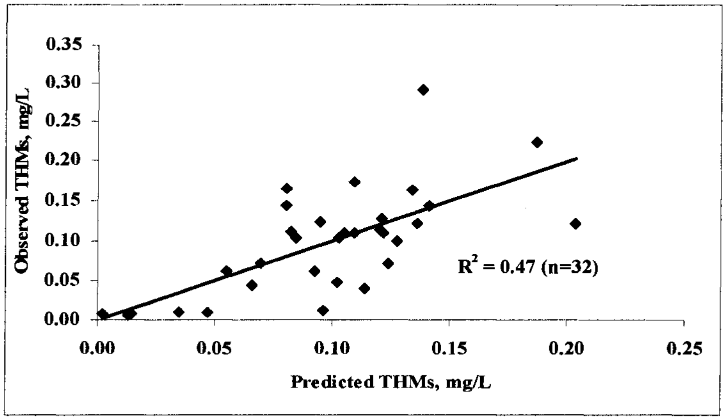


Figure 4.35: Regression analysis of THMs with treated water quality (fall)

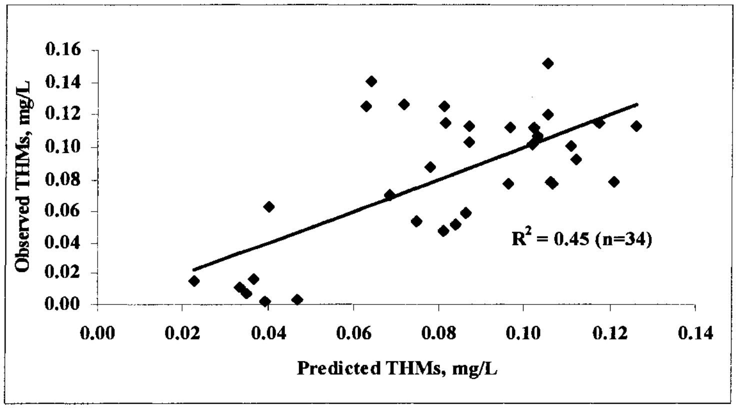


Figure 4.36: Regression analysis of THMs with treated water quality (winter)

Regression analyses excluding the calculated SUVA from the model parameters did not show any significant difference compared to previous analyses. These model equations are listed below:

Summer

$$\text{THMs} = (-0.02).(\text{Temperature})^{(+0.03)}.(\text{DOC})^{(+0.02)}.(\text{color})^{(-0.006)}.(\text{UV}_{254})^{(+1.31)}.(\text{pH})^{(-0.08)}.(\text{Cl}_2\text{ dose})^{(-0.008)}$$

$$[R^2=0.96] \text{-----} (10)$$

Fall

$$\text{THMs} = (+0.20).(\text{Temperature})^{(+0.002)}.\mathbf{(DOC)}^{(+0.01)}.(\text{color})^{(-0.001)}.(\text{UV}_{254})^{(-0.34)}.(\text{pH})^{(-0.03)}\,(\text{Cl}_2\text{ dose})^{(+0.004)}$$

$$[R^2=0.62] \text{-----} (11)$$

Winter

$$\text{THMs} = (+0.15).(\text{Temperature})^{(+0.003)}.(\text{DOC})^{(+0.003)}\,(\text{color})^{(-0.001)}.(\text{UV}_{254})^{(-0.16)}.(\text{pH})^{(-0.01)}.(\text{Cl}_2\text{ dose})^{(+0.004)}$$

$$[R^2=0.50] \text{-----} (12)$$

From the seasonal analyses, positive influences of temperature and DOC was observed on THMs formation and color and UV_{254} showed negative impact on THMs formation. Similar to the previous analyses, the positive or negative influence can not be confirmed due to the contrast pattern. The coefficients of some parameters were very low with high P-value. Among all the analyses, DOC of treated water in fall was observed to be the only significant factor at 95% confidence level with a P-value of 0.031.

4.6.3 Modeling with Back Propagation Artificial Neural Network

Back Propagation Neural Network (BPNN) was also used to predict THMs formation using combined datasets in Neuroshell 2 software. The THMs are used as output whereas the raw water quality parameters are used as the first set of inputs and the treated water quality as the second set of inputs. However, the correlation coefficients of both sets of modeling were very low and could not be used as a feasible model. Better ANN modeling can be achievable by a larger set of data which is more representable for the actual scenario. The best set of ANN modeling is briefly illustrated here. The characteristics of the best model with BPNN are as follows: output as THMs-3 with the input parameter of pH-1, temperature-1, DOC-1, color-1, UV_{254}-1, SUVA-1,Cl_2 Dose, free Cl_2 -3, total Cl_2 -3; random-momentum BPNN as architecture and neuron number in three layers—linear (9), logistic (12) and output layer linear (1). Figure 4.37 shows the actual and predicted THMs of the production data processed. Table 4.10 shows the number of pattern and the R^2 of this network.

Table 4.10: Pattern numbers and R^2 of BPN network

Pattern	**N**	**R^2**
Total pattern	75	0.21
Production set	15	0.36
Training set	45	0.14
Testing set	15	0.09

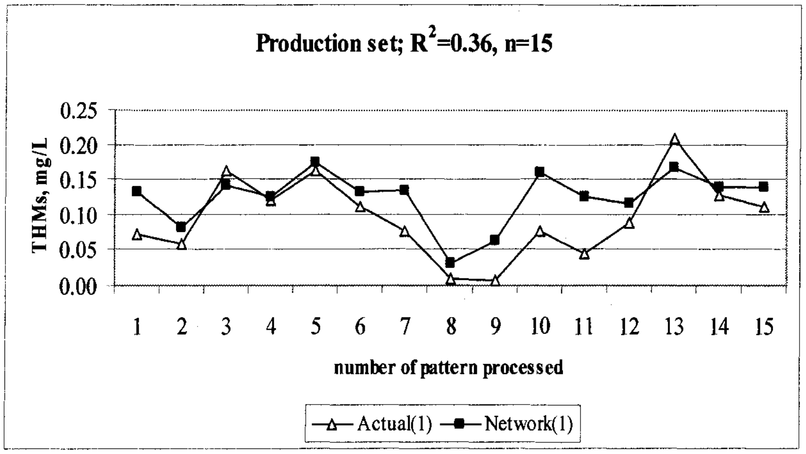


Figure 4.37: BPNN modeling of THMs with random-momentum

4.6.4 Relationship between THMs and HAAs

The THMs and HAAs correlation was analyzed for all three locations with the limited amount of data available. A strong to moderate relationship between THMs and HAAs is observed from the data. HAAs increase with an increase in TTHM concentration. At both Location 3 (entering the distribution system) and Location 5 (furthest point of distribution system), the correlation coefficient was found to be moderate: 0.75 and 0.74, respectively. But at the midpoint of distribution system, they were found to be strongly correlated with a R^2=0.94. Table 4.11 shows the correlation coefficient of THMs and HAAs at different locations in different seasons. A higher correlation of THMs and HAAs was observed in fall and spring than in winter at the midpoint of distribution system. Seasonal analysis showed that the relationship of THMs and HAAs was comparatively low in winter seasons at all locations. However, no summer data was available for HAAs.

Table 4.11: Correlation between THMs and HAAs

R^2	Location 3	Location 4	Location 5
Fall	0.97 (7)	0.99 (8)	0.79 (8)
Winter	0.87 (9)	0.91 (9)	0.76 (9)
Spring	0.99 (3)	0.99 (3)	0.94 (3)

() no. of data analyzed in the parenthesis

Figures 4.38 to 4.40 show the relationship between THMs and HAAs without classifying the dataset in seasons (combined dataset). The analysis was done using the available 20 HAAs data with corresponding THMs data from all eight facilities.

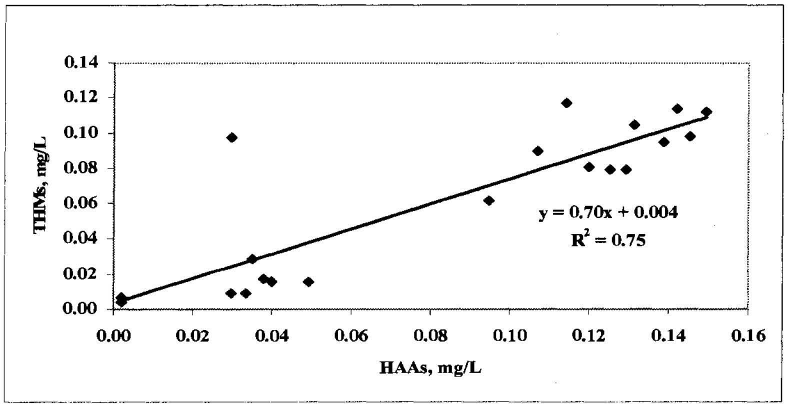


Figure 4.38: Relationship of THMs and HAAs at finished water

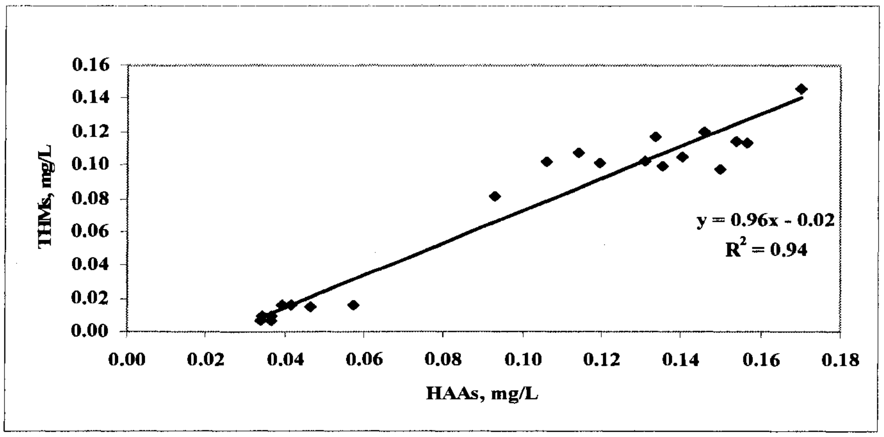


Figure 4.39: Relationship of THMs and HAAs at midpoint of distribution system

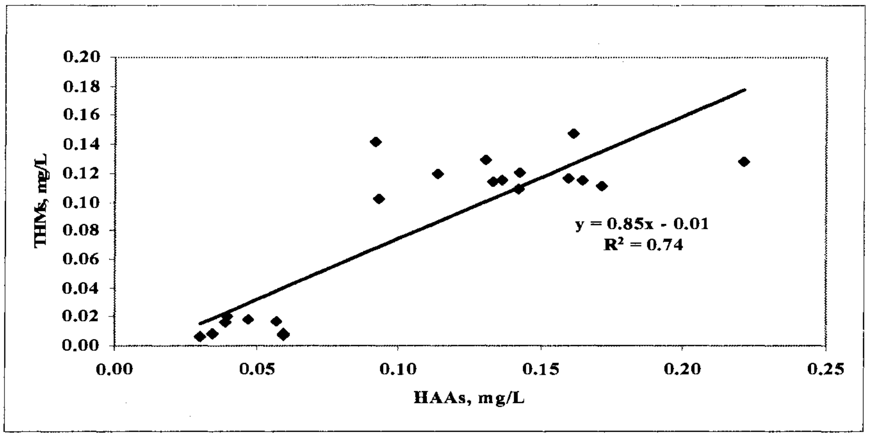


Figure 4.40: Relationship of THMs and HAAs at furthest point of distribution system

Niemiliski et al. (1993) found a very poor correlation (R^2=0.27) between THMs and HAAs (n=35). Serodes et al. (2003) observed moderate correlations between HAAs and THMs in experimental chlorinated water in Quebec. Nikolaou et al. (2004) observed a linear correlation between THMs and HAAs. The THMs-HAAs correlation in the previous studies may not be similar to the observed pattern of THMs and HAAs formation in this study. However, with only a combined 20 data item from all the facilities, the relation cannot be precisely confirmed. This result indicates the need for a more resourceful study and research in this area.

4.6.5 Relationship of THMs with Finished Water Quality Parameters

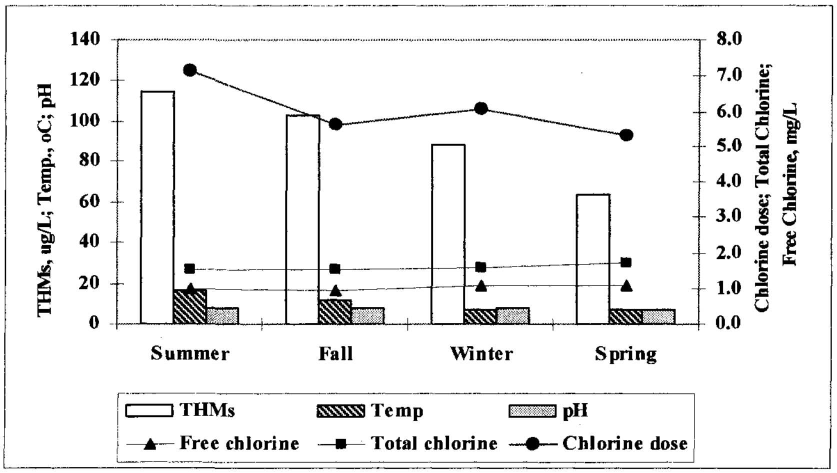
Parameters measured at Location 3 (finished water before entering the distribution system) are pH, temperature, total, and free residual chlorine, THMs, and HAAs. The relationship between THMs concentration and clear well parameters was also analyzed. Individual correlation coefficient and the average value of the parameters are shown in Table 4.12.

Table 4.12: Relationship of THMs with chlorinated water quality parameters

Location 3	**THM**	**Temp**	**pH**	**Free Cl_2**	**Total Cl_2**	**Cl_2 Dose**
Summer	0.115	16.82	7.64	1.01	1.52	7.13
R^2 (n=15)	-	0.23	***0.58***	0.07	0.04	0.33
Fall	0.103	11.45	7.62	0.95	1.55	5.60
R^2 (n=30)	-	0.07	0.27	0.11	0.00	0.07
Winter	0.088	6.98	7.53	1.07	1.57	6.07
R^2 (n=31)	-	0.10	0.37	0.28	0.03	0.04
Spring	0.064	6.81	7.46	1.07	1.69	5.29
R^2 (n=7)	-	0.30	0.33	***0.52***	0.08	0.17

*Temp-Temperature

From Figure 4.41, it can be observed that TTHM concentration was the highest when the chlorine dose was the highest (7.13 mg/L) in summer and was the lowest when the chlorine dose was the lowest (5.29 mg/L) in spring. Another important factor affecting the formation of TTHM could be the temperature of the finished water. The pH at the clear well did not vary significantly throughout the monitoring period.



*Temp-Temperature

Figure 4.41: THMs with chlorinated water quality

4.7 Bromodichloromethane (BDCM) Level in the Facilities

Although the concentration of BDCM is included in the concentration of total trihalomethanes in the MAC, a separate guideline for BDCM is also considered necessary because BDCM is considered to be a probable carcinogen in humans, with sufficient evidence in animals and some limited evidence in humans (Health Canada, 2006). The presence of brominated by-products such as BDCM will depend on the presence of bromine in the source water. According to the GCDWQ, the MAC for BDCM is 0.016 mg/L. In order to check the condition of BDCM concentration in finished water, the data was analyzed for eight waterworks at the clear well, at the midpoint of the distribution system, and at the furthest point of the distribution system. Table 4.13 shows the BDCM concentration (mg/L) for each facility at different locations.

Table 4.13: BDCM concentration treatment plants.

Waterworks	**Location 3**	**Location 4**	**Location 5**
	BDCM, mg/L	**BDCM, mg/L**	**BDCM, mg/L**
Bonnyville	0.011	0.013	0.016
Fort Chipwyean	0.004	0.004	0.005
Fort McKay	0.003	0.003	0.004
Westlock	0.002	0.003	0.003
Woking	0.014	0.015	0.016
Tangent	0.001	0.001	0.001
Vilna	0.007	0.008	0.011
St. Michael	0.002	0.003	0.003

The BDCM concentration was found to be well under the MAC (0.016 mg/L) for almost all the facilities during the monitoring period. However, it showed the highest concentration of 0.016 mg/L in Woking and Bonnyville waterworks based on the given data. The low concentration of BDCM also indicated that bromine present in the source water did not strongly affect THMs formation. This can further be explained by the speciation analysis of both THMs and HAAs in the following section. Figure 4.42 shows the seasonal analysis of the average BDCM concentration for the facilities over the monitoring period. Like other THMs concentrations (Section 4.4), BDCM also increased with distance and time traveled from the treatment plant within distribution system. The concentration of BDCM increased significantly from finished water at Location 3 to the furthest point of distribution system (Location 5). The increase rate was higher in warmer months than in colder months.

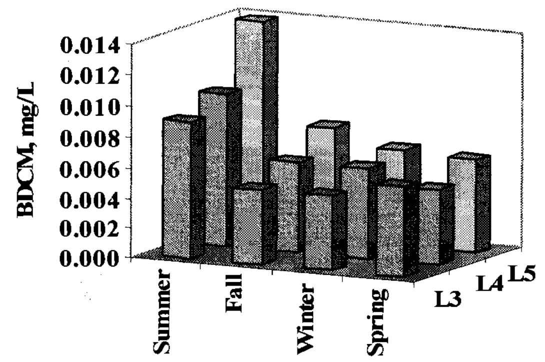


Figure 4.42: BDCM in finished water and within distribution system

4.8 Speciation Analysis of THMs and HAAs

The total THMs here were the sum of four species of trihalomethanes, i.e, chloroform, bromoform, bromodichloromethane, and dibromochloromethane. The haloacetic acids constituted six species and were the total sum of chloroacetic acid, dichloroacetic acid, trichloroacetic acid, bromoacetic acid, dibromoacetic acid, and bromochloroacetic acid. The speciation analysis was conducted for each waterworks in order to see the effect of chloride or bromide concentration on the formation of these THMs and HAAs. If bromine concentration was high in the water of the facilities under study, then the percentage of brominated by-products would be more than the chlorinated species. The following figures show the speciation analysis of THMs and HAAs of individual facilities over the monitoring period. These THMs and HAAs were measured at finished water (Location 3) and after chlorination at clear well for all the treatment plants. Figures 4.43 and 4.44 show the THMs and HAAs speciation from the waterworks that used lake water as source water. Chloroform was the dominant species among other THMs in both the facilities. Fort

Chipewyan had limited data compared to Bonnyville waterworks for analysis. In Fort Chipewyan, BDCM presented about 34% of total trihalomethanes. BDCM was the second-most dominant species. Among HAAs, Bonnyville waterworks showed dichloro and trichloroacetic acids (DCAA and TCAA) as the leading species. Fort Chipewyan waterworks showed chloroacetic acids as having the highest percentage at 47%. The water quality differs from source to source. The raw water data of Fort Chipewyan waterworks had very low DOC, UV, and color levels compared to other waterworks. This might be a cause of this variation in speciation from two different lake water-using waterworks.

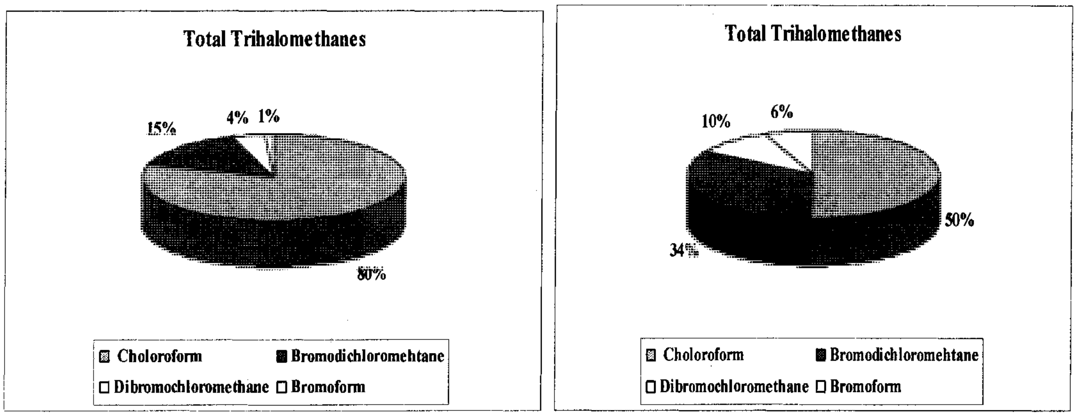


Figure 4.43: THMs speciation at Bonnyville and Fort Chipewyan waterworks

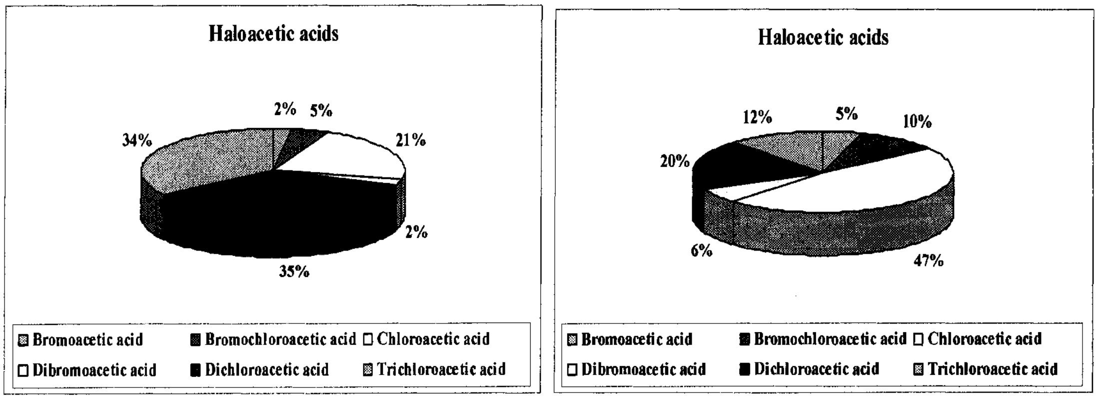


Figure 4.44: HAAs speciation at Bonnyville and Fort Chipewyan waterworks

Chloroform was the dominant species of the TTHMs in Fort McKay and Westlock waterworks, both of which use river water as source water (Figure 4.45). River water may contain a high amount of DBP precursors. Speciation analysis showed that the presence of brominated THMs was very low in these facilities. This pattern of speciation of THMs found here is the most common, and is similar to results in all previous studies (Whitaker et al., 2003).

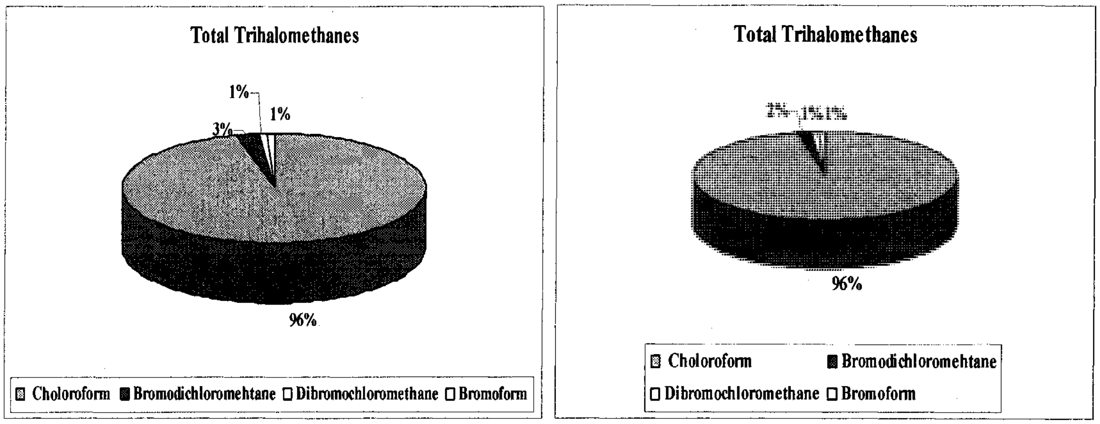


Figure 4.45: THMs speciation at Fort McKay and Westlock waterworks

Haloacetic acids speciation showed trichloro and dichloro acetic acids (TCAA and DCAA) as the dominant species for these facilities (Figure 4.46).

