Validation of a Canadian drinking source water quality index and its application to investigate the spatial scale of land use – source water quality relationships

by

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BSc, McMaster University, 2008

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Supervisory Committee

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Abstract

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Source water protection is a key component of the multiple barrier approach to drinking water. The management of contamination within source water ecosystems is associated with many benefits but also several challenges. By its very nature, source water protection is site specific and requires the cooperation of numerous watershed stakeholders to ensure sufficient financial resources and social will. This work focused on two critical aspects of source water protection:

1) The facilitation of effective communication to promote cooperation among watershed stakeholders and aid in public education programs.

A drinking source water quality index presents a potential communication and analysis tool to facilitate cooperation between diverse interest groups as well as represent composite source water quality. I tested the effectiveness of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) in capturing expert assessments of surface drinking source water quality. In cooperation with a panel of drinking water quality experts I identified a core set of parameters to reflect common Canadian surface source water concerns. Based upon existing source water guidelines, drinking source water target values were drafted for use in the index corresponding to two basic treatment levels. Index scores calculated using the core parameter set and associated source water target values were strongly correlated with expert assessments of source water quality. Amended with a modified index calculation procedure to accommodate parameters measured at different frequencies within any particular study period, the CCME WQI provides a valuable means of monitoring, communicating, and understanding surface source water quality.

2) The application of source water protection strategies to the appropriate spatial scale in order to manage contaminants of concern in a cost effective manner.

Using data gathered from 40 Canadian rivers across 4 western Canadian ecozones I examined the spatial scales at which landuse was most closely associated with drinking source water quality metrics. Linear mixed effects models revealed that different spatial areas of landuse influence drinking source water quality depending on the parameter and season investigated. Microbial risk, characterized using *E. coli* measures, was only associated with landuse at the local spatial scale. Turbidity measures exhibited a complex association with landuse suggesting that the landuse areas of greatest influence can range from the local to the watershed scale. Total organic carbon concentrations were only associated with landuse characterized at the entire watershed scale. The validated CCME WQI was used to provide a composite measure of seasonal drinking source water quality but did not provide additional information beyond the analyses of individual parameters. These results suggest that entire watershed management is required to safeguard drinking water sources with more focused efforts at targeted spatial scales to reduce identified risk parameters.

The source water protection tools and knowledge that I present have immediate application within Canada. Practitioners must be aware of the limitations of the CCME WQI however it provides a validated means of communicating complex source water quality information to non-specialized end users. Combined with the scale dependency of landuse-source water relationships that I elucidated, water quality managers can target contaminant reduction strategies in a more cost-effective manner and relay water quality status and trends to concerned groups.

Table of Contents

List of Tables

List of Figures

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Chapter 1 General Introduction

Within Canada, water has four primary designated uses: 1) habitat for aquatic life, 2) source water for domestic consumption (drinking), 3) water for recreational purposes, and 4) water for industrial uses (Canadian Council of Ministers of the Environment, 2006a). All four prescribed water uses rely on a sufficient supply of clean water. However, the connection between human health and wellbeing and the environment is manifested most strongly in our dependence on a clean supply of drinking water (Davies and Mazumder, 2003). Despite continued advancements in drinking water treatment technology, training and legislation, an estimated 90 000 illnesses and 90 deaths each year in Canada are attributed to unsafe drinking water (Environment Canada, 2001). Although first nations, rural and remote communities are particularly vulnerable to drinking water related health risks (Swain *et al*., 2006; Eggertson, 2008; Kot *et al*., 2011), large urban centres are not immune. Over a six year period in the 1990's, Aramini *et al*. (2000) estimated that approximately 17500 physician visits, 85 hospital admissions and 138 paediatric hospital emergency room visits were due to the consumption of unsafe municipal water in Vancouver. Furthermore, a study of tap-water drinkers in suburban Montreal estimated that greater than one third of all gastrointestinal illnesses were related to drinking water (Payment *et al*., 1991).

Of the greater than 250 waterborne disease outbreaks documented in Canada since the mid 1970's (Schuster *et al*., 2005) the events in Walkerton during the spring of 2000 have left the greatest mark on public consciousness and subsequently instigated comprehensive reviews of drinking water management at the municipal, provincial and federal levels (Patrick, 2009). *Escherichia coli* O157:H7 and *Campylobacter jejuni* contamination of one of Walkerton’s municipal wells left more than 2300 of the town’s 4800 citizens ill and resulted in 7 deaths (O’Connor, 2002a). The Walkerton Inquiry, an independent commission convened by the province of Ontario to investigate the outbreak, put forth a list of 122 recommendations to protect the future of drinking water (O’Connor, 2002b). These recommendations stress the importance of the multiple-barrier approach in ensuring drinking water safety. The multiple barrier approach is an integrated system of strategies to prevent the contamination of drinking water from source to tap (Canadian Council of Ministers of the Environment, 2004). Five separate but related barriers are commonly employed to protect drinking water safety: 1) Protection of source waters, 2) Robust water treatment, 3) A secure distribution system, 4) Comprehensive monitoring programs and 5) Response protocols for adverse conditions (O’Connor, 2002b; Canadian Council of Ministers of the Environment, 2004).

Considering that the majority of health risks posed by adverse water quality conditions originate in the source water ecosystems (Canadian Council of Ministers of the Environment, 2004), source water protection is the root of an effective drinking water management plan. Source water protection refers to watershed and aquifer management via land use planning and other initiatives to prevent contamination of drinking water supplies (Patrick, 2009). Surface source water is particularly susceptible to contamination as it lacks the natural soil protection and filtration functions offered by ground water sources (Kistemann *et al*., 2001). Surface source water is defined as raw (untreated and unfiltered) water from rivers, lakes, reservoirs, and streams that is extracted by utilities and individuals to be used for drinking purposes (Davies and Mazumder, 2003).

Commonly located close to the communities they serve, surface source water supplies are vulnerable to anthropogenic and natural pollution inputs.

Surface source water hazards can introduce microbiological, chemical and radiological contaminants into receiving waters thereby deteriorating the quality of water as a drinking source (Health Canada, 2010). Drinking source water quality describes the physical, chemical, and biological characteristics of a source water supply and the corresponding risks posed by those characteristics to drinking water consumers. The ultimate health or aesthetic implications of the contaminants present in surface source waters depend on a variety of intervening factors, the most important of which is treatment. The goal of effective treatment is to reduce the perceived risks posed by drinking water to a level so negligible that a reasonable, well-informed individual would not be concerned nor have any rational basis to change their behaviour to avoid such a small, but non-zero risk (Hrudey *et al*., 2006). Though treatment systems are designed to "fail safe" numerous examples exist of treatment systems failing, whether due to mechanical or operational errors, in such a way as to expose consumers to unacceptable risks (Schuster *et al*., 2005). Therefore, simply stated, a cleaner source of drinking water presents lower chronic and acute risks to consumers and is of higher drinking water quality (Davies and Mazumder, 2003). However, the protection of drinking source water quality requires the management of multiple, potentially competing yet often interrelated, risk factors.

1.1 Drinking source water quality risk factors

Microbiological pathogens, including bacterial, viral and protozoan organisms, are of the greatest public health concern due to the acuteness and severity of their effects (Canadian Council of Ministers of the Environment, 2004). The sheer variety of waterborne pathogens necessitates that the characterization of microbial health risk in a timely and cost effective manner rely on bacterial indicators of fecal pollution and potential pathogen presence (Yates, 2007, Wilkes *et al*, 2009). Fecal contamination of surface source waters increases drinking water health risks as it presents the potential for enteric pathogens to enter the drinking water system.

In order to reduce the risk of pathogens reaching the tap, primary disinfection of surface source waters is mandated in all Canadian jurisdictions. Chlorination remains the most common form of microbial inactivation in Canada due in part to its low cost and effectiveness (Province of Manitoba, 2005). Chlorination of drinking waters provides several advantageous functions along with the reduction of acute microbial risk however chronic chemical risks, in the form of disinfection by-products (DBPs), may be simultaneously introduced (Sadiq and Rodriguez, 2004). It has long been acknowledged that the oxidation of natural organic matter (NOM) can produce harmful DBPs (Rook, 1974). The formation of these DBPs is a function of operational parameters such a chlorine dose and contact time as well as source water conditions (Amy *et al*., 1987; Hong *et al*., 2003). In particular, the nature of the NOM present in source waters (namely the humic and fulvic acid composition), pH, temperature and bromide ion concentration influence DBP speciation and concentration (Sadiq and Rodriguez, 2004; Krasner *et al*., 2006). Aquatic organic matter is the product of both allochthonous and autochthonous processes (Gergel *et al*., 1999; Chow *et al*., 2007). Allochthonous organic matter makes up the majority of inputs to lotic systems whereas autochthonous contributions via algal and macrophyte exudates are well documented in lentic environments (Parks and Baker, 1997). Organic carbon concentration is commonly used to represent source water DBP potential because under standard conditions, waters with lower organic carbon levels will produce fewer DBPs thereby presenting lower risk when oxidized (Symons *et al*., 1975).

Nutrient inputs to drinking source waters pose direct and indirect risks to consumers. High levels of nitrogen, specifically nitrate and nitrite ions, can result in methaemoglobinaemia, a blood disorder to which infants are particularly susceptible (WHO, 2008). The combined effects of nitrogen and phosphorus additions to aquatic systems can result in enhanced aquatic productivity leading to eutrophication (Smith, 2003). The process of cultural eutrophication is associated with higher organic carbon concentrations (Smith *et al*., 1999) and thus increased DBP formation risks. Furthermore, induced shifts in algal communities can affect DBP levels and speciation (Hong *et al*., 2008). The growth of toxin producing cyanobacteria is also associated with high nutrient levels (Davies and Mazumder, 2003, Giani *et al*., 2005).

In addition to the drinking water quality impacts of inorganic nutrients, the Guidelines for Canadian Drinking Water Quality recommend over 80 chemical substances that should be limited in finished drinking water (Health Canada, 2010). These substances include heavy metals, pesticides and industrial chemicals known to have serious implications for health. Also included among the listed chemicals are several parameters with strictly aesthetic guidelines. These aesthetic considerations include such parameters as colour, iron, pH and temperature. Consumer perception of drinking water safety is often based on aesthetic concerns (Davies *et al*., 2004; Macguire, 1995; Levallois *et al*., 1999). Therefore, regardless of the actual health risks, perceived risk is a strong determinant of consumer confidence and treatment requirements (Canadian Council of Ministers of the Environment, 2004).

As outlined, drinking water treatment is imperative to reduce health risks to acceptable levels as well neutralize taste, colour, and odour compounds. The maintenance of an effective treatment and distribution system is a critical component of the multiple-barrier system (Canadian Council of Ministers of the Environment, 2004). Therefore, source water conditions that may not present individual health risks or aesthetic concerns but may compromise treatment or distribution system integrity have important management implications (WHO, 2008). Emelko *et al*. (2011) stress the need to consider source water “treatability” along with contaminants that present significant health risks. Under the Guidelines for Canadian Drinking Water Quality, turbidity is listed as a microbiological parameter in finished drinking water (Health Canada, 2010). Turbidity is often used as a proxy for microbial contamination due to the demonstrated correlation between turbidity and fecal contamination of water supplies (LeChevallier *et al*, 1991). However, high turbidity levels in source waters present several challenges to treatment systems. Turbidity increases disinfectant demand and decay rates, can shield pathogens from disinfection as well as stimulate bacterial growth (Province of Manitoba, 2005; WHO, 2008). Similarly, pH control is critical to reduce corrosion and precipitation in the distribution system while ensuring efficient, low DBP chlorination (Health Canada, 2010).

The preceding brief review of source drinking water contamination reveals three broad pollutant categories. Fecal and chemical pollutants in source drinking water present serious health risks to consumers. Aesthetic contaminants affect water palatability and consumer confidence in water safety. Finally several source water constituents, including physical characteristics, can interfere with treatment processes. Source water parameters need not fit neatly into one of the three pollutant categories. For example, NOM characterized as organic carbon presents health risks via DBP production upon oxidation (Krasner *et al*., 2006), aesthetic concerns in the form of taste and odour compounds and operational concerns as it increases the need for and difficulty in maintaining efficient solids removal processes (Emelko *et al*., 2011). These health, aesthetic and operational concerns all contribute to what we define as drinking source water quality.

1.2 Source water protection to manage drinking source water quality risks

The application of source water protection initiatives to help provide high quality drinking water offers an attractive alternative to traditional treatment-centric management philosophies. Source water protection can take several forms ranging from proactive land use planning strategies to the responsive application of best management practices (Patrick, 2008; Islam *et al*., 2011). Several studies have demonstrated the effectiveness of source water protection in reducing contaminants in the drinking water supply (LeChavalier *et al*., 1991; Larsen *et al*., 1994; Daniels and Gilliam, 1996; Ong *et al*., 1996; Hathaway *et al*., 2009). Along with the clear connection between source water protection and drinking water quality, source water protection offers economic and social benefits as well. Source water protection is an economically prudent means of providing safe drinking water for three primary reasons (Patrick, 2008): 1) remediation of contaminated water supplies is more expensive than the prevention of initial contamination, 2) investment in natural capital (watersheds) is more cost effective than the investment in physical capital (treatment technology) and 3) maintenance of a high quality drinking water source significantly reduces treatment challenges and costs. Source water protection also has the potential to reconnect health and place for communities, particularly First Nations peoples (Patrick, 2011). Watershed management at the local level has the potential to promote community engagement, facilitate partnerships, educate watershed users and integrate the concepts of water quality and quantity with land conservation (Patrick, 2011; Timmer *et al*., 2007).

Despite its numerous benefits, source water protection is not easily attainable (Patrick, 2008). Challenges to source water protection include issues of site specificity, scale, authority, communication, social will and economics (Ivey *et al*., 2006; Timmer *et al*., 2007; Patrick, 2008; Patrick, 2011). Source water protection is very much a site-specific management strategy due to the diversity of natural waters and watersheds (Timmer *et al*., 2007; Patrick *et al*., 2008). Therefore, the broad scale application of source water protection initiatives is not appropriate (Robbins *et al*., 1991). Instead the identification of current and future source water vulnerabilities followed by the development and implementation of suitable protection strategies is necessary on a source by source basis (Patrick *et al*., 2008). Watersheds frequently cross jurisdictional boundaries as well, necessitating the cooperation of multiple authorities and stakeholders (Ivey *et al*., 2006; Timmer *et al*., 2007). Large metropolitan areas may have the financial means to purchase the exclusive rights to source watersheds, resources which are not available to smaller scale water suppliers (Patrick *et al*., 2008).

Factors that have been identified as critical to facilitating source water protection, especially for nonmetropolitan areas, include the building of relationships and communication among watershed users (Patrick, 2008) as well as public education (Ivey *et al*., 2006; Patrick, 2008; Islam *et al*., 2011). Support of community members is especially critical to ensure the availability of sufficient financial resources for source water protection and to reduce opposition to restrictions on activities on private watershed lands (Timmer *et al*., 2007). This thesis aims to provide tools and knowledge that promote source water protection facilitating factors.

1.3 Thesis objectives and structure

The work presented in this thesis focuses on two primary aspects of source water protection: 1) the facilitation of effective communication to promote cooperation among stakeholders and educate the public and 2) the application of source water protection strategies to the appropriate spatial scale in order to manage contaminants of concern in a cost effective manner. These two research topics are presented in separate thesis chapters. Chapters 2 and 3 explore the application of a drinking source water quality index to characterize Canadian drinking source water quality while Chapter 4 utilizes the developed index tool to investigate the spatial extent of landuse-drinking source water quality relationships.

The multi-parametric nature of drinking source water quality makes the communication of quality status and trends to non-specialized stakeholders a difficult task (de Rosemond *et al*., 2009). Considering the importance of effective communication towards implementing and managing source water protection initiatives, the complex nature of drinking source water quality can impede relationship building and public education. Developed to integrate, interpret, and communicate environmental monitoring data, indices have been used to successfully characterize water quality and relay that information to concerned groups (Cude, 2001; Lumb *et al*. 2006). The objectives of the first component of this thesis were to: 1) develop/adapt a water quality index for the Canadian drinking source water context, 2) calibrate the resulting index using expert assessments of source water quality and 3) pilot test the index using real world data to investigate sensitivity to input variability. Chapter 2 titled *Water quality indices: Canadian drinking source water opportunities and challenges* first presents a review of existing index literature, highlighting the challenges specific to Canadian drinking source water quality characterization. Secondly an appropriate index template is selected to meet the challenges posed by drinking source waters. Chapter 3 titled *Adaptation and evaluation of the CCME WQI as an effective tool to characterize source water quality* utilizes a panel of drinking water quality experts to select appropriate index inputs to capture drinking source water quality risk. Expert assessments of drinking source water quality are then used to adjust the index output to reflect consensus evaluations of quality. Finally water quality data from British Columbia, Alberta and Manitoba sites are used to calculate real-world index scores and a sensitivity analysis performed.

Spatial scale is an important ecological concept (Levin, 1992; Schneider, 2001). It is well acknowledged that landuse activities have strong implications for water quality in general and drinking source water quality in particular (Allan, 2004). However, the spatial scales at which landuse influences water quality are not well understood (Gergel *et al*., 1999; Tong and Chen, 2002). With this in mind, the goals of the second research component of this thesis were to: 1) establish the long-term seasonal trends in western Canadian riverine drinking source water quality, 2) identify relationships between the spatial variability in drinking source water quality and watershed characteristics and 3) determine the upstream spatial scales at which quantified landuse is most strongly associated with drinking source water quality variability. Chapter 4 titled *Understanding the role of watershed characteristics in protecting surface source water quality: An investigation of the spatial scale of landuse impacts* examines drinking source water quality characterized using individual parameters representative of various risk factors as well as the validated composite index measure. Long-term seasonal trends among 40 river sites in British Columbia, Alberta and Manitoba are described to identify periods of peak contamination. Landuse, climate and natural physiographic features are then used to explain the spatial variability in seasonal drinking source water quality. In particular, the relationship between landuse and drinking source water quality is investigated across a range of spatial scales. Landuse is characterized at scales ranging from the immediate upstream area to the entire upstream watershed area to identify at what scale landuse and water quality are most strongly associated.

Chapter 5 provides a synthesis of the research findings of the previous chapters. The contributions of this work to source water protection are highlighted as well as some of the potential challenges to the application of the developed tools and knowledge. Unanswered and new questions are also identified to help guide future research.

Chapter 2 Water quality indices: Canadian drinking source water opportunities and challenges

A water quality index (WQI) is a single number that is derived from a mathematical aggregation of two or more subindices, with the subindices derived from measured parameter values (Ott, 1978). In other words, an index combines the measures of several water quality variables in such a way as to produce a single score that is representative of quality impairments or suitability of use (Dunnete, 1979). As such, indices are a simplification of real data that can result in a loss of information. It must be acknowledged that indices are not designed as a stand-alone monitoring tool but should instead be used in conjunction with a detailed analysis of environmental monitoring data (Canadian Council of Ministers of the Environment, 2001). Continued controversy exists surrounding index use due to several reasons:

1) The sensitivity of indices to their inputs and formulation (Swamee and Tyagi, 2000; Khan *et al.*, 2004; de Rosemond *et al.*, 2009,)
2) The loss of information regarding interactions (Khan *et al.*, 2003)
3) The potential for index misapplication (Ott, 1978; Dunnette, 1979)

However, if an index is well designed and applied as intended, the lost information should not seriously influence the answer that the index is designed to represent (Ott, 1978). It is estimated that over 100 scientists have been involved in the development of various water quality indices (Smith, 1990), several of which have been used extensively by government and international agencies (Boyacioglu, 2009). The advantages associated with water quality indices include:

1) The reduction of complex multi-parameter data to a single metric using a consistent and objective methodology (Canadian Council of Ministers of the Environment, 2001; Cude, 2001)
2) The facilitation of communication with stakeholders through the use of a clear diagnostic (Terrado *et al*., 2010)
3) The evaluation of spatial and temporal trends in water quality (House, 1989; Canadian Council of Ministers of the Environment, 2001; Cude, 2001)
4) The evaluation of existing management or pollution control practices (House, 1989; Cude, 2001)

Currently, policy makers rely on indices to draft, enact, monitor, and review environmental policies and programs while researchers use indices to analyze environmental impacts and trends (Swamee and Tyagi, 2007). Considering the continued application and development of water quality indices, the scientific consensus clearly supports the use of indices.

2.1 Water quality index development

In general, water quality index development employs a 3-step process (Figure 2.1.1). First, parameters are selected that are representative of overall quality with respect to a given end-use. These parameters should cover a wide range of water quality conditions, be frequently monitored, and have published maximum or minimum permissible criteria (House, 1989). In order to reduce the subjectivity associated with the selection of appropriate parameters for inclusion, consensus strategies using a panel of experts are often employed. Such consensus strategies include traditional surveys (Canadian Council of Ministers of the Environment, 2001) and the Delphi technique (Ott, 1978; Dunnette, 1979; House and Ellis, 1987; Smith, 1990). The Delphi technique is a systematic opinion gathering procedure in which panellists are polled, the results tabulated, and then reported back to each member, giving respondents the opportunity to compare their opinion with that of the group. Panellists are then polled again to arrive at a consensus (Ott, 1978).

Secondly, parameters are transformed to a common scale using subindex functions. These functions are derived based upon a detailed understanding of the relationship between the level of each parameter and the associated suitability of water for its intended use. The Delphi technique may be used again to integrate the opinions of various experts (Dunnette, 1979). Subindex transformation functions can take on a variety of forms. The most common subindex functions include linear increasing or decreasing, unimodal, segmented and nonlinear (Ott, 1978; Swamee and Tyagi, 2000).

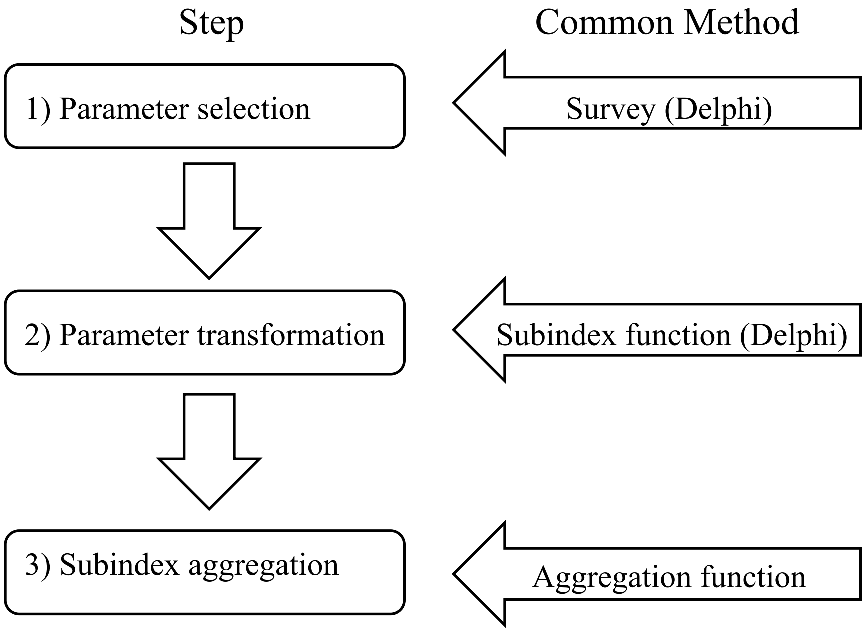

Figure 2.1.1 General index development procedure with common methods used to accomplish each of the 3 steps.