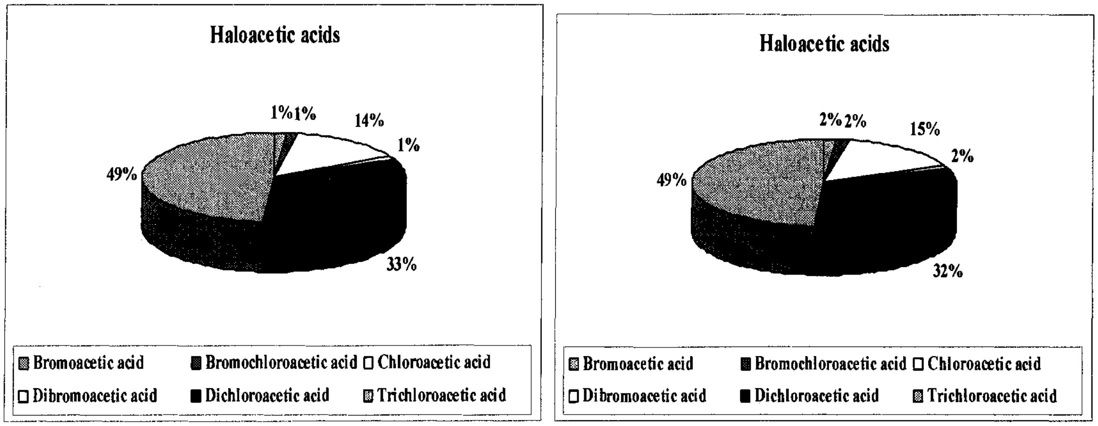


Figure 4.46: HAAs speciation at Fort McKay and Westlock waterworks

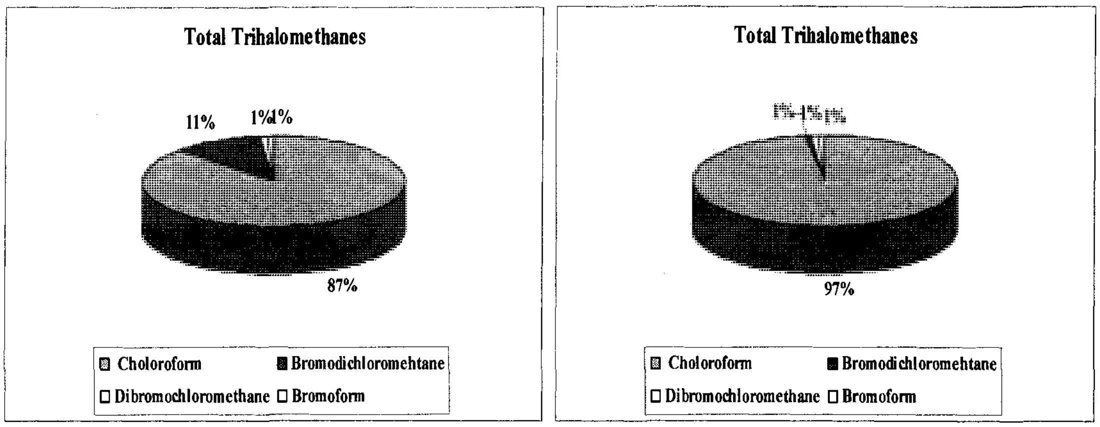


Figure 4.47: THMs speciation at Woking and Tangent waterworks

The highest percentage remained for chloroform among other THMs in Woking and Tangent waterworks, both of which use impoundment as source water (Figure 4.47). This runoff water should contain the highest level of organic materials, i.e., THMs and HAAs precursors, of any source water. Like river water- using waterworks the dominant species among HAAs for these waterworks were trichloro and dicholoro acetic acids (TCAA and DCAA) (Figure 4.48).

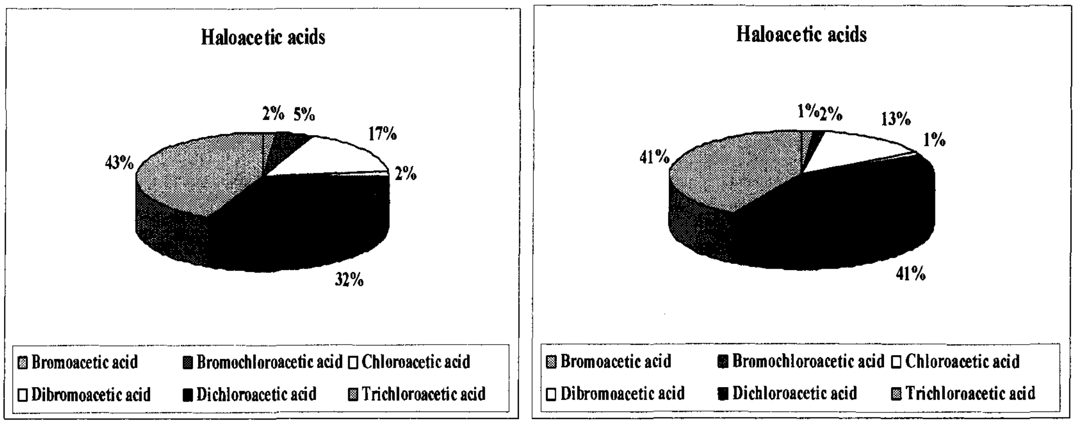


Figure 4.48: HAAs speciation at Woking and Tangent waterworks

Figures 4.49 and 4.50 show the speciation analysis of Vilna and St. Michael waterworks. Vilna and St. Michael waterworks used groundwater as raw water sources. Speciation analysis showed that the presence of bromoform was moderate in these facilities. Presence of bromine in groundwater might be an explanation for this speciation. Yet chloroform was the dominant species in both waterworks, and bromoform was the second dominant species after chloroform. The major species of haloacetic acids in the Vilna waterworks were found to be chloro and dichloro acetic acid, as in Figure 4.50. St. Michael waterworks had no data for haloacetic acids.

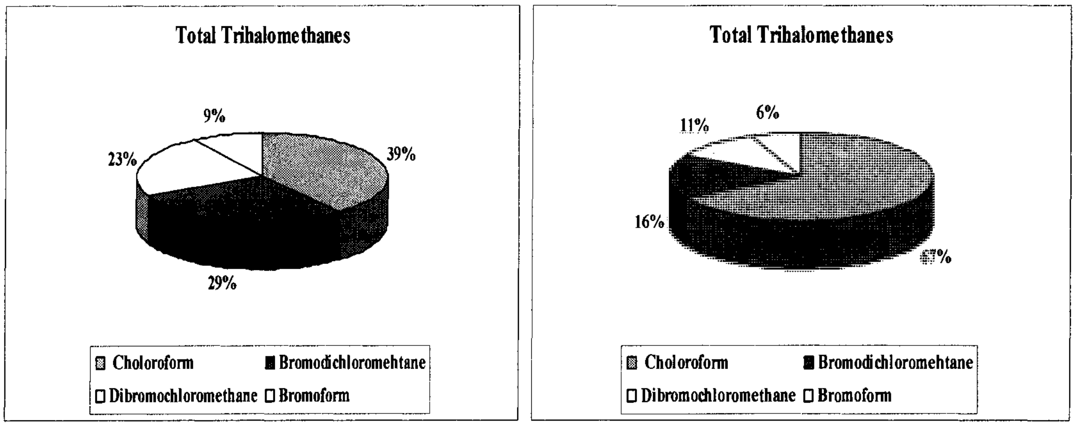


Figure 4.49: THMs speciation at Vilna and St. Michael waterworks

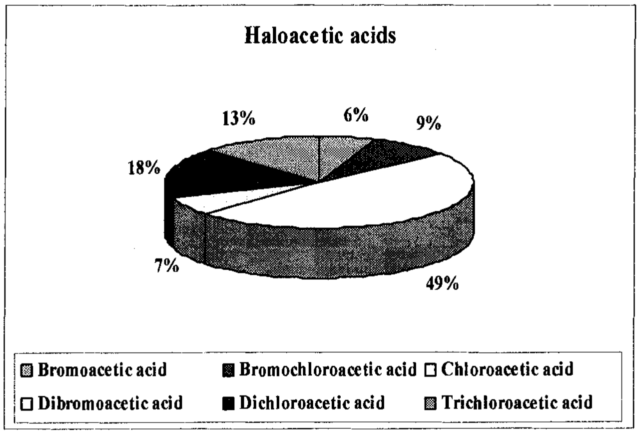


Figure 4.50: HAAs speciation at Vilna waterworks

No major portion of brominated acetic acids was observed in all the facilities except for Fort Chipewyan waterworks with 34% of TTHMs as BDCM. Chlorinated species entirely dominated for the formation of both THMs and HAAs.

4.9 Control of THMs and HAAs Formation

Small drinking water utilities have limited financial and technical resources, often lack full-time staff to manage the utility, and may be geographically isolated in rural areas where severe weather conditions and agricultural pollution are extensive. The waterworks studied here in this research are also located in remote areas of Northern Alberta where extremity of weather condition is also a great concern. Figures 4.51 and 4.52 show the service population in each facility in terms of THMs and HAAs formation. As observed from the analysis, Fort McKay, Woking, Westlock and Tangent waterworks have posed more concern with regard to controlling high levels of THMs and HAAs above the regulatory value. Among these waterworks, Westlock waterworks serves the highest number of consumers at 5091. The total service

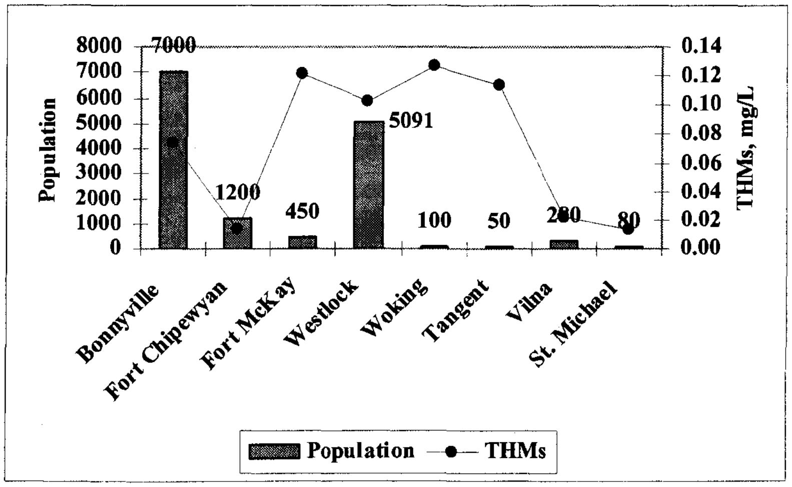


Figure 4.51: Population vs. THMs in individual facility

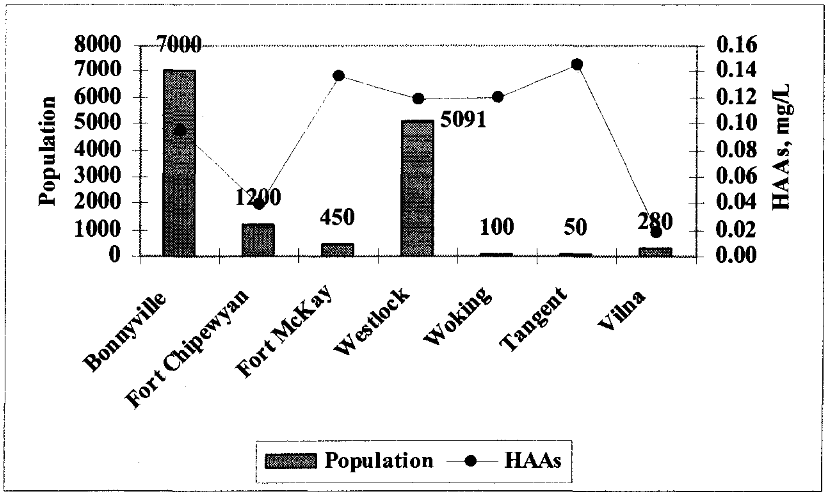


Figure 4.52: Population vs. HAAs in individual facility

population under direct threat of health concerns for high levels of THMs and HAAs formations is 5691. Although, the other four facilities using lake water and groundwater as source water were found to be well under the regulatory value of THMs and HAAs during the monitoring period, these facilities also have the potential of forming high levels of THMs and HAAs. However, in terms of service population, the total number of consumers for these eight facilities in insignificant in the context of Alberta's total population. However, the severity of the existing high level of THMs and HAAs formation in these facilities is not trivial. Small utilities are known to have more difficulty in ensuring regular distribution to their customers of drinking water that complies with established standards, and the majority of violations have concerned utilities serving fewer than 5000 people (Coulibaly and Rodriguez, 2003). The consequences for these small facilities have led authorities to consider and acquire essential steps for other water treatment facilities in Alberta. According to Nieminski et al. (1993), there is no significant difference in DBP formation between large and small water system. As such, larger facilities in Alberta may also experience the THMs and HAAs formation problem observed in these smaller facilities.

As stated earlier, the graphical analysis of the parameters showed scattered data for every season fluctuating within a wide range, which might be an indication of inconsistent operations in all the facilities. Increased levels of chlorine dose and DOC, pH, and temperature in water should increase the frequency of THMs and HAAs formation. The high residual chlorine level observed in finished water and within the distribution system might influence THMs and HAAs formation. Although these facilities showed good removal of DOC from raw water, the formation of THMs and HAAs may be influenced by the NOM that is still present. The high levels of THMs and HAAs have been observed in Fort McKay, Westlock, Tangent, and Woking waterworks, where the average DOC of treated water was in a relatively high range of 6.4 to 8.2 mg/L. Based on the analysis, THMs and HAAs formation might be influenced by a high pH of raw water, chlorine dose, high residual chlorine, and high temperature in summer. UV_{254} and residual chlorine level measurements can be used in the facilities as a surrogate to measure the existing THMs and HAAs levels. On average, UV absorbance higher than 0.110 /cm measured at 254 nm and residual chlorine levels higher than 1 mg/L in finished water had shown high level of THMs and HAAs in these facilities.

Therefore, the key control measures of these facilities would be assessment of technical and operational variability and optimization of the operation as well as of the treatment processes. Uses of coagulant, coagulant aid, chlorine doses, chlorination time with minimum residual testing and rechecking have been recommended in site-specific bench scale studies. Chlorine overdosing should be checked carefully by the operator to maintain the minimum residual required in the distribution system. The efficient application of chlorine dose to maintain the required CT value can minimize the THMs and HAAs significantly.

The service life and functional condition of pipes and connectors in the distribution system should also be rechecked and assessed since organic deposits in pipe walls might be a possible cause for increasing THMs and HAAs within the distribution system (Rossman, 2001). Enhanced coagulation might be the best cost effective option for controlling THMs and HAAs formation by removing the NOM that still present in the water of these drinking-water facilities (Xie, 2004). For the purpose of evaluating enhanced coagulation, jar testing is necessary prior to application in full-scale treatment plants. Enhanced coagulation is not a suitable option for any raw water supply with high alkalinity because of the higher acid and caustic required for lowering and readjusting pH level. Another alternative cost-effective treatment practice for these small facilities might be the use of chlorine/chloramine disinfectant rather than chlorine alone. Using UV disinfection can also be considered. Application of other alternative disinfectants, e.g., ozone and chlorine dioxide, might not be feasible for these small facilities and, moreover, they have some issues of maintaining secondary residuals within the distribution system and creating other DBPs.

Runoff water and river water-using waterworks impose more challenges than lake water and ground water-using waterworks in terms of THMs and HAAs control. Selection of control measures in these small facilities is very crucial and is a function of the source water, the capital and operating costs, and drinking water regulations.

Chapter 5: Conclusions and Recommendations

5.1 Research Summary

Considering the potential health risks posed by the presence of THMs and HAAs in drinking water, a successful small scale monitoring program was conducted by the Municipal Approval Team of Northern Region of Alberta Environment with a vision of creating a baseline database of THMs and HAAs along with other water quality parameters. The selected facilities for this program were well representative of various sources, including river, lake, impoundment, and groundwater. Numerous studies were reviewed which have focused on different DBPs formed in water treatment plants and distribution systems, including the possible causes of their formation and available control strategies, which have provided better understanding of the present research work. The collected data were thoroughly analyzed with different classifications and compared with similar research studies.

It has been observed that the mean and median of total THM concentration exceeded the guideline value of 0.100 mg/L in Fort McKay, Westlock, Woking, and Tangent waterworks throughout the monitoring period. DOC, chlorine dose, color, and other data were scattered in all seasons and no specific pattern or strong correlation was observed from the statistical and graphical analysis. Based on the analysis, THMs and HAAs formation were suspected to be influenced by observed high pH levels in the raw water, chlorine dose, high levels of residual chlorine, and high temperatures in summer. More data will be needed to confirm the formation characteristics.

Average THMs concentration in finished water was the highest in summer (0.110 mg/L) and lowest in spring season (0.056 mg/L), and showed an increasing trend with the distance traveled to the remote point of the distribution system. From the clear well to the midpoint of the distribution system the THMs concentration increased by 12.7% in summer and 23.2% in spring and to the furthest point of the distribution system it increased by 23.6% in summer and 51.8% in spring. THMs concentration in the finished water can be used to measure its concentration within the distribution system by observed percent increase from this study.

Although the data regarding HAAs concentration were limited, the overall picture of HAAs concentration in waterworks using river and impoundment water showed a much higher level of formation (above the guideline value) than the THMs formation. The HAAs concentration increased within the distribution system in a similar manner to the THMs concentration. The increasing rate of HAAs was not consistent all through the distribution system, however, a condition which may be due to the biodegradation of HAAs within the distribution system. No summer data was available for HAAs concentration. A strong correlation between HAAs and THMs has been observed within the distribution system; however, analysis with more data will be required in order to ensure the validity of the identified relationship.

The free and total residual chlorine data within the distribution system showed an obvious pattern of consumption of these residuals when increasing distance within the distribution system was observed. THMs showed an inverse relationship with chlorine residuals maintained in the finished water throughout the distribution system. Multiple Regression analysis of THMs provides some seasonal model correlating temperature, DOC, pH, UV_{254}, SUVA, and chlorine dose. Back propagation neural network analysis predicted THMs from the parameters with low R^2. Regression models, although generally quite good, are considered to be preliminary because of the limited data available for this study. Models need recalibration for application in full-scale treatment plants with more updated data. The lack of data limits a separate set of modeling of THMs with runoff and river water using facilities those posed greater concern. Chlorination time and residence time within the distribution system are also important factors to be accounted in order to arrive at a good model to predict THMs. A successful model must include other raw water parameters such as alkalinity (important parameter affecting coagulation performance). Operational parameters such as coagulant dose, flow, etc, must be considered as well.

From speciation analysis it can be observed that formation of these THMs and HAAs in the facilities is not influenced by bromine concentration. BDCM was marginal with the guideline value for runoff- (Woking) and lake water- (Bonnyville) using facilities. Chloroform was the dominant species of THMs, and BDCM was the second highest species for all the waterworks. DCAA and TCAA were the dominant species of HAAs.

Optimization of the treatment processes, i.e., uses of coagulant, coagulant aid, chlorine doses, chlorination time, and minimum residual testing, is needed in order to minimize the THMs and HAAs levels in these facilities. Groundwater and lake water-using facilities have THMs and HAAs levels under the regulatory value. However, control measures should also be taken in these facilities as they have the potential for high THMs and HAAs formation. Enhanced coagulation is the best option for treatment practice in terms of cost effectiveness and feasibility for minimizing this high level of THMs and HAAs from small facilities. The higher levels of SUVA (>2

L-mg/m) observed in Fort McKay, Tangent, Woking, and Westlock will provide an ideal venue in which to practice enhanced coagulation as well as the high pH of the raw water in these facilities can be an obstacle to achieving better TOC removal. An alternative cost-effective practice for these small facilities will be chlorine/chloramines as a second disinfectant to maintain residual in the distribution system. UV disinfection can also be considered. The limited operational and financial resources of these small facilities will be a barrier to adapting other available control strategies (using other alternative disinfectants—ozone and chlorine dioxide; membrane technologies; and carbon adsorption) in this case.

5.2 Recommendations for Future Work

Although this research has fulfilled its primary goal of providing the basis for identifying the causes of formation and measures of minimizing the high levels of THMs and HAAs, future research in this area is highly recommended. For the purpose of evaluating the recommended treatment technology, enhanced coagulation and jar tests are recommended for future research. More data will be needed for future modeling of THMs and HAAs prediction and for applying site-specific models. For collecting more full-scale data from the facilities, the prepared Microsoft Access DBP database can be updated centrally and can be used as a useful THMs and HAAs database for better modeling and improved understanding of the causes of their formation for future research. Waterworks with runoff and river as source water should be the key focus of conducting re-assessment and optimizing their treatment technology to control high level of THMs and HAAs.

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Appendix A Data Preprocessing

Table A1: Monthly average statistics of location 1 parameters

Location 1	pH	Temp °C	DOC mg/L	Color TCU	UV_{254} /cm
Mean	7.8	8.1	10.9	23.0	0.259
Median	7.9	5.5	11.2	22.6	0.273
Standard Deviation	0.3	5.4	2.0	5.4	0.042
Variation	0.1	28.7	4.0	28.9	0.002
Minimum	7.3	2.2	5.9	11.5	0.160
Percentile (0.01)	7.3	2.3	6.1	11.9	0.165
Percentile (0.05)	7.3	2.7	6.9	13.3	0.184
Percentile (0.25)	7.6	3.8	10.5	20.3	0.238
Percentile (0.75)	8.0	13.2	12.3	26.0	0.292
Percentile (0.95)	8.2	16.2	13.0	30.0	0.305
Percentile (0.99)	8.2	18.8	13.2	31.3	0.313
Maximum	8.2	19.5	13.2	31.6	0.315

Table A2: Monthly average statistics of location 2 parameters

Location 2	pH	Temp °C	DOC mg/L	Color TCU	UV_{254} /cm
Mean	7.5	9.3	7.2	9.7	0.130
Median	7.5	6.7	7.4	9.6	0.133
Standard Deviation	0.3	4.9	1.2	1.9	0.025
Variation	0.1	24.1	1.4	3.6	0.001
Minimum	6.9	4.2	4.4	5.2	0.075
Percentile (0.01)	6.9	4.2	4.5	5.4	0.078
Percentile (0.05)	7.1	4.4	5.1	6.4	0.089
Percentile (0.25)	7.4	5.8	6.8	8.9	0.117
Percentile (0.75)	7.7	13.8	8.1	11.3	0.142
Percentile (0.95)	7.8	16.6	8.5	12.0	0.170
Percentile (0.99)	7.9	19.3	8.7	12.0	0.173
Maximum	7.9	20.0	8.7	12.0	0.174

Table A3: Monthly average statistics of location 3 parameters

Location 3	pH	Temp °C	Chlorine Dose mg/L	Free Chlorine mg/L	Total Chlorine mg/L	THMs mg/L	HAAs mg/L
Mean	7.5	10.3	5.8	1.01	1.56	0.082	0.067
Median	7.5	8.2	5.9	0.99	1.58	0.074	0.077
Standard Deviation	0.4	4.7	1.3	0.17	0.19	0.022	0.029
Variation	0.2	22.4	1.6	0.03	0.04	0.000	0.001
Minimum	5.7	5.5	2.8	0.71	1.13	0.047	0.009
Percentile(0.01)	6.0	5.6	3.1	0.72	1.15	0.049	0.012
Percentile(0.05)	7.2	5.9	4.5	0.78	1.24	0.059	0.024
Percentile(0.25)	7.5	6.6	5.3	0.91	1.47	0.065	0.072
Percentile(0.75)	7.6	14.7	6.1	1.15	1.69	0.097	0.079
Percentile(0.95)	7.7	17.8	8.6	1.24	1.80	0.118	0.088
Percentile(0.99)	7.8	20.0	8.7	1.34	1.82	0.119	0.091
Maximum	7.9	20.5	8.7	1.36	1.82	0.119	0.091

Table A4: Monthly average statistics of location 4 parameters

Location 4	pH	Temp °C	Chlorine Dose mg/L	Free Chlorine mg/L	Total Chlorine mg/L	THMs mg/L	HAAs mg/L
Mean	7.5	10.8	5.8	0.72	1.25	0.095	0.067
Median	7.5	10.3	5.9	0.73	1.13	0.094	0.073
Standard Deviation	0.3	3.3	1.3	0.15	0.35	0.024	0.028
Variation	0.1	10.8	1.6	0.02	0.12	0.001	0.001
Minimum	6.6	6.4	2.8	0.43	0.91	0.064	0.013
Percentile(0.01)	6.7	6.5	3.1	0.44	0.91	0.065	0.016
Percentile(0.05)	7.2	6.6	4.5	0.50	0.92	0.068	0.027
Percentile(0.25)	7.4	8.1	5.3	0.63	1.10	0.075	0.069
Percentile(0.75)	7.6	13.7	6.1	0.84	1.31	0.110	0.081
Percentile(0.95)	7.7	15.8	8.6	0.92	1.61	0.133	0.089
Percentile(0.99)	7.7	16.2	8.7	0.93	2.33	0.144	0.091
Maximum	7.7	16.3	8.7	0.93	2.51	0.146	0.092

Table A5: Monthly average statistics of location 5 parameters

Location 4	pH	Temp °C	Chlorine Dose mg/L	Free Chlorine mg/L	Total Chlorine mg/L	THMs mg/L	HAAs mg/L
Mean	7.5	10.8	5.8	0.72	1.25	0.095	0.067
Median	7.5	10.3	5.9	0.73	1.13	0.094	0.073
Standard Deviation	0.3	3.3	1.3	0.15	0.35	0.024	0.028
Variation	0.1	10.8	1.6	0.02	0.12	0.001	0.001
Minimum	6.6	6.4	2.8	0.43	0.91	0.064	0.013
Percentile(0.01)	6.7	6.5	3.1	0.44	0.91	0.065	0.016
Percentile(0.05)	7.2	6.6	4.5	0.50	0.92	0.068	0.027
Percentile(0.25)	7.4	8.1	5.3	0.63	1.10	0.075	0.069
Percentile(0.75)	7.6	13.7	6.1	0.84	1.31	0.110	0.081
Percentile(0.95)	7.7	15.8	8.6	0.92	1.61	0.133	0.089
Percentile(0.99)	7.7	16.2	8.7	0.93	2.33	0.144	0.091
Maximum	7.7	16.3	8.7	0.93	2.51	0.146	0.092

A6: Time Series Plots at different locations.

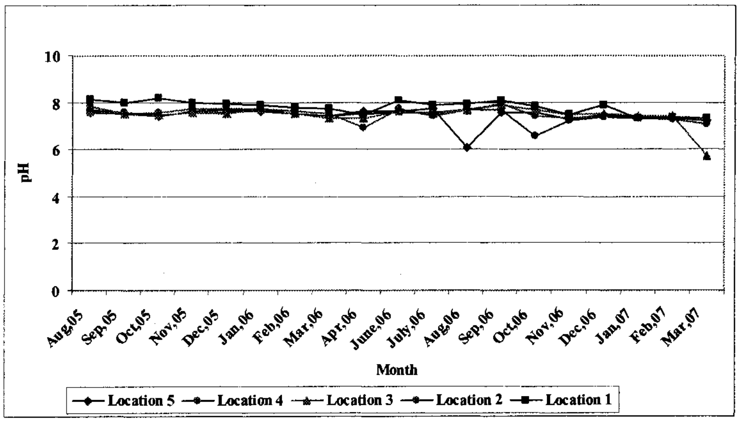


Figure A 6.1: Average water pH at different locations

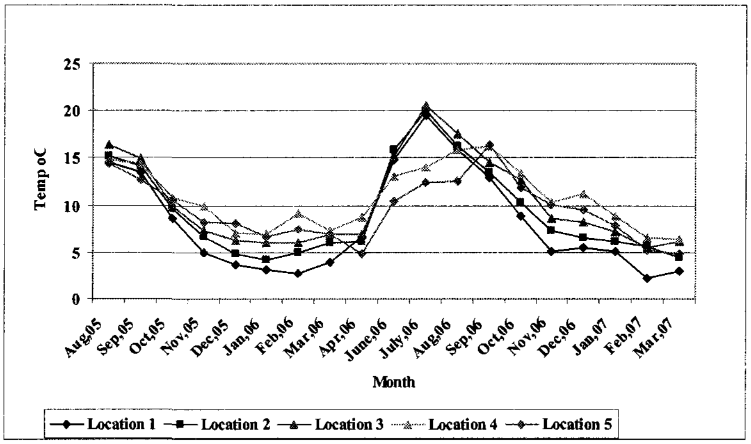


Figure A 6.2: Average water temperature at different locations

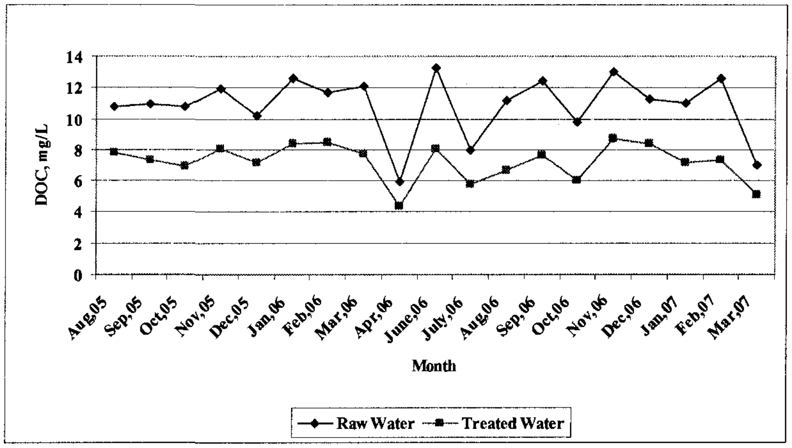


Figure A 6.3: Average DOC of raw and treated water

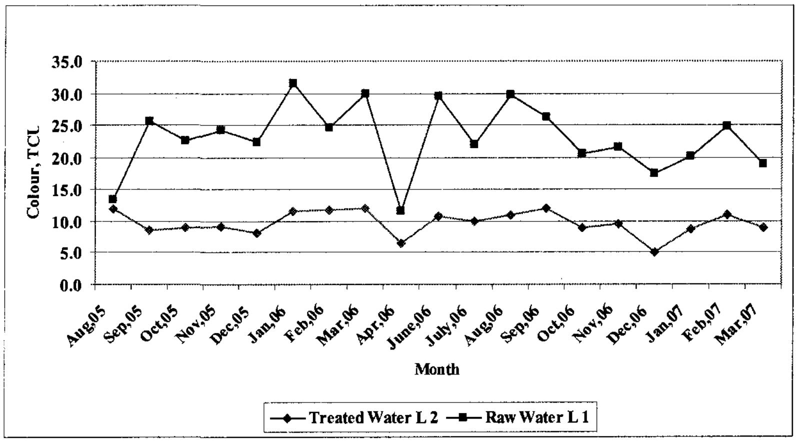


Figure A 6.4: Average color of raw and treated water

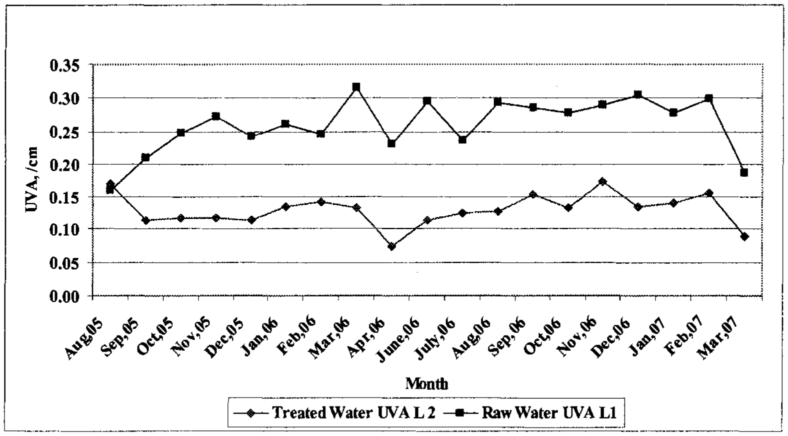


Figure A 6.5: Average UVA of raw and treated water

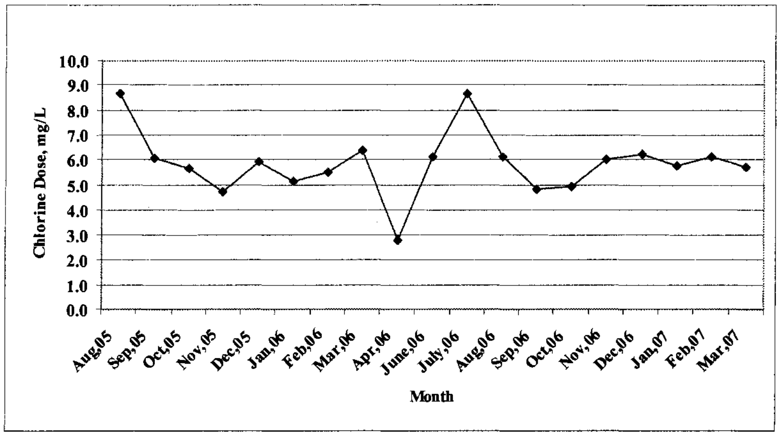


Figure A 6.6: Monthly average chlorine dose

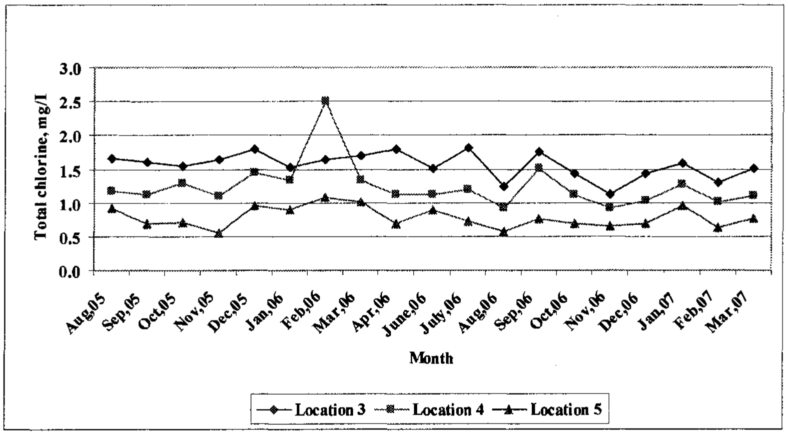


Figure A 6.7: Average total chlorine within distribution system

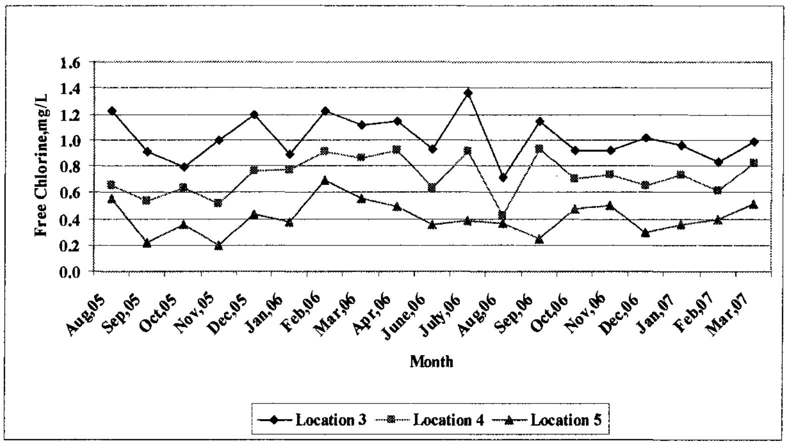


Figure A 6.8: Average free chlorine within the distribution system

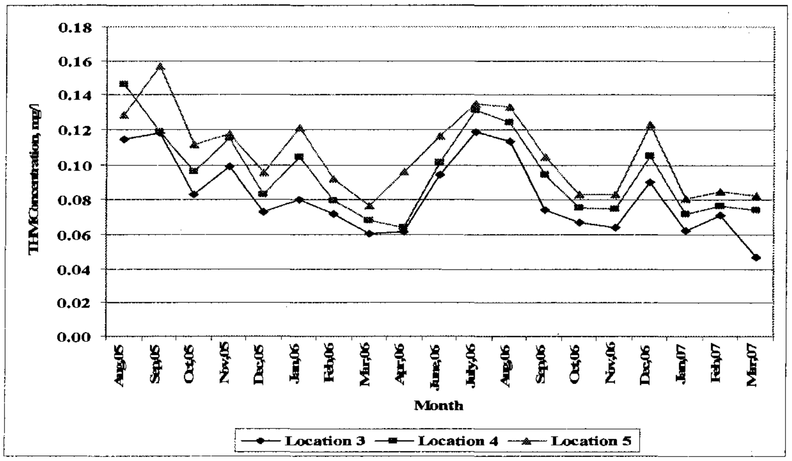


Figure A 6.9: Average trihalomethanes within the distribution system

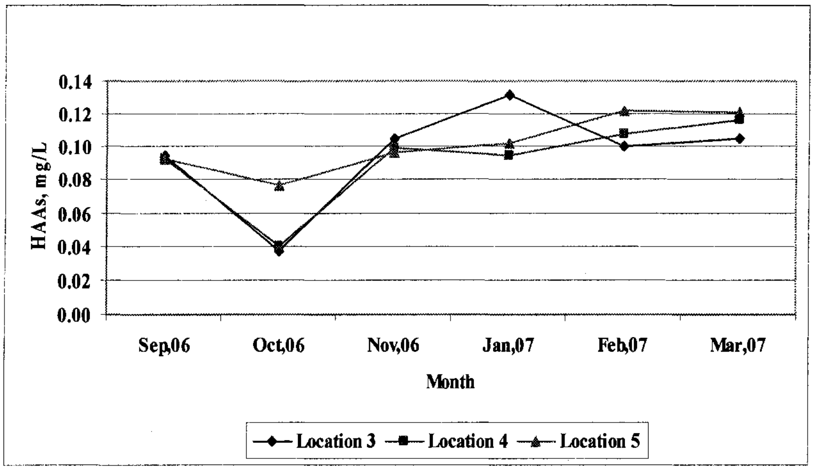


Figure A 6.10: Average haloacetic acids within the distribution system

Appendix B Graphical Analysis of THMs in Finished Water

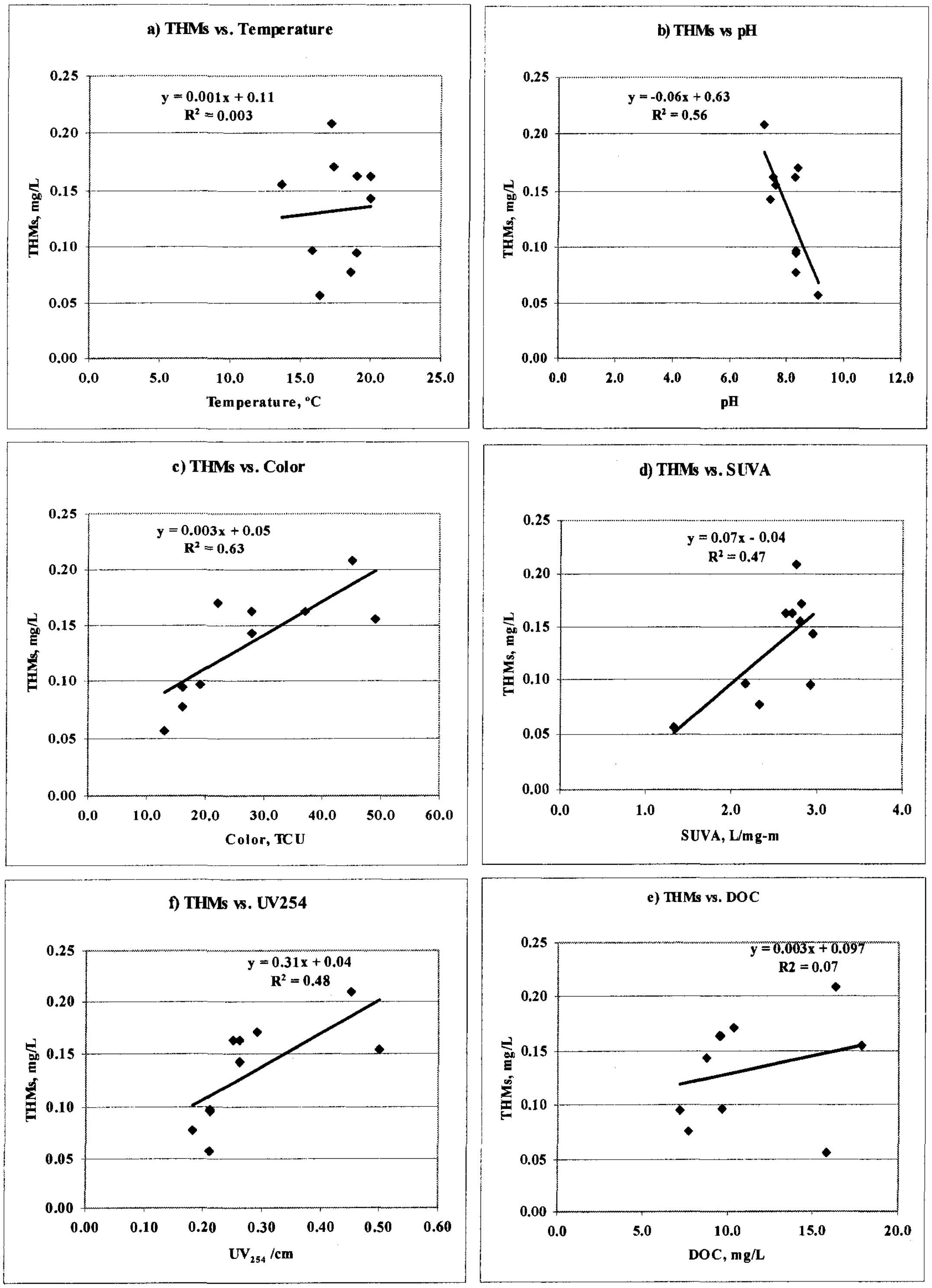


Figure B1:THMs with raw water quality parameters (Summer)

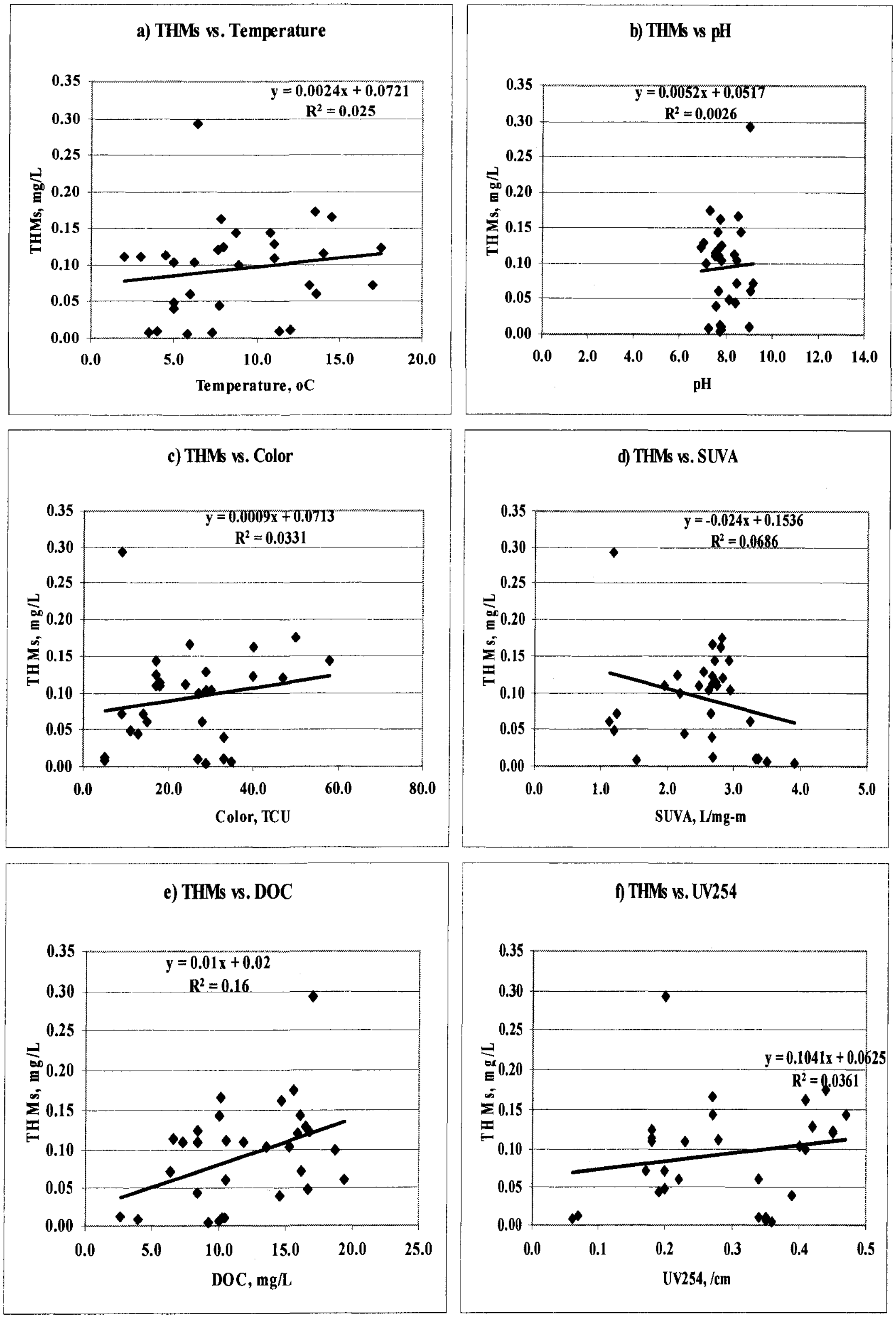


Figure B2:THMs with raw water quality parameters (Fall)

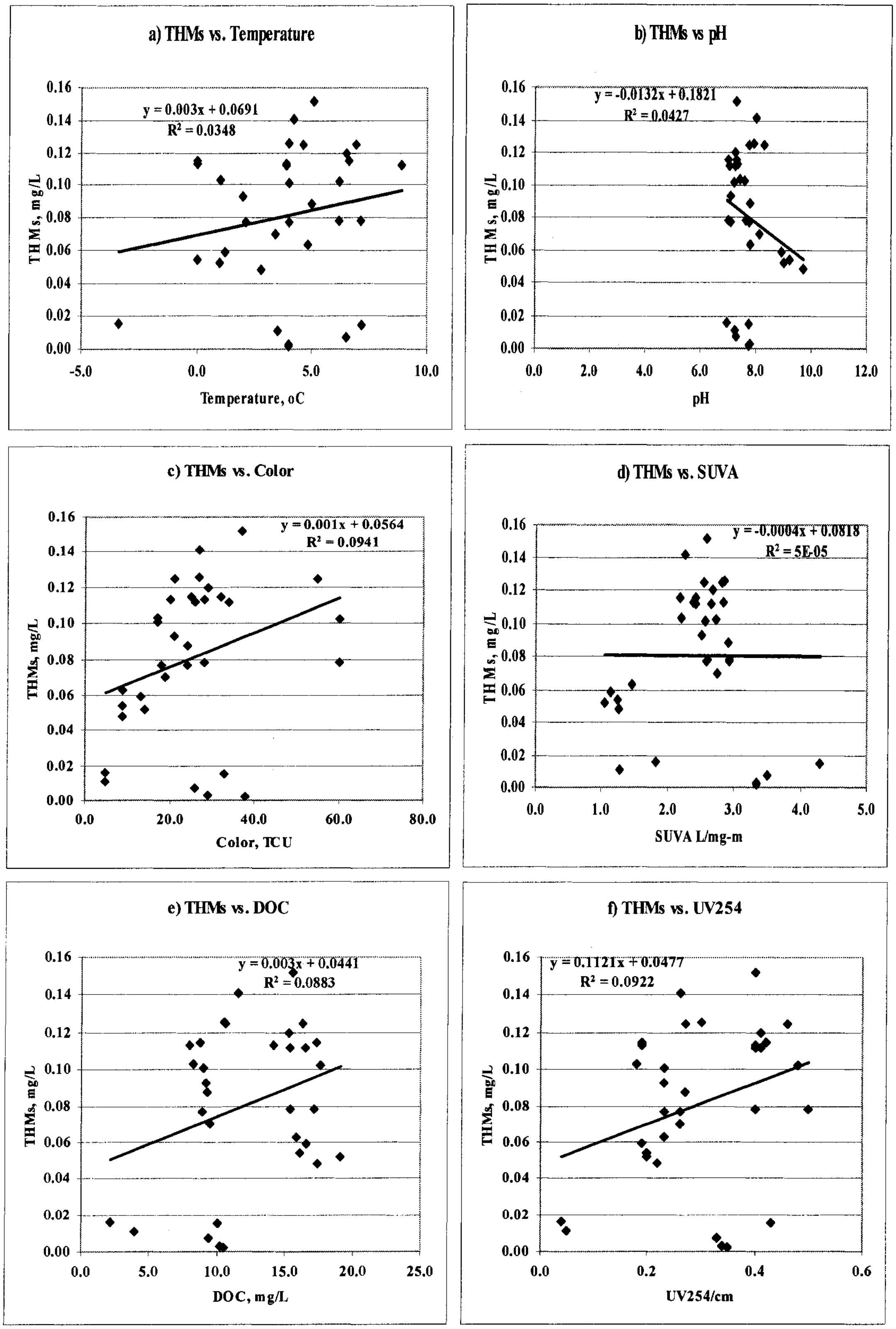


Figure B3:THMs with raw water quality parameters (Winter)