In the final step of index development, the subindices are combined to produce a single value via an aggregation formula. Aggregation formulas take on many different forms and are each associated with different advantages and disadvantages (Table 2.1.1). The broadest classification of aggregation functions concerns the scale of the resulting index. Pollution indices have an increasing scale (low scores represent better conditions than high scores) while quality indices, such as water quality indices, have a decreasing scale (high scores represent better conditions than low scores). Common aggregation approaches include logical operators (minimum operator), averaging operators (eg. arithmetic mean, weighted arithmetic mean, geometric mean, weighted product) and several other formulations (eg. linear sum, root sum power, root sum-square, and multiplicative approaches) (Sadiq and Tesfamariam, 2007). The three primary concerns surrounding any aggregation procedure are eclipsing, ambiguity, and rigidity (Swamee and Tyagi, 2000; Swamee and Tyagi, 2007). Eclipsing occurs when an overall index is insensitive to a single variable. Therefore, eclipsing can result in an acceptable index score despite one variable having extremely poor quality (Ott, 1978; Swamee and Tyagi, 2000). Ambiguity (or exaggeration) is somewhat of the opposite problem in which the overall index is reflective of poor quality conditions despite no single subindex having a poor score (Ott, 1978). Both eclipsing and ambiguity tend to increase with increasing numbers of parameters (Swamee and Tyagi, 2000). Rigidity is the direct result of adding parameters to an index formulation. Rigidity arises when additional parameters are included in an index to address quality concerns and due to the index formulation, artificially reduce the resulting score (Swamee and Tyagi, 2007). Table 2.1.2 outlines some important issues that must be taken into account when selecting an appropriate index aggregation technique.

Table 2.1.1 Characteristics of select index aggregation formulas (adapted from D'Costa, 2008 and UKWIR, 2007). K = number of subindices used in the aggregation (k = 1,2,…k), F_k = transformed value of the kth subindex, w_k = normalized weight of the kth subindex ($\Sigma w_k = 1$), r = power constant (recommended range is 2 to 3).

Aggregation Function	Mathematical Formulation	Quality Index Attributes
Minimum operator	$\min(F_1, F_2, \ldots, F_k)$	- no eclipsing, no ambiguity but does not provide a composite measure of quality (Ott, 1978; Swamee and Tyagi, 2000), rigidity
Weighted arithmetic mean	$\sum_{k=1}^{K} F_k \circ w_k$	- eclipsing, no ambiguity (Ott, 1978), rigidity
Weighted product	$\prod_{k=1}^{K} F_k^{w_k}$	- potential eclipsing (Ott, 1978; Swamee and Tyagi, 2000), rigidity
Root sum additive and Root mean additive	$\left(\sum_{k=1}^{K} F_k^r\right)^{1/r}$ $\left(\frac{1}{K}\sum_{k=1}^{K} F_k^r\right)^{1/r}$	- eclipsing, no ambiguity (Ott, 1978), rigidity
Swamee and Tyagi (2000) function	$\left(1 - K + \sum_{k=1}^{K}\left(F_k^{-r}\right)\right)^{-1/r}$	- no eclipsing, no ambiguity when r = 0.4 (Swamee and Tyagi, 2000), no rigidity when variable k employed (Swamee and Tyagi, 2007)
Arithmetic solway weighted formulation	$\frac{1}{100}\left(\sum_{k=1}^{K} F_k^r \circ w_k\right)^2$	- underestimates quality at low end of scale (House and Ellis, 1987), rigidity
Unweighted harmonic mean square	$\sqrt{\frac{K}{\sum_{k=1}^{K}\frac{1}{F_k^2}}}$	- eclipsing unlikely, ambiguity (Swamee and Tyagi, 2000), rigidity

Numerous examples of water quality indices exist. Ott (1978) and Abbasi (2002) provide detailed descriptions of many of the foundational and widely applied varieties. The majority of indices developed to date concern general use water quality (Dinius, 1972; Dunnette, 1979; House, 1989; Liou *et al.*, 2004; Smith, 1990; Dojlido *et al.*, 1994; Cude, 2001; Hambright *et al.*, 2000; Pesce and Wunderlin, 2000; Sargoankar and Deshpande, 2003). Specific applications for which water quality indices have been applied include recreational waters (Smith, 1990), the protection of aquatic life (House, 1989, Smith, 1990), as well as the public water supply (House, 1989, Smith, 1990). Flexible index formulations, including the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI), facilitate the assessment of water quality for any prescribed use (Canadian Council of Ministers of the Environment, 2001).

Table 2.1.2 Important considerations when selecting an index aggregation technique (adapted from UKWIR, 2007).

Characteristic	Considerations
Functional form	• Increasing scale • Decreasing Scale
Aggregation concerns	• Eclipsing • Ambiguity • Rigidity
Parsimony principle	• If more than one function produces the same results with respect to eclipsing and ambiguity, the mathematically simpler function should be chosen
Transparency	• Aggregation should be transparent and simple • Aggregation should be sensitive to changes in subindices • Aggregation should not be biased towards quality extremes

2.2 Application of a water quality index to Canadian drinking source waters

Considering the outlined advantages of water quality indices along with the factors that facilitate source water protection there is a clear opportunity for index application in the Canadian drinking source water context. A Canadian drinking source water quality index offers the potential to communicate complex quality status and trend data to watershed stakeholders in an easily understood manner (Cude, 2001; Lumb *et al*. 2006; Terrado *et al*., 2010). Despite the successes of water quality indices in synthesizing and communicating water quality, their application to drinking source water in general and Canadian surface sources in particular has been limited.

In order to draft an effective index tool to characterize Canadian surface source drinking water quality, the monitoring framework and theoretical context of Canadian surface sources must first be understood. The Canadian constitution gives provinces the proprietary rights to water and the responsibility for managing water pollution (Davies and Mazumder, 2003). As such, Canada lacks an established national water quality monitoring program (Khan *et al*., 2003). With the exception of Newfoundland and Labrador, which has attached particular significance to the monitoring of drinking water quality (Khan *et al*., 2004), monitoring of surface sources is spatially and temporally fragmented. Instead, key operational parameters are relied upon to ensure the safety of many public water supplies. Those source waters that are monitored are surveyed using a site specific risk based approach. Parameters of concern at one location and thus necessitating monitoring may not be of concern elsewhere and therefore receive limited attention.

In part, this site specific monitoring is reflective of the inherent diversity of natural waters (Patrick, 2008). Such site specificity poses several problems for index development. If quality is to be effectively characterized by an index score, all parameters that are of significance should be considered. However, if these parameters are not monitored on a routine basis at all sites then alternative versions of the index are required – one employing a core set of parameters for comparative purposes and a second including all parameters of concern. Depending on the aggregation technique employed, such parameter addition may result in rigidity (Swamee and Tyagi, 2000).

An additional challenge is posed by the very nature of the concept of drinking source water quality. Source water is ultimately intended for human consumption. Within Canada, all waters must, at minimum, receive some form of microbial disinfection. Therefore, there exists an intermediate quality altering process between the parameters measured at the source and the end use of the water. Chlorination remains the primary means of providing microbial disinfection (Province of Manitoba, 2005). The process of chlorination has clear implications for quality. Along with the inactivation of microbes, a process that serves to increases the suitability of source waters for consumption, chlorination can also alter source waters in such a way as to have competing negative implications for quality (WHO, 2008). Primary among health risks introduced by treatment processes are DBPs (Sadiq and Rodriguez, 2004) In this way, surface drinking source water quality is highly contingent upon treatment. Furthermore, different treatment techniques have the capacity to remove or inactivate different levels of contaminants. A drinking source water quality index must consider the effects of treatment and be adaptable to various treatment regimes so as to accurately reflect quality.

The site specificity and treatment considerations of surface source water limit the index development strategies that can be employed. Rigidity is a clear problem introduced by the site specific nature of source water monitoring. The contingency of source water quality on treatment along with site specificity necessitate the development of subindices for each parameter that could be of concern in any particular source along with variations of those subindices for different treatment techniques. Such an onerous task would only serve to produce an unmanageable index tool. What is instead required is a flexible index template allowing for parameter omissions, substitutions, and additions along with alternative treatment based assessment scenarios. The CCME WQI provides an appropriate template design to deal with the challenges posed by Canadian drinking source waters.

2.3 The Canadian Council of Ministers of the Environment Water Quality Index

The CCME WQI is an objective based index that compares measured water quality values to guidelines or objectives to produce a score ranging from 0, representing worst quality, to 100, representing best quality. The index score is calculated by aggregating 3 factors: F_1, F_2, and F_3 representing the scope, frequency and amplitude of guideline / objective violations respectively. In contrast to traditional indices in which each subindex is based upon a transformed parameter value, each of the three factors of the CCME WQI is calculated considering all measured parameters. Therefore, regardless of the number of parameters used to calculate the index, 3 subindices are always computed and combined via a root mean additive aggregation function with r =2. The final score (CCME WQI) and factors values (F_1, F_2 and F_3) are calculated as follows (Statistics Canada, 2007):

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right)$$

Where:

The divisor 1.732 normalizes the index score to a value between 0 (worst quality) to 100 (best quality)

F₁ (scope) represents the percentage of the selected parameters that do not meet their respective objective at least once during the time period considered, relative to the total number of parameters included in the index calculation.

$$F_1 = \left(\frac{\text{number of failed parameters}}{\text{total number of parameters}} \right) x100$$

F₂ (frequency) represents the percentage of individual sample measurements (tests) that do not meet their respective objective in the time period considered, relative to the total number of measurements of all parameters.

$$F_2 = \left(\frac{\text{number of failed tests}}{\text{total number of tests}} \right) x100$$

F₃ (amplitude) represents the amount by which failed measurements do not meet their respective objective, calculated in 3 steps:

i) when a measured variable does not meet its objective it is deemed an excursion and calculated as follows:

When the measured variable must not exceed the objective

$$\text{excursion}_{\text{i}} = \left(\frac{\text{failed test value}_{\text{i}}}{\text{objective}_{\text{i}}} \right) - 1$$

When the measured variable must not fall below the objective

$$\text{excursion}_{\text{i}} = \left(\frac{\text{objective}_{\text{i}}}{\text{failed test value}_{\text{i}}} \right) - 1$$

ii) The total amount by which measurements are out of compliance with their objective is calculated by summing the individual excursions and dividing by the total number of measurements made (both those that meet and do not meet their objective). This is the normalized sum of excursions (nse).

$$\text{nse} = \frac{\sum_{\text{i}=1}^{\text{n}} \text{excursion}_{\text{i}}}{\text{total number of tests}}$$

iii) F3 is then calculated by scaling the nse to a value between 0 and 100.

$$F_3 = \left(\frac{\text{nse}}{0.01\text{nse} + 0.01} \right)$$

The CCME WQI has been used to characterize the quality of water for several intended uses. Within Canada, the index has been used to assess spatial and temporal changes in water quality for agriculture and the protection of aquatic life (Khan *et al*., 2003; Lumb *et al*., 2006) as well as to communicate treated drinking water quality data to the public (Khan *et al*., 2004). Internationally the index has been adopted to assess quality using data gathered with automated systems (Terrado *et al*., 2010). Though previously applied to characterize water intended as a source for drinking purposes (Khan *et al.,* 2003; Boyciaglu, 2009; Rickwood and Carr, 2009) a standardized methodology for index application has not been proposed nor has the effectiveness of the resulting index scores in capturing expert understanding of quality been tested.

Chapter 3 Adaptation and evaluation of the CCME WQI as an effective tool to characterize source water quality

Abstract

Protecting drinking source water quality is a critical step in ensuring a safe supply of drinking water. Increasingly, source water protection programs rely on the active participation of various stakeholders with differing degrees of water science knowledge. A drinking source water quality index presents a potential communication and analysis tool to facilitate cooperation among diverse interest groups as well as represent composite source water quality. I tested the effectiveness of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) in capturing expert assessments of surface drinking source water quality. In cooperation with a panel of drinking water quality experts I identified a core set of parameters to reflect common Canadian surface source water concerns. Drinking source water target values were drafted for use in the index corresponding to two basic treatment levels. Index scores calculated using the core parameter set and associated source water target values were strongly correlated with expert assessments of water quality. I recommend a modified index calculation procedure to accommodate parameters measured at different frequencies within any particular study period. The resulting drinking source water CCME WQI provides a valuable means of monitoring, communicating, and understanding surface source water quality.

3.1 Introduction

The adoption of the multi-barrier approach to providing safe drinking water highlights the acknowledged importance of water system protection and maintenance from source to tap. The raw water that is extracted from rivers, lakes, reservoirs, streams, and aquifers presents the initial and most susceptible point of drinking water contamination (Canadian Council of Ministers of the Environment, 2004). Drinking source waters polluted by urban, agricultural, or industrial activities are associated with higher treatment costs. Even under increased treatment regimes poor source water quality inherently poses a greater risk to public health (Davies and Mazumder, 2003). An effective strategy to minimize source water risks must operate at the broad scale and as such requires the cooperation of many different stakeholders. Watersheds frequently span multiple municipal, provincial and even federal jurisdictions (Ivey *et al*., 2006; Timmer *et al*., 2007). Communication among watershed stakeholders, particularly in the realm of public education has been identified as a key facilitating factor for source water protection (Ivey *et al*., 2006; Patrick, 2008; Islam *et al*., 2011). Therefore appropriate analysis and knowledge translation tools are required to bridge communication gaps among scientists, policy makers, and the public.

Traditional drinking source water quality assessments have relied on a parameter by parameter assessment of all variables that, either individually or through interactive effects, contribute to quality conditions (Chang *et al*., 1999). Such analysis requires a comprehensive knowledge of drinking water science to understand and may not provide a composite measure of source drinking water quality (de Rosemond *et al*., 2009). Developed to integrate, interpret, and communicate environmental monitoring data, indices have been used to successfully characterize water quality status and trends and relay that information to concerned groups (Cude, 2001; Lumb *et al*. 2006).

A water quality index (WQI) combines the measures of several water quality variables in such a way as to produce a single score that is representative of quality impairments or suitability of use (Dunnete, 1979). To date, the application of an index to characterize and communicate drinking source water quality data has not been fully explored and more importantly, the effectiveness of any resulting index scores have not been sufficiently verified. The very nature of drinking source water quality may be responsible for the lack of an effective source water quality index. Drinking source waters provide two primary challenges to index development:

1) Site specificity - Parameters of concern at one location and thus necessitating monitoring may not be of concern elsewhere and therefore are rarely monitored. Such site specificity poses several problems for index development. If a consistent set of parameters is not monitored on a routine basis at all sites then alternative indices are required that can incorporate all parameters of concern at all locations.

2) Treatment considerations - Since source waters are ultimately intended for human consumption, they generally must undergo some form of treatment. A drinking source water quality index must consider the effects of treatment, both beneficial (e.g. microbial inactivation) and unfavourable (e.g. disinfection byproducts), and be adaptable to various treatment regimes so as to accurately reflect ultimate quality.

The Canadian Council of Ministers of the Environment (CCME) WQI provides a flexible index template adaptable to the site specificity and treatment considerations of drinking source water. In this study I present a modified version of the CCME WQI that effectively characterizes surface drinking source water quality. In consultation with a panel of drinking water quality experts I propose a core set of parameters for use in the index. Based on available literature, defensible drinking source water target values are drafted for each of the core parameters. Resulting quality scores calculated using the core set of parameters are verified against expert assessments of drinking source water quality. Pilot testing of the index is carried out using historical monitoring data and an alternative index calculation procedure adopted to reduce the impact of parameter unevenness. Finally a sensitivity analysis is performed and challenges to widespread index implementation discussed.

3.2 Methods

3.2.1 Parameter selection

In order to facilitate spatial and temporal comparisons among index scores, a core set of source water parameters was identified to which appropriate site specific parameters of concern could be subsequently added. A comprehensive multi-step procedure similar to that of Dunnette (1979) was employed to identify a suite of priority drinking source water parameters. Listed in order, the parameter selection procedure involved: 1) a review of existing index literature, 2) use of a rejection rationale to produce a screened set of source water parameters, and 3) a parameter selection survey e-mailed to a panel of drinking water quality experts from academia, government and industry.

The rejection rationale (step 2 of the parameter selection procedure) was based upon three distinct requirements. Parameters satisfying any of the following criteria were excluded from future consideration:

1) Parameter is not sufficiently monitored (minimum of once per season/year) in commonly collected raw water quality data in Canada

2) Parameter does not have significant implications or its implications are questionable in regards to the effectiveness of treatment processes (specifically chlorination) or the aesthetic or health concerns of drinking water
3) Published source water quality guidelines/objectives do not exist for the parameter

Step 3 of the parameter selection procedure involved a single survey instead of the commonly used Delphi technique due to the time and logistic requirements of the Delphi approach (Appendix A). Prospective participants were identified based upon job title, experience, published work, referrals, and existing relationships. The composition of the panel was specifically selected to gather the opinions of academics, government workers, industry personnel, and service providers. A total of 34 surveys were e-mailed to individuals who had confirmed their willingness to participate. Panellists were asked to identify a set of 10 parameters that should be monitored in source water to identify the most common risks (health risks, treatment interference, etc.) within Canada prior to next stages: chlorination and distribution. Respondents were instructed to designate parameters as “include” or “don’t include” and assign a relative significance rating between 1 and 5 (where 1 suggests that the parameter has little significance in assessing source water quality while 5 suggests that the parameter is very significant). Freedom was given to add variables if desired.

3.2.2 Source water target value selection

Three published, accessible drinking source water guideline sets were used to draft drinking source water target values for the identified core parameters. The three source water quality guideline documents used were: the European Economic Community’s

Drinking Water Abstraction Directive 75/440/EEC amended by Directives 79/869/EEC and 91/692/EEC (Office for Official Publications of the European Communities, 1975), Chang et al.'s Taiwanese source water quality standards (Chang *et al*.,1999) and the British Columbia Ministry of the Environment's (BC MOE) water quality guidelines (BC MOE, 2010). Drafted target values aimed to reflect a conservative consensus among the three guideline documents. If available guidelines differed substantially, BC MOE guideline values were accepted due to the availability of supporting documentation. Source water quality target values are proposed anticipating two levels of treatment: 1) chlorination alone and 2) chlorination preceded by (slow sand) filtration. The proposed source water target values are not intended to represent a definitive set of source water criteria for the 2 respective treatment levels. Instead, the target values provide a defensible benchmark against which parameter measures can be compared and violations quantified.

3.2.3 Index score validation

To support index applicability and any inferences drawn from the resulting index score, calibration with reference to expert opinion is a commonly used index validation technique (Smith, 1990; Khan *et al.*, 2004, Canadian Council of Ministers of the Environment, 2009). The panellists that completed the initial parameter selection survey were e-mailed a second survey asking for their assessment of 20 water quality scenarios (Appendix B). The scenarios were drafted using actual source water data along with simulated parameter values. Each scenario was composed of 6 values, with the exception of one scenario that only had 5 values, for 6-8 of the selected core parameters. A total of six values for each parameter were chosen based on CCME recommendations (Canadian

Council of Ministers of the Environment, 2006b). The 20 water quality scenarios were specifically selected to span a broad range of quality conditions. Expert panellists were asked to provide a rank and score for each scenario corresponding to a slightly modified CCME WQI scoring system tailored to drinking source water quality (Appendix B). Furthermore, the ranks and scores were to be made considering the two different treatment levels for which guidelines were drafted. Experts were also asked to indicate which parameters were most important in deciding on each rank and score.

Average expert scores for each scenario were calculated and compared to the corresponding index scores. The arithmetic mean of all expert numeric scores was used to represent the central tendency of the sampled panel. Simple linear regression was used to assess the relationship between index and expert scores under both treatment scenarios. The resulting regression line was compared to a theoretical 1:1 line (y = x) to gauge index effectiveness in characterizing drinking source water quality.

3.2.4 Exploration of factor weights

In its traditional root mean additive aggregation form, the factors that compose the CCME WQI are unweighted / equally weighted. No weights are assigned to the individual constituent parameters as the relative significance of the individual parameters is considered to be addressed in their corresponding guideline / target values (Canadian Council of Ministers of the Environment, 2001). However, assigning different weightings to the factors F_1, F_2 and F_3 has not been explored.

Using Excel Solver software (Frontline Systems Inc., North Lake Tahoe, Nevada) alternative factor weightings were investigated. Factor values for each of the 20 scenarios were calculated using standard CCME methods. The incorporation of factor weights into the CCME WQI index aggregation function produces the following weighted formula:

$$CCME\ \mathrm{WQI}_{\mathrm{weighted}} = 100 - \left(\frac{\sqrt{w_1 F_1^2 + w_2 F_2^2 + w_3 F_3^2}}{\sqrt{w_1 + w_2 + w_3}} \right)$$

Factor weightings were optimized so as to minimize the deviation between the mean expert rating of each scenario and the resulting weighted index score. Optimized weights were not permitted to be zero, which would effectively remove that factor from the index calculation. Scenarios in which optimized weights were heavily skewed toward 1 factor, assigning weights of near zero to the other 2 were excluded from the analysis. This was done to ensure that all 3 factors contributed to the index scores. It was felt that each of the factors individually reflected important quality considerations that should be captured within the index formulation. Normality was verified using the Shapiro-Wilk test before testing for differences in mean optimized factor weightings under each treatment level.

3.2.5 Index application and sensitivity analysis

Index scores calculated using historical general water quality monitoring data were used to investigate the relative contribution of each factor and parameter to resulting scores. Seasonal scores (Winter: December-February, Spring: March-May, Summer: June-August, Fall: September-November) were calculated for a total of 47 sites located in 3 Canadian provinces (Figure 3.2.1). Data spanned various time periods between 1990 and 2009. Scores were tabulated separately for the two treatment level target value sets. Due to inconsistent monitoring programs, scores could not be calculated for all seasons at all sites. A total of 186 scores were calculated under each treatment scenario. British Columbia water quality data were provided by the Water and Aquatic Sciences Research Program at the University of Victoria (3 sites) as well as the BC MOE Environmental

Monitoring System Web Reporting (6 sites). Alberta data were collected from the Alberta Environment's publicly accessible River Network Station Water Quality Data program (26 sites). Manitoba values were provided by request from Manitoba Water Stewardship's Water Management Section (12 sites).

The effect of the number of samples of each parameter on index score was investigated using Pielou's evenness index (Pielou, 1966). Developed as an index of biodiversity, Pielou's evenness index measures how close in number the populations of each species in a community are to each other. The index is bounded by 0 and 1, with a value of 1 representing a community where all species are equally abundant and a value of 0 representing a community dominated by a single species. Adapted to the source water quality context, the water quality parameters represent the different species while their respective number of samples are equivalent to the abundance of each species. Parameter evenness index values were calculated as follows:

$$\text{Evenness} = \frac{-\sum_{j=1}^{m} p_j \ln p_j}{\ln m}$$

Where:

j represents the different parameters included in the index calculation numbered 1 to m and p_j represents the number of samples (tests) of parameter j expressed as a proportion of the total number of samples (tests) of all parameters

$$p_j = \left(\frac{\text{number of parameter } j \text{ samples}}{\text{total number of samples of all parameters}} \right).$$

The remainder of the sensitivity analysis was based on the approach of Rickwood and Carr (2009).