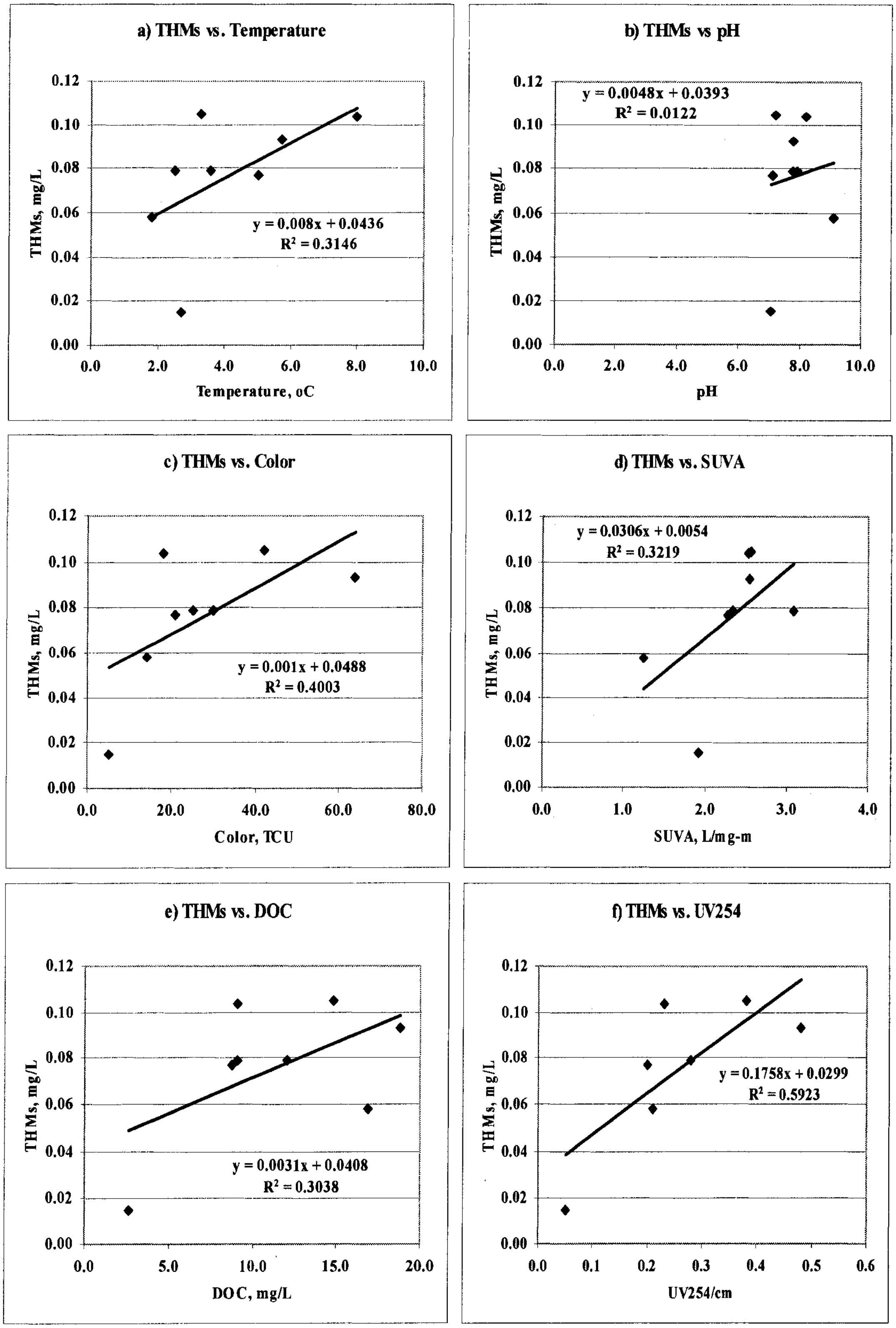


Figure B4:THMs with raw water quality parameters (Spring)

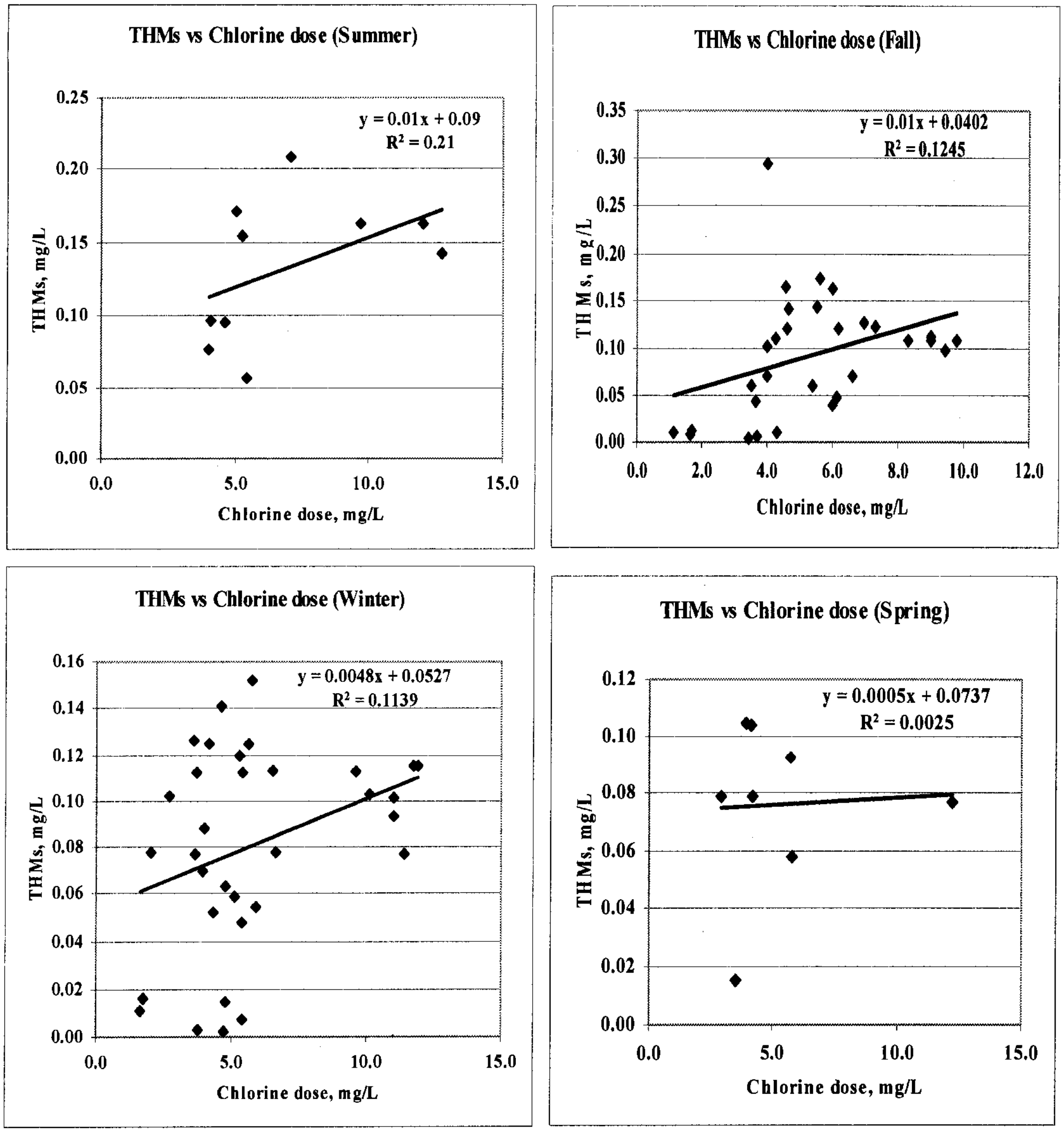


Figure B5:THMs with monthly chlorine dose for all seasons

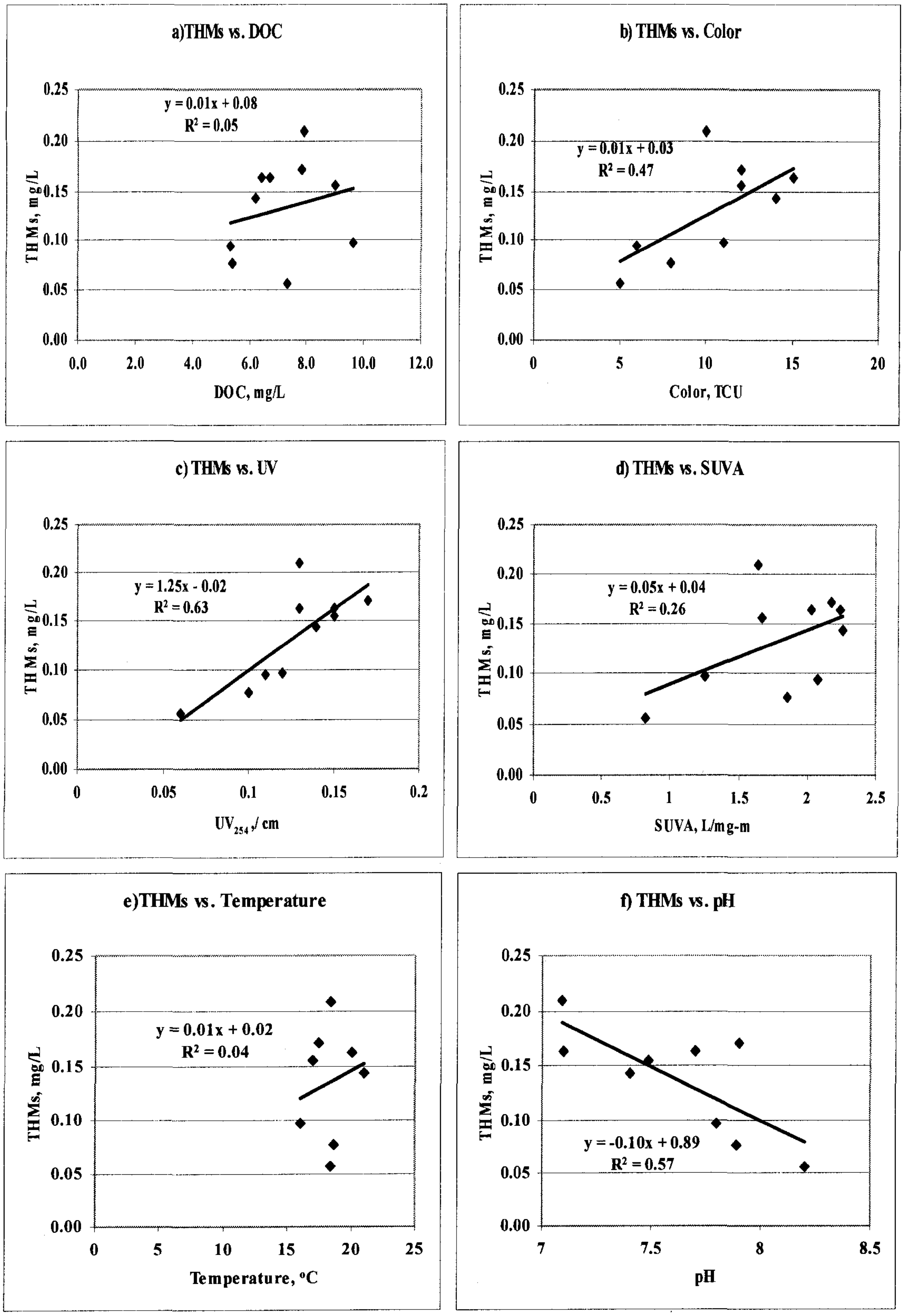


Figure B6: THMs with treated water quality parameter (Summer)

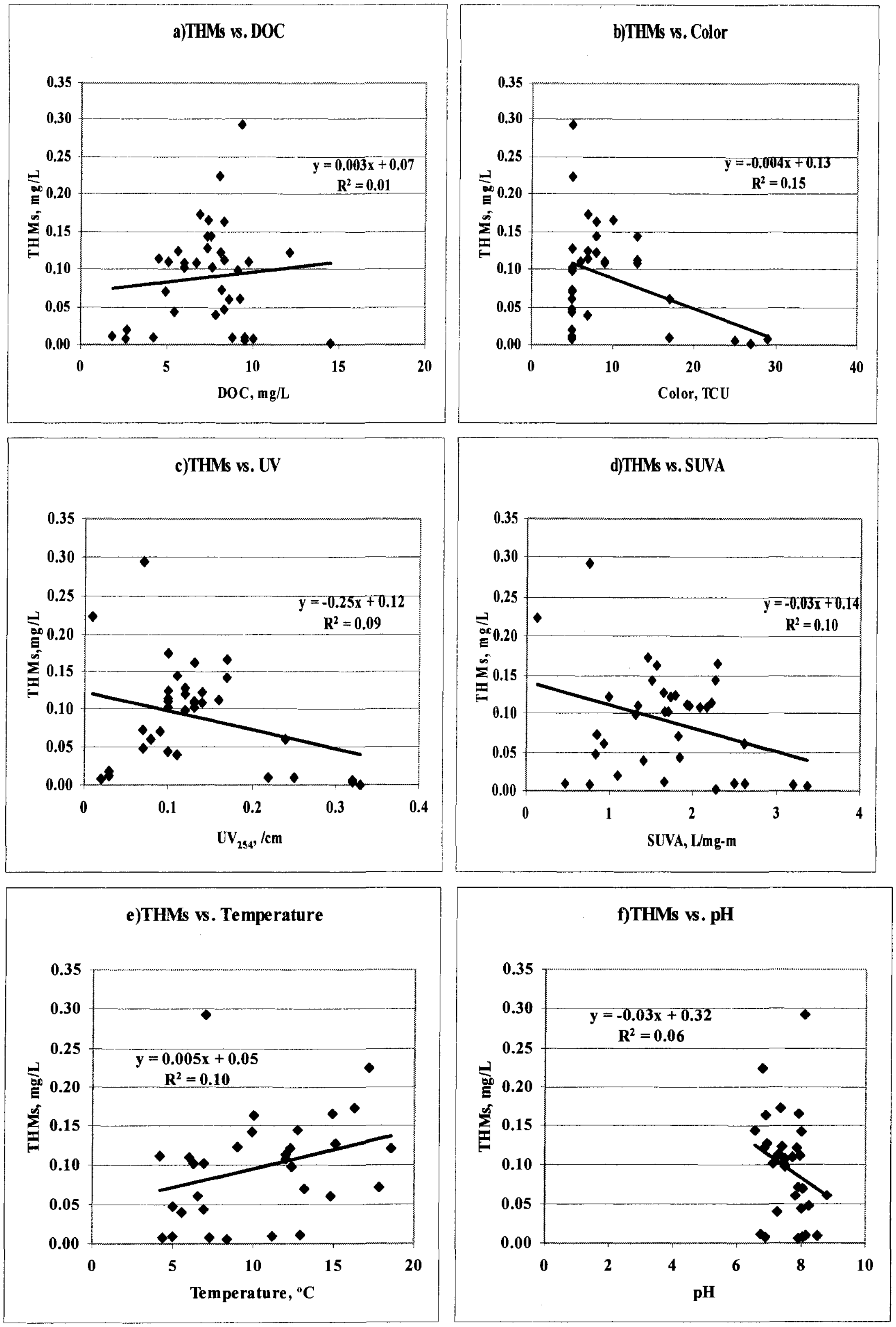


Figure B7: THMs with treated water quality parameter (Fall)

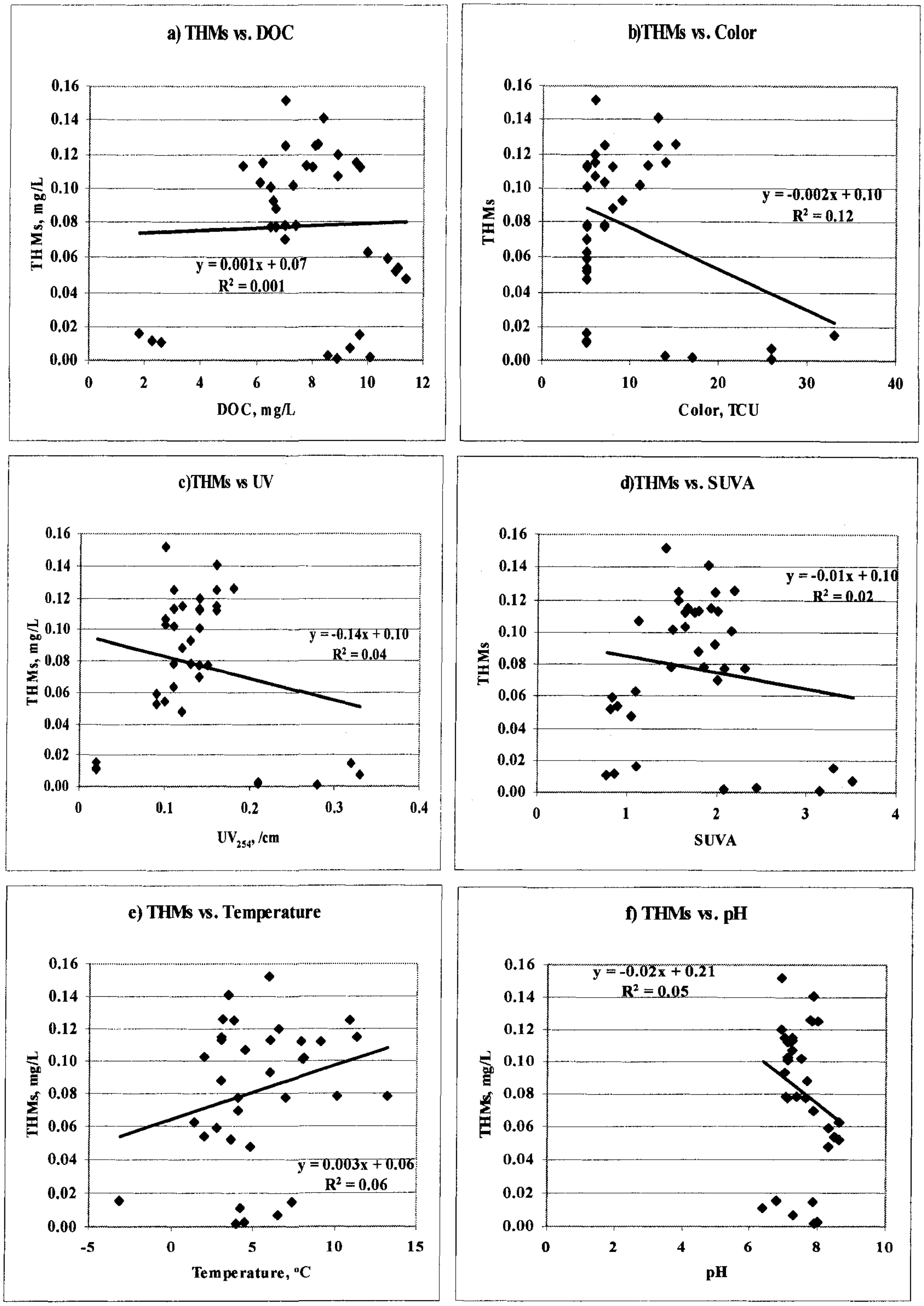


Figure B8: THMs with treated water quality parameter (Winter)

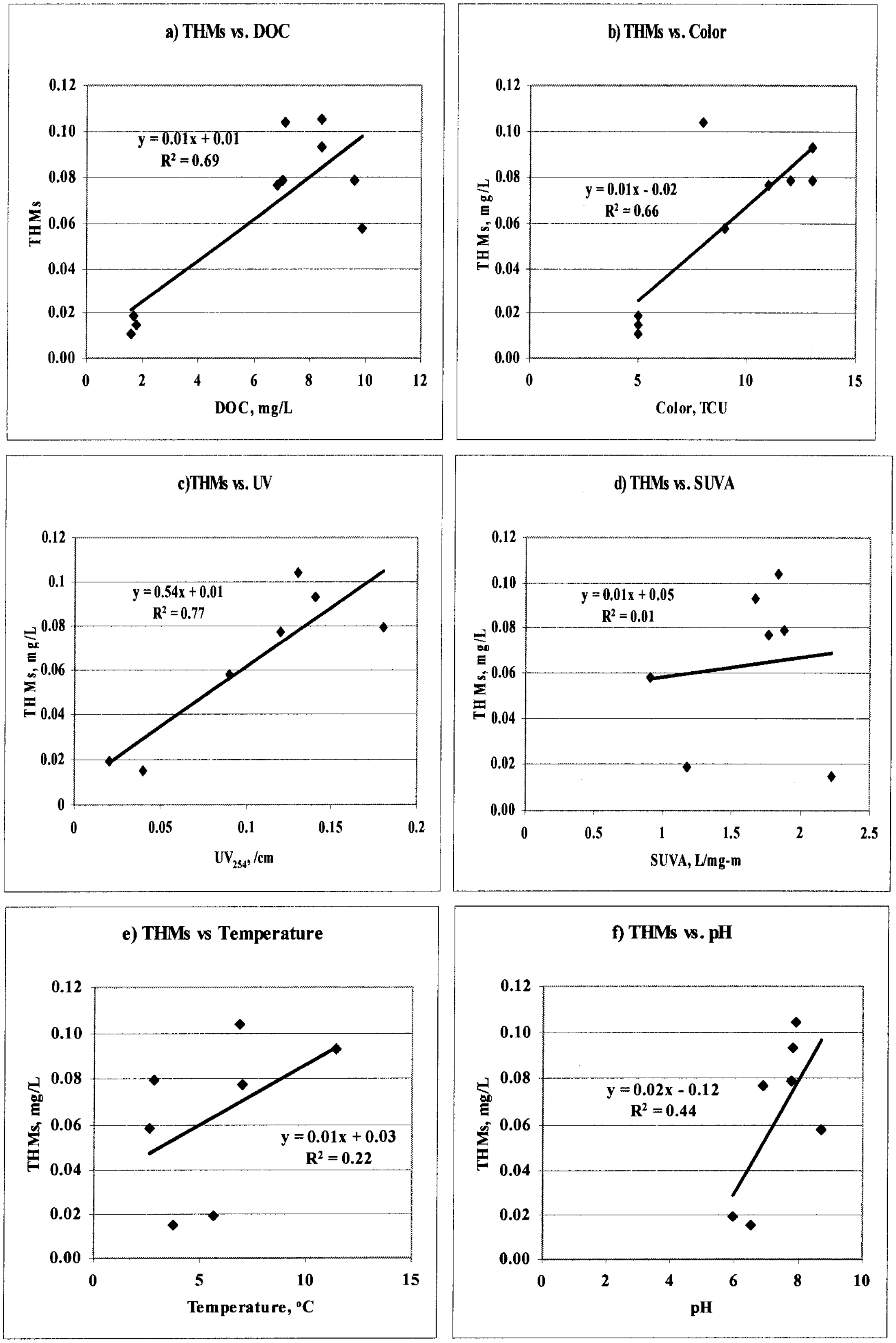


Figure B9: THMs with treated water quality parameter (Spring)

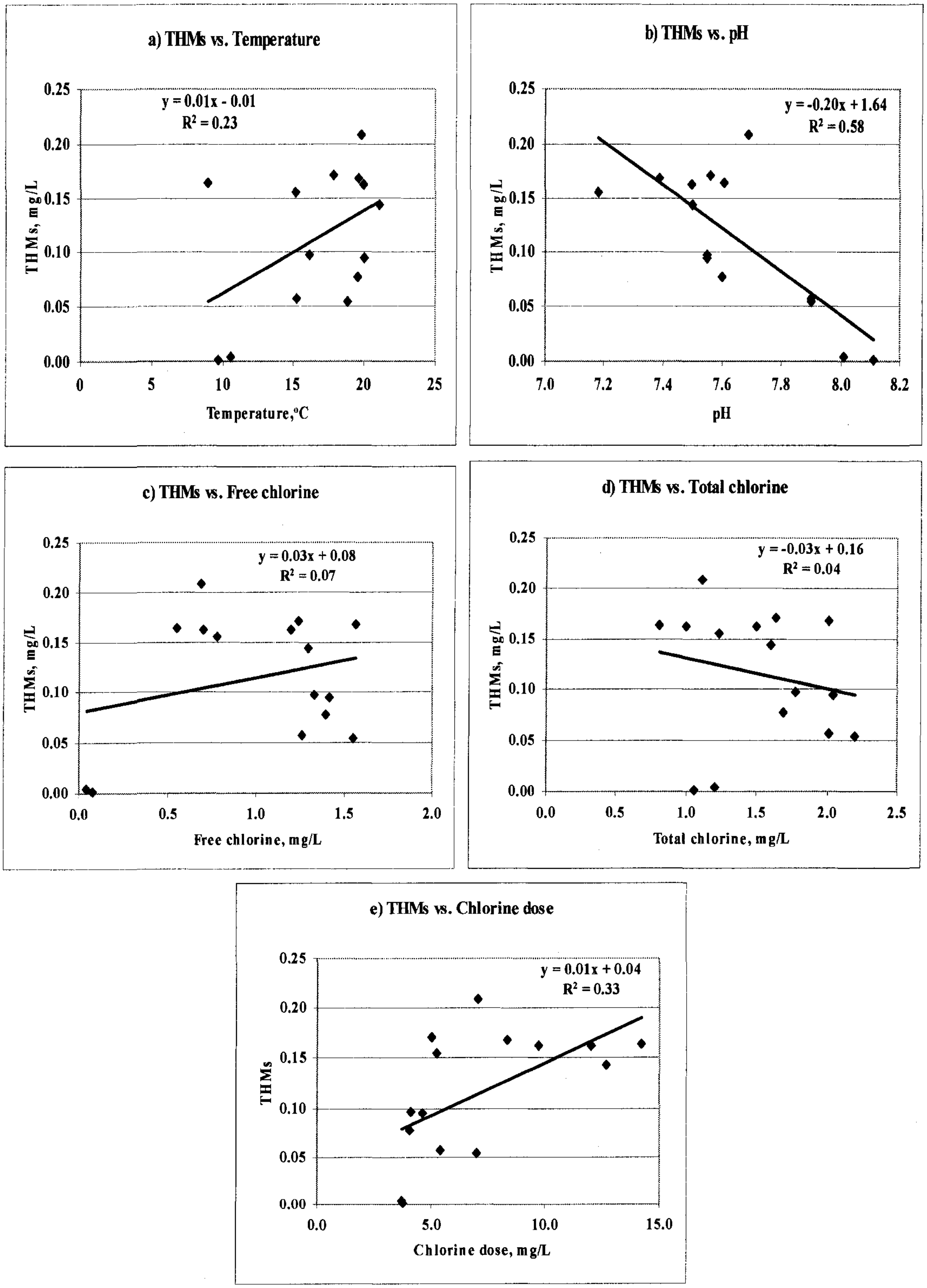


Figure B10: THMs with chlorinated water quality parameter (Summer)