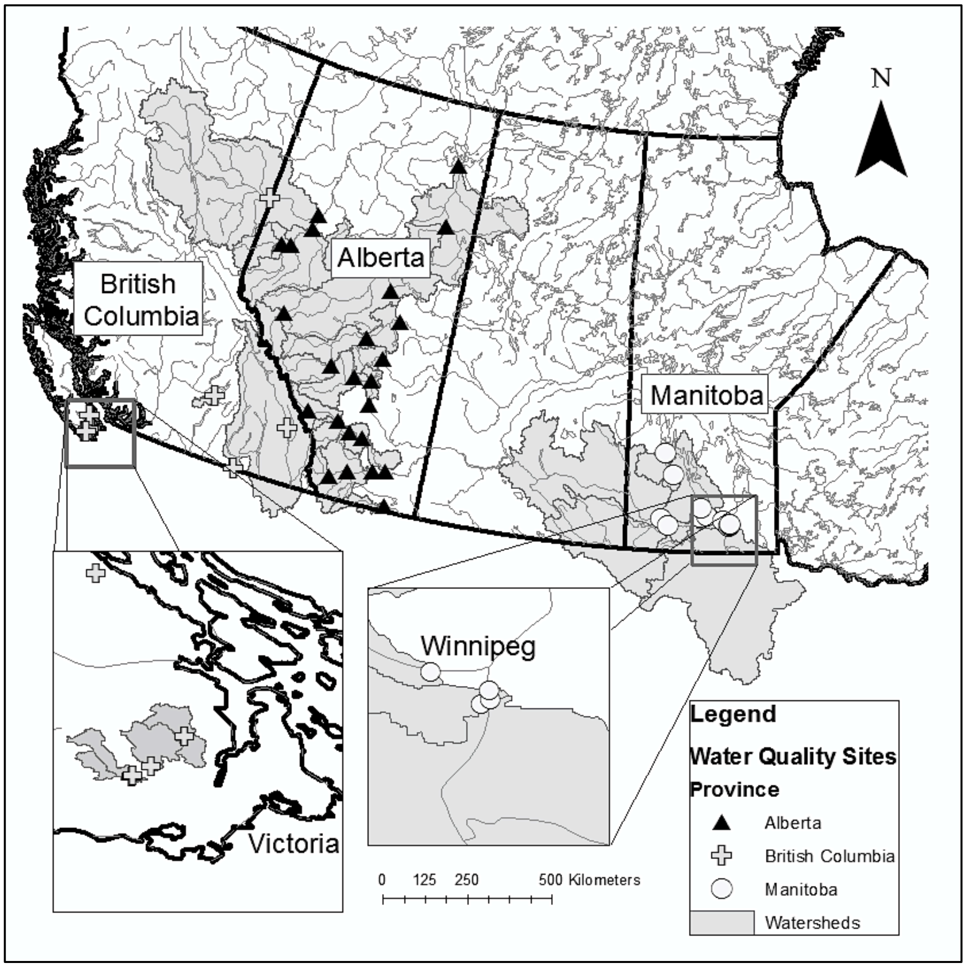

Figure 3.2.1 Map of Canadian water quality sites used in sensitivity analysis.

3.3 Results

3.3.1 Parameter Selection

The review of existing source water quality indices and associated literature produced a list of 39 potential parameters for inclusion in the core parameter set. Application of the rejection rationale reduced the number of parameters to a total of 27 for consideration by the expert panel. A total of 24 completed surveys were returned, a response rate of 71% (see Appendix C for list of panellists). The majority of respondents recommended that turbidity, pH, total organic carbon (TOC), *E. coli*, nitrate, total coliforms, iron, and pesticides be included among the variables used to assess general source water quality conditions. These eight parameters meet the recommendation that seven parameters be used when calculating CCME WQI scores (Canadian Council of Ministers of the Environment, 2006b), this recommendation being more conservative than the 4 parameter absolute minimum, and could potentially serve as a core set of source water quality parameters. However, several survey respondents suggested that pesticides is too vague a term and that different pesticides should be considered individually instead of as a single unit. This fact, along with the inconsistency in monitoring of pesticides resulted in the exclusion of pesticides from the set of core parameters. Temperature, a very frequently monitored parameter with aesthetic and treatment efficacy implications was designated as "include" by 46% of panellists, placing it just outside of the top eight selections. The inclusion of temperature along with the expert recommendation that nitrate and nitrite be considered together so as to allow for comparisons to guideline values produced a core set of 8 representative source water quality parameters (Table 3.3.1). *E. coli* was identified as the most important parameter, followed by turbidity and total organic carbon. Iron received the lowest significance rating. Figure 3.3.1 presents all parameters identified by the survey panel as important in characterizing surface drinking source water quality risks. The list is not meant to be exhaustive but instead convey the diversity of variables that may be used to monitor surface source water quality concerns.

Table 3.3.1 Core parameters identified by survey panellists. Parameters are listed in order of the percent of surveys that designated the parameter as "include". Mean significance ratings were calculated based on each experts relative significance rating.

Core Parameter	Common Units	Percent "include"	Mean Significance Rating (1 = little significance, 5 = very significant)
pH	pH units	92	3.41
Turbidity	NTU	88	4.29
Total organic carbon	mg/L	83	4.25
E. coli	CFU/100mL	79	4.95
Nitrate and Nitrite	mg/L as N	75	3.33
Total coliforms	CFU/100mL	63	4.00
Iron	mg/L	50	2.33
Temperature	Degrees Celsius	46	3.18

3.3.2 Source water target value selection

Proposed source water target values are presented in Table 3.3.2. Target values are presented for two anticipated levels of treatment:

Treatment level 1 - chlorination alone

Treatment level 2 - chlorination preceded by (slow sand) filtration

Several of the target values correspond with treated drinking water quality guidelines. Initially the turbidity target value for source waters receiving chlorination alone was set at 1 NTU. However, subsequent comparison of expert scores to index scores suggested that a turbidity target value of 1 NTU was too high. Survey respondents placed a considerable importance on turbidity values when assessing drinking source water quality, even those turbidity values less than 1 NTU. Therefore, the treatment level 1 turbidity target was reduced from 1 NTU to 0.3 NTU. A turbidity target of 0.3 NTU corresponds to the United States Environmental Protection Agency (USEPA) standard against which 95% of treated water samples in a month must be lower (USEPA, 2009). Appendix D presents additional information regarding drinking source water target value selection.

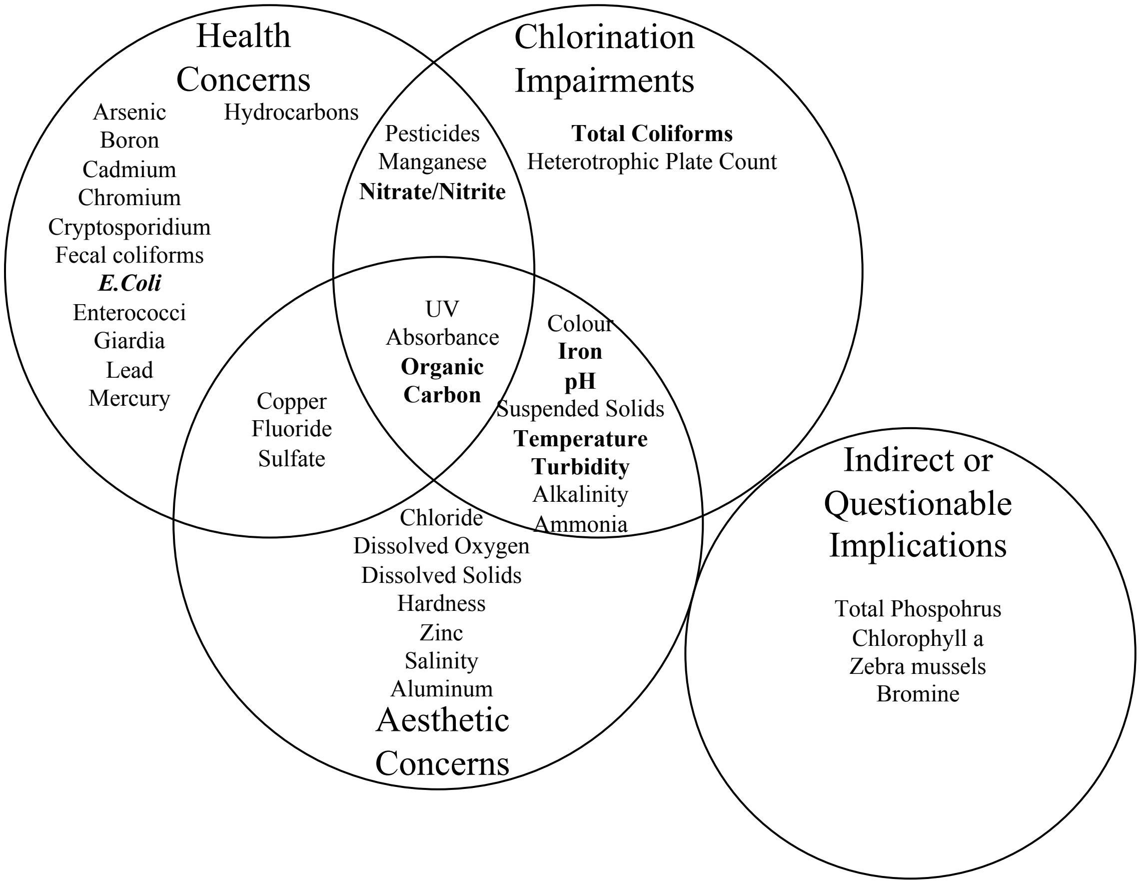

Figure 3.3.1 Surface source water parameters identified by the expert panel as important in characterizing drinking source water risks. Parameters are broadly categorized as health concerns, impairments to effective chlorination or aesthetic concerns. Core source water parameters are identified in bold

Table 3.3.2 Proposed surface drinking source water target values for 8 core parameters. Target values refer to two treatment levels: 1) chlorination alone and 2) slow sand filtration and chlorination.

	Treatment Level 1: Chlorination alone		Treatment Level 2: Slow sand filtration and chlorination	
Parameter (units)	Maximum Acceptable Value	Minimum Acceptable Value	Maximum Acceptable Value	Minimum Acceptable Value
pH	8.5	6.5	8.5	6.5
Turbidity (NTU)	0.3		5	
Total organic carbon (mg/L)	4		4	
E. coli (CFU/100mL)	10		100	
Nitrite and Nitrate as N (mg/L)	10		10	
Total coliforms (CFU/100mL)	100		100	
Iron (mg/L)	0.3		0.3	
Temperature (°C)	15		15	

3.3.3 Index score validation

A total of 11 of the 24 panellists that completed the parameter selection survey responded to the second survey, a 46% response rate (see Appendix D for list of respondents). A close association between expert and index scores is clear (Figure 3.3.2) . The mean absolute deviation of the CCME WQI from the expert scores was 7.17±1.11 for treatment level 1 and 7.48±1.14 for treatment level 2. In both cases, the regression line characterizing the relationship between the mean expert rating and the CCME WQI score (Treatment Level 1: CCME WQI = 1.03(Mean expert rating) – 0.50, $r^2 = 0.77$, $p < 0.01$, df = 18; Treatment Level 2: CCME WQI = 1.11(Mean expert rating) – 8.49, $r^2 = 0.77$, $p < 0.01$, df = 18) was not significantly different ($P < 0.05$) from a theoretical 1:1 relationship (y = x).

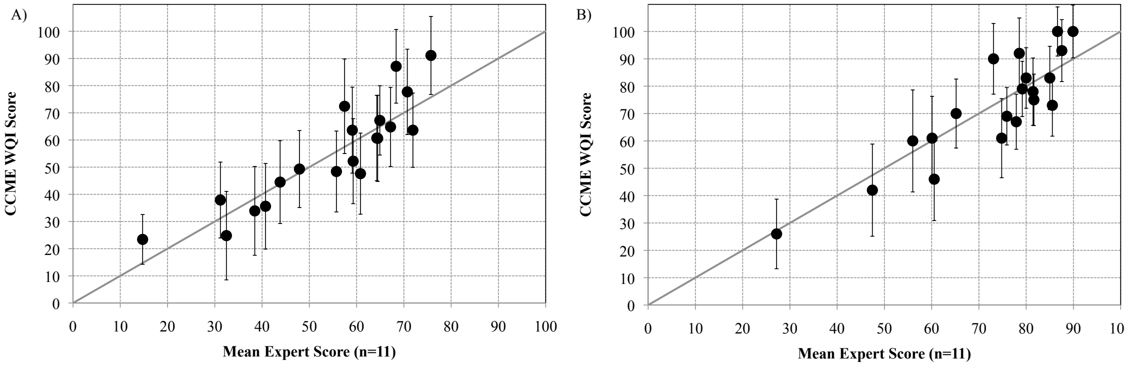

Figure 3.3.2 Mean expert scores (n=11) for each of the 20 water quality scenarios plotted against calculated CCME WQI index scores. Expert assessments were made considering two different treatment levels: Panel A) Treatment Level 1 – chlorination only and Panel B) Treatment Level 2 – slow sand filtration and chlorination. The mean expert scores for each treatment level are plotted against CCME WQI scores calculated using the corresponding treatment level target values. Error bars represent the 95% confidence intervals. The continuous solid line represents a theoretical line with gradient = 1 corresponding to a perfect match between index and expert score.

3.3.4 Exploration of factor weights

Mean optimized factor weights and standard errors under both treatment levels are presented in Table 3.3.3. A total of 4 scenarios under treatment level 1 and 5 scenarios under treatment level 2 were excluded due to optimized weights of near zero for 2 of the 3 factors. Factor weight optimization reduced the difference between index scores and corresponding mean expert scores to within at least 8.0×10^{-7} points for all included scenarios. Treatment level 1 optimized factor weightings were not significantly different from one another (ANOVA; F(2,42) = 1.45, p = 0.25). Similarly, treatment level 2 mean optimized factor weightings did not provide evidence for the application of unequal weights to the 3 index factors (ANOVA; F(2,42) = 0.88, p = 0.42).

Table 3.3.3 Mean optimized factor weights and standard errors for treatment levels 1 and 2

	Treatment Level 1: Chlorination alone			Treatment Level 2: Slow sand filtration and chlorination		
Weight	n	Mean	Standard Error	n	Mean	Standard Error
w_1	16	0.92	0.09	15	0.83	0.19
w_2	16	0.93	0.09	15	1.07	0.12
w_3	16	1.14	0.13	15	1.05	0.12

3.3.5 Index application and sensitivity analysis

Data limitations only permitted index calculations to be made using a total of six parameters (pH, turbidity, total organic carbon, *E. coli*, nitrate and nitrite as N, and temperature). Several sites monitored dissolved organic carbon (DOC) instead of total organic carbon. DOC makes up greater than 80% of TOC in natural waters (Owen *et al.*, 1995; Larsen *et al.*, 2011). However, to accommodate sites where only DOC was measured, a regression equation was computed to describe the relationship between DOC and TOC (for 6 of the 47 sites). The regression equation was then used to convert DOC measures to TOC estimates.

Immediate concerns became apparent in regards to the number of measures of each parameter. Though not all 47 sites were specifically monitored for drinking source water quality considerations, all share the issue of an unequal number of samples among the six core parameters analyzed. Pielou's evenness index values ranged from 0.80 to 1 with a mean value of 0.97. This unequal number of samples results in a score bias, the magnitude and direction of which depends on the behaviour of the parameter measures relative to their target values. Overrepresented parameters with a high proportion and/or magnitude of failures will drive down the score while an overabundance of a parameter with a low probability and/or magnitude of failure will artificially inflate the score. In order to reduce the effect of deviation from parameter evenness I have a modified CCME WQI in which factors F_2 and F_3 are calculated on a parameter by parameter basis before being averaged. Factor F_1 is calculated using the original formulation. Original and modified factor formulas are presented in Table 3.3.4. Of note, the relationship between water quality scenario scores calculated using the modified CCME WQI formulation and mean expert scores was the same as that depicted in Figure 3.3.2. The scenarios evaluated by the expert panel were specifically constructed with high evenness. Of the 20 scenarios, 19 had Pielou's evenness index scores of 1. The single scenario that strayed from perfect evenness had an evenness index score of 0.995 due to one parameter having 5 measures instead of the standard 6 common to all other parameters.

Rank distributions for the modified CCME WQI scores calculated under both treatment scenarios are presented in Figure 3.3.3. Approximately 74% of scores were ranked as poor when chlorination was the only anticipated form of treatment. No stations received an excellent rank under treatment level 1. On average, treatment level 2 scores were 20.17±0.53 points higher than their corresponding treatment level 1 scores. Under treatment level 2, approximately 7% of scores were ranked as excellent. The largest proportion of treatment level 2 scores was marginal (40%) however roughly a quarter of all scores were still classified as poor.

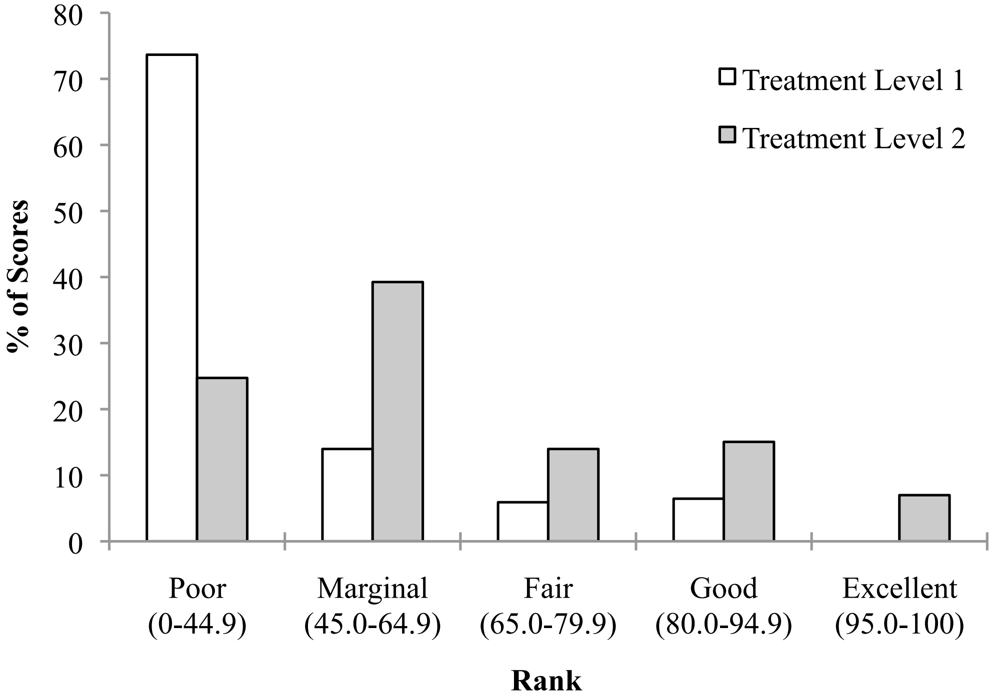

Figure 3.3.3 Percent of scores classified as poor, marginal, fair, good, and excellent using treatment level 1 and 2 drinking source water target values

Turbidity was the parameter that most frequently violated source water target values for both treatment levels (Figure 3.3.5). The mean proportion of turbidity measures that violated the treatment level 1 target value of 0.3 NTU was 0.94±0.01 across all sites and seasons. The treatment level 2 target value of 5 NTU reduced the mean turbidity violation rate to approximately 0.55±0.02 for each calculated score. TOC target values were the same for both levels of treatment and resulted in a mean violation rate of 0.47±0.03. Under treatment level 1, the average proportion of *E. coli* measures that exceeded the drafted 10 CFU/100mL target value was 0.36±0.02 for each seasonal score. The treatment level 2 target value reduced the mean violation rate to 0.08±0.01. No nitrate and nitrite as N values were greater than the 10 mg/L target value.

Table 3.3.4 CCME WQI original factor formulas and recommended modified formulations to control for parameter unevenness

Factor	Original CCME WQI Formula	Modified CCME WQI Formula
F_1	$F_1 = \left(\frac{\text{number of failed parameters}}{\text{total number of parameters}}\right)x100$	F_1 calculation unchanged from original formulation
F_2	$F_2 = \left(\frac{\text{number of failed tests}}{\text{total number of tests}}\right)x100$	$F_2 = \frac{\sum_{j=1}^{m}\left(\frac{\text{Number of failed samples}_j}{\text{Total number of samples}_j}\right)}{m}x100$ where: j represents the different parameters included in the index calculation numbered from 1 to *m*
F_3	i) when a measured variable does not meet its guideline it is deemed an excursion and calculated as follows: When the measured variable must not exceed the guideline (objective) $\text{excursion}_i = \left(\frac{\text{failed test value}_i}{\text{objective}_i}\right) - 1$ When the measured variable must not fall below the guideline (objective) $\text{excursion}_i = \left(\frac{\text{objective}_i}{\text{failed test value}_i}\right) - 1$ where: j represents the different parameters included in the index calculation numbered from 1 to *m* ii) Normalized sum of excursions (nse) $\text{nse} = \frac{\sum_{i=1}^{n}\text{excursion}_i}{\text{total number of tests}}$ iii) $F_3 = \left(\frac{\text{nse}}{0.01\text{nse} + 0.01}\right)$	i) when a measured variable does not meet its guideline it is deemed an excursion and calculated by parameter as follows: When the measured variable must not exceed the guideline (objective) $\text{excursion}_{i,j} = \left(\frac{\text{failed test value}_{i,j}}{\text{objective}_j}\right) - 1$ When the measured variable must not fall below the guideline (objective) $\text{excursion}_{i,j} = \left(\frac{\text{objective}_j}{\text{failed test value}_{i,j}}\right) - 1$ where: j represents the different parameters included in the index calculation numbered from 1 to m ii) Average Excursion calculated by parameter for n total excursions $\text{Average Excursion}_j = \frac{\sum_{i=1}^{n}\text{excursion}_{i,j}}{n}$ iii) Normalized sum of average excursions (nsae) $\text{nsae} = \frac{\sum_{j=1}^{m}\text{Average Excursion}_j}{m}$ where: Total number of variables is equivalent to m iv) $F_3 = \left(\frac{\text{nsae}}{0.01\text{nsae} + 0.01}\right)$

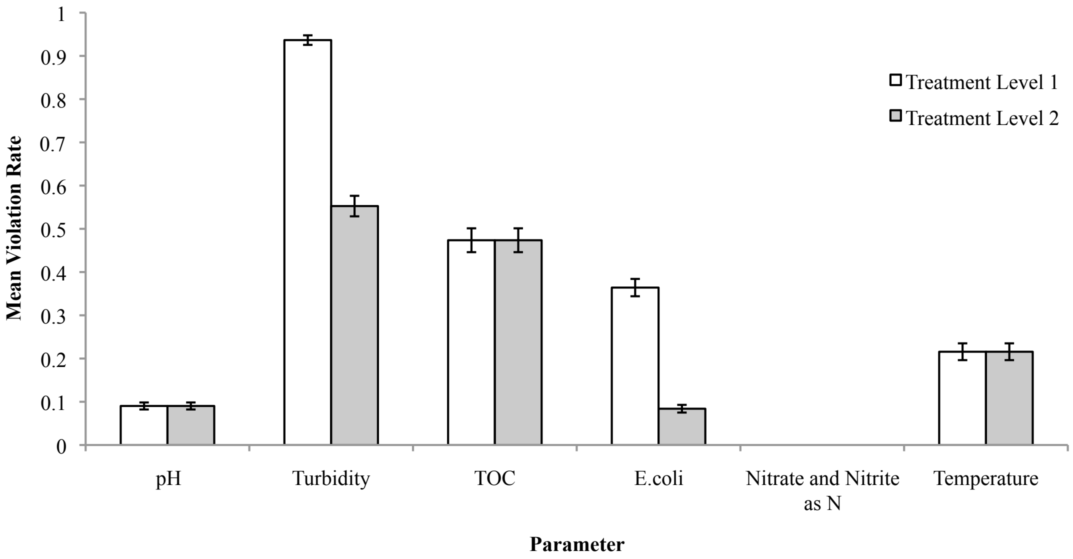

Figure 3.3.4 Mean proportion of samples per index score in violation of source water target values. Proportions are presented for each of the 6 parameters used to calculate 186 seasonal scores under treatment levels 1 and 2. Error bars represent the standard error of the mean.

In order to evaluate the relative impact of the included parameters on the modified index scores, each of the six core parameters included in the calculation were individually removed and the scores recalculated. The recalculated scores were then compared to the modified score produced when the parameter was part of the index aggregation. For scores calculated using treatment level 1 target values, the removal of turbidity caused the largest change in index scores. Excluding turbidity from the index resulted in a mean increase in score of 19.03±1.01 under treatment level 1 and a mean increase of 7.70 ±0.93 under treatment level 2 (Figure 3.3.6). The removal of nitrate and nitrite as N resulted in the greatest change in treatment level 2 scores (-8.27±0.57). The removal of *E. coli* caused a mean increase in treatment level 1 scores (1.12±0.49) but a mean decrease in treatment level 2 scores (-3.12±0.59). TOC exclusion produced a mean increase in score under both treatment scenarios (Figure 3.3.6). All calculated scores were significantly inter-correlated for each treatment level (Spearman's correlation; $p < 0.01$). Turbidity removed scores showed the least strong Spearman's correlation with the scores calculated when all six parameters were included (treatment level 1 $\rho = 0.78$, $p < 0.01$; treatment level 2 $\rho = 0.79$, $p < 0.01$).

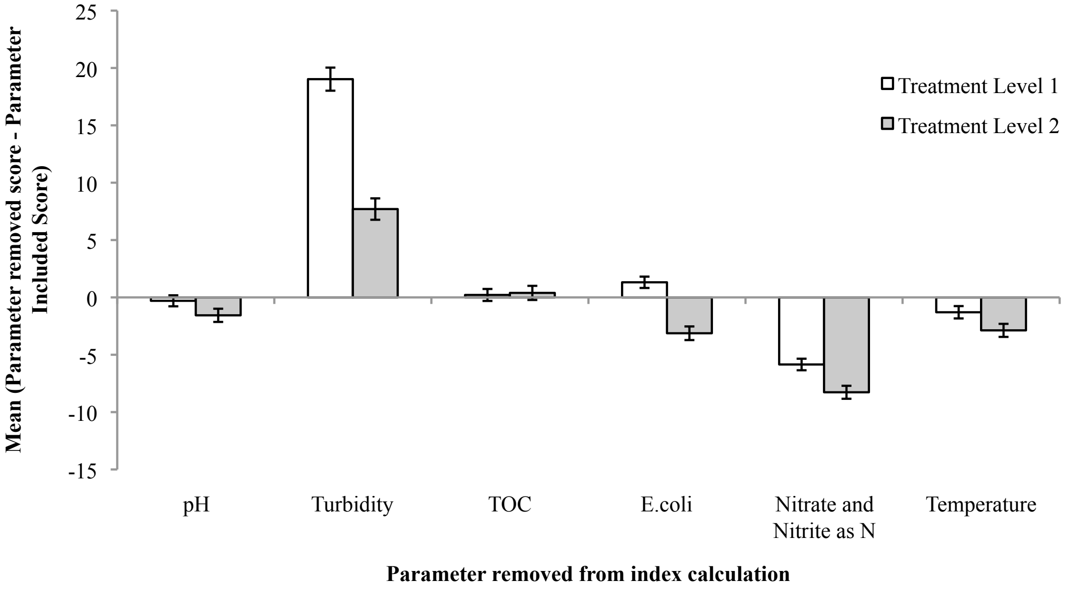

Figure 3.3.5 Effect of parameter removal on index score. n = 186 for each parameter and treatment level. Error bars represent the standard error of the mean.

The average excursions of all parameters except nitrate and nitrite as N were significantly correlated with modified index scores (Table 3.3.4; $p < 0.05$). Turbidity was most strongly correlated with modified index scores under both treatment level 1 and treatment level 2 ($\rho = -0.81$, $p < 0.01$; $\rho = -0.87$, $p < 0.01$).

Table 3.3.5 Spearman's correlation values for average excursion of parameters against corresponding modified index score. Average excursions and modified index scores were calculated separately using treatment level 1 and treatment level 2 source water target values.

	Treatment Level 1: Chlorination alone			Treatment Level 2: Slow sand filtration and chlorination		
Parameter	n	ρ	p	n	ρ	p
pH	186	-0.19	0.01	186	-0.16	0.03
Turbidity	186	-0.82	<0.01	186	-0.87	<0.01
TOC	186	-0.52	<0.01	186	-0.53	<0.01
E. coli	186	-0.59	<0.01	186	-0.52	<0.01
Nitrite and Nitrate as N	186	-	-	186	-	-
Temperature	186	-0.66	<0.01	186	-0.65	<0.01

3.4 Discussion

Drinking source water protection is increasingly encouraged and applied as a strategy to ensure the safety of Canadian drinking water (Patrick, 2008). Effective source water protection requires cooperation among watershed stakeholders and government regulators as well as public education (Ivey *et al*., 2006; Patrick, 2008; Islam *et al*., 2011). The increased community involvement highlights the need for effective data analysis and communication tools to synthesize and convey important source water quality trends. The Canadian Council of Ministers of the Environment Water Quality Index has previously been shown to be a useful means of communicating treated drinking water quality data (Khan *et al*, 2004). Though the index has been applied to characterize drinking source water quality (Boyciaglu, 2009; Rickwood and Carr, 2009), the effectiveness of the resulting scores has not been verified. I present a modified CCME WQI that effectively characterizes drinking source water quality when evaluated anticipating 2 different levels of treatment.

3.4.1 Parameter selection to capture source water quality risks

A core set of parameters was identified to characterize common Canadian source water quality concerns. These core parameters are intended to serve as a guide for parameter selection and provide a standard parameter set to facilitate comparisons among scores. Only scores calculated using the same set of parameters can be compared in any meaningful way (Canadian Council of Ministers of the Environment, 2001). The 8 core parameters are frequently monitored, have significant implications for source water quality, cover a wide range of quality conditions, and are supported by recommended source water guideline/objective values. Furthermore, the core set is in close agreement with the parameters suggested by the Canadian Council of Ministers of the Environment for monitoring drinking water sources (Table 3.4.1). Where differences exists, such as between dissolved organic carbon and total organic carbon or total dissolved solids and turbidity, the same broad quality impairment (disinfection byproduct formation and clarity respectively) is addressed using a different metric. Notably, iron is among the 8 core parameters identified by the panel of experts though it is recommended as a supplementary parameter by the CCME.

Table 3.4.1 CCME proposed core and supplementary parameters for consideration in the protection of the suitability of source water for use as a drinking water supply (Canadian Council of Ministers of the Environment, 2006a)

Core parameters	• *E. coli* • Total coliform • Nitrate/Nitrite • Colour • Odour • Taste • Chloride • Ammonia • Temperature • Total Dissolved Solids • Dissolved Organic Carbon • pH • Flow (where applicable)
Supplementary Parameters	• Other parameters of concern (on a site specific basis) eg. iron, managanese, bromide

The flexibility of the CCME WQI allows for the incorporation of any additional or supplementary parameters while avoiding rigidity (Islam *et al.*, 2011). Rigidity is the direct result of adding parameters to an index formulation. Rigidity arises when additional parameters are included in an index to address quality concerns and due to the index formulation, artificially reduce the resulting score (Swamee and Tyagi, 2007). I do recommend that the core set of parameters be supplemented by other site specific parameters of concern. In particular, the CCME WQI provides the opportunity to communicate information related to the management of local parameters of concern. Source waters are very diverse, reflecting natural and anthropogenic watershed inputs (Timmer *et al*., 2007; Patrick *et al*., 2008). Therefore, to effectively characterize drinking source water quality, supplementary parameters may need to be included in the index calculation. Additional parameters may include pesticides such as atrazine or chlorpyrifos as well as heavy metals, all of which have previously been used to assess source water quality (Islam *et al*., 2011). However, supplementary parameters and target values must be relevant to source drinking water quality and provide information about local stressors. For example, clear concern was expressed by various panellists in regards to the need for the inclusion of protozoan pathogens among the core variables. *Giardia* and *Cryptosporidium* are serious drinking water health concerns due in part to their low infective dose, resistance to common disinfection techniques, and common occurrence in surface waters (LeChevallier *et al.*, 1991). When sufficiently monitored and associated with appropriate source water target values their inclusion in the index calculation would provide valuable information regarding source water risks.

3.4.2 The use of drinking source water target values as a management tool

The adoption of drinking source water quality standards as a means of protecting public health is a contentious issue (Chang et al. 1999). Very few jurisdictions have proposed source water quality guidelines. Research revealed three examples of non-binding guidelines for the protection of drinking source waters: the European Economic Community’s Drinking Water Abstraction Directive 75/440/EEC amended by Directives 79/869/EEC and 91/692/EEC (Office for Official Publications of the European Communities, 1975), Chang et al.’s Taiwanese source water quality standards (Chang *et al*.,1999) and the British Columbia Ministry of the Environment’s (BC MOE) water quality guidelines (BC MOE, 2010). Environment Canada has recommended that Health Canada work towards developing source water guidelines under different treatment processes. However, the drafting of source water quality guidelines is not a trivial undertaking due to a variety of issues including variability in treatment efficiencies, interactive effects and the time and resources required (D’Costa, 2008).

Alternatively, the use of source water quality standards as a basis for tracking and understanding changes in source water conditions is a concept that is yet to be fully appreciated and utilized. I employ drinking source water target values strictly for comparative purposes. Though supported by existing source water guidelines, the drafted target values are not intended to represent maximum allowable concentrations to protect public health but rather to serve as a defensible quality benchmark. The two treatment levels were chosen to represent minimal but widespread treatment requirements. Chlorination in particular remains the primary means of providing microbial disinfection in small and First Nations communities (Indian and Northern Affairs Canada, 2006).

3.4.3 CCME WQI application to surface drinking source water

The high correlation between mean expert scores and CCME WQI scores (Figure 3.3.2) supports the use of the CCME WQI as a valuable tool to track and communicate drinking source water quality. Optimization of factor weights did not provide support for assigning unequal weightings to the factor values (Table 3.3.3). This is contrary to previous studies that have proposed alternative F_1 formulations to reduce the contribution of the scope of guideline violations (Canadian Council of Ministers of the Environment, 2006b). The use of the alternative F_1 formulations proposed by the Canadian Council of Minister of the Environment (2006b) caused an increase in the absolute difference between index and expert scores in this study. This evidence for the continued application of the unmodified F_1 may be the product of the use of an appropriate number of parameters that do not co-vary (Canadian Council of Ministers of the Environment, 2003). However, the nature of drinking source water quality may also be the reason for the importance of the unmodified F_1 formulation. Drinking source waters that are subject to episodic events in which one or more contaminants are present in high levels are associated with increased risk (Curriero *et al*., 2001). These rare events may not be captured in factors F_2 or F_3 due to their scarcity. Conversely, a single sample failure is equally as important as multiple failures for the same parameter in F_1. Of note, variability was cited by several expert panellists as an important consideration when deciding on their evaluations of the provided source water quality scenarios. Reduction of F_1's influence may decrease the capacity of the index to capture such episodic events.

Unequal numbers of samples for different parameters, referred to as unevenness, can bias CCME WQI scores. The issue of parameter unevenness has been ignored in CCME WQI literature to date. Data processing techniques can be used to address this issue. Such data processing techniques include reducing the number of samples of each parameter to that of the least frequently monitored variable by using the maximum value measured within the corresponding time period. However, such techniques result in a loss of data. To mitigate the effects of parameter unevenness I adopted a modified formula for factors F_2 and F_3 (Table 3.3.4). The modification of the CCME WQI formulation did not affect the relationship between mean expert scores and index scores illustrated in Figure 3.3.2. However, due to the high evenness of the source water quality scenarios provided to the expert panel, the data does not allow for a detailed comparison of the original versus modified formulations. The modified CCME WQI appears to provide an improved means of deriving index scores though further analysis is required.

Calculation of 6 parameter seasonal index scores revealed that no single parameter was dominating the scores. The scores calculated by removing each of the individual parameters one at a time were significantly inter-correlated. Therefore, the

CCME WQI appears to be a robust, composite measure of drinking source water quality. Though no single parameter exerted a disproportionally large impact on the calculated scores, turbidity appeared to have the strongest influence among all variables. Turbidity was the parameter with the highest rate of violation under both treatment scenarios (Figure 3.3.4). The removal of turbidity caused the greatest change in treatment level 1 index scores and the second greatest change in treatment level 2 scores (Figure 3.3.5). Also, turbidity average excursions were most strongly correlated with scores calculated under both treatment scenarios (Table 3.3.5). Turbidity was identified as a parameter of high significance for assessing source water quality by the expert panel (Table 3.3.1). Also, turbidity was most frequently cited by the expert panel as the parameter of greatest significance for deciding on scenario ranks and scores. Turbidity has been shown to be correlated with microbial contamination of surface waters (LeChevallier *et al*, 1991). Furthermore, high turbidity reduces disinfection efficiency by increasing disinfectant demand and decay rates (Province of Manitoba, 2005). Turbid water can also shield pathogens from disinfection and stimulate bacterial growth in the distribution system (WHO, 2008). Therefore such a strong influence may not be unwarranted.

In contrast, nitrate and nitrite as N did not have a single violation in any of the scores. Terrado *et al*. (2010) recommend that parameters with guidelines that are difficult to exceed not be used in CCME WQI calculations as they tend to inflate the resulting scores. The removal of nitrate and nitrite as N from the index caused a relatively large decrease in score under both treatment scenarios (Figure 3.3.5). The proposed heath based nitrate and nitrite as N target value of 10 mg/L is rarely exceeded by surface source waters. Such high nitrate/nitrite concentrations are more of a concern in Canadian groundwater (Van der Kamp and Grove, 2001). Therefore it may be appropriate to exclude nitrate/nitrite from the core set of parameters used for surface source waters, leaving it as a supplementary parameter whose inclusion is up to the discretion of the index practitioner.

Though not explored in this analysis, the root mean additive CCME WQI aggregation formula is prone to eclipsing (Ott, 1978). Several aggregation alternatives exist in the literature (Sadiq and Tesfamariam, 2007). In particular, Swamee and Tyagi's improved aggregation function with $r = 2$ (Swamee and Tyagi, 2000) avoids all three common aggregation shortcomings and may provide more robust scores than the existing CCME WQI formulation. Further research is required to investigate alternative aggregation strategies and how well they characterize drinking source water quality conditions.

Though the CCME WQI can be used to quantify composite water quality conditions, it should not be substituted for a more detailed intensive assessment. As with all indices, the limits to the use of the CCME WQI must be kept in mind. The developed Canadian surface source water quality index provides an effective tool for communicating quality data to the public, policy makers, and other stakeholders. The index can also be used as a means of examining trends in quality. This report provides the first example of an index specifically designed to assess Canadian source water quality conditions. Considering the anticipated dual threats of population growth and climate change to Canadian drinking waters (Statistics Canada, 2005; IPCC, 2007; Lemmen et al., 2008) this type of management tool is required in order to sustainably manage Canadian water resources and communicate quality related issues to diverse audiences.

3.5 Conclusion

Investment in source water protection has been shown to provide safer and more affordable drinking water (Patrick, 2011). However, the cooperation and support of local community members is critical to the implementation of source water protection initiatives (Timmer *et al*., 2007). I have verified that the CCME WQI is an effective tool for summarizing composite drinking source water quality.

I adapted the CCME WQI for use in the Canadian source water context. The nature of the index allows for the accommodation of the site specific and treatment challenges posed by source waters. In cooperation with a panel of drinking water quality experts I provide practitioners with a core set of source water quality variables for use in the CCME WQI that address common Canadian source water quality concerns. These parameters reflect general microbial, aesthetic and treatment considerations. However, the addition of supplementary parameters to characterize site specific quality concerns is encouraged. The flexibility of the employed CCME WQI allows for the tailoring of scores to reflect source quality anticipating various treatment scenarios. Using source water target values for two basic levels of treatment, resulting index scores were in strong agreement with expert assessments of source water quality. The employed source water target values are meant only to be used as benchmarks, an application that appears to be supported considering the high level of association between index scores and expert scores. Updated with a modified index calculation procedure to control for the effect of parameter unevenness, resulting scores were not disproportionally influenced by any single parameter input. As with any index, care must be taken in its calculation and interpretation however the CCME WQI presents a potential communication and trends analysis tool to aid in the delivery of high quality water to all Canadians.

Chapter 4 Understanding the role of watershed characteristics in protecting surface source water quality: An investigation of the spatial scale of landuse impacts

Abstract

Drinking water purveyors are increasingly relying on land conservation and management to ensure the safety of the water that they provide to consumers. To cost-effectively implement any such landscape initiatives, resources must be targeted to the appropriate spatial scale to address quality impairments of concern. Using data gathered from 40 Canadian rivers across 4 ecozones I examined the spatial scales at which landuse was most closely associated with drinking source water quality metrics. Linear mixed effects models revealed that different spatial areas of landuse influence drinking source water quality depending on the parameter and season investigated. *E. coli* spatial variability was only associated with landuse at a local (5 km – 10 km) spatial scale. Turbidity measures exhibited a complex association with landuse suggesting that the landuse areas of greatest influence can range from a 1 km sub-catchment to the entire watershed depending on the season of the year. Total organic carbon concentrations were only associated with landuse characterized at the entire watershed scale. The Canadian Council of Ministers of the Environment Water Quality Index was used to calculate a composite measure of seasonal drinking source water quality but did not provide additional information beyond the analyses of individual parameters. These results suggest that entire watershed management is required to safeguard drinking water sources with more focused efforts at targeted spatial scales to reduce identified risk parameters.

4.1 Introduction

Drinking water serves as a nexus between human health and environmental quality and processes. Watershed characteristics such as land use, climate, and natural physiographic features influence both the quantity and quality of drinking water sources. Increasingly water suppliers are relying on natural hydrological services to protect the safety of the water that they provide for consumption (Wickham *et al*., 2011). Land management and conservation programs have been shown to be cost effective alternatives to investment in constructing or upgrading treatment facilities (Postel and Thompson, 2005). However, population growth and climate change present uncertain challenges to existing and proposed watershed conservation measures (Charron *et al*., 2004). In order to prepare for and adapt to future drinking water demands, a detailed understanding of the contribution of watershed characteristics to drinking source water quality is required. The scales at which these contributing factors exert the strongest influence must also be considered such that restoration and conservation efforts can be most effectively targeted (Buck *et al*., 2004).

Many different historic, economic and technical factors have resulted in a close association between human development and drinking water watersheds. Greater than 78% of the conterminous United States is part of a watershed from which water is extracted for drinking purposes (Wickham et al., 2011). However, human induced alterations within drinking water catchment areas have resulted in increased cost and risk to water consumers. A global analysis of primary watersheds revealed conversion to agriculture or urban-industrial use with corresponding loss of original vegetation cover in nearly one third of the 106 case studies examined (Revenga *et al*., 1998). Decreased forest cover in source watersheds has been associated with increased drinking water treatment cost (Ernst *et al*., 2004). The loss of natural forest cover minimizes the uptake of nutrients and the retention of soils leading to increased productivity and turbidity in surrounding water courses (Wahl *et al*., 1997; Abelho, 2001). Agricultural land has been associated with increased levels of several source drinking water quality parameters of concern as well including nitrogen, phosphorus, organic carbon and fecal coliform bacteria (Fisher *et al*., 2000) while urban development has been shown to increase nutrients and contribute to more turbid surface water quality conditions (Tong and Chen, 2002).

Landuse activities within a watershed frequently present the initial source of contamination to receiving waters (Canadian Council of Ministers of the Environment, 2004). However, due to many different factors that influence the transport and fate of contaminants, the spatial extent at which landuse activities influence downstream water quality my vary. Research concerning the relative importance of land use within a riparian buffer versus at the entire catchment scale has produced contrasting results due to the different study regions and parameters investigated as well as the land use classification processes employed (Guo *et al*., 2010). Landuse close to the water course has been shown to explain greater variation in water quality than land use at the whole catchment scale in several studies (Johnson *et al*., 1997; Sawyer *et al*., 2004) while entire watershed land use has provided greater explanatory power in others (Hunasker and Levine, 1995; Sliva and Williams, 2001; Meynendonckx *et al*., 2006). The uncertainty regarding the spatial scale at which landuse activities exert their greatest impact presents challenges for drinking source water quality conservation measures. Analysis of landuse-water quality relationships within a source drinking water framework is therefore required to help explain these uncertainties and guide planning decisions.

Though landuse activities can introduce contaminants directly into receiving waters, climatic events serve as the major means of mobilization of land based risks factors. Surface water quality has been shown to be significantly influenced by surrounding climatic conditions (Clark *et al.*, 1996; Bergmire-Sweat *et al.*, 1999; Kistemann *et al.*, 2001; Hunter, 2003). Heavy rainfall or snowmelt events can increase flow, turbidity, nutrients, natural organic matter, and pathogens within a water body (Davis et al., 1977; Hunter, 2003; Logsdon et al., 2004; WHO, 2004). The interaction between land use and climate has strong implications for surface source water quality as well. In a comparative study of urban and forested sites, Turner *et al.* (1977) showed a marked difference in the response of water quality parameters to storm events dependent on surrounding landuse. Urban water bodies were been shown to experience marked peaks in runoff, suspended solids and nutrients after storm events. However, runoff, suspended solids and nutrients were moderated by the vegetation of forested sites during the same rainfall episodes (Turner et al., 1977). Furthermore, disturbed sites have been shown to exhibit greater seasonal variation in nutrient parameters when compared to sites on the same water course with lower population density (Perona *et al.*, 1999). Such variability can increase drinking water risks by stressing treatment systems and potentially leading to failure (Curriero *et al.*, 2001).

Considering the importance of public safety through clean and healthy drinking water sources, investigations of the drivers of water quality and their spatial areas of influence are infrequently designed in an appropriate drinking water context. Despite the acknowledged link between climate and water quality, the role of landuse in controlling water quality is often analyzed independent of climate variability. Furthermore, studies of land use and scale are often carried out on low order streams as they present more manageable systems. However, natural waters used for drinking purposes are frequently drawn from large rivers (Wickham *et al*., 2011). In addition, parameters selected for analysis may not effectively capture drinking water risks. Even when representative parameters are included, drinking source water quality is a difficult concept to quantify. Treatment techniques must be a consideration when assessing source water quality as treatment can serve to both reduce health risk as well as inadvertently introduce them. For example, certain disinfection processes, such as chlorination, have the potential to produce harmful byproducts, the nature and quantity of which are related to source conditions (Hong *et al*., 2008).

In this paper, I characterize and quantify the effects of land use, climate and natural physiographic features on drinking source water quality. In particular, the spatial scales at which upstream landuse characteristics are most strongly associated with source drinking water quality are characterize and quantified. The spatial variability in water quality data collected from a variety of high order western Canadian rivers is related to a suite of watershed characteristics. Parameters representing common source water quality concerns are considered individually as well as in combination using the modified CCME WQI presented in Chapter 3. Adaptable to different treatment scenarios, the index is used to calculate drinking source water quality scores anticipating two basic levels of treatment. Interactions among watershed features and drinking source water quality are characterized from the watershed to the local scales. This broad scale analysis of the drivers of drinking source water quality presents the first landuse spatial scale-water quality study specifically designed within a drinking water and public health framework.

4.2 Methods

4.2.1 Study Sites

A total of 40 river sites were selected spanning central and western Canada (Figure 4.2.1). All sites were identified from pre-existing water quality monitoring programs based on the following criteria: 1) sampled water quality parameters reflect general suitability for use as a drinking water source (see Section 4.2.2) and 2) water quality parameters were sampled a minimum of three times during any given month in the time period December 1999 –November 2009. Sites were distributed throughout the Canadian provinces of British Columbia (6 sites), Alberta (24 sites) and Manitoba (10 sites).

Study sites were located in four Canadian ecozones. Defined as terrestrial areas representative of broad scale ecological units, ecozones are characterized by interacting biotic and abiotic features (eg. climate, relief, soil, flora, fauna and human activities) (The Atlas of Canada, 2009). Two sites were located in the Pacific Maritime ecozone, dominated by mountainous topography and temperate coniferous rainforests. Climate conditions are characterized by heavy rainfall with little variation in mean monthly temperature. Three sites were located in the Montane Cordillera ecozone composed of the Rocky Mountains and several major interior plains. Precipitation varies with altitude but winters are typically long and cold interrupted by short warm summers. Ten sites were located in the Boreal Plains ecozone, a region characterized by boreal forests covering low-lying valleys and plains. The climate is moist and typified by short warm summers and long cold winters. Twenty-five sites were part of the Prairie ecozone. The prairie ecozone is a low relief area dominated by farmland. Precipitation is low and variable during the cold winters and short summers. Upstream watersheds often spanned two ecozones.