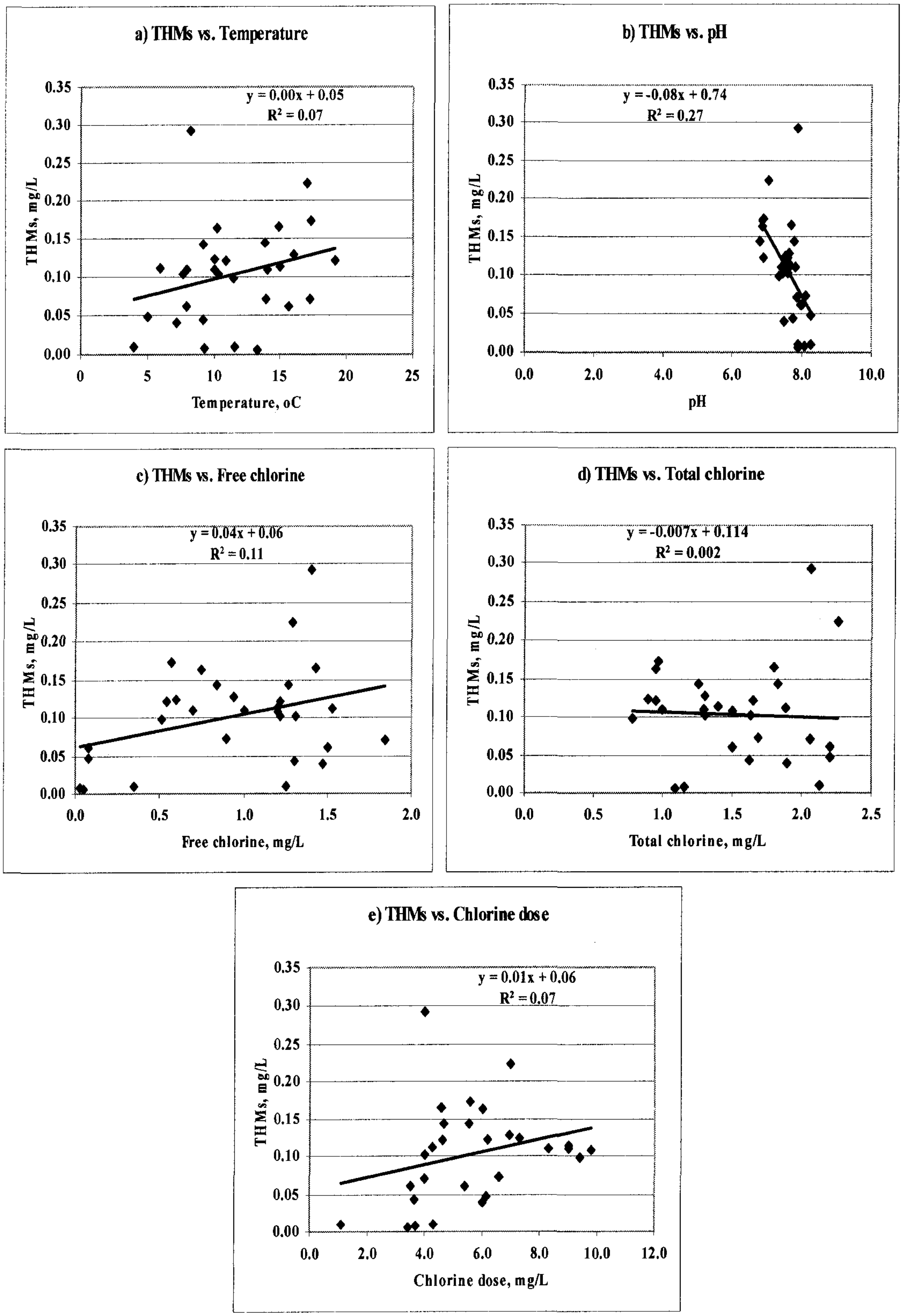


Figure B11: THMs with chlorinated water quality parameter (Fall)

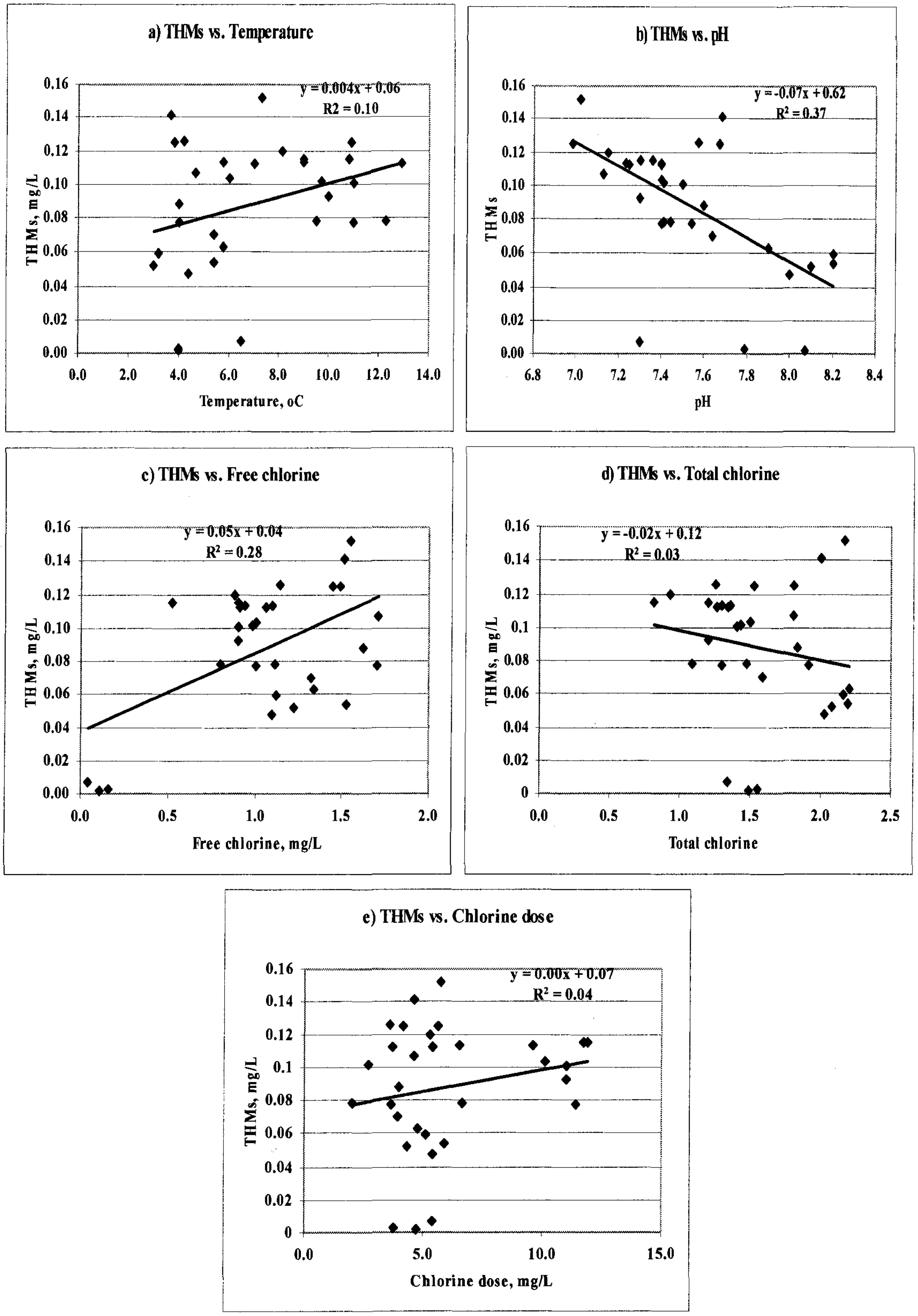


Figure B12: THMs with chlorinated water quality parameter (Winter)

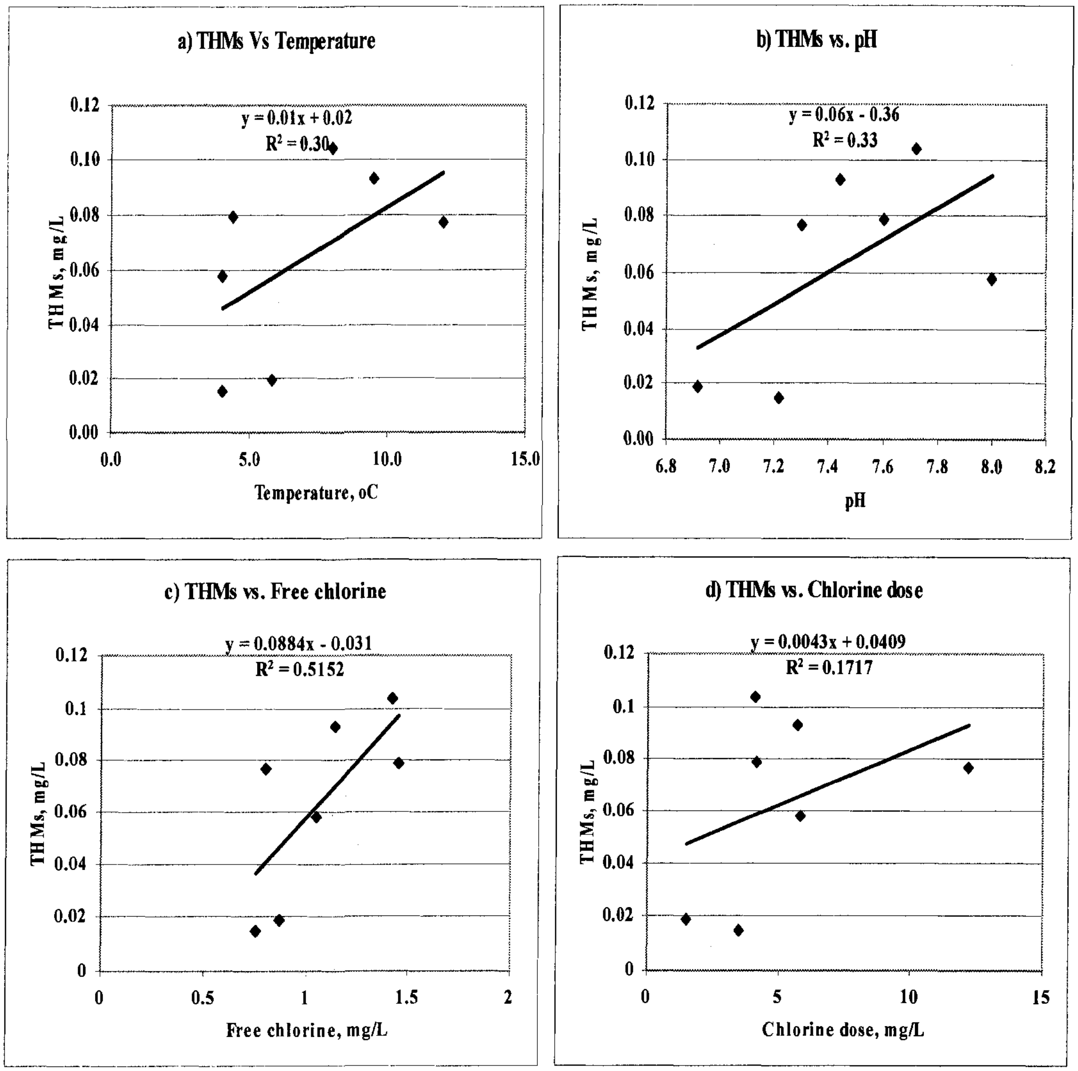
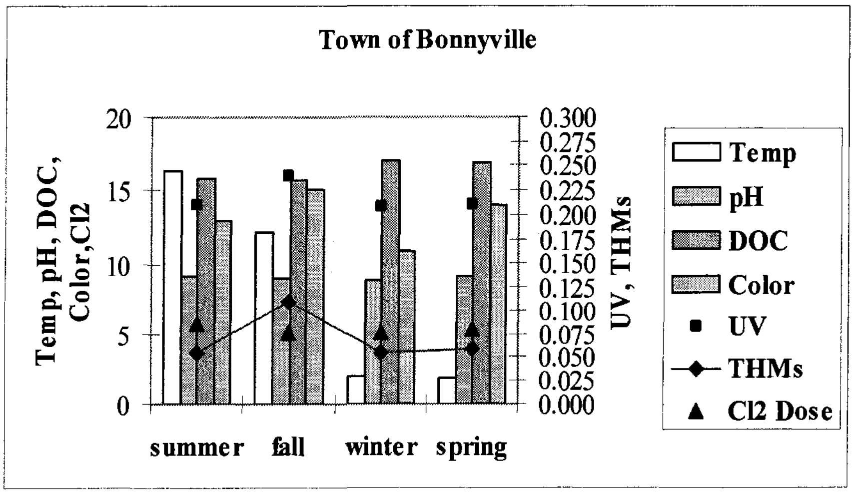
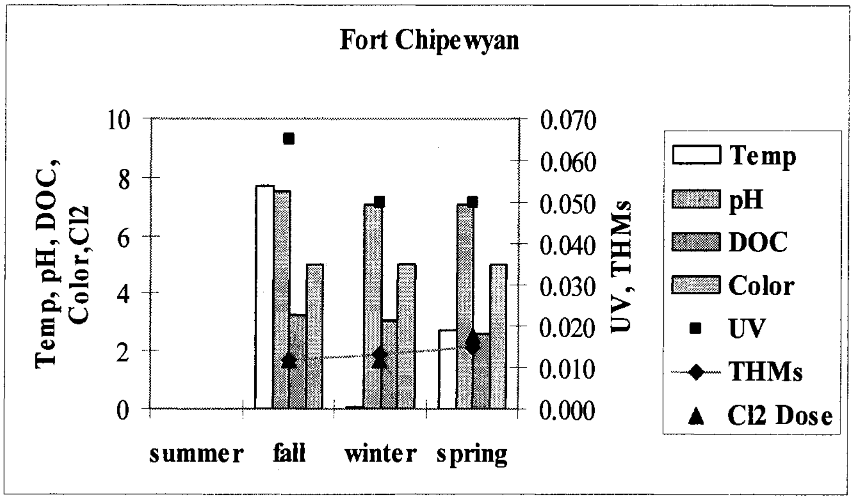


Figure B13: THMs with chlorinated water quality parameter (Spring)



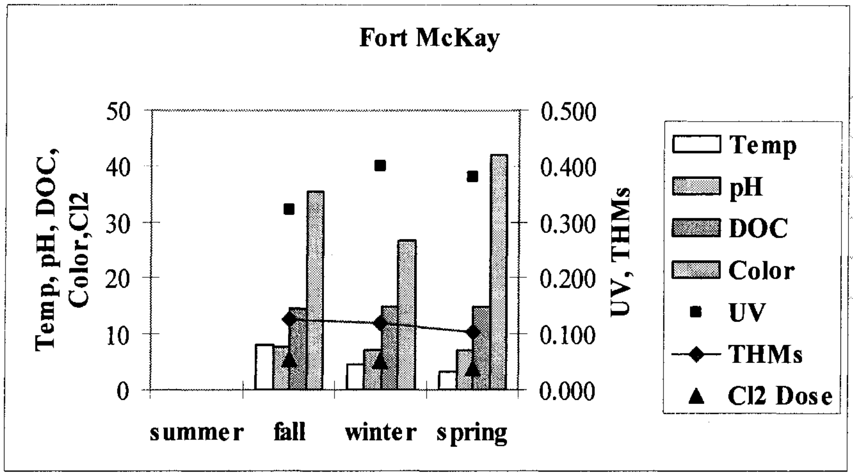
	n
summer	1
fall	4
winter	5
spring	1

Figure B14: THMs formation with raw water quality in Bonnyville waterworks



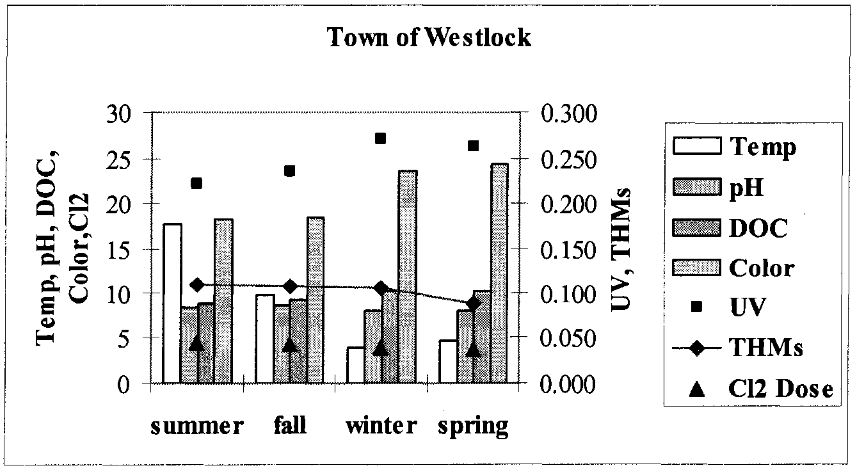
	n
summer	0
fall	2
winter	2
spring	1

Figure B15: THMs formation with raw water quality in Fort Chipewyan waterworks



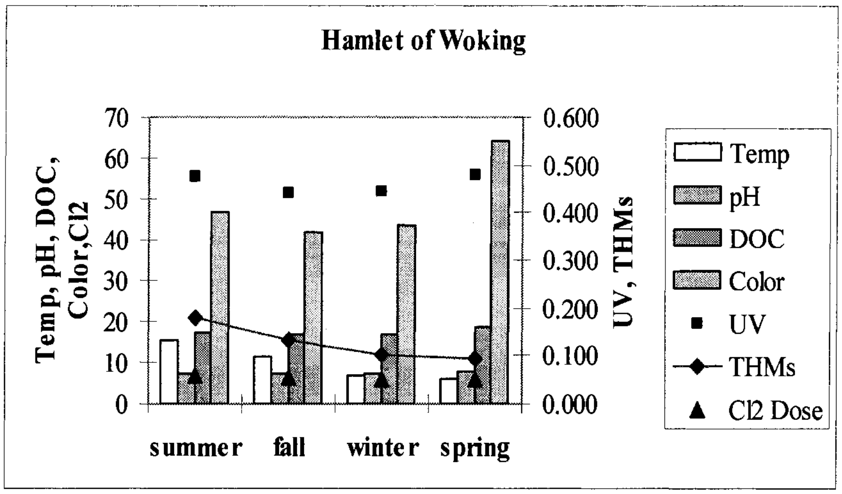
	n
summer	0
fall	5
winter	5
spring	1

Figure B16: THMs formation with raw water quality in Fort McKay waterworks



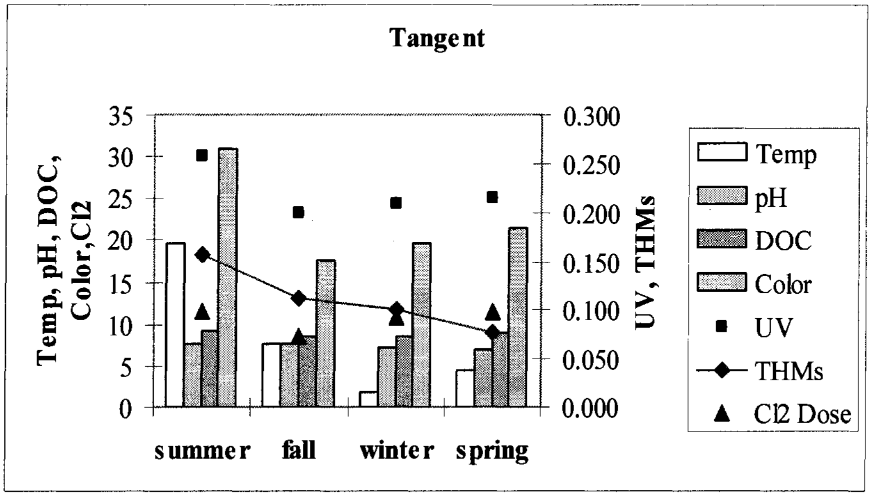
	n
summer	4
fall	5
winter	6
spring	3

Figure B17: THMs formation with raw water quality in Westlock waterwork



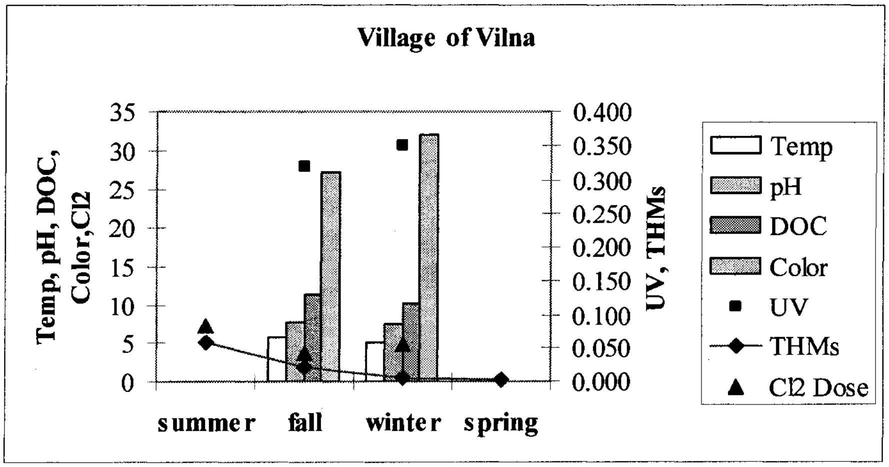
	n
summer	2
fall	6
winter	6
spring	1

Figure B18: THMs formation with raw water quality in Woking waterwork



	n
summer	3
fall	5
winter	6
spring	2

Figure B19: THMs formation with raw water quality in Tangent waterwork



	n
summer	0
fall	5
winter	3
spring	0

Figure B20: THMs formation with raw water quality in Vilna waterwork

Table B1: Multiple regression analysis with raw water quality parameters

(Winter Modeling)

Regression Statistics	
Multiple R	0.62
R Square	0.39
Adjusted R Square	0.22
Standard Error	0.04
Observations	33

ANOVA

	degree of freedom	Sum of squares	MS	F	Significance F
Regression	7	0.023	0.003	2.260	0.063
Residual	25	0.036	0.001		
Total	32	0.059			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.116	0.118	0.976	0.338	-0.128	0.360
Temp-1	-0.002	0.005	-0.337	0.739	-0.011	0.008
DOC-1	-0.010	0.009	-1.078	0.292	-0.029	0.009
Color-1	0.000	0.001	0.215	0.831	-0.002	0.003
UV-1	0.642	0.489	1.313	0.201	-0.365	1.649
pH-1	0.005	0.020	0.250	0.805	-0.037	0.047
Cl_2 Dose	0.006	0.003	2.286	0.031	0.001	0.012
SUVA	-0.073	0.044	-1.679	0.106	-0.163	0.017

Appendix C Raw data

Water Works Name	Loc.	Date	Time	Temp (°C)	pH	Chlorine Dose (mg/L)	DOC (mg/L)	Color (CU)	UVA (/cm)
Town of Bonnyville	1	15-Aug-05	9:35	17	9.00	7			
Town of Bonnyville	1	6-Sep-05	8:32	17	9.20	6.6	16.20	9.00	0.20
Town of Bonnyville	1	11-Oct-05	9:45	11.4	9.00	4.3	10.20	27.00	0.34
Town of Bonnyville	1	7-Nov-05	10:10	6.4	9.00	4	17.00	9.00	0.20
Town of Bonnyville	1	5-Dec-05	9:45	0	9.20	5.9	16.10	9.00	0.20
Town of Bonnyville	1	9-Jan-06	9:20	1.2	8.90	5.1	16.60	13.00	0.19
Town of Bonnyville	1	Feb-8-06	8:30	1	9	4.3	19.1	14	0.2
Town of Bonnyville	1	Mar-6-06	9:10	1.8	9.1	5.8	16.9	14	0.21
Town of Bonnyville	1	Jun-5-06	10:45	16.4	9.10	5.40	15.80	13.00	0.21
Town of Bonnyville	1	Sep-25-06	8:40	13.6	9.10	5.4	19.40	15.00	0.22
Town of Bonnyville	1	Dec-04-06	9:06	2.8	9.70	5.4	17.40	9.00	0.22
Town of Bonnyville	1	Jan-17-07	9:55	4.8	7.80	4.8	15.80	9.00	0.23
Town of Bonnyville	2	15-Aug-05	10:02	18.4	8.10	7			
Town of Bonnyville	2	6-Sep-05	8:39	17.8	7.90	6.6	8.20	5.00	0.07
Town of Bonnyville	2	11-Oct-05	10:05	11.2	8.50	4.3	8.80	17.00	0.22
Town of Bonnyville	2	7-Nov-05	10:20	7	8.10	4	9.30	<5	0.07
Town of Bonnyville	2	5-Dec-05	9:55	2	8.50	5.9	11.10	<5	0.10
Town of Bonnyville	2	9-Jan-06	9:10	2.8	8.30	5.1	10.70	5.00	0.09
Town of Bonnyville	2	Feb-8-06	8:10	3.6	8.60	4.3	11.00	5.00	0.09
Town of Bonnyville	2	Mar-6-06	9:20	2.6	8.70	5.8	9.90	9.00	0.09
Town of Bonnyville	2	Jun-5-06	11:00	18.4	8.20	5.40	7.30	<5	0.06
Town of Bonnyville	2	Sep-25-06	8:50	14.8	8.80	5.4	8.60	5.00	0.08
Town of Bonnyville	2	Dec-04-06	9:16	4.8	8.30	5.4	11.40	<5	0.12
Town of Bonnyville	2	Jan-17-07	10:10	1.4	8.60	4.8	10.00	<5	0.11
Fort Chipewyan	1	Oct-05					7.40	6.00	0.08
Fort Chipewyan	1	Nov-05					8.10	6.00	0.06
Fort Chipewyan	1	Dec-05					3.20	6.00	0.05

Water Works Name	Loc.	Date	Time	Temp (°C)	pH	Chlorine Dose (mg/L)	DOC (mg/L)	Color (CU)	UVA (/cm)
Fort Chipewyan	1	Mar-27-06	10:15	4	6.75		3.00	5.00	0.05
Fort Chipewyan	1	Apr-18-06	9:30	5.4	6.72	1.52	2.70	<5	0.04
Fort Chipewyan	1	Oct-2-06	10:00	12	7.76	1.69	2.60	<5	0.07
Fort Chipewyan	1	Nov-6-06	10:00	3.6	7.26	1.65	3.90	<5	0.06
Fort Chipewyan	1	Nov-21-06	9:15	3.5	7.32	1.07	3.80	<5	0.04
Fort Chipewyan	1	Jan-9-07	13:10	3.5	7.25	1.64	3.90	<5	0.06
Fort Chipewyan	1	Feb-13-07	14:00	-3.4	6.95	1.73	2.20	<5	0.04
Fort Chipewyan	1	Mar-7-07	13:00	2.7	7.07	3.5	2.60	<5	0.05
Fort Chipewyan	2	Oct-05					2.70	<5	0.03
Fort Chipewyan	2	Nov-05					4.20	<5	0.02
Fort Chipewyan	2	Dec-05					2.30	<5	0.02
Fort Chipewyan	2	Mar-27-06	10:25	5	6.77		1.60	5.00	0.02
Fort Chipewyan	2	Apr-18-06	9:35	5.6	5.95	1.52	1.70	<5	0.02
Fort Chipewyan	2	Oct-2-06	10:25	12.9	6.74	1.69	1.10	<5	0.02
Fort Chipewyan	2	Oct-06					1.80	<5	0.03
Fort Chipewyan	2	Nov-6-06	11:30	5	5.91	1.65	2.60	<5	0.02
Fort Chipewyan	2	Nov-21-06	9:30	4.4	6.90	1.07	2.30	<5	0.02
Fort Chipewyan	2	Jan-9-07	13:20	4.2	6.40	1.64	2.60	<5	0.02
Fort Chipewyan	2	Feb-13-07	14:10	-3.1	6.77	1.73	1.80	<5	0.02
Fort Chipewyan	2	Mar-7-07	13:30	3.7	6.51	3.5	1.80	<5	0.04
Fort McKay	1	8-Sep-05	13:00	16.1	7.60	7	15.60	45.00	<0.01
Fort McKay	1	18-Oct-05	10:20	7.8	7.74	6	14.70	40.00	0.41
Fort McKay	1	7-Nov-05	11:43	5	7.56	6	14.60	33.00	0.39
Fort McKay	1	Dec-6-05	11:26	5.1	7.30	5.75	15.50	37.00	0.40
Fort McKay	1	Feb-23-06	10:03	2.6	7.25	4.6	14.10	<5	0.38
Fort McKay	1	Mar-15-06	9:00	3.3	7.22	3.9	14.80	42.00	0.38
Fort McKay	1	Oct-18-06	11:05	6.2	8.44	4	13.60	29.00	0.40
Fort McKay	1	Nov-15-06	12:00	5	7.82	4	15.30	30.00	0.40
Fort McKay	1	Dec-6-2006	8:40	6.5	7.25	5.3	15.30	29.00	0.41
Fort McKay	1	Jan-15-07	12:00	3.9	7.34	6.5	14.10	28.00	0.40
Fort McKay	1	Feb-12-07	11:05	3.9	7.27	3.7	15.40	34.00	0.41
Fort McKay	2	8-Sep-05	13:53	17.2	6.81	7	8.00	5.00	<0.01
Fort McKay	2	18-Oct-05	10:20	10	6.87	6	8.30	8.00	0.13
Fort McKay	2	7-Nov-05	12:25	5.5	7.24	6	7.80	7.00	0.11
Fort McKay	2	Dec-6-05	11:30	5.9	6.91	5.75	7.00	6.00	0.10
Fort McKay	2	Feb-23-06	11:00	4.5	7.21	4.6	8.90	9.00	0.11
Fort McKay	2	Mar-15-06	9:00	7.3	7.17	3.9	8.40	6.00	0.10
Fort McKay	2	Oct-18-06	11:08	6.9	7.44	4	6.00	<5	0.10
Fort McKay	2	Nov-15-06	12:05	6.3	7.13	4	7.60	5.00	0.13
Fort McKay	2	Dec-6-06	10:30	6.5	6.90	5.3	8.90	6.00	0.14
Fort McKay	2	Jan-15-07	11:30	6	7.21	6.5	7.80	<5	0.14
Fort McKay	2	Feb-12-07	11:06	7.9	7.19	3.7	9.70	8.00	0.16
Hamlet of Woking	1	Aug-23-05	10:55	16.7	7.64	8.36			
Hamlet of Woking	1	Sep-20-05	10:05	13.5	7.29	5.6	15.60	50.00	0.44
Hamlet of Woking	1	18-Oct-05	10:10	10.8	7.66	5.52	16.10	58.00	0.47

Water Works Name	Loc.	Date	Time	Temp (°C)	pH	Chlorine Dose (mg/L)	DOC (mg/L)	Color (CU)	UVA (/cm)
Hamlet of Woking	1	15-Nov-05	10:30	7.6	7.71	4.63	15.90	47.00	0.45
Hamlet of Woking	1	13-Dec-05	9:40	6.9	7.73	5.62	16.30	55.00	0.46
Hamlet of Woking	1	10-Jan-06	10:15	6.2	7.57	2.72	17.60	60.00	0.48
Hamlet of Woking	1	Feb-24-06	11:00	6.2	7.63	2.03	17.10	>60	0.50
Hamlet of Woking	1	Mar-24-06	11:00	5.7	7.78	5.74	18.80	64.00	0.48
Hamlet of Woking	1	Jun-13-06	10:55	13.7	7.61	5.25	17.80	49.00	0.50
Hamlet of Woking	1	Aug-10-06	10:45	17.2	7.22	7.07	16.30	45.00	0.45
Hamlet of Woking	1	Sep-5-06	10:30	17.5	6.90	6.19	16.80	40.00	0.45
Hamlet of Woking	1	Oct-10-06	11:30	11	7.00	6.95	16.50	29.00	0.42
Hamlet of Woking	1	Nov-14-06	10:10	8.9	7.14	9.42	18.70	27.00	0.41
Hamlet of Woking	1	Dec-12-06	12:30	8.9	7.04	5.38	16.50	26.00	0.40
Hamlet of Woking	1	Jan-16-07	10:15	7.1	7.02	6.63	15.40	28.00	0.40
Hamlet of Woking	1	Feb-20-07	10:50	6.6	7.28	11.74	17.30	32.00	0.42
Hamlet of Woking	2	Aug-23-05	11:12	18	7.49	8.36			
Hamlet of Woking	2	Sep-20-05	10:13	16.3	7.37	5.6	6.90	7.00	0.10
Hamlet of Woking	2	18-Oct-05	10:20	12.7	6.58	5.52	7.30	8.00	0.11
Hamlet of Woking	2	15-Nov-05	10:35	12.3	7.87	4.63	12.10	8.00	0.12
Hamlet of Woking	2	13-Dec-05	9:50	10.9	7.83	5.62	7.00	7.00	0.11
Hamlet of Woking	2	10-Jan-06	10:21	8.1	7.51	2.72	7.30	11.00	0.11
Hamlet of Woking	2	Feb-24-06	11:10	10.1	7.36	2.03	7.40	7.00	0.11
Hamlet of Woking	2	Mar-24-06	11:05	11.4	7.80	5.74	8.40	13.00	0.14
Hamlet of Woking	2	Jun-13-06	11:12	17	7.49	5.25	9.00	12.00	0.15
Hamlet of Woking	2	Aug-10-06	10:56	18.4	7.09	7.07	7.90	10.00	0.13
Hamlet of Woking	2	Sep-5-06	10:40	18.5	6.84	6.19	8.10	8.00	0.14
Hamlet of Woking	2	Oct-10-06	11:37	15.1	6.91	6.95	7.30	<5	0.12
Hamlet of Woking	2	Nov-14-06	10:15	12.4	7.48	9.42	9.10	<5	0.12

Water Works Name	Loc.	Date	Time	Temp (°C)	pH	Chlorine Dose (mg/L)	DOC (mg/L)	Color (CU)	UVA (/cm)
Hamlet of Woking	2	Dec-12-06	12:40	9.1	7.08	5.38	8.00	<5	0.14
Hamlet of Woking	2	Jan-16-07	10:25	13.2	7.07	6.63	7.00	<5	0.13
Hamlet of Woking	2	Feb-20-07	11:03	11.3	7.25	11.74	9.60	6.00	0.16
Town of Westlock	1	16-Aug-05	1:35	17.4	8.36	5	10.30	22.00	0.29
Town of Westlock	1	13-Sep-05	1:25	14.5	8.54	4.56	10.10	25.00	0.27
Town of Westlock	1	13-Oct-05	10:36	8.7	8.63	4.65	10.00	17.00	0.27
Town of Westlock	1	29-Nov-05	2:00	4.5	8.33	4.27	10.50	24.00	0.28
Town of Westlock	1	13-Dec-05	10:20	4.6	8.28	4.15	10.60	21.00	0.27
Town of Westlock	1	30-Jan-06	10:55	4	7.91	3.58	10.50	27.00	0.30
Town of Westlock	1	Feb-14-06	1:25	4.2	8.01	4.58	11.50	27.00	0.26
Town of Westlock	1	Mar-27-06	11:50	3.6	7.91	4.18	12.00	25.00	0.28
Town of Westlock	1	Apr-27-06	14:05	8	8.22	4.09	9.10	18.00	0.23
Town of Westlock	1	Jun-26-06	11:39	15.9	8.32	4.09	9.70	19.00	0.21
Town of Westlock	1	July-18-06	11:35	19	8.33	4.61	7.20	16.00	0.21
Town of Westlock	1	Aug-23-06	1:40	18.7	8.34	4.04	7.70	16.00	0.18
Town of Westlock	1	Sep-20-06	1:45	13.2	8.47	4.02	6.40	14.00	0.17
Town of Westlock	1	Oct-25-06	11:53	7.7	8.42	3.66	8.40	13.00	0.19
Town of Westlock	1	Dec-5-06	1:05	3.4	8.12	3.91	9.50	19.00	0.26
Town of Westlock	1	Jan-23-07	11:15	5	7.80	3.97	9.30	24.00	0.27
Town of Westlock	1	Feb-20-07	2:45	2.1	7.73	3.63	8.90	24.00	0.26
Town of Westlock	1	Mar-6-07	2:01	2.5	7.78	2.91	9.10	30.00	0.28
Town of Westlock	2	16-Aug-05	1:40	17.5	7.90	5	7.80	12.00	0.17
Town of Westlock	2	13-Sep-05	1:25	14.9	7.92	4.56	7.40	10.00	0.17
Town of Westlock	2	13-Oct-05	10:35	9.9	7.99	4.65	7.50	13.00	0.17
Town of Westlock	2	29-Nov-05	2:05	4.2	7.97	4.27	8.30	13.00	0.16
Town of Westlock	2	13-Dec-05	10:25	3.8	7.98	4.15	8.10	13.00	0.16

Water Works Name	Loc.	Date	Time	Temp (°C)	pH	Chlorine Dose (mg/L)	DOC (mg/L)	Color (CU)	UVA (/cm)
Town of Westlock	2	30-Jan-06	11:00	3.1	7.76	3.58	8.20	15.00	0.18
Town of Westlock	2	Feb-14-06	1:30	3.5	7.86	4.58	8.40	13.00	0.16
Town of Westlock	2	Mar-27-06	12:00	2.8	7.75	4.18	9.60	13.00	0.18
Town of Westlock	2	Apr-27-06	14:13	6.8	7.89	4.09	7.10	8.00	0.13
Town of Westlock	2	Jun-26-06	11:34	16	7.80	4.09	9.60	11.00	0.12
Town of Westlock	2	July-18-06	11:40	19		4.61	5.30	6.00	0.11
Town of Westlock	2	Aug-23-06	1:45	18.6	7.89	4.04	5.40	8.00	0.10
Town of Westlock	2	Sep-20-06	1:50	13.2	8.03	4.02	4.90	<5	0.09
Town of Westlock	2	Oct-25-06	12:01	6.9	7.99	3.66	5.40	<5	0.10
Town of Westlock	2	Dec-5-06	1:12	4.1	7.85	3.91	7.00	5.00	0.14
Town of Westlock	2	Jan-23-07	11:25	3	7.70	3.97	6.70	8.00	0.14
Town of Westlock	2	Feb-20-07	2:38	4.1	7.63	3.63	6.50	5.00	0.12
Town of Westlock	2	Mar-6-07	2:05	2.5	7.69	2.91	7.00	12.00	0.15
Village of Vilna	1	Aug-17-05	11:53	7	7.62	14.2			
Village of Vilna	1	16-Sep-05	7:56	6	7.70	3.52	10.50	28.00	0.34
Village of Vilna	1	12-Oct-05	11:24	5	8.11	6.15	16.70	11.00	0.20
Village of Vilna	1	8-Nov-05	2:00pm	4	7.78	1.11	10.40	33.00	0.35
Village of Vilna	1	13-Dec-05	9:35	4	7.78	3.77	10.20	29.00	0.34
Village of Vilna	1	12-Jan-06	10:42	4	7.75	4.7	10.50	38.00	0.35
Village of Vilna	1	Feb-06					9.60	37.00	0.36
Village of Vilna	1	Mar-06					10.60	38.00	0.34
Village of Vilna	1	Jun-7-06	8:35	7.8	7.85	3.79			
Village of Vilna	1	Aug-9-06	9:45	8.4	7.82	3.71			
Village of Vilna	1	Sep-13-06	8:40	7.3	7.82	3.7	10.00	35.00	0.35
Village of Vilna	1	Oct-3-06	9:21	5.8	7.77	3.42	9.20	29.00	0.36
Village of Vilna	1	Nov-06					15.30	28.00	0.35
Village of Vilna	1	Jan-3-07	8:59	7.5	7.12	5.39	9.80	29.00	0.36
Village of Vilna	1	Feb-14-07	9:30	7.2	7.77	4.8	10.00	33.00	0.43
Village of Vilna	2	Aug-17-05	11:45	7	7.75	14.2			
Village of Vilna	2	16-Sep-05	8:05	6.5	7.82	3.52	9.20	17.00	0.24
Village of Vilna	2	12-Oct-05	11:45	5	8.21	6.15	8.30	<5	0.07
Village of Vilna	2	8-Nov-05	2:14pm	5	8.12	1.11	9.50	17.00	0.25
Village of Vilna	2	13-Dec-05	9:33	4.5	8.00	3.77	8.60	14.00	0.21
Village of Vilna	2	12-Jan-06	10:45	4	7.90	4.7	10.10	17.00	0.21
Village of Vilna	2	Feb-06					8.90	26.00	0.28
Village of Vilna	2	Mar-06					9.40	21.00	0.25
Village of Vilna	2	Jun-7-06	8:38	7.9	8.06	3.79			

Water Works Name	Loc.	Date	Time	Temp (°C)	pH	Chlorine Dose (mg/L)	DOC (mg/L)	Color (CU)	UVA (/cm)
Village of Vilna	2	Aug-9-06	9:56	7.8	8.00	3.71			
Village of Vilna	2	Sep-13-06	8:45	7.3	8.03	3.7	10.00	29.00	0.32
Village of Vilna	2	Oct-3-06	9:25	8.4	7.92	3.42	9.50	25.00	0.32
Village of Vilna	2	Nov-06					14.50	27.00	0.33
Village of Vilna	2	Jan-3-07	9:05	8.1	7.26	5.39	9.40	26.00	0.33
Village of Vilna	2	Feb-14-07	9:40	7.4	7.84	4.8	9.70	33.00	0.32
Tangent	1	7-Sep-05	9:40	14	7.50	9	6.60	18.00	0.18
Tangent	1	6-Oct-05	8:00	8	7.80	7.3	8.40	17.00	0.18
Tangent	1	3-Nov-05	8:30	2	7.50	8.3	7.30	17.00	0.18
Tangent	1	7-Dec-05	9:00	1	7.40	10.1	8.20	17.00	0.18
Tangent	1	4-Jan-06	8:00	0	7.30	9.6	8.00	20.00	0.19
Tangent	1	Feb-8-06	8:30	0	7.00	11.9	8.70	25.00	0.19
Tangent	1	Mar-08-06	8:40	5	7.10	12.2	8.80	21.00	0.20
Tangent	1	14-Jun-06	8:30	20	7.50	12	9.60	37.00	0.26
Tangent	1	20-Jul-06	8:50	20	7.40	12.7	8.80	28.00	0.26
Tangent	1	Aug-17-06	8:45	19	8.30	9.7	9.50	28.00	0.25
Tangent	1	Sep-06					9.60	27.00	0.24
Tangent	1	Oct-05-06	8:30	11	7.60	9.8	8.40	18.00	0.23
Tangent	1	Nov-14-06	8:40	3	7.70	9	11.80	18.00	0.23
Tangent	1	Dec-12-06	8:30	4	7.20	11	9.00	17.00	0.23
Tangent	1	Jan-2-07	9:00	4	7.10	11.4	8.90	18.00	0.23
Tangent	1	Feb-5-07	9:00	2	7.10	11	9.20	21.00	0.23
Tangent	1	Mar-5-07	8:30	4	7.10	10.7	9.20	22.00	0.23
Tangent	2	7-Sep-05	9:50	12	7.30	9	4.50	7.00	0.10
Tangent	2	6-Oct-05	8:10	9	7.40	7.3	5.60	7.00	0.10
Tangent	2	3-Nov-05	8:35	6	7.20	8.3	5.10	9.00	0.10
Tangent	2	7-Dec-05	9:00	2	7.10	10.1	6.10	7.00	0.10
Tangent	2	4-Jan-06	8:00	3	7.10	9.6	5.50	12.00	0.11
Tangent	2	Feb-8-06	8:40	3	7.00	11.9	6.20	14.00	0.12
Tangent	2	Mar-08-06	8:45	7	6.90	12.2	6.80	11.00	0.12
Tangent	2	14-Jun-06	8:32	20	7.10	12	6.40	15.00	0.13
Tangent	2	20-Jul-06	8:55	21	7.40	12.7	6.20	14.00	0.14
Tangent	2	Aug-17-06	8:50	20	7.70	9.7	6.70	15.00	0.15
Tangent	2	Sep-06					6.70	13.00	0.14
Tangent	2	Oct-05-06	8:30	12	7.50	9.8	6.00	9.00	0.13
Tangent	2	Nov-14-06	8:45	6	7.70	9	9.70	6.00	0.13
Tangent	2	Dec-12-06	8:30	8	7.10	11	6.50	<5	0.14
Tangent	2	Jan-2-07	9:10	7	7.10	11.4	6.70	7.00	0.14
Tangent	2	Feb-5-07	9:10	6	7.00	11	6.60	9.00	0.13
Tangent	2	Mar-5-07	8:45	7	7.00	10.7	6.60	10.00	0.14
St. Michael	1	Aug-05					11.30	5.00	0.03
St. Michael	1	Sep-05					2.30	5.00	0.03
St. Michael	1	31-Oct-05	10:10		7.17		2.80	< 5	0.03
St. Michael	1	Dec-05					1.70	5.00	0.03
St. Michael	1	Feb-06					1.80	<5	0.03
St. Michael	2	Aug-05							
St. Michael	2	Sep-05							
St. Michael	2	31-Oct-05							

Water Works Name	Loc.	Date	Time	Temp (^{o}C)	pH	Chlorine Dose (mg/L)	DOC (mg/L)	Color (CU)	UVA (/cm)
St. Michael	2	Dec-05							
St. Michael	2	Feb-06							