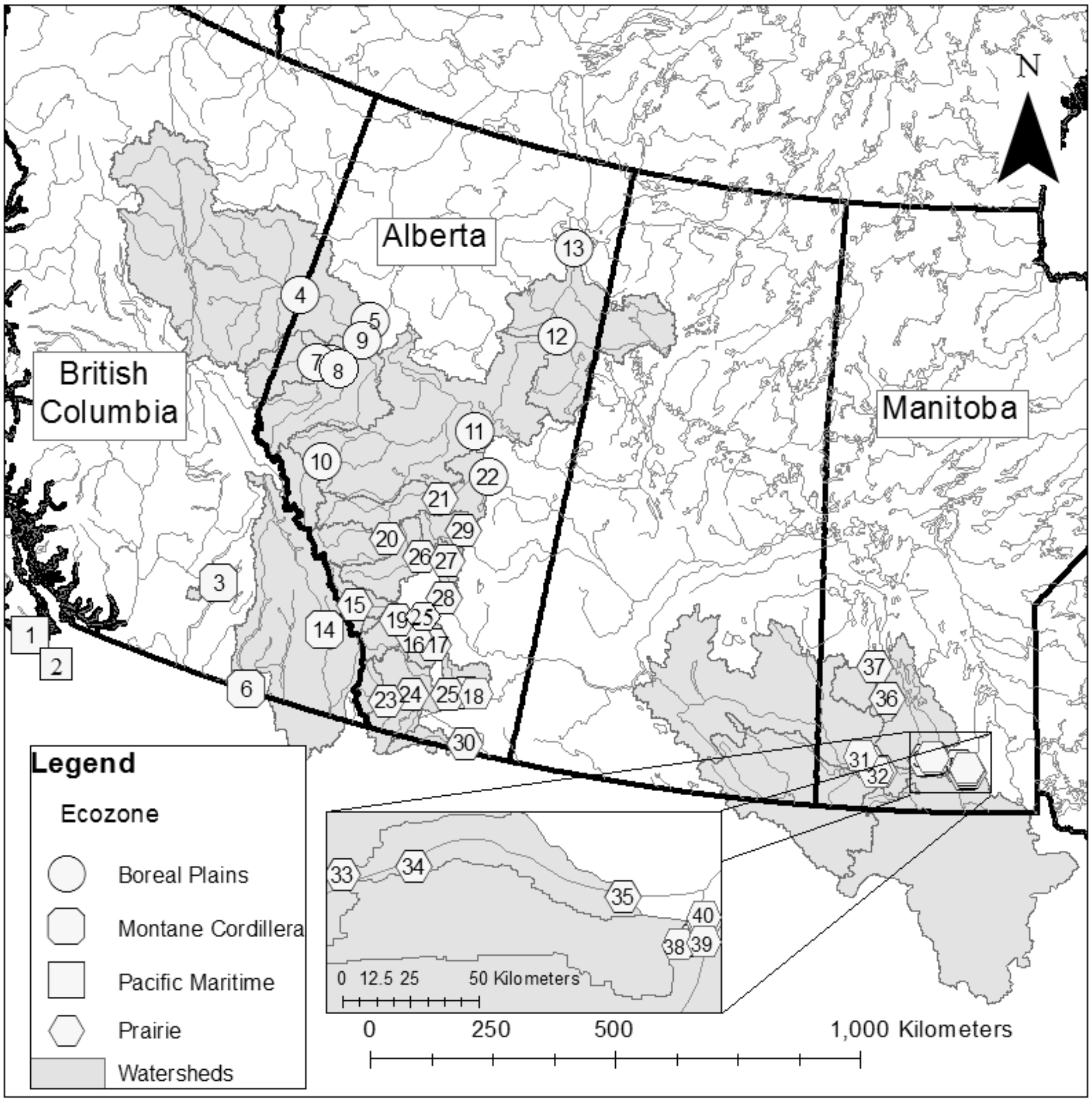

Figure 4.2.1 Location of study sites and upstream watersheds by province and ecozone. The number within site markers represents the site ID.

4.2.2 Water quality data

Water quality data were primarily accessed through Canadian provincial government authorities. British Columbia water quality data were provided by the BC MOE Environmental Monitoring System Web Reporting database as well as the Water and

Aquatic Sciences Research Program at the University of Victoria. Alberta data were collected from the Alberta Environment's publicly accessible River Network Station Water Quality Data program. Manitoba values were provided by request from Manitoba Water Stewardship's Water Management Section. Data sets were compiled for the period December 1999 – November 2009.

A comprehensive multi-step procedure similar to that of Dunnette (1979) was employed to identify a suite of priority drinking source water parameters to represent common source water quality concerns. The procedure is outlined in Section 3.3.1. When assessing source water quality, the expert panel assigned the highest mean significance rating to *E. coli* , TOC and turbidity (Table 3.3.1). Therefore these three parameters were chosen for further individual investigation. In combination, the parameters capture aspects of microbial risk, disinfection byproduct formation risk and treatment interference and aesthetics concerns. Several sites monitored dissolved organic carbon (DOC) instead of total organic carbon. DOC makes up a very high proportion of TOC in natural waters (Owen *et al.*, 1995; Larsen *et al.*, 2011). However, to accommodate these sites, a regression equation was computed to describe the relationship between DOC and TOC at 6 of the 40 sites. The regression equation was then used to convert DOC measures to TOC estimates.

Parameter measures were grouped into 4 seasons: winter (December – February), spring (March – May), summer (June – August) and fall (September – November). Previous studies have grouped parameter samples based on flow regimes (Sliva and Williams, 2001; Meynendonckx *et al*., 2006) however I included flow (both absolute and relative to site specific historic values) as an explanatory variable in this study. The discharge patterns among the investigated sites varied widely. Therefore, grouping variable measures based on flow would not improve the ability of the study to identify the explanatory power of flow towards the spatial variability in water quality.

The secondary nature of the gathered water quality data sets resulted in inconsistent monitoring of the selected drinking source water quality parameters. At a minimum, all parameters were sampled three times during any given month in the period December 1999 – November 2009. For all four seasons, each parameter was measured in an average of 8 of the 10 years periods between December 1999 and November 2009 (range: 3 - 10 years samples for each of winter, spring, summer and fall). Variables were averaged by season to reduce the effect of measurement error and the inconsistent sampling programs.

4.2.3 CCME WQI calculation

The CCME WQI formulation adapted to accommodate parameter unevenness that was validated in Chapter 3 was used to calculate index scores at all 40 sites. Seasonal scores for the period December 1999 - November 2009 were calculated based on six parameters: pH, turbidity, TOC, *E. coli*, nitrate and nitrite and temperature. Separate scores were calculated for each of the two treatment levels employed in Chapter 3. The source water target values in Table 3.3.2 were employed as objective values for treatment levels 1 and 2.

4.2.4 Watershed characteristics

ArcGIS 9.3 (ESRI, 2008) was used to characterize land use and physiographic features in catchment areas upstream of sample sites. Table 4.2.1 presents all watershed characteristics investigated in this study. Several watersheds crossed the Canadian/USA border therefore necessitating the use of both Canadian and American data layers.

Natural Resources Canada's Canadian Digital Elevation Data digital elevation models (minimum resolution 90 m) and the United States Geological Survey's (USGS) National Elevation Data Set digital elevation models (minimum resolution 30 m) were used along with ArcHydro software to delineate upstream watersheds. Upstream watersheds were verified using delineations provided by Natural Resources Canada.

Landuse and physiographic feature data were compiled at four spatial scales. Watersheds were delineated for the entire area upstream of sample points and the watershed areas within 10 km, 5 km, and 1 km upstream of the sample locations (Figure 4.2.2). Watershed characteristics were not described in narrow riparian buffers due to concerns regarding the resolution of the available data layers. Watershed slope was calculated as a zonal mean percent of slope value (eg. a 45° average degree of slope being equivalent to a 100% percent of slope value as (rise/run) x 100 = 100).

Natural Resources Canada's GeoBase land cover shapefiles circa 2000 were used to compile Canadian land use compositions. American land use was extracted from the USGS's 2001 National Land Cover Data. Land use classifications from both sources were aggregated into three general groups: 1) urban land, 2) agricultural land (including pasture lands) and 3) forested land. These three groupings were chosen in order to reflect major point and non-point sources of contamination as well as potential contaminant retention by landuse. Land use values for each of the general groups were expressed as a proportion of the associated catchment area.

Table 4.2.1 Watershed characteristics and investigated scales used as predictive variables of drinking source water quality.

Factor group	Watershed characteristic	Investigated scales	Units
Physiographic features	Catchment area	Upstream watershed	km^2
	Average slope	Upstream watershed, 10 km, 5 km, 1 km	%
Landuse	Urban land	Upstream watershed, 10 km, 5 km, 1 km	proportion of characterized upstream area
	Agricultural land	Upstream watershed, 10 km, 5 km, 1 km	proportion of characterized upstream area
	Forested land	Upstream watershed, 10 km, 5 km, 1 km	proportion of characterized upstream area
Climate	Mean seasonal temperature	3 day	°C
	Mean seasonal rainfall (absolute)	3 day	mm
	Mean seasonal rainfall (percent rank)	3 day	%
	Mean seasonal stream flow (absolute)	3 day	m^3/s
	Mean seasonal stream flow (percent rank)	3 day	%

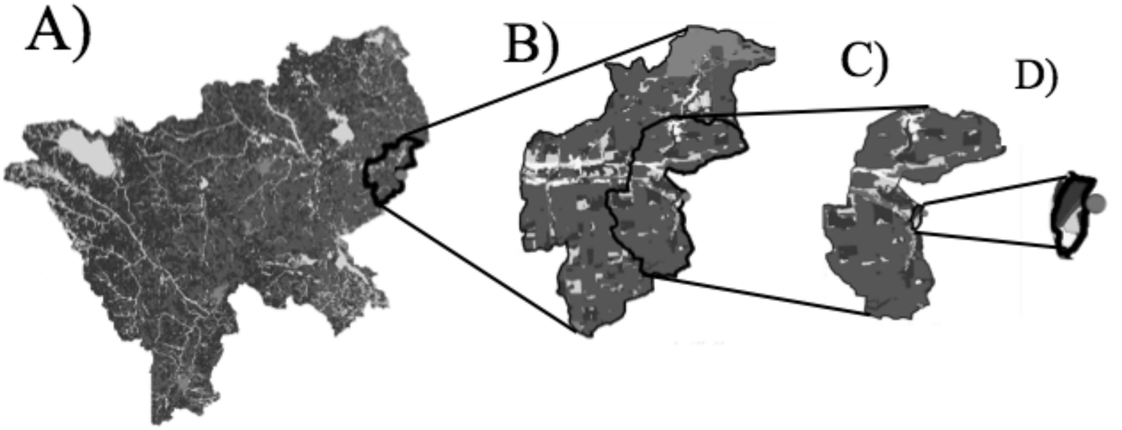

Figure 4.2.2 Four spatial scales at which land use and physiographic features were characterized. Catchment areas were delineated for A) the entire upstream area and the drainage areas within B) 10 km, C) 5 km and D) 1 km of the sample location.

Daily total rainfall and mean temperature data were provided by Environment Canada's National Climate Data and Information Archive. Weather stations closest to the water quality sample sites were selected as representative measures of local climatic conditions. Weather stations were located a mean distance of 20.3 km from sample sites (range 0.1 km – 58.8 km). Stream flow data was provided by Environment Canada's HYDAT database. The closest hydrometric station on the same water course was selected as a representative measure of stream flow at the sample site. Effort was made to ensure that selected hydrometric stations were not affected by any type of control structure (eg. dam) that did not control the flow at the water quality sample site as well. Hydrometric stations were on average 14.0 km from water quality sites (range: 0 km – 63.5 km). Rainfall, temperature and flow data were matched with water quality data by date. Mean 3-day temperature, cumulative 3-day rainfall and mean 3-day flow values were then computed for each sample measure. Three day cumulative and mean values were calculated as they were shown to be more strongly correlated with microbial contamination levels than single day values (Wilkes *et al*., 2009). The use of longer term climatic values was investigated including 7-day cumulative and mean metrics however they were shown to be very strongly correlated with 3-day measures (Spearman's rank order correlation; temperature $\rho = 0.99$, $p < 0.01$; rainfall $\rho = 1.00$, $p < 0.01$, flow $\rho = 1.00$, $p < 0.01$). Using 20-year (1990 – 2009) historic rainfall and flow values at each sample site, the percent rank of the 3-day cumulative rainfall and mean flow values were also calculated. Percent rank values were used to provide a measure of the long-term relative magnitude of 3-day rainfall and flow events. Climate parameters were then averaged by season for winter, spring, summer and fall. Seasonal climate averages were computed separately for each water quality parameter using climate values matched with parameter sample dates. Similarly, climate values for all parameter sample dates used as inputs in the CCME WQI were used to calculate associated mean seasonal climate values. In this way, only those climatic events occurring within 3-days of parameter samples were considered in subsequent analyses.

4.2.5 Statistical analyses

All mean seasonal water quality values were log transformed and the normality of the resulting distributions tested using the Kolmogorov-Smirnov goodness of fit test. Linear mixed effects models were used to identify the watershed characteristics listed in Table 4.2.1 that were significantly associated with seasonal source water quality. Separate analyses were conducted for each water quality metric, including the calculated index scores, and season. The fact that several of the investigated sites were found along the same water course, necessitated the use of a model type that could account for the spatial autocorrelation of the data. Sites were grouped into 19 major watersheds/nests based upon connectivity. Sites within the same watershed/nest were numbered in ascending order from upstream to downstream sample locations. Within the mixed effects model, non-nested sites were treated as independent sample measures while the degree of correlation between nested sites was assumed to be proportional to the Euclidian distance between them (Dodds and Oakes, 2006). Model type and correlation structure were selected using the general methodology outlined by Zuur *et al.* (2009). Models were constructed separately using average slope and landuse data at the four different spatial scales. Seasonal climate data were consistent among all models of the same water quality response parameter and season. In particular, the scales at which landuse provided significant predictive power were identified for all water quality variables and seasons.

In order to characterize the strength of the relationship between landuse classes at the 4 distinct spatial scales identified as significant by the linear mixed effects models and surface drinking source water quality, linear multiple regression models were used. Due to the violation of independence, the models are strictly descriptive (Roth *et al.*, 1996; Dodds and Oakes, 2006). R^2 values were used to describe the strength of any significant landuse-drinking source water quality relationships irrespective of climate or physiographic contributions.

4.3 Results

4.3.1 Seasonal patterns of source water quality

Source water quality showed both spatial and seasonal variation (Table 4.3.1). Mean seasonal *E. coli* concentrations ranged from 449 CFU/100mL to 4 CFU/100mL. The majority of sites experienced peak seasonal *E. coli* contamination in the summer (Figure 4.3.1). However, the season of peak *E. coli* contamination varied within ecozones as well as within watersheds/nests. Mean seasonal *E. coli* values did not exhibit any consistent pattern from upstream to downstream sites within the same watershed/nest.

Mean seasonal turbidity values were highest in spring and summer for all sites except those in the Pacific Maritime ecozone (Figure 4.3.1). Sites 1 and 2 in the Pacific Maritime ecozone experienced different peak turbidity seasons (fall and winter respectively) despite being found on the same relatively low order river. Sites experienced considerable differences in mean turbidity values among seasons (Table 4.3.1). Site 28 had the highest range in mean seasonal turbidity levels of 252.3 NTU and also had the highest single season mean turbidity. Conversely, site 1 experienced the lowest range in mean seasonal turbidity (0.3 NTU) as well as the lowest single season mean value (0.2 NTU). In general, mean turbidity within a single season tended to increase from upstream to downstream sites within a single watershed/nest. Several watershed/nests showed consistency in the season of peak turbidity among all of their sites. Those watersheds in which all sites did not experience the same season of peak turbidity did not exhibit any consistent pattern in peak season from upstream to downstream sites.

Maximum seasonal TOC values showed considerable variability among sites (Table 4.3.1). All ecozones, except for the Pacific Maritimes, contained sites with different seasons of peak TOC (Figure 4.3.1). The 2 sites in the Pacific Maritimes both witnessed maximum mean TOC values in the fall. Among sites and seasons, mean TOC values ranged from 28.3 mg/L during the winter at site 29 to 0.4 mg/L at site 10, also during the winter. Mean seasonal TOC values showed a consistent increase from upstream to downstream sites within the same watershed. Though all sites in several watersheds experienced peak mean TOC levels in the same season, this was not universal. Again there was no clear spatial pattern in season of peak TOC for those watersheds with sites exhibiting variable periods of maximum organic carbon.

Table 4.3.1 Seasonal parameter means and CCME WQI scores for December 1999 – November 2009. Sites within the same watershed/nest are numbered in ascending order from upstream to downstream (W. = Winter, Sp. = Spring, Su. = Summer, F. = Fall; R. = River, N. = North, Sask. = Saskatchewan)

		Mean *E .coli* (CFU/100mL)				Mean Turbidity (NTU)				Mean TOC (mg/L)				CCME WQI Treatment Level 1				CCME WQI Treatment Level 2			
Site ID	Watershed/Nest	W.	Sp.	Su.	F.	W.	Sp.	Su.	F.	W.	Sp.	Su.	F.	W.	Sp.	Su.	F.	W.	Sp.	Su.	F.
1	Leech R.	18	8	17	41	0.4	0.2	0.3	0.5	1.9	1.7	1.1	2.2	66.5	70.5	66.8	60.4	89.9	90.3	89.6	80.1
2	Leech R.	6	3	7	9	0.8	0.5	0.3	0.6	2.5	2.2	1.5	3.0	57.8	69.1	59.3	57.2	80.7	90.3	78.9	80.0
3	Salmon R.	31	95	153	195	2.5	18.5	5.3	1.6	2.9	7.1	4.6	2.7	58.2	37.1	39.6	48.9	90.6	68.9	76.2	90.4
4	Peace R.	3	8	46	9	4.2	94.9	126.4	30.9	2.4	4.6	4.4	2.9	58.1	39.1	37.4	44.7	94.6	54.3	52.1	78.0
5	Peace R.	10	11	23	10	5.3	79.3	26.5	7.0	2.4	4.3	3.6	2.9	55.5	35.1	29.4	52.5	89.8	53.3	57.6	87.6
6	Columbia R.	4	4	-	4	0.4	0.6	0.8	0.4	1.2	1.6	1.6	1.4	89.3	82.6	76.0	86.4	99.7	99.3	94.4	97.7
7	Wapiti/Smoky R.	10	12	15	12	2.8	113.3	88.8	12.4	2.2	5.6	4.3	3.4	60.1	29.6	28.2	41.1	80.7	45.3	47.6	76.2
8	Wapiti/Smoky R.	63	104	40	40	4.2	128.5	124.6	14.8	10.7	10.2	5.5	5.9	34.7	22.3	26.2	32.1	55.4	31.0	37.5	55.4
9	Wapiti/Smoky R.	12	21	23	19	8.4	194.6	137.3	22.7	5.6	8.8	6.3	5.1	42.1	22.2	25.4	31.5	75.0	27.5	38.1	60.0
10	Athabasca R.	10	10	12	10	10.0	13.4	46.7	19.0	0.4	0.9	0.9	0.7	49.2	43.7	30.8	42.8	85.2	69.4	52.4	70.9
11	Athabasca R.	10	10	23	10	2.0	50.3	73.7	8.5	6.8	8.4	6.4	5.8	52.2	23.4	20.6	35.6	77.4	43.2	38.0	57.5
12	Athabasca R.	10	26	28	12	10.0	71.8	106.8	10.3	8.1	10.1	9.4	8.7	43.3	23.1	24.5	25.9	71.3	35.7	34.3	53.0
13	Athabasca R.	12	10	12	10	59.0	44.0	98.7	21.1	8.2	9.7	11.2	10.1	34.9	29.8	25.7	25.5	61.2	45.7	39.8	49.9
14	Holland Creek	1	2	39	5	1.2	0.4	1.5	0.7	2.8	2.3	1.7	4.1	85.3	92.3	71.9	84.5	98.8	99.1	97.7	94.0
15	Bow R.	1	53	37	2	1.0	7.1	10.5	1.0	0.7	1.2	1.3	0.9	68.1	41.1	30.4	64.7	80.7	60.8	50.5	90.4
16	Bow R.	14	49	76	28	3.1	37.7	18.1	2.6	1.4	2.8	2.3	1.7	46.0	25.7	21.6	36.6	70.4	45.4	38.1	51.8
17	Bow R.	2	33	42	6	3.1	27.7	22.6	4.1	1.4	3.0	2.6	2.1	47.4	25.6	22.0	40.6	80.2	44.6	38.2	61.0
18	Bow R.	3	13	67	13	3.9	23.2	42.5	10.9	1.9	3.3	3.7	2.4	40.2	25.2	19.3	28.9	70.4	52.8	35.3	49.7
19	Elbow R.	105	51	449	277	2.4	8.7	40.3	4.3	1.2	2.1	2.8	1.7	38.6	35.9	27.5	44.0	60.9	60.1	46.7	75.4
20	N. Sask. R.	10	10	39	18	5.3	7.4	133.1	3.8	0.5	1.0	2.0	0.9	57.3	41.8	29.0	50.4	89.4	68.2	39.7	80.4
21	N. Sask. R.	10	17	34	45	2.6	45.6	57.0	37.5	1.6	3.3	3.6	2.4	61.2	25.5	26.8	33.6	80.7	40.8	40.6	56.0
22	N. Sask. R.	33	271	114	220	9.0	41.9	41.8	12.7	3.2	4.1	3.7	3.0	43.1	23.4	19.7	28.5	69.7	36.1	31.8	48.5
23	Oldman R.	12	3	57	26	4.7	4.5	11.6	7.4	1.8	1.9	2.8	2.2	52.6	54.5	28.6	37.4	89.5	89.8	49.1	60.0
24	Oldman R.	8	36	243	238	10.4	42.0	114.5	29.0	1.7	2.3	3.3	2.5	37.2	23.9	19.6	25.3	69.5	33.5	32.1	42.0
25	Oldman R.	8	21	194	13	7.0	40.0	105.0	32.7	2.1	2.8	3.6	2.9	33.5	23.9	18.1	24.7	51.4	36.5	30.1	42.9
26	Red Deer R.	9	165	147	184	2.0	16.1	47.8	4.5	2.4	5.9	6.0	3.7	49.8	26.5	20.2	31.4	71.1	46.0	37.9	50.3
27	Red Deer R.	30	78	162	68	2.5	30.3	82.9	4.5	2.8	6.8	7.2	4.3	45.2	22.7	18.1	32.0	61.3	40.6	30.5	50.2
28	Red Deer R.	8	48	144	119	1.3	73.7	252.3	20.6	2.8	7.2	6.4	4.3	44.6	22.1	17.0	24.4	61.3	35.2	24.7	41.5
29	Battle R.	15	17	36	17	26.0	38.7	19.1	23.0	28.3	19.4	18.9	21.7	30.4	22.3	18.8	23.8	49.7	41.7	33.8	44.8
30	Milk R.	2	32	268	55	3.8	144.8	123.1	26.2	3.4	4.2	2.0	2.5	55.8	28.4	20.3	24.8	80.1	37.0	29.1	44.9
31	Assiniboine R.	10	12	47	15	11.8	32.9	42.6	10.2	11.0	12.4	12.7	10.4	42.7	37.2	26.2	35.5	68.5	56.7	48.0	60.8
32	Assiniboine R.	44	55	31	18	8.2	34.9	39.7	7.0	11.3	11.8	12.4	10.5	41.5	30.7	29.8	36.6	69.2	53.1	47.5	64.5
33	Assiniboine R.	212	202	23	51	22.0	64.8	34.1	53.9	11.1	10.9	12.4	9.3	34.0	31.0	26.8	29.0	55.6	47.6	48.2	40.2
34	Assiniboine R.	101	63	48	59	21.9	67.4	41.0	47.9	11.9	11.0	12.1	9.3	35.8	32.4	25.3	30.5	58.7	48.0	45.8	49.4
35	Assiniboine R.	80	44	35	28	14.7	64.8	69.1	44.5	10.6	10.3	11.8	9.3	34.5	30.7	24.3	29.6	62.9	47.0	43.2	48.5
36	Turtle R.	-	14	128	15	2.0	58.9	15.8	4.7	5.7	10.5	12.7	7.7	-	36.8	29.9	35.2	-	57.3	57.4	60.8
37	Mossy R.	-	10	48	50	12.4	17.2	13.6	11.1	2.7	13.2	18.1	11.2	-	41.7	31.3	35.4	-	65.8	54.4	65.0
38	La Salle R.	10	16	35	15	4.0	53.1	33.5	21.2	16.8	12.4	14.3	16.6	50.3	36.6	28.2	36.7	73.2	54.0	48.8	59.6
39	Red R.	10	13	72	38	9.3	88.8	86.7	58.0	12.9	11.3	12.2	11.6	42.7	36.2	28.2	32.2	67.2	49.0	40.3	49.5
40	La Salle R.	90	10	110	85	11.4	25.7	38.8	22.0	10.0	12.6	18.4	18.2	35.0	38.6	27.1	31.2	61.7	57.2	46.4	53.7

Seasonal CCME WQI scores ranged from poor to good under treatment level 1 and poor to excellent under treatment level 2. Level 2 CCME WQI scores were on average 20.8±0.6 points greater than Level 1 CCME WQI scores. The majority of sites had the lowest CCME WQI in the summer regardless of treatment level (Figure 4.3.1). However, the season of poorest composite drinking source water quality varied for several sites depending on the treatment level employed in calculating the CCME WQI score. A total of 8 sites, found in all ecozones and across several watersheds, had different seasons of lowest CCME WQI score when calculated anticipating treatment level 1 as compared to treatment level 2. Consistent for both treatment levels, CCME WQI scores showed a decreasing trend from upstream to downstream sites within the same watershed. Furthermore, the season of poorest CCME WQI score was more consistent within watersheds when assessed under treatment level 2 than under treatment level 1.

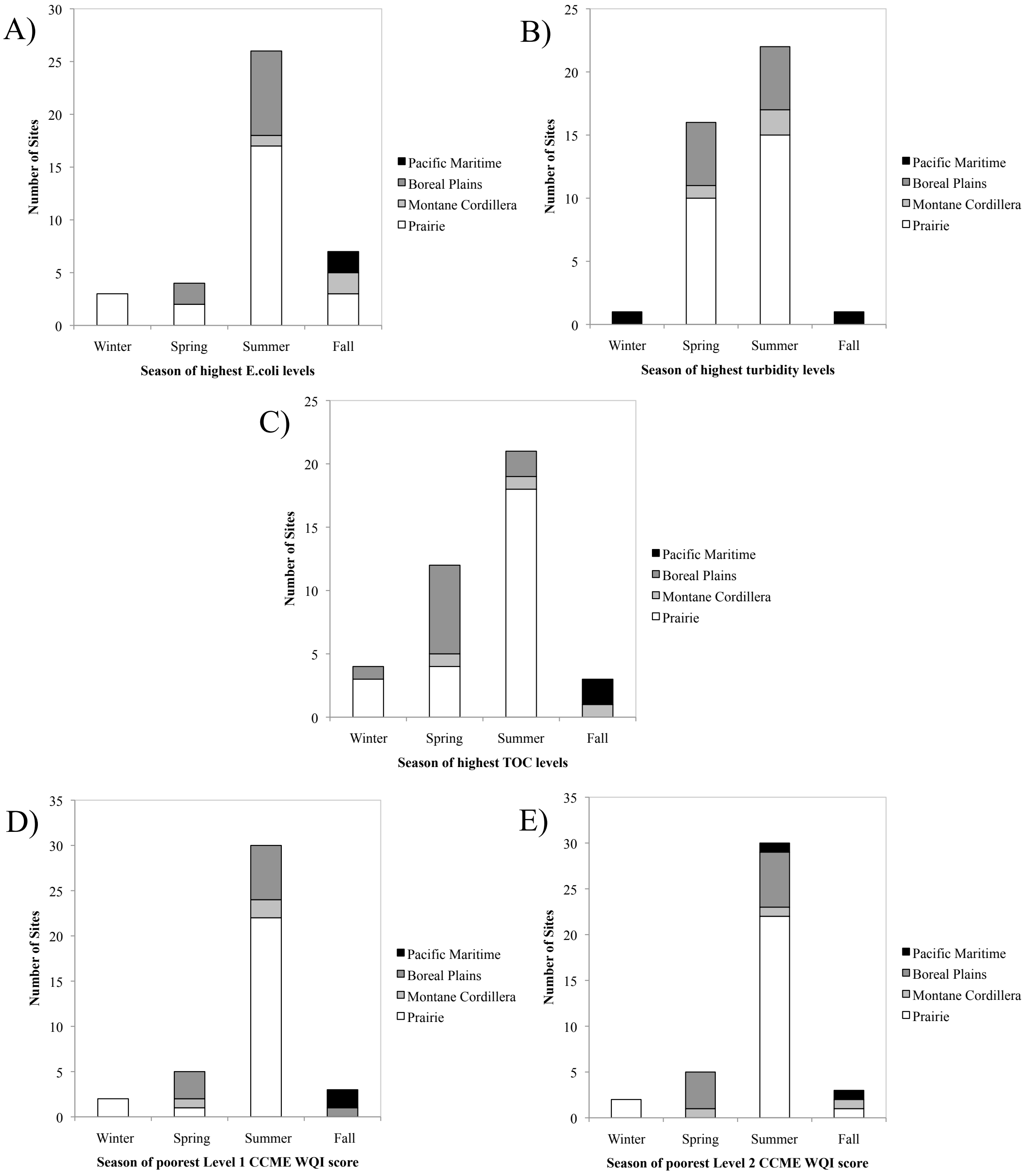

Figure 4.3.1 Distributions of seasons of peak contamination for the 40 riverine water quality sites. Sites are grouped by ecozone. Plots A, B and C reflect the seasonal distribution of maximum mean *E. coli*, turbidity and TOC values respectively. Plots D and E illustrate the seasons of poorest CCME WQI score calculated using treatment level 1 and 2 source water target values.

4.3.2 Watershed characteristics

Upstream watershed area ranged over several orders of magnitude reflective of the lower order rivers and large river networks investigated. Mean watershed slope varied by site as well as scale. Several sites showed a maximum slope value at the entire watershed scale as compared to finer spatial scales likely due to the inclusion of steep mountainous headwater terrain. On average, urban, agricultural and forested land accounted for 72±3 % of total land in upstream watersheds. Forested land was the most dominant individual landuse class at the entire watershed scale representing a mean of 37±4 % of total land area. However, at all finer spatial scales, agricultural land was the dominant class, accounting for an average of 26±4 %, 39±5 % and 44± 5 % of land at the 1 km, 5 km and 10 km scales respectively.

Landuse characterized at the different spatial scales was correlated though correlation strength decreased as the difference between spatial extents increased (Table 4.3.2). Comparisons within the same land use classes showed the weakest correlation strength between landuse proportions characterized at the 1 km and watershed scales. Urban land was only significantly correlated with other landuse types at watershed scales greater than 1 km. Weak positive correlations were described between urban and agricultural land while the correlation between urban and forested land was weakly negative. The correlation between agricultural and forested land was negative across all spatial scales. Correlation strength of the agricultural-forested relationship increased as the extent of the watershed described increased.

Flow regimes and rainfall patterns were fairly consistent within ecozones. Sites in the Pacific Maritime ecozone experienced peak flow in winter, followed closely by fall. Among all sites, average annual rainfall was greatest at those sites in the Pacific Maritime ecozone with peak rainfall occurring in winter and fall. The Montane Cordillera ecozone contained sites that exhibited different flow and rainfall patterns likely due to both the regulation of flow by impoundment structures and differences in elevation. Greatest flow was measured in spring and summer. Rainfall was generally greatest in the spring and summer as well however the season of greatest rainfall was less pronounced at elevation. Sites in the Boreal Plains ecozone all experienced highest flow in the summer except for sites on the Peace River which experienced maximum flow in the spring due to regulation by the W.A.C Bennett Dam. Rainfall across all sites in the Boreal Plains was greatest in the summer. Finally, sites in the Prairie ecozone tended to cluster by longitude with flow peaking in the spring for those sites in Manitoba and the summer for sites in Alberta. Rainfall was greatest in the summer for all Prairie sites.

Table 4.3.2 Correlations among landuse proportions characterized at the 4 different spatial scales (1 km, 5 km, 10 km and entire watershed [WS]). Only significant Spearman's rank correlation ρ values are reported (α = 0.05). Urb. = Urban land, Agr. = Agricultural Land, For. = Forested land

	Urb.-1km	Agr.-1km	For.-1km	Urb.-5km	Agr.-5km	For.-5km	Urb.-10km	Agr.-10km	For.-10km	Urb.-WS	Agr.-WS	For.-WS
Urb.-1km	1											
Agr.-1km		1										
For.-1km		-0.43	1									
Urb.-5km	0.87			1								
Agr.-5km		0.83	-0.39	0.31	1							
For.-5km		-0.42	0.77	-0.29	-0.54	1						
Urb.-10km	0.64			0.86	0.35	-0.35	1					
Agr.-10km		0.73	-0.39	0.37	0.94	-0.60	0.45	1				
For.-10km		-0.41	0.73	-0.31	-0.51	0.96	-0.35	-0.59	1			
Urb.-WS	0.39		-0.30	0.47	0.29	-0.43	0.59	0.33	-0.46	1		
Agr.-WS		0.44	-0.54	0.29	0.62	-0.73	0.38	0.67	-0.72	0.51	1	
For.-WS			0.43	-0.32	-0.36	0.64	-0.38	-0.42	0.64	-0.54	-0.78	1

4.3.3 Watershed-drinking source water quality linkages

Linear mixed effects models revealed different drivers of drinking source water quality depending on the season and metric of quality considered. Seasonal *E. coli* levels were best explained without the incorporation of a correlation structure within the mixed effects models. Across all seasons, *E. coli* variability was only significantly associated with landuse characterized at the 5 km and 10 km spatial scales (Figure 4.3.2). Landuse within 1 km catchment areas was not a significant predictor of *E. coli* levels in any season. Similarly, landuse quantified at the whole watershed scale did not provide significant predictive power. Winter, summer and fall *E. coli* levels were significantly associated with land cover when characterized at the 5 km and 10 km watershed scales. Summer *E. coli* concentrations, the season of peak contamination across the majority of sites, showed a significant negative association with forested land at both the 5km and 10km scales and a significant positive association with urban land at the 5km scale. Agricultural land quantified at the 5 km and 10 km extent showed a significant positive association with fall *E. coli* levels. Climate and physiographic features contributed to the explanatory power of the mixed effects models in different ways depending on the season examined. Within the 5 km and 10 km mixed effects models, mean 3-day stream flow showed a significant negative association with mean *E. coli* values in winter and fall. Furthermore, total watershed area was positively associated with *E. coli* in the fall. Spring *E. coli* concentrations, which were not associated with landuse at any of the 4 scales, were negatively associated with mean percent rank stream flow values in the 5 km and 10 km mixed effects models. Landuse characterized at the 5 km scale explained more of the variation in summer and fall *E. coli* levels than did landuse characterized at the 10 km scale (Figure 4.3.2). The same trend was observed in the winter though landuse alone explained very little of the variability in winter *E. coli* concentrations.

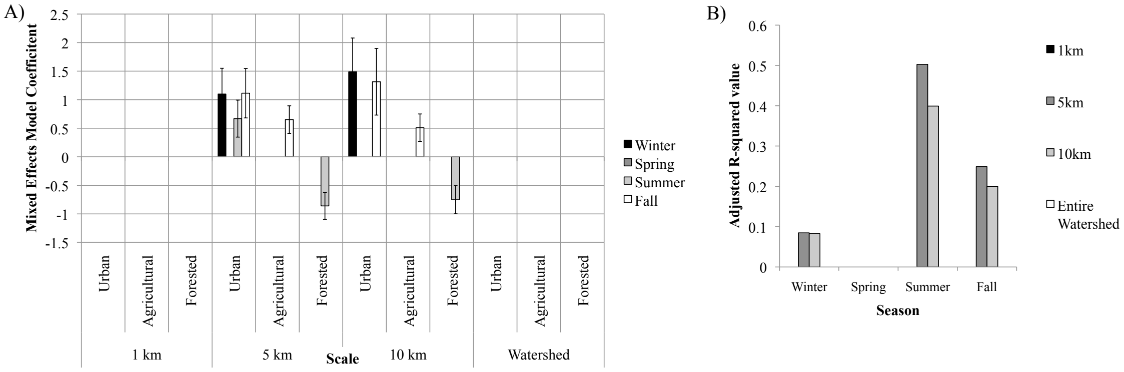

Figure 4.3.2 Significant associations among landuse and mean seasonal *E. coli*. Panel A) Linear mixed effects model coefficients for landuse classes characterized at four spatial scales that were significantly associated with mean seasonal *E. coli* concentrations ($\alpha = 0.05$); Panel B) Linear multiple regression model adjusted R^2 values describing the strength of the relationship between landuse identified as significant in the linear mixed effects models and mean seasonal *E. coli* concentrations

Variations in winter and summer turbidity values were best explained by incorporating a correlation structure in the mixed effects models. Turbidity values in all seasons were significantly associated with landuse characterized at the 1 km scale (Figure 4.3.3). The proportion of urban land within the delineated 1km watersheds was negatively associated with turbidity in all seasons while forested land characterized at the 1 km scale was negatively associated with turbidity levels in all seasons except winter. In addition, spring and fall turbidity values were significantly associated with landuse characterized at the entire watershed scale. Entire watershed forested land was negatively associated with spring and fall seasonal turbidity data sets while agricultural land within the total upstream catchment area was negatively associated with fall turbidity levels. Significant associations between turbidity and physiographic or climate characteristics varied among as well as within seasons. Landuse alone explained little of the variability in turbidity values within any single season (Figure 4.3.3). Landuse characterized at the 1 km spatial scale provided greater explanatory power towards spring turbidity variability than did landuse within the entire watershed. The opposite was true for fall turbidity levels.

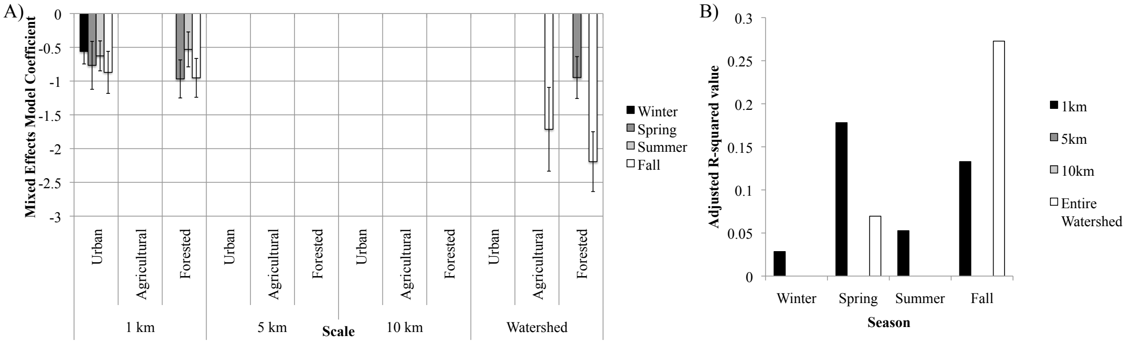

Figure 4.3.3 Significant associations among landuse and mean seasonal turbidity. Panel A) Linear mixed effects model coefficients for landuse classes characterized at four spatial scales that were significantly associated with mean seasonal turbidity ($\alpha = 0.05$); Panel B) Linear multiple regression model adjusted R^2 values describing the strength of the relationship between landuse identified as significant in the linear mixed effects models and mean seasonal turbidity levels.

The inclusion of a correlation structure in the linear mixed effects models describing the relationship between seasonal TOC values and watershed characteristics improved fit in all seasons except for winter. TOC levels across all seasons were only significantly associated with landuse characterized at the entire watershed scale (Figure 4.3.4). Landuse quantified at finer spatial scales did not provide significant explanatory power towards seasonal TOC concentrations. Winter, spring, summer and fall TOC levels were positively associated with both upstream agricultural and forested land described as a proportion of the total upstream watershed area. Across all seasons, agricultural land had a larger effect within the models than did forested land. Climatic parameters of significance varied by season. Consistent among all seasons, TOC values were positively associated with total upstream watershed area. In all seasons, total watershed landuse alone explained greater than 45% of the variance in TOC among sites (Figure 4.3.4). The greatest amount of variance in TOC levels was explained in the summer ($R^2 = 0.52$).

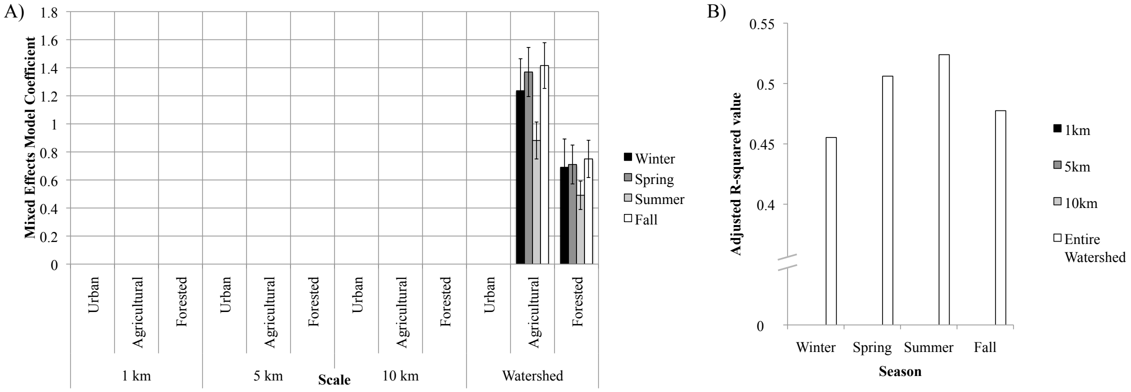

Figure 4.3.4 Significant associations among landuse and mean seasonal TOC. Panel A) Linear mixed effects model coefficients for landuse classes characterized at four spatial scales that were significantly associated with mean seasonal TOC ($\alpha = 0.05$); Panel B) Linear multiple regression model adjusted R^2 values describing the strength of the relationship between landuse identified as significant in the linear mixed effects models and mean seasonal TOC levels.

The relationship between landuse and CCME WQI scores did not show any consistent pattern among seasons or between treatment levels. Including a correlation structure in the mixed effects models improved fit in all seasons except summer for scores calculated anticipating both treatment levels 1 and 2. CCME WQI treatment level 1 scores were significantly associated with landuse at the 1 km and entire watershed scales during winter, summer and fall (Figure 4.3.5). Landuse characterized at the 10 km scales also provided significant explanatory power towards explaining fall treatment level 1 score variability. The only landuse type and scale that spring level 1 scores were significantly associated with was urban land within a 1 km watershed. Significant associations between landuse and treatment level 1 scores across all spatial scales were positive. Significant physiographic and climate relationships also showed little consistency among scales and seasons within CCME WQI level 1 mixed effects models. Entire watershed landuse explained the greatest amount of variation in winter and fall CCME WQI level 1 scores (Figure 4.3.5). Summer level 1 scores showed a marginally stronger association with 1 km landuse than with entire watershed landuse. Due to the fact that spring level 1 scores were only significantly associated with 1 km landuse, the relative strength of associations could not be assessed.

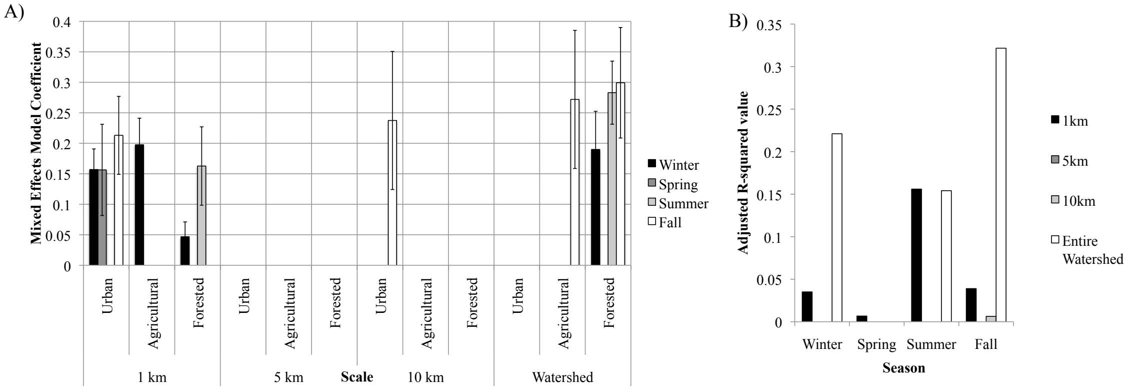

Figure 4.3.5 Significant associations among landuse and seasonal CCME WQI treatment level 1 scores. Panel A) Linear mixed effects model coefficients for landuse classes characterized at four spatial scales that were significantly associated with seasonal CCME WQI treatment level 1 scores ($\alpha = 0.05$); Panel B) Linear multiple regression model adjusted R^2 values describing the strength of the relationship between landuse identified as significant in the linear mixed effects models and seasonal CCME WQI treatment level 1 scores.

Spring and summer CCME WQI treatment level 2 scores were significantly associated with landuse when characterized at the 1 km and 5 km scales (Figure 4.3.6). Similar to level 1 scores, summer level 2 scores also showed a significant relationship with entire watershed landuse. Fall CCME WQI treatment level 2 scores were significantly related to landuse characterized at each of the 4 spatial scales. Whereas under treatment level 1, winter scores were significantly associated with 1 km and entire watershed landuse, under treatment level 2 target values, CCME WQI scores showed a significant association with landuse at the 10 km and as well as the entire watershed scales. Within the mixed effects models, most landuse-CCME WQI treatment level 2 relationships were positive. Negative associations between index score and landuse were described in the spring for agricultural and forested land at the 5 km scale and in the winter for urban land at the entire watershed scale. Again, physiographic feature and climatic relationships with CCME WQI level 2 scores were highly variable among seasons and scales. Of note, a consistent significant positive relationship was described between fall Level 2 scores and the mean percent rank of 3 day rainfall. Entire watershed landuse explained the greatest amount of variance in fall CCME WQI level 2 scores however finer spatial scales provided greater power in winter and summer (the 10 km and 5 km spatial scales respectively) (Figure 4.3.6). Entire watershed landuse was not significantly associated with spring level 2 scores and therefore its relative explanatory power could not be assessed. Instead, linear multiple regression models revealed a stronger relationship between spring CCME WQI treatment level 2 scores and landuse characterized at the 5 km scale as opposed to the 1 km scale.