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Town of Bonnyville	3	15-Aug-05	11:26	18.8	7.90	7	1.55	2.20	0.039	0.011	0.004	<0.001
Town of Bonnyville	3	6-Sep-05	8:45	17.2	8.10	6.6	0.90	1.69	0.054	0.013	0.005	<0.001
Town of Bonnyville	3	11-Oct-05	10:15	11.6	7.90	4.3	1.25	2.13	0.005	0.003	0.002	<0.001
Town of Bonnyville	3	7-Nov-05	10:45	8.2	7.90	4	1.40	2.06	0.291	0.002	<0.001	<0.001
Town of Bonnyville	3	5-Dec-05	10:15	5.4	8.20	5.9	1.53	2.19	0.038	0.012	0.004	<0.001
Town of Bonnyville	3	9-Jan-06	9:40	3.2	8.20	5.1	1.12	2.16	0.040	0.014	0.005	<0.001
Town of Bonnyville	3	Feb-8-06	9:05	3	8.10	4.3	1.22	2.08	0.036	0.012	0.004	<0.001
Town of Bonnyville	3	Mar-6-06	9:30	4	8.00	5.8	1.05	2.14	0.040	0.015	0.003	<0.001
Town of Bonnyville	3	Jun-5-06	11:15	15.2	7.90	5.40	1.26	2.01	0.043	0.011	0.003	<0.001
Town of Bonnyville	3	Sep-25-06	9:30	15.6	8.00	5.4	1.50	2.20	0.043	0.014	0.004	<0.001
Town of Bonnyville	3	Dec-04-06	9:45	4.4	8.00	5.4	1.10	2.03	0.037	0.009	0.002	<0.001
Town of Bonnyville	3	Jan-17-07	10:30	5.8	7.90	4.8	1.34	2.20	0.046	0.014	0.003	<0.001
Town of Bonnyville	4	15-Aug-05	10:58	16.8	7.70	7	1.09	1.92	0.076	0.017	0.005	<0.001
Town of Bonnyville	4	6-Sep-05	9:07	18.4	7.80	6.6	0.91	1.57	0.062	0.017	0.005	<0.001
Town of Bonnyville	4	11-Oct-05	10:45	13.2	7.70	4.3	1.44	1.95	0.005	0.003	0.002	<0.001
Town of Bonnyville	4	7-Nov-05	11:10	9.6	7.70	4	1.12	1.81	0.298	0.002	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Town of Bonnyville	4	5-Dec-05	10:40	7.8	7.90	5.9	0.96	1.99	0.055	0.015	0.005	<0.001
Town of Bonnyville	4	9-Jan-06	10:15	10.8	8.10	5.1	0.95	2.02	0.046	0.017	0.005	<0.001
Town of Bonnyville	4	Feb-8-06	9:45	17	8.00	4.3	1.17	1.97	0.053	0.015	0.005	<0.001
Town of Bonnyville	4	Mar-6-06	10:00	8.8	7.90	5.8	0.91	1.95	0.045	0.016	0.003	<0.001
Town of Bonnyville	4	Jun-5-06	11:45	12.8	7.70	5.40	0.88	1.80	0.054	0.015	0.004	<0.001
Town of Bonnyville	4	Sep-25-06	10:45	15.6	7.60	5.4	1.36	2.20	0.056	0.019	0.005	<0.001
Town of Bonnyville	4	Dec-04-06	11:30	8.6	7.50	5.4	0.94	1.94	0.040	0.011	0.002	<0.001
Town of Bonnyville	4	Jan-17-07	10:55	11.4	7.70	4.8	1.16	2.10	0.056	0.012	0.002	<0.001
Town of Bonnyville	5	15-Aug-05	10:28	17.6	7.80	7	1.11	1.92	0.082	0.017	0.005	<0.001
Town of Bonnyville	5	6-Sep-05	9:28	19.2	8.00	6.6	0.16	0.97	0.091	0.020	0.006	<0.001
Town of Bonnyville	5	11-Oct-05	11:25	15.2	7.70	4.3	0.27	0.95	0.006	0.004	0.003	<0.001
Town of Bonnyville	5	7-Nov-05	11:35	9.8	8.00	4	0.25	0.88	0.249	0.002	<0.001	<0.001
Town of Bonnyville	5	5-Dec-05	11:00	12.2	8.00	5.9	0.20	0.96	0.066	0.018	0.005	<0.001
Town of Bonnyville	5	9-Jan-06	10:35	12.6	8.00	5.1	0.12	0.95	0.082	0.022	0.006	<0.001
Town of Bonnyville	5	Feb-8-06	10:05	12.4	8.10	4.3	0.31	1.15	0.062	0.017	0.005	<0.001
Town of Bonnyville	5	Mar-6-06	10:25	7.6	8.00	5.8	0.20	1.13	0.057	0.021	0.004	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Town of Bonnyville	5	Jun-5-06	11:55	7.8	7.60	5.40	0.39	1.28	0.070	0.018	0.004	<0.001
Town of Bonnyville	5	Sep-25-06	11:10	24.2	7.50	5.4	0.21	1.12	0.075	0.022	0.005	<0.001
Town of Bonnyville	5	Dec-04-06	11:45	9.4	7.70	5.4	0.20	1.24	0.074	0.014	0.002	<0.001
Town of Bonnyville	5	Jan-17-07	11:15	10.8	7.80	4.8	0.26	1.98	0.068	0.021	0.004	<0.001
Fort Chipewyan	3	Oct-05							0.013	0.004	0.002	<0.001
Fort Chipewyan	3	Nov-05							0.006	0.003	<0.001	<0.001
Fort Chipewyan	3	Dec-05							0.007	0.003	0.002	<0.001
Fort Chipewyan	3	Mar-27-06	10:30	5.3	6.68		0.80		0.007	0.004	<0.001	<0.001
Fort Chipewyan	3	Apr-18-06	9:40	5.8	6.92	1.52	0.87		0.011	0.006	0.002	<0.001
Fort Chipewyan	3	Oct-2-06	10:30	13.3	7.46	1.69	0.70		0.006	0.004	0.002	<0.001
Fort Chipewyan	3	Oct-06							0.017	0.008	0.003	<0.001
Fort Chipewyan	3	Nov-6-06	9:30	5.6	6.93	1.65	0.94		0.004	0.002	0.001	<0.001
Fort Chipewyan	3	Nov-21-06	9:00	5.5	7.23	1.07	0.79		0.004	0.003	0.001	<0.001
Fort Chipewyan	3	Jan-9-07		4.6	7.24	1.64	0.68		0.006	0.003	0.002	<0.001
Fort Chipewyan	3	Feb-13-07	2:15	-4.3	7.07	1.73	0.77		0.009	0.005	0.002	<0.001
Fort Chipewyan	3	Mar-7-07	2:00	4	7.22	3.5	0.76		0.008	0.005	0.002	<0.001
Fort Chipewyan	4	Oct-05							0.012	0.004	0.002	<0.001
Fort Chipewyan	4	Nov-05							0.008	0.004	0.002	<0.001
Fort Chipewyan	4	Dec-05							0.007	0.003	0.002	<0.001
Fort Chipewyan	4	Mar-27-06	10:40	6.7	6.97		0.73		0.008	0.002	<0.001	<0.001
Fort Chipewyan	4	Apr-18-06	10:30	5.5	7.30	1.52	0.72		0.011	0.006	<0.001	<0.001
Fort Chipewyan	4	Oct-2-06	11:15	14.3	7.44	1.69	0.66		0.007	0.004	0.002	<0.001
Fort Chipewyan	4	Oct-06							0.009	0.004	0.001	<0.001
Fort Chipewyan	4	Nov-6-06	11:00	8.9	6.79	1.65	0.62		0.005	0.003	0.001	<0.001
Fort Chipewyan	4	Nov-21-06	1:25	8	7.25	1.07	0.77		0.004	0.003	0.001	<0.001
Fort Chipewyan	4	Jan-9-07		5	7.15	1.64	0.72		0.007	0.004	0.002	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Fort Chipewyan	4	Feb-13-07	3:00	-5.8	7.06	1.73	0.73		0.008	0.005	0.002	<0.001
Fort Chipewyan	4	Mar-7-07	2:30	5.3	6.70	3.5	0.73		0.008	0.005	0.002	<0.001
Fort Chipewyan	5	Oct-05							0.012	0.005	0.002	<0.001
Fort Chipewyan	5	Nov-05							0.007	0.004	0.002	<0.001
Fort Chipewyan	5	Dec-05							0.007	0.003	<0.001	<0.001
Fort Chipewyan	5	Mar-27-06	10:50	7.9	6.98		0.66		0.009	0.005	0.002	<0.001
Fort Chipewyan	5	Apr-18-06	10:40	4.8	7.40	1.52	0.67		0.014	0.007	0.003	<0.001
Fort Chipewyan	5	Oct-2-06	11:00	14.9	7.47	1.69	0.59		0.007	0.004	0.002	<0.001
Fort Chipewyan	5	Oct-06							0.010	0.005	0.002	<0.001
Fort Chipewyan	5	Nov-6-06	10:30	10	6.52	1.65	0.23		0.006	0.003	0.001	<0.001
Fort Chipewyan	5	Nov-21-06	2:00	7.6	7.23	1.07	0.61		0.004	0.003	0.001	<0.001
Fort Chipewyan	5	Jan-9-07		5	7.17	1.64	0.64		0.009	0.050	0.002	<0.001
Fort Chipewyan	5	Feb-13-07	3:30	-5.2	7.08	1.73	0.69		0.011	0.006	0.002	<0.001
Fort Chipewyan	5	Mar-7-07	2:40	5.4	6.77	3.5	0.50		0.009	0.005	0.002	<0.001
Fort McKay	3	8-Sep-05	2:03	17	7.05	7	1.29	2.26	0.222	0.002	<0.001	<0.001
Fort McKay	3	18-Oct-05	10:25	10.2	6.86	6	0.75	0.95	0.161	0.002	<0.001	<0.001
Fort McKay	3	7-Nov-05	11:10	7.2	7.49	6	1.47	1.89	0.027	0.009	0.004	<0.001
Fort McKay	3	Dec-6-05	11:50	7.3	7.02	5.75	1.55	2.17	0.150	0.002	<0.001	<0.001
Fort McKay	3	Feb-23-06	11:05	4.7	7.13	4.6	1.71	1.81	0.105	0.002	<0.001	<0.001
Fort McKay	3	Mar-15-06	9:30	6.3	7.07	3.9	1.46	1.92	0.103	0.002	<0.001	<0.001
Fort McKay	3	Oct-18-06	12:20	10.3	7.59	4	1.31	1.63	0.102	0.001	<0.001	<0.001
Fort McKay	3	Nov-15-06	12:00	7.7	7.45	4	1.22	1.31	0.101	0.002	<0.001	<0.001
Fort McKay	3	Dec-6-2006	9:50	8.1	7.15	5.3	0.88	0.93	0.118	0.002	<0.001	<0.001
Fort McKay	3	Jan-15-07	12:00	5.8	7.23	6.5	0.94	1.36	0.109	0.004	<0.001	<0.001
Fort McKay	3	Feb-12-07	11:00	7	7.25	3.7	1.06	1.34	0.108	0.004	<0.001	<0.001
Fort McKay	4	8-Sep-05	2:22	15.1	6.87	7	0.65	1.24	0.217	0.002	<0.001	<0.001
Fort McKay	4	18-Oct-05	10:50	10	6.72	6	0.89	1.27	0.187	0.002	<0.001	<0.001
Fort McKay	4	7-Nov-05	11:55	13	7.33	6	0.43	0.49	0.037	0.013	0.004	<0.001
Fort McKay	4	Dec-6-05	12:40	6.4	7.32	5.75	1.42	1.92	0.162	0.002	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Fort McKay	4	Feb-23-06	11:55	4	7.22	4.6	1.80	7.90	0.105	0.002	<0.001	<0.001
Fort McKay	4	Mar-15-06	11:22	3.4	7.06	3.9	1.57	1.88	0.101	0.002	<0.001	<0.001
Fort McKay	4	Oct-18-06	11:15	11	1.67	4	1.01	1.19	0.079	0.001	<0.001	<0.001
Fort McKay	4	Nov-15-06	12:20	8.9	7.17	4	1.03	1.09	0.113	0.002	<0.001	<0.001
Fort McKay	4	Dec-6-06	10:00	8.9	7.12	5.3	0.56	0.59	0.123	0.002	<0.001	<0.001
Fort McKay	4	Jan-15-07	12:30	6	7.15	6.5	0.89	1.18	0.110	0.003	<0.001	<0.001
Fort McKay	4	Feb-12-07	12:00	5.7	7.15	3.7	0.97	1.21	0.113	0.005	<0.001	<0.001
Fort McKay	5	8-Sep-05	1:35	10	6.85	7	0.13	0.85	0.270	0.003	<0.001	<0.001
Fort McKay	5	18-Oct-05	11:05	10.2	6.74	6	0.63	1.00	0.201	0.002	<0.001	<0.001
Fort McKay	5	7-Nov-05	12:05	8	7.68	6	0.40	0.85	0.063	0.017	0.005	<0.001
Fort McKay	5	Dec-6-05	12:20	9.9	7.30	5.75	0.33	1.11	0.200	0.002	<0.001	<0.001
Fort McKay	5	Feb-23-06	12:14	5.6	7.25	4.6	1.58	1.67	0.128	0.002	<0.001	<0.001
Fort McKay	5	Mar-15-06	11:00	6.1	7.06	3.9	1.32	1.89	0.114	0.002	<0.001	<0.001
Fort McKay	5	Oct-18-06	11:35	11.5	7.35	4	1.02	1.26	0.096	0.001	<0.001	<0.001
Fort McKay	5	Nov-15-06	12:38	10	7.27	4	0.80	0.86	0.112	0.002	<0.001	<0.001
Fort McKay	5	Dec-6-06	10:20	11.4	7.04	5.3	0.31	0.33	0.141	0.003	<0.001	<0.001
Fort McKay	5	Jan-15-07	12:45	8	7.13	6.5	0.45	0.69	0.110	0.004	<0.001	<0.001
Fort McKay	5	Feb-12-07	12:25	6.9	7.12	3.7	0.58	0.81	0.111	0.004	<0.001	<0.001
Hamlet of Woking	3	Aug-23-05	11:20	19.6	7.39	8.36	1.57	2.01	0.151	0.015	0.002	<0.001
Hamlet of Woking	3	Sep-20-05	10:21	17.3	6.89	5.6	0.57	0.97	0.155	0.017	0.002	<0.001
Hamlet of Woking	3	18-Oct-05	10:30	13.8	6.80	5.52	0.84	1.26	0.128	0.014	0.002	<0.001
Hamlet of Woking	3	15-Nov-05	10:45	10.9	6.88	4.63	0.54	0.95	0.106	0.013	0.002	<0.001
Hamlet of Woking	3	13-Dec-05	10:00	10.9	6.98	5.62	1.45	1.81	0.110	0.013	0.002	<0.001
Hamlet of Woking	3	10-Jan-06	10:35	9.7	7.41	2.72	0.98	1.43	0.091	0.009	0.002	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Hamlet of Woking	3	Feb-24-06	11:15	9.5	7.41	2.03	0.80	1.09	0.066	0.010	0.002	<0.001
Hamlet of Woking	3	Mar-24-06	11:15	9.5	7.44	5.74	1.14	1.52	0.078	0.015	<0.001	<0.001
Hamlet of Woking	3	Jun-13-06	11:20	15.1	7.18	5.25	0.78	1.23	0.140	0.015	<0.001	<0.001
Hamlet of Woking	3	Aug-10-06	11:05	19.8	7.69	7.07	0.69	1.11	0.185	0.023	0.001	<0.001
Hamlet of Woking	3	Sep-5-06	10:50	19.1	7.58	6.19	1.22	1.65	0.104	0.017	0.001	<0.001
Hamlet of Woking	3	Oct-10-06	11:45	16	7.64	6.95	0.94	1.31	0.113	0.014	0.001	<0.001
Hamlet of Woking	3	Nov-14-06	10:20	11.5	7.35	9.42	0.51	0.78	0.086	0.012	0.001	<0.001
Hamlet of Woking	3	Dec-12-06	12:42	12.9	7.40	5.38	0.91	1.26	0.102	0.010	<0.001	<0.001
Hamlet of Woking	3	Jan-16-07	10:45	12.3	7.44	6.63	1.11	1.47	0.062	0.014	0.002	<0.001
Hamlet of Woking	3	Feb-20-07	11:20	10.8	7.36	11.74	0.52	0.82	0.101	0.014	<0.001	<0.001
Hamlet of Woking	4	Aug-23-05	11:35	14.8	7.59	8.36	1.03	1.61	0.166	0.016	0.002	<0.001
Hamlet of Woking	4	Sep-20-05	10:42	15.4	7.47	5.6	0.44	0.88	0.146	0.016	0.002	<0.001
Hamlet of Woking	4	18-Oct-05	10:40	15.1	7.52	5.52	0.69	1.04	0.135	0.015	0.002	<0.001
Hamlet of Woking	4	15-Nov-05	11:00	14.1	7.44	4.63	0.42	0.77	0.116	0.014	<0.001	<0.001
Hamlet of Woking	4	13-Dec-05	10:20	11.4	7.21	5.62	1.09	1.49	0.115	0.014	0.002	<0.001
Hamlet of Woking	4	10-Jan-06	10:45	12.1	7.42	2.72	1.07	1.51	0.115	0.011	0.002	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Hamlet of Woking	4	Feb-24-06	11:30	10.1	7.37	2.03	0.43	0.73	0.071	0.012	0.002	<0.001
Hamlet of Woking	4	Mar-24-06	11:45	10.2	7.57	5.74	0.94	1.33	0.082	0.016	<0.001	<0.001
Hamlet of Woking	4	Jun-13-06	11:35	12.6	7.12	5.25	0.64	1.02	0.141	0.015	<0.001	<0.001
Hamlet of Woking	4	Aug-10-06	11:20	15.7	7.17	7.07	0.41	0.82	0.197	0.024	<0.001	<0.001
Hamlet of Woking	4	Sep-5-06	11:10	19.6	7.14	6.19	0.75	1.10	0.144	0.024	<0.001	<0.001
Hamlet of Woking	4	Oct-10-06	12:15	16	6.75	6.95	0.73	1.08	0.123	0.014	0.001	<0.001
Hamlet of Woking	4	Nov-14-06	10:55	15.3	6.89	9.42	0.51	0.78	0.087	0.012	0.001	<0.001
Hamlet of Woking	4	Dec-12-06	1:00	14.5	6.96	5.38	0.44	0.75	0.109	0.011	<0.001	<0.001
Hamlet of Woking	4	Jan-16-07	11:05	12.4	6.99	6.63	0.78	1.14	0.085	0.017	0.002	<0.001
Hamlet of Woking	4	Feb-20-07	11:43	12.6	7.00	11.74	0.19	0.43	0.093	0.013	<0.001	<0.001
Hamlet of Woking	5	Aug-23-05	11:55	14	7.33	8.36	0.85	1.15	0.179	0.016	0.002	<0.001
Hamlet of Woking	5	Sep-20-05	10:51	11.5	7.24	5.6	0.22	0.56	0.163	0.017	0.002	<0.001
Hamlet of Woking	5	18-Oct-05	10:55	13.7	7.22	5.52	0.16	0.45	0.151	0.017	0.002	<0.001
Hamlet of Woking	5	15-Nov-05	11:15	12.4	7.27	4.63	0.19	0.44	0.129	0.016	0.002	<0.001
Hamlet of Woking	5	13-Dec-05	10:30	11.7	7.40	5.62	0.56	0.97	0.126	0.016	0.002	<0.001
Hamlet of Woking	5	10-Jan-06	10:54	10.6	7.24	2.72	0.71	1.10	0.130	0.012	0.002	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Hamlet of Woking	5	Feb-24-06	11:45	9.5	7.30	2.03	0.89	1.23	0.109	0.014	0.002	<0.001
Hamlet of Woking	5	Mar-24-06	11:50	9.4	7.51	5.74	0.42	0.78	0.088	0.017	<0.001	<0.001
Hamlet of Woking	5	Jun-13-06	11:55	12	7.05	5.25	0.54	1.00	0.153	0.017	<0.001	<0.001
Hamlet of Woking	5	Aug-10-06	11:35	6.98	0.38	7.07	0.75	1.00	0.206	0.026	0.001	<0.001
Hamlet of Woking	5	Sep-5-06		15.5	6.76	6.19	0.28	0.59	0.131	0.026	0.003	<0.001
Hamlet of Woking	5	Oct-10-06	12:30	13.7	6.90	6.95	0.11	0.44	0.140	0.016	0.001	<0.001
Hamlet of Woking	5	Nov-14-06	11:10	12.1	7.05	9.42	0.11	0.30	0.126	0.014	0.001	<0.001
Hamlet of Woking	5	Dec-12-06	1:10	14.2	7.28	5.38	0.18	0.48	0.128	0.013	<0.001	<0.001
Hamlet of Woking	5	Jan-16-07	11:15	10.2	7.11	6.63	0.19	0.49	0.097	0.020	0.002	<0.001
Hamlet of Woking	5	Feb-20-07	12:15	10.3	6.93	11.74	0.15	0.39	0.123	0.004	<0.001	<0.001
Town of Westlock	3	16-Aug-05	1:01	17.9	7.56	5	1.24	1.64	0.169	0.002	<0.001	<0.001
Town of Westlock	3	13-Sep-05	1:30	14.9	7.71	4.56	1.43	1.80	0.163	0.003	<0.001	<0.001
Town of Westlock	3	13-Oct-05	10:30	9.2	7.77	4.65	1.27	1.83	0.141	0.002	<0.001	<0.001
Town of Westlock	3	29-Nov-05	2:10	6	7.66	4.27	1.53	1.88	0.110	0.002	<0.001	<0.001
Town of Westlock	3	13-Dec-05	10:00	3.8	7.67	4.15	1.49	1.53	0.123	0.002	<0.001	<0.001
Town of Westlock	3	30-Jan-06	11:08	4.2	7.57	3.58	1.14	1.25	0.123	0.003	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Town of Westlock	3	Feb-14-06	1:32	3.7	7.68	4.58	1.51	2.00	0.139	0.002	<0.001	<0.001
Town of Westlock	3	Mar-27-06	1:30	4.4	7.60	4.18	1.45	1.87	0.077	0.002	<0.001	<0.001
Town of Westlock	3	Apr-27-06	11:35	8	7.72	4.09	1.42	1.80	0.102	0.002	<0.001	<0.001
Town of Westlock	3	Jun-26-06	11:45	16.1	7.55	4.09	1.33	1.77	0.097	<0.001	<0.001	<0.001
Town of Westlock	3	July-18-06	11:10	20	7.55	4.61	1.42	2.04	0.092	0.003	<0.001	<0.001
Town of Westlock	3	Aug-23-06	1:25	19.5	7.60	4.04	1.40	1.69	0.074	0.003	<0.001	<0.001
Town of Westlock	3	Sep-20-06	1:23	13.9	7.83	4.02	1.84	2.06	0.068	0.003	<0.001	<0.001
Town of Westlock	3	Oct-25-06	11:37	9.2	7.75	3.66	1.30	1.62	0.043	0.001	<0.001	<0.001
Town of Westlock	3	Dec-5-06	11:40	5.4	7.64	3.91	1.32	1.59	0.069	0.001	<0.001	<0.001
Town of Westlock	3	Jan-23-07	11:00	4	7.60	3.97	1.62	1.83	0.086	0.002	<0.001	<0.001
Town of Westlock	3	Feb-20-07	1:15	4	7.54	3.63	1.70	1.91	0.075	0.002	<0.001	<0.001
Town of Westlock	3	Mar-6-07	1:40	4.3	2.55	2.91	1.40	1.91	0.077	0.002	<0.001	<0.001
Town of Westlock	4	16-Aug-05	1:55	15.5	7.68	5	0.29	0.57	0.245	0.003	<0.001	<0.001
Town of Westlock	4	13-Sep-05	3:15	17.7	7.94	4.56	0.39	0.66	0.195	0.003	<0.001	<0.001
Town of Westlock	4	13-Oct-05	1:45	10.1	7.66	4.65	0.58	0.98	0.163	0.002	<0.001	<0.001
Town of Westlock	4	29-Nov-05	3:15	8.7	7.67	4.27	0.43	0.64	0.165	0.003	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Town of Westlock	4	13-Dec-05	3:30	8	7.74	4.15	0.49	0.78	0.144	0.002	<0.001	<0.001
Town of Westlock	4	30-Jan-06	1:50	6	7.70	3.58	0.21	0.50	0.178	0.004	<0.001	<0.001
Town of Westlock	4	Feb-14-06	3:05	9.7	7.80	4.58	0.65	1.03	0.162	0.003	<0.001	<0.001
Town of Westlock	4	Mar-27-06	11:20	8.2	7.87	4.18	0.71	0.93	0.109	0.004	<0.001	<0.001
Town of Westlock	4	Apr-27-06	11:00	12	7.77	4.09	1.12	1.13	0.108	0.003	<0.001	<0.001
Town of Westlock	4	Jun-26-06	11:10	19	7.77	4.09	0.79	1.12	0.115	<0.001	<0.001	<0.001
Town of Westlock	4	July-18-06	10:35	18	7.87	4.61	1.11	1.41	0.097	0.003	<0.001	<0.001
Town of Westlock	4	Aug-23-06	11:20	19	7.80	4.04	0.95	1.21	0.095	0.004	<0.001	<0.001
Town of Westlock	4	Sep-20-06	11:35	16	7.93	4.02	1.56	1.73	0.077	0.003	<0.001	<0.001
Town of Westlock	4	Oct-25-06	10:40	14	7.89	3.66	1.10	1.17	0.068	0.002	<0.001	<0.001
Town of Westlock	4	Dec-5-06	10:55	17	7.80	3.91	0.83	0.99	0.106	0.002	<0.001	<0.001
Town of Westlock	4	Jan-23-07	10:40	13	7.60	3.97	1.04	1.27	0.097	0.003	<0.001	<0.001
Town of Westlock	4	Feb-20-07	12:55	13	7.57	3.63	1.15	1.44	0.092	0.003	<0.001	<0.001
Town of Westlock	4	Mar-6-07	10:46	9	7.68	2.91	1.14	1.31	0.094	0.003	<0.001	<0.001
Town of Westlock	5	16-Aug-05	3:00	14.8	7.66	5	0.20	0.36				
Town of Westlock	5	13-Sep-05	2:30	17.5	7.93	4.56	0.11	0.39	0.258	0.004	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Town of Westlock	5	13-Oct-05	2:02	9.9	7.73	4.65	0.60	0.87	0.234	0.003	<0.001	<0.001
Town of Westlock	5	29-Nov-05	3:25	8.6	7.72	4.27	0.12	0.46	0.172	0.003	<0.001	<0.001
Town of Westlock	5	13-Dec-05	2:49	8.1	7.81	4.15	0.31	0.54	0.178	0.003	<0.001	<0.001
Town of Westlock	5	30-Jan-06	3:20	5.1	7.74	3.58	0.20	0.49	0.205	0.004	<0.001	<0.001
Town of Westlock	5	Feb-14-06	3:30	7.1	7.78	4.58	0.19	0.53	0.174	0.004	<0.001	<0.001
Town of Westlock	5	Mar-27-06	11:10	5.4	7.91	4.18	0.41	0.65	0.123	0.005	<0.001	<0.001
Town of Westlock	5	Apr-27-06	10:30	5	7.87	4.09	0.31	0.68	0.165	0.004	<0.001	<0.001
Town of Westlock	5	Jun-26-06	10:45	16.2	7.93	4.09	0.41	0.70	0.130	<0.001	<0.001	<0.001
Town of Westlock	5	July-18-06	10:05	15	8.05	4.61	0.37	0.64	0.106	0.003	<0.001	<0.001
Town of Westlock	5	Aug-23-06	11:10	16	8.04	4.04	0.41	0.58	0.118	0.004	<0.001	<0.001
Town of Westlock	5	Sep-20-06	11:20	10	7.97	4.02	0.46	0.59	0.117	0.004	<0.001	<0.001
Town of Westlock	5	Oct-25-06	10:14	10	8.04	3.66	0.50	0.61	0.089	0.002	<0.001	<0.001
Town of Westlock	5	Dec-5-06	10:40	8	8.03	3.91	0.38	0.55	0.105	0.002	<0.001	<0.001
Town of Westlock	5	Jan-23-07	10:25	6	7.80	3.97	0.49	0.67	0.109	0.003	<0.001	<0.001
Town of Westlock	5	Feb-20-07	11:50	7	7.41	3.63	0.50	0.65	0.125	<0.001	<0.001	<0.001
Town of Westlock	5	Mar-6-07	8:24	4	7.62	2.91	0.53	0.71	0.110	0.004	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Village of Vilna	3	Aug-17-05	11:35	9	7.61	14.2	0.55	0.81	0.055	0.052	0.042	0.015
Village of Vilna	3	16-Sep-05	7:50	8	7.95	3.52	0.08	1.50	0.018	0.019	0.018	0.006
Village of Vilna	3	12-Oct-05	11:57	5	8.23	6.15	0.08	2.20	0.033	0.011	0.004	<0.001
Village of Vilna	3	8-Nov-05	2:05	4	8.24	1.11	0.35	2.13	0.005	0.003	0.002	<0.001
Village of Vilna	3	13-Dec-05	9:47	4	7.79	3.77	0.16	1.55	0.002	0.001	<0.001	<0.001
Village of Vilna	3	12-Jan-06	10:49	4	8.07	4.7	0.11	1.49	0.001	0.001	<0.001	<0.001
Village of Vilna	3	Feb-06							0.001	<0.001	<0.001	<0.001
Village of Vilna	3	Mar-06							0.001	0.001	<0.001	<0.001
Village of Vilna	3	Jun-7-06	8:42	9.7	8.11	3.79	0.08	1.06	<0.001	<0.001	<0.001	<0.001
Village of Vilna	3	Aug-9-06	10:01	10.6	8.01	3.71	0.04	1.20	0.003	0.002	<0.001	<0.001
Village of Vilna	3	Sep-13-06	8:50	9.3	8.06	3.7	0.03	1.16	0.003	0.003	0.001	<0.001
Village of Vilna	3	Oct-3-06	9:31	13.3	7.90	3.42	0.05	1.09	0.003	0.002	<0.001	<0.001
Village of Vilna	3	Nov-06							<0.001	<0.001	<0.001	<0.001
Village of Vilna	3	Jan-3-07	9:09	7.4	7.30	5.39	0.04	1.34	0.004	0.003	<0.001	<0.001
Village of Vilna	3	Feb-14-07	9:46	6.5	7.96	4.8	0.04	1.19	0.006	0.006	0.003	<0.001
Village of Vilna	4	Aug-17-05	11:15	12	7.65	14.2	0.20	0.62	0.059	0.056	0.053	0.017
Village of Vilna	4	16-Sep-05	9:45	11	7.90	3.52	0.20	1.50	0.018	0.018	0.017	0.006
Village of Vilna	4	12-Oct-05	12:09	10	8.16	6.15	0.04	2.01	0.054	0.013	0.001	<0.001
Village of Vilna	4	8-Nov-05	2:30	6	7.88	1.11	0.28	2.20	0.005	0.003	0.002	<0.001
Village of Vilna	4	13-Dec-05	10:27	6	7.97	3.77	0.02	1.50	0.002	0.001	0.002	<0.001
Village of Vilna	4	12-Jan-06	12:02	3	7.83	4.7	0.73	1.48	0.002	0.001	<0.001	<0.001
Village of Vilna	4	Feb-06							0.001	0.001	<0.001	<0.001
Village of Vilna	4	Mar-06							0.001	0.001	<0.001	<0.001
Village of Vilna	4	Jun-7-06	8:58	13.2	8.09	3.79	0.03	0.67	<0.001	<0.001	<0.001	<0.001
Village of Vilna	4	Aug-9-06	6:43	14.4	8.03	3.71	0.04	1.11	0.003	0.002	<0.001	<0.001
Village of Vilna	4	Sep-13-06	9:15	13.8	8.07	3.7	0.04	1.03	0.003	0.003	<0.001	<0.001
Village of Vilna	4	Oct-3-06	9:48	13.6	7.95	3.42	0.02	1.20	0.003	0.002	<0.001	<0.001
Village of Vilna	4	Nov-06							0.003	0.002	<0.001	<0.001
Village of Vilna	4	Jan-3-07	9:20	7.4	7.29	5.39	0.04	1.21	0.004	0.003	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Village of Vilna	4	Feb-14-07	9:58	7	8.00	4.8	0.03	1.07	0.006	0.006	0.003	<0.001
Village of Vilna	5	Aug-17-05	11:05	11	7.60	14.2	0.07	0.21	0.101	0.094	0.095	0.033
Village of Vilna	5	16-Sep-05	10:00	10	7.84	3.52	0.09	0.55	0.027	0.028	0.026	0.008
Village of Vilna	5	12-Oct-05	12:28	8	8.04	6.15	0.02	0.45	0.072	0.018	0.005	<0.001
Village of Vilna	5	8-Nov-05	2:45	6	7.98	1.11	0.02	0.16	0.003	0.002	0.002	<0.001
Village of Vilna	5	13-Dec-05	10:18	4	8.03	3.77	0.03	0.62	0.002	0.001	0.002	<0.001
Village of Vilna	5	12-Jan-06	11:45	3	7.90	4.7	0.14	0.96	0.002	0.002	0.002	<0.001
Village of Vilna	5	Feb-06							0.001	0.001	<0.001	<0.001
Village of Vilna	5	Mar-06							0.002	0.001	<0.001	<0.001
Village of Vilna	5	Jun-7-06	9:05	8.2	8.21	3.79	0.02	0.75	0.002	0.002	<0.001	<0.001
Village of Vilna	5	Aug-9-06	10:40	13.5	8.10	3.71	0.02	0.23	0.002	0.002	<0.001	<0.001
Village of Vilna	5	Sep-13-06	9:30	15.7	8.17	3.7	0.03	0.76	0.003	0.003	0.001	<0.001
Village of Vilna	5	Oct-3-06	13:55	11.2	8.05	3.42	0.02	0.24	0.002	0.002	<0.001	<0.001
Village of Vilna	5	Nov-06							0.003	0.002	0.001	<0.001
Village of Vilna	5	Jan-3-07	9:30	7.8	7.39	5.39	0.04	1.12	0.004	0.003	0.001	<0.001
Village of Vilna	5	Feb-14-07	10:15	5.8	8.08	4.8	0.03	0.62	0.006	0.006	0.003	<0.001
Tangent	3	7-Sep-05	9:40	15	7.60	9	1.20	1.40	0.113	0.001	<0.001	<0.001
Tangent	3	6-Oct-05	8:20	10	7.50	7.3	0.60	0.90	0.123	0.001	<0.001	<0.001
Tangent	3	3-Nov-05	8:45	8	7.40	8.3	0.70	1.00	0.109	0.001	<0.001	<0.001
Tangent	3	7-Dec-05	9:15	6	7.40	10.1	1.00	1.50	0.102	0.001	<0.001	<0.001
Tangent	3	4-Jan-06	8:15	9	7.40	9.6	1.10	1.30	0.112	0.001	<0.001	<0.001
Tangent	3	Feb-8-06	8:50	9	7.30	11.9	0.90	1.20	0.114	0.001	<0.001	<0.001
Tangent	3	Mar-08-06	8:50	12	7.30	12.2	0.80	1.10	0.076	0.001	<0.001	<0.001
Tangent	3	14-Jun-06	8:40	20	7.50	12	1.20	1.50	0.161	0.002	<0.001	<0.001
Tangent	3	20-Jul-06	9:10	21	7.50	12.7	1.30	1.60	0.141	0.002	<0.001	<0.001
Tangent	3	Aug-17-06	9:00	20	7.50	9.7	0.70	1.00	0.163	<0.001	<0.001	<0.001
Tangent	3	Sep-06							0.107	0.002	<0.001	<0.001
Tangent	3	Oct-05-06	8:30	14	7.60	9.8	1.20	1.50	0.108	0.001	<0.001	<0.001
Tangent	3	Nov-14-06	8:55	10	7.80	9	1.00	1.30	0.109	0.001	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Tangent	3	Dec-12-06	8:45	11	7.50	11	0.90	1.40	0.100	0.001	<0.001	<0.001
Tangent	3	Jan-2-07	9:20	11	7.40	11.4	1.00	1.30	0.077	<0.001	<0.001	<0.001
Tangent	3	Feb-5-07	9:15	10	7.30	11	0.90	1.20	0.092	0.001	<0.001	<0.001
Tangent	3	Mar-5-07	8:50	10	7.30	10.7	0.80	1.10	0.095	0.001	<0.001	<0.001
Tangent	4	7-Sep-05	9:00	9	7.40	9	0.60	0.90	0.087	0.001	<0.001	<0.001
Tangent	4	6-Oct-05	8:50	7	7.30	7.3	0.20	0.50	0.147	0.001	<0.001	<0.001
Tangent	4	3-Nov-05	8:55	8	7.40	8.3	0.40	0.70	0.130	0.001	<0.001	<0.001
Tangent	4	7-Dec-05	9:30	3	7.40	10.1	0.60	1.00	0.117	0.001	<0.001	<0.001
Tangent	4	4-Jan-06	8:45	3	7.30	9.6	0.90	1.20	0.140	0.001	<0.001	<0.001
Tangent	4	Feb-8-06	9:00	5	7.20	11.9	0.50	0.90	0.111	0.002	<0.001	<0.001
Tangent	4	Mar-08-06	9:00	7	7.20	12.2	0.30	0.60	0.085	0.001	<0.001	<0.001
Tangent	4	14-Jun-06	9:00	8	7.30	12	0.80	1.00	0.162	0.002	<0.001	<0.001
Tangent	4	20-Jul-06	9:20	10	7.30	12.7	0.70	1.00	0.160	0.002	<0.001	<0.001
Tangent	4	Aug-17-06	9:15	14	7.80	9.7	0.30	0.50	0.170	0.002	<0.001	<0.001
Tangent	4	Sep-06							0.135	0.002	<0.001	<0.001
Tangent	4	Oct-05-06	8:40	11	7.70	9.8	0.70	1.00	0.144	0.001	<0.001	<0.001
Tangent	4	Nov-14-06	9:15	9	7.60	9	0.60	0.90	0.143	0.001	<0.001	<0.001
Tangent	4	Dec-12-06	9:00	7	7.40	11	0.50	0.90	0.120	0.001	<0.001	<0.001
Tangent	4	Jan-2-07	9:30	7	7.30	11.4	0.50	0.80	0.097	0.001	<0.001	<0.001
Tangent	4	Feb-5-07	9:20	7	7.30	11	0.60	0.90	0.110	0.002	<0.001	<0.001
Tangent	4	Mar-5-07	9:10	5	7.30	10.7	0.60	0.90	0.109	0.002	<0.001	<0.001
Tangent	5	7-Sep-05	9:30	8	7.40	9	0.60	0.80	0.154	0.002	<0.001	<0.001
Tangent	5	6-Oct-05	9:00	7	7.30	7.3	0.20	0.50	0.138	0.001	<0.001	<0.001
Tangent	5	3-Nov-05	9:15	5	7.20	8.3	0.20	0.50	0.146	0.001	<0.001	<0.001
Tangent	5	7-Dec-05	9:40	3	7.40	10.1	1.20	1.50	0.116	0.001	<0.001	<0.001
Tangent	5	4-Jan-06	8:30	2	7.30	9.6	0.70	1.00	0.136	0.001	<0.001	<0.001
Tangent	5	Feb-8-06	9:20	3	7.20	11.9	0.50	0.90	0.106	0.001	<0.001	<0.001
Tangent	5	Mar-08-06	9:15	5	7.20	12.2	0.30	0.60	0.085	0.002	<0.001	<0.001
Tangent	5	14-Jun-06	9:10	8	7.30	12	0.40	0.80	0.185	0.002	<0.001	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	Chlorine Dose (mg/L)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	THM Ch.form (mg/L)	THM Brm. mehtane (mg/L)	THM Dib. methane (mg/L)	THM Bromoform (mg/L)
Tangent	5	20-Jul-06	9:25	10	7.40	12.7	0.40	0.80	0.159	0.002	<0.001	<0.001
Tangent	5	Aug-17-06	9:25	14	7.80	9.7	0.30	0.50	0.172	0.002	<0.001	<0.001
Tangent	5	Sep-06							0.130	0.002	<0.001	<0.001
Tangent	5	Oct-05-06	8:40	10	7.50	9.8	0.60	0.90	0.132	0.001	<0.001	<0.001
Tangent	5	Nov-14-06	9:30	8	7.60	9	0.50	0.80	0.145	0.001	<0.001	<0.001
Tangent	5	Dec-12-06	9:15	7	7.40	11	0.40	0.80	0.133	<0.001	<0.001	<0.001
Tangent	5	Jan-2-07	9:45	7	7.30	11.4	0.40	0.80	0.102	0.001	<0.001	<0.001
Tangent	5	Feb-5-07	9:30	7	7.30	11	0.40	0.70	0.105	0.002	<0.001	<0.001
Tangent	5	Mar-5-07	9:20	5	7.30	10.7	0.50	0.80	0.118	<0.001	<0.001	<0.001
St. Michael	3	Aug-05							0.011	0.003	0.002	<0.001
St. Michael	3	Sep-05							0.011	0.003	0.002	<0.001
St. Michael	3	31-Oct-05	10:15		7.25		0.73		0.009	0.002	0.002	<0.001
St. Michael	3	Dec-05							0.009	0.002	<0.001	<0.001
St. Michael	3	Feb-06							0.007	0.002	0.002	<0.001
St. Michael	4	Aug-05							0.012	0.003	0.002	<0.001
St. Michael	4	Sep-05							0.014	0.003	0.002	<0.001
St. Michael	4	31-Oct-05	10:20		7.27		0.56		0.012	0.003	0.002	<0.001
St. Michael	4	Dec-05							0.011	0.002	<0.001	<0.001
St. Michael	4	Feb-06							0.009	0.002	0.002	<0.001
St. Michael	5	Aug-05							0.014	0.003	0.002	<0.001
St. Michael	5	Sep-05							0.013	0.003	0.002	<0.001
St. Michael	5	31-Oct-05	10:35		7.20		0.61		0.012	0.003	0.002	<0.001
St. Michael	5	Dec-05							0.011	0.003	<0.001	<0.001
St. Michael	5	Feb-06							0.012	0.003	0.002	<0.001