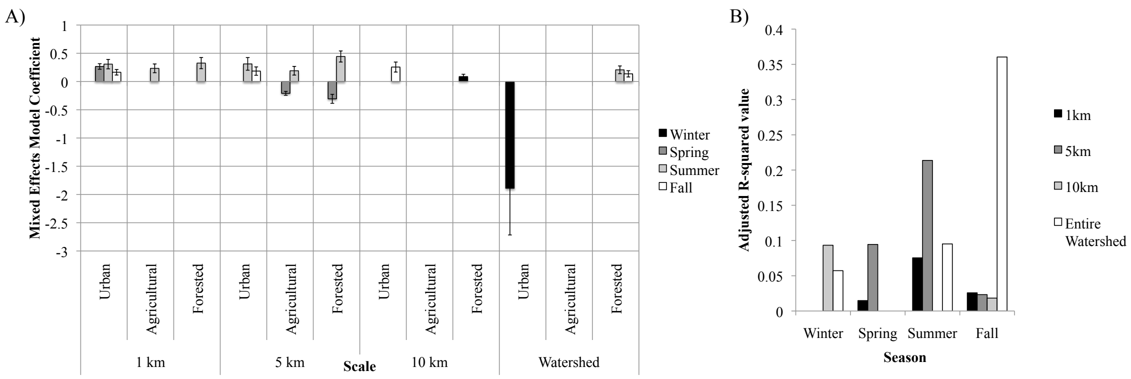

Figure 4.3.6 Significant associations among landuse and seasonal CCME WQI treatment level 2 scores. Panel A) Linear mixed effects model coefficients for landuse classes characterized at four spatial scales that were significantly associated with seasonal CCME WQI treatment level 2 scores ($\alpha = 0.05$); Panel B) Linear multiple regression model adjusted R^2 values describing the strength of the relationship between landuse identified as significant in the linear mixed effects models and seasonal CCME WQI treatment level 2 scores.

4.4 Discussion

Greater than 85% of Canadians rely on surface water as a drinking water source (Davies and Mazumder, 2003). Linkages between surface water quality and watershed characteristics such as landuse and climate are well acknowledged (Meybeck *et al.*, 1989). However, few studies have looked at the combined effects of these drivers of quality (Tu, 2009). Furthermore, though the impact of landuse on water quality has received considerable attention in the literature, the scales at which these impacts are detectable are not well known (Gergel *et al.*, 1999). Operating under Baker's first criteria which outlines that in order for a landuse-water quality relationship to be observed, the water quality parameter must be conservative enough for the upstream landuse signal to be preserved at the sampling site (Baker, 2003), I set out to investigate the spatial scales at which landuse is most strongly associated with drinking source water quality. The results of my analysis suggest that the scale of landuse impacts on source water quality range from the local to the entire watershed, supporting the need for watershed scale conservation measures with targeted efforts to address parameters of concern.

4.4.1 Local scale drivers of seasonal *E. coli* contamination

Reaching the greatest mean concentration during summer at the majority of sites, *E. coli* levels did not show any trends in upstream to downstream levels. Furthermore, the fit of the linear mixed effects models was not greater with the incorporation of a correlation structure. These 2 points suggest an absence of cumulative watershed scale inputs to the large river sites examined. Though some studies have suggested that fecal bacteria such as *E. coli* can survive and reproduce in the environment (Byappanahalli and Fujioka, 1998), it is generally accepted that the presence of fecal bacteria is due to direct fecal contamination. There is therefore no, or very little, cycling of *E. coli* in natural waters. The measured levels within a river are due to the initial loading and the bacterial decay rate which is a function of such factors as the time and distance of travel, light, temperature and salinity (Eleria and Vogel, 2005).

The spatial variability in mean *E. coli* concentrations was associated with different watershed characteristics during different seasons. This is consistent with the results of Kelsey *et al*. (2004) who found that different processes and variables are important at different times of year for describing fecal coliform variability. Landuse was only significantly associated with *E. coli* when characterized at the 5 km and 10 km spatial scales. Finer resolution landuse (at the 1 km scale) and broad scale landuse (at the watershed scale) were not significantly associated with seasonal *E. coli* concentrations. In agreement with previous findings, both urban and agricultural land were positively associated with *E. coli* concentrations (Fisher *et al*., 2000; Sliva and Williams, 2001) while forested land showed a negative association. Landuse described at the 5 km spatial scale was more strongly related to *E. coli* concentrations in spring, summer and winter than landuse at the 10 km spatial scale. Spring concentrations did not show a significant association with landuse at any scale.

Others have found that sub-catchment scale landuse was better at predicting fecal coliform levels than landuse within a narrow riparian corridor (Sliva and Williams, 2001; Buck *et al*., 2004). These studies were conducted using sites in smaller watersheds than those considered here. Despite this discrepancy, there appears to be a consensus among my work and that of previous studies in terms of the need to consider landuse beyond the immediate scale when characterizing *E. coli* concentrations. The large watersheds investigated in my study provide a new perspective for assessing the spatial scale of landuse impacts on *E. coli*. Though the landuse-*E. coli* relationship does extend to a broad scale, there appears to be a dynamic complex (Guo *et al*., 2010) in which the strongest linkage between landuse and fecal contamination is exhibited at the 5 km – 10 km scale with a diminishing association at greater spatial scales.

4.4.2 The variable spatial relationship between turbidity and landuse

Turbidity showed a consistent spatial pattern, increasing from upstream to downstream sites within the same watershed. This, along with the correlation structure present in winter and summer turbidity models supports the additive nature of turbidity loading to a river system put forth by the river continuum concept (Vannote *et al.*, 1980). Sediments can be transported long distances suggesting that landuse along the entire length of a river's course should be important in determining turbidity levels (Allen, 2004).

However, linear mixed effects models did not align with expectations. Entire watershed landuse was significantly associated with seasonal turbidity levels only in the spring and fall. During all seasons, landuse within a 1 km delineated watershed was significantly associated with turbidity values. Furthermore, only in fall was there evidence that whole watershed landuse was the best predictor of turbidity variation. Interestingly, landuse types were only negatively associated with turbidity levels.

Others have found a complex relationship between turbidity and landuse (Buck *et al.*, 2004). Gove *et al.* (2001) found that the strength of the association between turbidity and landuse increased with increasing scale but only to a point; the strongest relationship was not described at the entire upstream watershed scale. Instead they suggest that within stream processing reduces the impact of any upstream loading. My results seem to support this view in which local landuse plays a more important role in driving turbidity than does whole watershed landuse composition during most seasons. The finding that fall whole watershed landuse was most strongly related to seasonal turbidity levels among all seasons and scales suggests that whole watershed landuse does play an important role in some circumstances. Furthermore, area was significantly positively associated with turbidity spatial variability in winter and spring, perhaps reflective of the expected increase in turbidity from upstream to downstream sites.

4.4.3 Watershed scale influence on seasonal TOC levels

Similar to turbidity spatial dynamics, seasonal TOC levels exhibited a consistent increasing pattern from upstream to downstream sites on the same river and the incorporation of a correlation structure within seasonal mixed effects models provided greater explanatory power in all seasons at all spatial scales. Furthermore, there was a consistent positive association between total upstream watershed area and seasonal TOC variability. Others have found a strong correlation between aerial parameters and organic carbon levels in lakes. Drainage area and ratio (the ratio of watershed area to lake area) have been shown to be positively correlated with dissolved organic carbon levels (Rasmussen *et al.*, 1989; Houle *et al.*, 1995). With a greater terrestrial productive area, allochthonous organic loadings are higher in lakes with larger watersheds. Extending this same principle to rivers, downstream sites and those sites in larger watersheds receive greater allochthonous inputs from upstream areas. Though the majority of lotic organic carbon is terrestrial in origin (Stanley *et al.*, 2011), larger rivers, with large upstream catchment areas, may also have greater autochthonous TOC production.

Landuse was only significantly associated with seasonal TOC variability when characterized at the entire watershed scale. Across all seasons, entire watershed agricultural and forested lands were positively associated with TOC concentrations. Agricultural land has been associated with high export of dissolved organic carbon to river systems (Raymond *et al.*, 2008). Intense drainage of agricultural lands can more than double the export of organic matter (Dalzell *et al.*, 2011). Furthermore, conversion to agricultural land can increase nutrient export to receiving waters as well (Fisher *et al.*, 2000), stimulating the autochthonous sequestration of organic carbon.

In contrast with my results, other studies have found a negative relationship between the proportion of forested land within a watershed and organic carbon levels (Wilson and Xenopoulos, 2008). Leaf litter is not a significant source of organic carbon (Meyer *et al.*, 1998) therefore the positive relationship between forested land and organic carbon levels is suspect. However, the proportion of forested land at the watershed scale was strongly correlated with the proportion of wetland area (Spearman's rank order correlation; $\rho = 0.99$, $p < 0.01$). The proportion of watershed land occupied by wetlands has been shown to be a strong positive predictor of organic carbon levels (Dillon and Molot, 1997; Gergel *et al*., 1999). Therefore, the relationship documented between forested land and organic carbon levels in this study may in fact be a product of an underlying wetland area-organic carbon linkage.

Other studies have similarly found the strongest relationship between organic carbon and landuse when landuse was characterized at a broad scale. Gergel *et al*. (1999) found that watershed scale wetland area always explained a greater amount of the variation in DOC than riparian wetland area. In addition, Gove *et al*. (2001) found that particulate organic carbon was best characterized by landuse at the broadest spatial scale that was considered (a 1 km by 5 km stream buffer). Lotic organic carbon is primarily the product of terrestrial accumulation, hydrological transfer and in stream processing (Stanley *et al*., 2011). These processes vary seasonally (Wilson and Xenopoulos, 2008), reflected in the seasonal differences within the mixed effects models.

4.4.4 The influence of watershed characteristics on composite drinking source water quality

The CCME WQI index measure used to characterized composite drinking source water quality showed a consistent decreasing pattern in scores from upstream to downstream sites within the same watershed. Mixed effects models incorporated correlation structures in all seasons except summer, suggesting that composite quality under both treatment level 1 and treatment level 2 is driven in part by cumulative upstream processes. The absence of a correlation structure in summer mixed effects models may be due to the increased target value violations by temperature and *E. coli* during the summer (Table

4.4.1). These two parameters do not exhibit cumulative patterns from upstream to downstream sites and may veil correlation structures in the summer models.

Table 4.4.1 Mean frequency of treatment level 1 and treatment level 2 target value violations by individual parameters used to calculate CCME WQI scores

Season	Winter		Spring		Summer		Fall	
Treatment Level	1	2	1	2	1	2	1	2
E. coli violation frequency	0.26	0.07	0.30	0.06	0.60	0.13	0.37	0.05
Turbidity violation frequency	0.94	0.34	0.94	0.67	0.94	0.73	0.95	0.52
TOC violation frequency	0.39	0.39	0.56	0.56	0.55	0.55	0.45	0.45
Temperature violation frequency	0	0	0.05	0.05	0.70	0.70	0.09	0.09
Nitrate and Nitrite violation frequency	0	0	0	0	0	0	0	0
pH violation frequency	0.03	0.03	0.06	0.06	0.14	0.14	0.10	0.10

CCME WQI scores were associated with landuse at several different spatial scales under both treatment levels 1 and 2. Treatment level 1 scores showed significant associations with landuse primarily at the 1 km and entire watershed scales whereas treatment level 2 scores were associated with landuse at all spatial scales. Though in Chapter 3 the index measure was shown to not be disproportionately influenced by any single parameter, turbidity did have the strongest impact on calculated scores. Similarly, among the 40 riverine sites studied in this chapter, turbidity measures exceeded target values more frequently than any other parameter in all cases except for winter under treatment level 2 (Table 4.4.1). Therefore, the pattern in landuse associations with CCME

WQI scores may be the result of this strong turbidity influence. Turbidity-landuse spatial patterns are fairly closely mirrored in CCME WQI level 1-landuse spatial patterns. Scores calculated anticipating a more intensive treatment regime (treatment level 2) were significantly associated with landuse characterized at all spatial scales. Furthermore, the strength of the relationship between landuse and composite quality varied among seasons and treatment regimes. Entire watershed landuse provided the greatest explanatory power in fall under both treatment levels however finer scales were more important in all other seasons.

The complex relationship exhibited between landuse and CCME WQI score variability is perhaps due to the formulation of the index and the target values employed. Of note, the relationships between the individual factors that contribute to the CCME WQI (F_1, F_2 and F_3) and landuse at each of the 4 spatial scales was investigated. Considering the index factors individually did not produce clearer spatial trends in landuse associations. The use of treatment level target values allows for contamination of source waters while still reflecting a high quality source. In this way, low levels of contamination are considered equivalent to no contamination. The target values therefore decrease the resolution of resulting scores, especially among sites with low level contamination. The greater the permissible contamination under each treatment scenario, the lower the resolution of the index. The combination of this decreased resolution along with the aggregation of several different parameters that are influenced by landuse at different spatial scales may obscure landuse-water quality relationships.

4.4.5 Management implications

Drinking source water quality is a multi-parameter concept. Individual parameters of concern that contribute to overall quality are influenced by watershed characteristics in complex and often highly variable ways (Buck *et al.*, 2004; Kelsey *et al.,* 2004; Wilson and Xenopoulos, 2008). However, general parameter specific patterns exist in the spatial extent of upstream contributing areas. My work suggests that microbial risk, characterized by the *E. coli* indicator organism, is regional in its scope. Due to natural dynamics and instream processing, landuse influences are limited to a sub-catchment scale with the strongest linkages existing when landuse is characterized at the 5 km-10 km upstream watershed extent. In contrast, total organic carbon inputs, serving as a metric for disinfection byproduct potential, appear to be significant at the entire watershed scale. This is not to suggest that more local TOC sources are not important but instead that in order to effectively characterize and possibly manage organic carbon in source waters, entire watershed landuse must be considered. Turbidity appears to be driven by both local and watershed scale landuse to varying seasonal degrees. Management of individual risk parameters therefore requires targeted scale-specific land conservation and management. However, my work indicates that in order to mitigate cumulative risk, a watershed scale land management program is required.

The use of a composite measure of drinking source water quality provided subjective insight into landuse-water quality relationships. Others have documented difficulty in interpreting the behaviour of aggregate index measures (Watzin and McIntosh, 1999). Though the index measure did exhibit interpretable relationships with landuse characterized at the various different scales, these relationships appeared to reflect the trends observed for those parameters that most strongly influenced scores.

Furthermore, with increased levels of anticipated treatment, any existing landuse signal was diluted. As with any index measure, practitioners must be aware of the limitations and caveats of its application. The CCME WQI does not appear to provide additional insight into landuse-water quality relationships beyond that provided by individual parameter measures. Instead, the CCME WQI, as outlined by the supporting literature, serves as a valuable communication and trend analysis tool that should not supersede detailed individual parameter analyses (Canadian Council of Ministers of the Environment, 2001).

Due to the lack of available data, some important predictive parameters were not included in the analysis. For example, soil type has been shown to have strong implications for stream organic carbon concentrations (Wilson and Xenopoulos, 2008). Also, landuse was only characterized as a proportion of the 4 described catchment areas. However, the pattern and location of landuse types within the described catchment areas may be as important as strict composition metrics (Meynendonckx *et al*., 2006). Furthermore, though 3-day and 7-day climatic measures were strongly correlated, time scales extending beyond 7 days may be important in influencing parameter measures that are under the influence of entire watershed landuse. The omission of these variables may have affected the results of my analysis though the documented relationships between landuse and water quality were highly significant in all models. Of note, the mixed effects model outputs were very sensitive to the scale at which landuse was characterized. This observation highlights the necessity of characterizing landuse at the appropriate scale when modeling watershed-water quality relationships. The inclusion of landuse described at too broad or too fine a spatial scale may yield erroneous associations between climate or physiographic features and water quality parameters. Potentially of greater concern is the nature of the water quality data used in this study. The frequency of monitoring at some sites may not have been adequate to effectively capture seasonal trends. Though initially appealing, the use of such secondary data may only provide preliminary and exploratory insight (Sliva and Williams, 2001).

4.5 Conclusion

Landuse management within source watersheds is a key component of source water protection. Large municipalities may have the means to purchase entire drinking water catchment areas however such resources are not available to small communities. Therefore the targeting of landuse management initiatives to the appropriate spatial scale is critical to ensuring cost effective contaminant control.

In this study, the source water quality of riverine ecosystems was found to be associated with landuse characterized at different spatial scales depending on the parameter and season investigated. Exploratory models linking watershed characteristics with drinking source water quality revealed that:

1) *E. coli*, an indicator of microbial risk in source drinking waters, did not exhibit evidence of cumulative upstream watershed inputs. Instead, across all seasons, *E. coli* was only associated with landuse characterized at a local scale with the strongest association apparent at the 5 km spatial scale.

2) Turbidity-landuse relationships were contrary to expectations. Though entire watershed landuse was most strongly associated with fall values, turbidity spatial variability in all other seasons was better explained by landuse within a 1 km upstream watershed.

3) Reflective of the cycling of organic matter, total organic carbon was only associated with entire watershed scale landuse. Watershed area also served as a consistent positive predictor of organic carbon levels reflective of the regional nature of organic carbon inputs.

4) The use of the CCME WQI to characterize composite source water quality did not provide insight into the spatial scale of landuse-water quality relationships beyond the results of individual parameter analyses. The use of treatment based target values combined with the contribution of several different parameters within the index computation may have masked any trends in landuse effects.

Though the secondary nature of the data employed was not ideally suited to this type of study, the spatial extent of landuse impacts does appear to be an important consideration when assessing source water risks. Cumulative risk management must operate at the entire watershed scale to address all common source water concerns. However, the management of individual risk parameters may be more cost-effective via targeted scale-specific land conservation and management.

Chapter 5 General Conclusion

Drinking water remains an important public health issue in Canada (Charron *et al*., 2004). Increasingly incorporated as a barrier for preventing contaminants from reaching consumer's taps, source water protection can be impeded by many different political, social and economic factors. The involvement and support of community members is especially important in securing funding for and reducing opposition to source water protection initiatives (Timmer *et al*., 2007). The aim of this thesis was to help overcome some of these impeding factors through specialized tools and knowledge. I validated the CCME WQI as an appropriate and effective index tool for characterizing source water quality status and trends. Furthermore, riverine drinking source water was revealed to be influenced by landuse at scales ranging from the local to the regional. However, when attempting to control specific drinking water risks, my work suggests that landuse planning resources may be of the greatest value when applied to targeted spatial scales.

Regulatory tools such as legislation as well as non-regulatory tools including stewardships and education are important components of source water protection (Simms *et al*., 2010). Several Canadian jurisdictions have adopted source water protection legislation to help prevent contamination of drinking sources. For example, Ontario's *Clean Water Act* mandates the drafting of source water protection plans to indentify and address threats to water quality. Source water protection plans are also required by Prince Edward Island's *Environmental Protection Act*. Education and outreach are important parts of these and other source water protection programs. It is perhaps in the realm of public outreach that the validated CCME WQI may be most valuable.

Khan *et al.* (2004) previously explored the utility of the CCME WQI to communicate treated drinking water quality in Newfoundland and Labrador. In their experience, quarterly index scores have been successful in reducing complex water quality data to a simple metric that is easily understood by the public. Along with the communication opportunities presented by the CCME WQI, the index has previously been used as a trend analysis tool for non-drinking water uses (Khan *et al*., 2003; Lumb *et al*., 2006). In a source water context, the CCME WQI could be equally as effective. Though Newfoundland has been deservingly commended on their source monitoring and water quality communication initiatives it is not the finished water that should be the only measure of such a program's success. Rather, in order to encourage and evaluate source water protection measures, it is the quality of the untreated water that should be considered. Through the tracking of source water quality and the relaying of that information to the public, the immediate impact of watershed management can be assessed at the community level.

In Chapter 3, a high correspondence between expert and index scores was illustrated thus confirming the effectiveness with which the CCME WQI can distil multi-parameter source quality. However, the index aggregation procedure does present concerns that must be understood by practitioners. As outlined, the root mean additive aggregation function employed by the CCME WQI is prone to eclipsing. Though rigidity is not a serious concern for the CCME WQI, like any index, scores are sensitive to the nature of the input variables. The number of parameters, number of samples and most importantly the identity of the selected parameters can all affect resulting scores (Canadian Council of Ministers of the Environment, 2006b). I provide a drinking water quality expert selected core set of parameters to capture common Canadian source water concerns and guide index application. The use of these parameters is not mandatory as evidenced in the incorporation of only 6 of the 8 core parameters in Chapter 3’s sensitivity analysis and Chapter 4’s index calculations. Different source water quality monitoring programs may not measure all of the suggested core parameters. Fortunately the CCME WQI is able to accommodate the fragmented nature of source water monitoring in Canada. Furthermore, I do recommend that supplementary parameters be included in the index calculation to account for source specific risk factors. The inclusion of such parameters may affect scores beyond the quality implications of the measured parameter values alone. In order to produce stable scores, others have made recommendations such as including 10 parameters each with 30 samples over a 3 year period (Environment Canada, 2003) or a minimum of 7 parameters each with 6 sample measures (Canadian Council of Ministers of the Environment, 2006b). Unfortunately there are no simple rules regarding the number of parameters or number of samples to include in the index calculation. Using the modified factor formulas to accommodate parameter unevenness (Table 3.3.4) introduces a new dimension to these recommendations. Further research is required to understand the sensitivity of the traditional and modified CCME WQI’s to parameter inputs.

In addition to the mathematical considerations of the CCME WQI, more fundamental limitations must also be made clear to index end users. Like any model, the CCME WQI results in a loss of information (Khan *et al*., 2004). More specifically, important source water concerns such as parameter absolute levels and variability are ignored. Also, scores provide no indication as to how external factors such as weather events may have influenced parameter measures and results during the study period (Environment Canada, 2003). In this way, the message that the CCME WQI conveys is limited in its scope and should not be over-interpreted. Instead, again I stress that the index provides a communication tool that should be used in combination with more detailed analyses of source water quality.

The application of the CCME WQI in conjunction with analyses of individual parameter trends in Chapter 4 revealed some of the weaknesses of index use. Namely, since the index is an aggregation of multiple parameters, the effect of landuse on composite quality is also an aggregation of the landuse signal from each of those individual parameters. Therefore the CCME WQI does not appear to provide insight into landuse-water quality relationships except at a very coarse resolution.

In contrast, analyses of the impact of landuse on separate water quality parameters revealed distinct spatial trends. Others have cautioned against the use of secondary water quality data to examine landuse-water quality relationships (Sliva and Williams, 2001). The inconsistent frequency of parameter measures among Chapter 4 sites is a concern however general trends are readily apparent. My results suggest that source water microbial risk is primarily due to local landuse activities in all seasons of the year. This is not surprising given that fecal indicator organisms do not typically reproduce in the environment (Meays *et al*., 2006) and die off or are trapped via sedimentation in natural waters (Eleria and Vogel, 2005). The observation that organic carbon was only significantly associated with landuse at the watershed scale implies that organic carbon inputs are important at broad scales, extending to the entire watershed. Turbidity on the other hand did not exhibit a clear discernable trend in its spatial relationship with landuse.

Chapter 4 analyses reduced long-term parameter measures (up to 10 years worth of data) to seasonal means. This aggregation helped to reduce the effect of inconsistent monitoring such that spatial variability could be related to watershed characteristics. However, the reduction techniques employed ignore a critical component of source water quality – temporal variability. Both short-term and long-term source water variability are important quality considerations as they can lead to failures in water treatment processes (Curriero *et al*., 2001). In fact, several water quality experts reported that variability was an important factor that they used to assign scores to the water quality scenarios in Chapter 3. The effect of watershed characteristics, particularly landuse and climate, on source water variability is an important area of research that requires attention. The incorporation of variability as a core parameter within the CCME WQI could be very informative of source quality conditions. A simple method of accounting for variability could be to calculate the standard error of the mean for each of the parameters used to compute the index score and use these standard errors as samples for a new core parameter. This variability parameter could then be treated in the same manner as all other source water parameters resulting in a total of 9 core parameters instead of 8. Clearly if such a variability term is included in the index, an appropriate variability metric and defensible guideline must be investigated.