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	HAA Brm. acid (mg/L)	HAA Brm-chl. acid (mg/L)	HAA Chl. acid (mg/L)	HAA Dib. acid (mg/L)	HAA Dichl. acid (mg/L)	HAA Trichl. acid (mg/L)
Town of Bonnyville	3	Sep-25-06	9:30	15.6	8.00	<0.002	0.0055	<0.02	<0.002	0.0374	0.0278
Town of Bonnyville	4	Sep-25-06	10:45	15.6	7.60	0.002	0.0052	0.02	0.002	0.0363	0.0276
Town of Bonnyville	5	Sep-25-06	11:10	24.2	7.50	0.002	0.0027	0.02	0.002	0.0248	0.0414
Fort Chipewyan	3	Oct-06				<0.002	<0.002	<0.02	<0.002	0.0049	0.0041
Fort Chipewyan	3	Nov-21-06	9:00	5.5	7.23	<0.002	<0.002	<0.02	<0.002	0.0047	0.0026
Fort Chipewyan	3	Feb-13-07	2:15	-4.3	7.07	<0.002	0.0035	<0.02	<0.002	0.006	0.0045
Fort Chipewyan	3	Mar-7-07	2:00	4	7.22	<0.002	0.0089	<0.02	0.0052	0.0111	<0.002
Fort Chipewyan	4	Oct-06				0.002	0.002	0.02	0.002	0.0165	0.0041
Fort Chipewyan	4	Nov-21-06	1:25	8	7.25	0.002	0.0028	0.02	0.002	0.0047	0.003
Fort Chipewyan	4	Feb-13-07	3:00	-5.8	7.06	0.002	0.0038	0.02	0.002	0.0066	0.005
Fort Chipewyan	4	Mar-7-07	2:30	5.3	6.70	0.002	0.009	0.02	0.0047	0.0116	0.01
Fort Chipewyan	5	Oct-06				0.002	0.0037	0.02	0.002	0.0113	0.0078
Fort Chipewyan	5	Nov-21-06	2:00	7.6	7.23	0.002	0.0028	0.02	0.002	0.0049	0.003
Fort Chipewyan	5	Feb-13-07	3:30	-5.2	7.08	0.002	0.0038	0.02	0.002	0.0068	0.0052
Fort Chipewyan	5	Mar-7-07	2:40	5.4	6.77	0.002	0.0089	0.02	0.0048	0.0114	0.01
Fort McKay	3	Nov-15-06	12:00	7.7	7.45	<0.002	<0.002	<0.02	<0.002	0.0422	0.0634
Fort McKay	3	Feb-12-07	11:00	7	7.25	<0.002	<0.002	<0.02	<0.002	0.0494	0.0666
Fort McKay	4	Nov-15-06	12:20	8.9	7.17	0.002	0.002	0.02	0.002	0.0406	0.0671
Fort McKay	4	Feb-12-07	12:00	5.7	7.15	0.002	0.002	0.02	0.002	0.0509	0.069
Fort McKay	5	Nov-15-06	12:38	10	7.27	0.002	0.002	0.02	0.002	0.0416	0.0688
Fort McKay	5	Feb-12-07	12:25	6.9	7.12	0.002	0.002	0.02	0.002	0.0562	0.0775
Hamlet of Woking	3	Jan-16-07	10:45	12.3	7.44	<0.002	0.008	<0.02	<0.002	0.0437	0.0495
Hamlet of Woking	3	Feb-20-07	11:20	10.8	7.36	<0.002	0.0052	<0.02	<0.002	0.0402	0.0449
Hamlet of Woking	4	Nov-14-06	10:55	15.3	6.89	0.002	0.0047	0.02	0.002	0.0391	0.0517

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	HAA Brm. acid (mg/L)	HAA Brm-chl. acid (mg/L)	HAA Chl. acid (mg/L)	HAA Dib. acid (mg/L)	HAA Dichl. acid (mg/L)	HAA Trichl. acid (mg/L)
Hamlet of Woking	4	Jan-16-07	11:05	12.4	6.99	0.002	0.0083	0.02	0.002	0.0501	0.058
Hamlet of Woking	4	Feb-20-07	11:43	12.6	7.00	0.002	0.005	0.02	0.002	0.0408	0.0442
Hamlet of Woking	5	Nov-14-06	11:10	12.1	7.05	0.002	0.002	0.02	0.002	0.0095	0.0565
Hamlet of Woking	5	Jan-16-07	11:15	10.2	7.11	0.002	0.0062	0.02	0.002	0.0374	0.0459
Hamlet of Woking	5	Feb-20-07	12:15	10.3	6.93	0.002	0.0053	0.02	0.002	0.043	0.0585
Town of Westlock	3	July-18-06	11:10	20	7.55	<0.002	<0.002	<0.02	<0.002	<0.002	<0.002
Town of Westlock	3	Jan-23-07	11:00	4	7.60	<0.002	<0.002	<0.02	<0.002	0.0353	0.0457
Town of Westlock	3	Feb-20-07	1:15	4	7.54	<0.002	<0.002	<0.02	<0.002	0.043	0.0604
Town of Westlock	3	Mar-6-07	1:40	4.3	2.55	<0.002	<0.002	<0.02	<0.002	0.0365	0.0573
Town of Westlock	4	July-18-06	10:35	18	7.87	0.002	0.002	0.02	0.002	0.0419	0.063
Town of Westlock	4	Jan-23-07	10:40	13	7.60	0.002	0.002	0.02	0.002	0.034	0.0462
Town of Westlock	4	Feb-20-07	12:55	13	7.57	0.002	0.002	0.02	0.002	0.0549	0.069
Town of Westlock	4	Mar-6-07	10:46	9	7.68	0.002	0.002	0.02	0.002	0.0455	0.0637
Town of Westlock	5	July-18-06	10:05	15	8.05	0.002	0.002	0.02	0.002	0.0507	0.0947
Town of Westlock	5	Jan-23-07	10:25	6	7.80	0.002	0.002	0.02	0.002	0.0358	0.0711
Town of Westlock	5	Feb-20-07	11:50	7	7.41	0.002	0.002	0.02	0.002	0.0754	0.12

Water Works Name	Loc.	Date	Time	Temp (oC)	pH	HAA Brm. acid (mg/L)	HAA Brm-chl. acid (mg/L)	HAA Chl. acid (mg/L)	HAA Dib. acid (mg/L)	HAA Dichl. acid (mg/L)	HAA Trichl. acid (mg/L)
Town of Westlock	5	Mar-6-07	8:24	4	7.62	0.002	0.002	0.02	0.002	0.052	0.0866
Village of Vilna	3	Oct-3-06	9:31	13.3	7.90	<0.002					
Village of Vilna	3	Nov-06				<0.002					
Village of Vilna	3	Jan-3-07	9:09	7.4	7.30	<0.002	<0.002	<0.02	<0.002	<0.002	<0.002
Village of Vilna	3	Feb-14-07	9:46	6.5	7.96	<0.002	0.0056	<0.02	0.0041	0.0057	0.0028
Village of Vilna	4	Oct-3-06	9:48	13.6	7.95	0.002	0.002	0.02	0.002	0.0057	0.002
Village of Vilna	4	Nov-06				0.002	0.0037	0.02	0.0021	0.0062	0.0025
Village of Vilna	4	Jan-3-07	9:20	7.4	7.29	0.002	0.0037	0.02	0.0021	0.0062	0.0025
Village of Vilna	4	Feb-14-07	9:58	7	8.00	0.002	0.006	0.02	0.0043	0.0065	0.0028
Village of Vilna	5	Oct-3-06	13:55	11.2	8.05	0.002	0.002	0.02	0.002	0.002	0.002
Village of Vilna	5	Nov-06				0.002	0.0026	0.02	0.002	0.0163	0.0168
Village of Vilna	5	Jan-3-07	9:30	7.8	7.39	0.002	0.0026	0.02	0.002	0.0163	0.0168
Village of Vilna	5	Feb-14-07	10:15	5.8	8.08	0.002	0.0051	0.02	0.0043	0.0055	0.0022
Tangent	3	Nov-14-06	8:55	10	7.80	<0.002	<0.002	<0.02	<0.002	0.0585	0.0647
Tangent	3	Feb-5-07	9:15	10	7.30	<0.002	<0.002	<0.02	<0.002	0.0497	0.0629
Tangent	3	Mar-5-07	8:50	10	7.30	<0.002	<0.002	<0.02	<0.002	0.0617	0.0578
Tangent	4	Nov-14-06	9:15	9	7.60	0.002	0.0052	0.02	0.002	0.0706	0.0705
Tangent	4	Feb-5-07	9:20	7	7.30	0.002	0.002	0.02	0.002	0.0595	0.0685
Tangent	4	Mar-5-07	9:10	5	7.30	0.002	0.002	0.02	0.002	0.0745	0.0561
Tangent	5	Nov-14-06	9:30	8	7.60	0.002	0.002	0.02	0.002	0.0703	0.0653
Tangent	5	Feb-5-07	9:30	7	7.30	0.002	0.002	0.02	0.002	0.0528	0.0629
Tangent	5	Mar-5-07	9:20	5	7.30	0.002	0.002	0.02	0.002	0.0639	0.0526