Ultimately, the two products of this thesis could be very useful to water quality managers. My work verifies the adaptability of the CCME WQI to Canadian source waters as well as the effectiveness of resulting scores in capturing expert assessments of quality. The CCME WQI is a tested index formulation with acknowledged benefits as well as limitations. The core parameters and drafted source water quality target values provide clear guidance to practitioners but allow flexibility to tailor the index to site specific source water monitoring programs and treatment regimes. As with all indices, by testing with use and refinements through experience the CCME WQI as a source water assessment and communication tool can be further improved (Ott, 1978). Therefore my study serves only as a baseline for CCME WQI application to Canadian source waters. The scale dependency of landuse-source water quality relationships revealed by my work can also be used to help manage water quality. Specific parameters of concern can be mitigated through targeted landscape management though my results confirm that watershed scale processes must be addressed in a comprehensive source water protection plan. Source water protection is a cost effective means of helping to ensure healthy Canadian drinking water under the dual threats of population growth and a climate change. The validated index paired with the elucidated landuse relationships offer novel tools and knowledge to manage and communicate Canadian source water quality now and in the uncertain future.

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Appendix A
Source water parameter selection survey

Thank you for your participation in this project intended to produce a Canadian source drinking water quality index to assess the suitability of surface water for human consumption post chlorination. Though the survey is meant to be completed with minimal interaction between respondent and coordinator, should you have any questions that you feel must be answered in order to provide your responses please contact Tim Hurley via e-mail at **hurleytj@uvic.ca**. Be assured that your name will not be associated with your individual responses in any document related to this work. However, you will be listed as a participant in the survey group. If for any reason you have issue with this, feel no pressure to participate. Where answers are required simply click on the appropriate field, remove the existing text and insert your response. When complete, save the document and attach it in an e-mail to **hurleytj@uvic.ca**.

Assessment Scenario

Raw water was drawn from a Canadian surface source. Measurements were made for a suite of parameters in an attempt to assess the suitability of the source water for chlorination followed by some unknown form of distribution and subsequent human consumption.

Directions

On the following page you will find a list of 27 frequently monitored drinking source water parameters. Drawing on your experience in the Canadian context please produce a list of **10 parameters that you feel can be used to identify the most common risks (health risks, treatment interference, etc.) prior to next stages: chlorination and distribution.** Keep in mind that the raw water is to be exclusively drawn from a Canadian **surface source**. Though the parameter values in the assessment scenario are measurements of the untreated water, the list of 10 parameters should consider the resulting quality of the water for human consumption after chlorination and distribution. If you feel that a parameter not listed in the 27 provided should be included, you may list that parameter in the space provided though it will represent one of your 10 selected parameters. For each of the 10 selected parameters, please provide a **relative significance value** between 1 and 5 indicative of the importance of each of the 10 parameter measures in providing the required assessment. A value of 1 suggesting that the parameter is not very significant while a value of 5 suggesting that the parameter is very significant. Beside each parameter name please indicate whether or not the parameter should be included in the list of ten by writing include or don't include in the appropriate text box along with the relative significance value for the "include" parameters. Refer to the examples below for clarification. The final page is available for any comments you may have. Please do not hesitate to comment.

Parameter	Include / Don't include	Relative Significance Value
Example A	include	4
Example B	don't include	

Parameter Selection

Parameter	Include / Don't include	Relative Significance Value
boron		
cadmium		
chlorides		
chromium		
coliforms (fecal)		
coliforms (total)		
colour		
copper		
dissolved oxygen		
E. coli		
fluorides		
hardness		
iron		
lead		
mercury		
nitrate		
nitrite		
organic carbon (total)		
pesticides		
pH		
phosphorus (total)		
solids (dissolved)		
solids (suspended)		
sulfate		
temperature		
turbidity		
zinc		

Additional Parameters

Parameter	Include / Don't include	Relative Significance Value

Comments:

Appendix B
Expert evaluation of source water quality survey

Thank you for your participation in this project intended to produce a Canadian source drinking water quality index. Though the survey is designed to be completed with minimal interaction between respondent and coordinator, should you have any questions that you feel must be answered in order to provide your responses please contact Tim Hurley via e-mail at **hurleytj@uvic.ca**. Be assured that your name will not be associated with your individual responses in any document related to this work. However, you will be listed as a participant in the survey group (unless you have requested otherwise). Where answers are required simply click on the appropriate field, remove any existing text and insert your response. When complete, save the document and attach it in an e-mail to **hurleytj@uvic.ca**.

Instructions:

Attached you will find 20 water quality scenarios identified by a number between 1 and 20. Each scenario is presented in tabular form and is composed of six sample events for which corresponding parameter measures are listed. These parameter measures are based on water sampled from a surface water source and therefore represent water quality **prior to any form of treatment**.

For each water quality scenario (1-20) please provide rankings and scores corresponding to the scoring system outlined in table 1 (page 2). **Your ranks and scores should reflect your opinion regarding the quality of the water in each scenario as a drinking water source**. Ranks and scores must be based exclusively on the values given. Since source quality is dependent on the treatment applied, the rankings and scores are to be made considering two different treatment levels.

Treatment Level 1: The source water will receive chlorination as the only treatment.

Treatment Level 2: The source water will be filtered (slow sand filtration) and chlorinated only

Therefore, for each scenario (1-20) please provide a rank and a score reflective of the quality of the water as a drinking water source if chlorination is the only anticipated treatment and a second rank and score reflective of the quality of the water as a drinking water source if both filtration (slow sand) and chlorination are anticipated treatments. Along with each of the two rank and score sets please indicate the parameters whose values were most important in deciding on your responses. Refer to the examples on page 2 for clarification. Tables for your responses are provided below each water quality scenario beginning on page 3. The final page is reserved for comments and recommendations.

Table 1: Source Water Quality Scoring System

Rank	Score	Interpretation
Excellent	**95.0 - 100.0**	Water quality meets all criteria for use as a source of drinking water
Good	**80.0 - 94.9**	Water quality rarely or narrowly violates criteria for use as a source of drinking water
Fair	**65.0 - 79.9**	Water quality sometimes violates criteria, possibly by a wide margin, for use as a source of drinking water
Marginal	**45.0 - 64.9**	Water quality often violates criteria for use as a source of drinking water by a considerable margin
Poor	**0 - 44.9**	Water quality does not meet criteria for use as a source of drinking water

Examples:

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
#	Good	87	E.coli, TOC,	Excellent	97	E.coli

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
#	Poor	10	E.coli, iron, nitrate and nitrite	Poor	20	E.coli, iron, nitrate and nitrite

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
#	Marginal	50	All parameters	Marginal	50	All parameters

Water Quality Scenarios

Legend

Turb. – Turbidity
Temp. – Temperature
NO_3^- and NO_2^- as N – Nitrate and Nitrite as N
TOC – Total Organic Carbon

1.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	111	1	6.6	0.3	5.8	0.043	3.4	0.09
2	213	1	7	0.23	6.3	0.060	2	0.11
3	96	1	6.8	0.14	11.7	0.068	2.2	0.221
4	184	2	6.5	1.05	14.8	0.029	3.1	0.183
5	287	1	7.1	0.22	24.6	0.025	2.1	0.518
6	464	8	7.3	0.14	17.1	0.029	1.9	0.03

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
1						

2.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	1	0	6.98	0.30	1.0	0.0008	1.6	
2	127	0	6.71	0.74	6.7	0.0087	2.2	
3	88	5	7.73	0.30	12.8	0.0288	3.3	
4	292	13	7.60	0.53	13.3	0.1524		
5	871	4	6.83	0.12	7.0	0.0552	1.0	
6	20	0	6.53	2.00	4.3	0.0162	7.9	

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
2						

3.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	84	8	7.68	0.31	5.20	0.032	2.6	0.01
2	48	0	6.74	0.34	8.33	0.027	2.4	0.05
3	77	0	7.53	0.68	14.80	0.004	2.9	0.08
4	63	1	7.54	0.3	14.96	0.005	2.9	0.04
5	61	1	7.33	0.41	13.82	0.004	2.8	0.02
6	52	0	7.15	0.3	5.49	0.027	2.2	0.09

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
3						

4.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	30	3	6.8	1.1	13.64	0.35	3	0.046
2	2	2	6.8	0.6	11.46	0.33	4.	0.009
3	43	3	7.1	0.7	8.24	0.24	3	0.037
4	180	8	7.1	0.4	10.18	0.21	2.7	0.047
5	84	4	7.1	0.4	17.52	0.15	2.9	0.055
6	280	12	7.2	0.3	13.33	0.12	4.3	0.039

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
4						

5.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	8014	3	8.95	154	18	1.38	41.74	0.08
2	7974	2	9.09	213	19	1.78	55.39	0.12
3	6812	4	8.94	126	20	1.96	77.95	0.06
4	3622	4	8.79	342	20	1.04	26.67	0.14
5	8117	4	9.24	165	23	1.85	54.57	0.13
6	7814	3	9.23	138	19	0.98	75.65	0.24

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
5						

6.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	3299	96	6.75	4.6	13.24	0.140	2.6	0.09
2	1760	85	7.23	3.2	16.42	0.110	2.4	0.12
3	567	44	7.48	3.9	12.67	0.060	3.0	0.15
4	1321	69	7.3	4.7	10.92	0.080	3.2	0.14
5	2174	83	6.5	1.1	8.23	0.220	3	0.08
6	2866	92	7.24	2.2	6.74	0.130	2.5	0.1

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
6						

7.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	9	1	7.3	0.5	11	0.002	2.4	0.12
2	15	1	7.4	0.5	12	0.002	2.2	0.09
3	69	1	7.4	0.4	13	0.002	1.9	0.07
4	32	2	6.9	1.4	13	0.004	3.1	0.1
5	88	2	6.8	0.7	14	0.016	1.9	0.08
6	78	2	7.2	0.6	9	0.010	1.5	0.11

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
7						

8.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1		1	7.3	0.4		0.003	5.7	0.15
2		6	7	0.5		0.011	4.3	0.22
3		300	6.1	2.8		0.006	20.2	0.133
4		2	6.9	0.3		0.004	6	0.138
5		3	6.7	0.7		0.016	8	0.185
6		2	6.9	1.6		0.009	6.9	0.212

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
8						

9.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	24	0	7.68	0.6	5.20	0.032	3.1	0.08
2	15	0	6.44	0.3	8.33	0.027	3.9	0.05
3	10	0	7.53	0.7	14.80	0.004	3.6	0.07
4	626	23	7.54	3.2	15.85	0.005	5.7	0.06
5	322	17	7.33	3.1	13.82	0.004	4.2	0.08
6	31	0	7.15	0.6	5.49	0.027	2.1	0.08

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
9						

10.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	14	1	6.8	0.5	8	0.129	3	0.21
2	22	2	6.6	0.8	12	0.098	3.1	0.13
3	45	2	6.5	0.3	14	0.113	3.6	0.11
4	37	7	6.7	0.2	14	0.092	3.8	0.14
5	103	13	6.4	2.4	18	0.094	4.2	0.36
6	24	6	6.8	0.6	13	0.099	2.8	0.11

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
10						

11.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1			7.9	6.2	2.2	0.172	8.5	2.26
2		50	7.6	36.9	14	0.110	7.7	0.48
3		22	7.7	18.2	16	0.060	10.2	1.43
4		40	7.9	22.3	19	0.040	11	1.04
5		18	7.85	13.3	12	0.060	10.2	0.87
6		160	6.65	9.8	4.3	0.210	6.8	

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
11						

12.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	15	2	7.4	0.5	6.7	0.02	2.3	0.02
2	24	1	7.5	0.4	8.7	0.02	2.6	0.02
3	153	15	7.5	0.3	9.2	0.02	3.4	0.02
4	16	1	7.1	0.2	11.1	0.02	3.1	0.01
5	8	2	6.7	0.3	12.3	0.02	3.3	0.01
6	3	2	6.7	0.3	9	0.02	2.8	0.06

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
12						

13.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (°C)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	28	1	7.80	0.30	2.8		2.0	0.01
2	97	3	7.75	0.50	7		2.5	0.02
3	48	5	7.75	0.70	9.2		2.3	0.02
4	45	1	7.20	0.50	16		2.1	0.02
5	224	30	6.93	0.43	12		2.9	0.01
6	51	1	7.50	0.30	5.1		2.2	0.02

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
13						

14.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (°C)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	2632	170	7.97	18	13.5	0.044	7.1	0.402
2	433	25	8.04	4.05	14.5	0.053	4.2	0.266
3	674	35	7.90	1.11	12.65	0.048	2.2	0.324
4	3864	130	8.07	2.44	8	0.025	3	0.189
5	324	14	8.02	0.36	2.8	0.034	3.4	0.24
6	454	18	7.73	0.18	0.25	0.028	2.2	0.458

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
14						

15.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1		96	6.75	4.6	13.24	0.140	2.6	0.09
2		85	7.23	3.2	16.42	0.110	2.4	0.12
3		44	7.48	3.9	12.67	0.060	3.0	0.15
4		69	7.3	4.7	10.92	0.080	3.2	0.14
5		83	6.5	1.1	8.23	0.220	3	0.08
6		92	7.24	2.2	6.74	0.130	2.5	0.1

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
15						

16.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	24	0	7.68	0.31	5.20	0.032	2.6	
2	15	0	6.44	0.34	8.33	0.027	2.4	
3	10	0	7.53	0.68	14.80	0.004	2.9	
4	626	1	7.54	0.3	21.85	0.005	2.9	
5	322	9	7.33	0.41	13.82	0.004	2.8	
6	31	0	7.15	0.3	5.49	0.027	2.2	

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
16						

17.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	225	22	6.75	0.38	13.24	0.005	2.6	0.08
2	213	12	7.23	0.35	14.42	0.006	2.4	0.1
3	195	6	7.48	0.46	12.94	0.004	3.0	0.03
4	433	76	7.3	0.38	10.62	0.003	3.2	0.05
5	342	9	6.8	0.38	9.83	0.003	3	0.09
6	695	49	7.24	0.61	11.14	0.006	2.5	0.09

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
17						

18.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1		10	8.2	119	4.5	0.074	2.1	0.448
2		23	7.9	65.6		0.038	1.1	0.605
3		3	8.1	4.1	12	0.027	3.4	0.261
4		2	7.7	2	10.5	0.024		0.251
5		1	8.1	3.5	4	0.045		0.327
6		2	8.1	3.1	1	0.070	7.2	0.527

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
18						

19.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^{o}C)	NO$_3^-$ and NO$_2^-$ as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1		1	7.65	0.1	1.5	0.206	2.7	0.0798
2		2	7.95	0.1	1.1	0.127	1.8	0.201
3		3	7.3	6.3	1.9	0.145	2	0.0701
4		1	8.05	0.1	2.7	0.121	2.3	0.0706
5		4	8.4	1.2	10	0.097	2.6	0.0896
6		1	7.95	3.7	1	0.129	2.1	0.119

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
19						

20.

Sample	Total coliforms (CFU/100mL)	E.coli (CFU/ 100 mL)	pH	Turb. (NTU)	Temp. (^oC)	NO_3^- and NO_2^- as N (mg/L)	TOC (mg/L)	Total Iron (mg/L)
1	836	0	6.3	0.6	18.2	0.050	2.3	0.09
2	1200	1	6.4	0.5	17.3	0.070	2.5	0.12
3	784	1	6.5	0.7	22.1	0.050	3.1	0.15
4	633	2	6.8	0.4	23.4	0.090	2.6	0.23
5	698	0	7.2	0.9	20.6	0.040	2.8	0.16
6	576	1	6.8	0.7	19.3	0.080	3.2	0.19

Water Quality Scenario	Treatment Level 1: Chlorination			Treatment Level 2: Filtration and chlorination		
	Rank	Score	Parameters most important in deciding on rank and score	Rank	Score	Parameters most important in deciding on rank and score
20						

Comments/Recommendations:

Appendix C
Composition of drinking source water quality expert panel

Panellists that completed both surveys

Rick Nordin
Senior Research Scientist - Water and Aquatic Sciences Research Program and Assistant Adjunct Professor Department of Biology University of Victoria
Sector: Government/Academia
Field: Biology

Kevin Rieberger
Water Quality Science Specialist
Science & Information Branch
Water Stewardship Division
BC Ministry of Environment
Sector: Government
Field: Biology

Benoit Barbeau
Associate Professor Department of Civil, Geological and Mining Engineering
Ecole Polytechnique, Montreal
Sector: Academia
Field: Engineering and technology

Jamieson Dixon
Leader, Watershed Protection
Water Quality and Compliance Monitoring
City of Calgary Water Resources
Sector: Service provider
Field: Biology

Dan Conrad
Assistant Superintendent/Plant Chemist
Buffalo Pound Water Administration Board
City of Regina
Sector: Service Provider
Field: Biology

Michael Lukich
Manager, Toronto Water Laboratory
City of Toronto
Sector: Service provider
Field: Chemistry

Ian Douglas
Water Quality Engineer
Erin Gorman
Water Quality Technologist
City of Ottawa - Drinking Water Services
Sector: Service provider
Field: Engineering and technology

Blake McDonald
Facilities Engineer
Water and Wastewater Branch
Nova Scotia Environment
Sector: Government
Field: Water quality management and operations

Syed Imran
Research Officer, Centre for Sustainable Infrastructure Research
NRC Institute for Research in Construction
Sector: Government
Field: Engineering and technology

Manuel Rodriguez
Professor, School of Planning and Regional Development
Université Laval
Sector: Academia
Field: Water quality management and operations

Ian Wright
VP Water
Associated Engineering
Sector: Industry
Field: Engineering and technology

Panellists that only completed the Source water parameter selection survey

Bill Sims
Manager, Water Resources
City of Nanaimo
Sector: Service provider
Field: Water quality management and operations

Hassen Khan
Director
Annette Tobin
Water Resources Engineer
Water Resource Management Division
Department of Environment and Conservation
Government of Newfoundland and Labrador
Sector: Government
Field: Engineering and technology

Drew Gibson
Superintendent/Water Quality Control,
City of Vancouver
Sector: Service provider
Field: Water quality management and operations

Stephen Craik
Senior Manager, Water Laboratory
EPCOR Water Services
Sector: Service provider
Field: Engineering and technology

Raymond Rockwell
Water Quality Technician
Environmental Standards
City of Winnipeg
Sector: Service provider
Field: Engineering and technology

Reid Campbell
Director of Water Services
Halifax Regional Municipality
Sector: Service provider
Field: Engineering and technology

Carrie Rickwood
UNEP GEMS/Water Programme
Sector: Academia
Field: Biology

Sam Ferris
Executive Director
Municipal Branch
Saskatchewan Ministry of Environment
Sector: Government
Field: Water quality management and operations

Laura D’Costa
Engineer
Water, Air and Climate Change Bureau
Health Canada
Sector: Government
Field: Engineering and technology

Irfan Gehlen
Sector Leader
Water & Wastewater Treatment
Kerr Wood Leidal Associates Ltd.
Sector: Industry
Field: Engineering and technology

Francois Proulx
Directeur
Division de la qualité de l'eau
Service de l'environnement
Ville de Québec
Sector: Service provider
Field: Water quality management and operations

Geno Lehman
MWH Global
Sector: Industry
Field: Engineering and technology

Appendix D
Core parameter drinking source water target values: Supporting literature

1) pH

pH, a measure of the acidity of a solution, is an important operational parameter for drinking water utilities. Both treatment and distribution processes are pH dependent. Chlorine based disinfection efficiency is highest at pH values below 8. However, low pH water promotes corrosion in the distribution system which can result in contamination and taste and odour issues (WHO, 2008). The optimal pH of a particular water system depends on the nature of the source water and the construction materials used in the distribution system. The Guideline for Canadian Drinking Water Quality value of 6.5 to 8.5 is suggested to reduce corrosion and precipitation in the distribution system while ensuring efficient, low disinfection byproduct chlorination (Health Canada, 2008).

pH Target Value for Raw Water Receiving Receiving Chlorination Only or Slow Sand Filtration and Chlorination

pH should not fall outside the range of 6.5-8.5

2) Turbidity

Turbidity provides a measure of water clarity and carries with it health based and aesthetic implications. Caused by particulate matter suspended in water, high turbidity reduces disinfection efficiency by increasing disinfectant demand and decay rates (Province of Manitoba, 2005). High turbidity can also shield pathogens from disinfection and stimulate bacterial growth (WHO, 2008). Generally, turbidity measures less than 5 NTU are aesthetically acceptable. Health Canada recommends a treated water turbidity health based target of 0.1 NTU to ensure effective disinfection. When the 0.1 NTU target cannot be met, slow sand or diatomaceous earth filters must produce water with turbidity less than 1.0 NTU in 95% of samples or at least 95% of the time in each calendar month - at no time should filtered water have a turbidity greater than 3.0 NTU (Health Canada, 2008). Similarly, the Province of Manitoba (2005) recommends that turbidity prior to chlorination be less than 1 NTU seeing as the influence of turbidity on disinfection is minimal at such low levels. British Columbia, like other jurisdictions, recommends guidelines for raw drinking water not receiving any treatment to remove particulates based upon background turbidity levels. The rationale employed in such guidelines being that changes from background turbidity levels can overburden the existing treatment infrastructure. It is recommended that no drinking water source experience a change in turbidity of 5 NTU at any time and that when the background turbidity level is less that 5 NTU, a change of no greater than 1 NTU be acceptable (BC MOE, 2010). Considering the existing literature, a target value of 1.0 NTU will be adopted for source waters receiving chlorine disinfection as the only means of treatment. A 5.0 NTU target value for source waters filtered and chlorinated will be adopted.

Turbidity Target Value for Raw Water Receiving Chlorination Only

Turbidity should not exceed 1.0 NTU

Turbidity Target Value for Raw Water Receiving Slow Sand Filtration and Chlorination

Turbidity should not exceed 5.0 NTU

Comparison of expert assessments of surface source water quality to index scores necessitated a reduction in the acceptable turbidity level for raw water receiving chlorination only (See 3.3.2). The reduce turbidity target corresponds to the USEPA guideline for 95% of treated water samples in any given month (USEPA, 2009)

Amended Turbidity Target Value for Raw Water Receiving Chlorination Only

Turbidity should not exceed 0.3 NTU

3) Total Organic Carbon (TOC)

Total organic carbon in aquatic environments provides a measure of the organic matter suspended in solution. High TOC may be indicative of anthropogenic pollution sources however the primary concern surrounding the level of organics in source drinking water is in regards to the formation of harmful disinfection byproducts (DBPs) upon chlorination. Organic compounds have been shown to react with chlorine to produce haloacetic acids (HAAs) and trihalomethanes (THMs), both of which have been linked to cancer and birth defects (White, 1999). According to the USEPA, a high TOC concentration is indicative of a high potential for disinfection byproduct formation (USEPA, 1999). If no means of DBP precursor removal is employed, organic matter must be limited in the source waters. The BC MOE recommends that raw drinking waters receiving chlorination not contain TOC at a concentration greater than 4 mg/L (BC MOE, 2010). The USEPA Stage 1 Disinfectants and Disinfection Byproducts Rule requires water utilities to remove a alkalinity dependent percentage of TOC for all surface waters containing greater than 2.0 mg/L TOC (USEPA, 1998). A target value of 2 mg/L is anticipated to be too stringent for use in the CCME WQI necessitating the adoption of the more lenient 4mg/L value as the target for source water TOC.

Total Organic Carbon Target Value for Raw Water Receiving Chlorination Only or Slow Sand Filtration and Chlorination

Total Organic Carbon should not exceed 4 mg/L

4) *E. coli*

Escherichia coli is a member of the thermotolerant (fecal) coliforms. It is considered the most suitable index of fecal contamination and provides evidence of recent fecal inputs (WHO, 2008). *E. coli* is much more susceptible to chlorine disinfection than enteric viruses or protozoa and therefore should not be present in post-treatment water (Health Canada, 2008). Literature guideline levels in drinking source water receiving minimal treatment (chlorination only) consistently range from 10-20 organisms/100mL (Warrington, 1998). A guideline of 10 organisms/100mL assumes an approximate 4 log removal of *E. coli* via chlorination to produce water in microbial compliance with the

Guidelines for Canadian Drinking Water Quality (Health Canada, 2008). Sufficient chlorination to achieve 3 log Giardia inactivation and an acceptable residual should achieve such removal assuming a properly functioning system. Therefore, from a treatment perspective a guide limit of 10 organism/100mL is very conservative

E. coli Target Value for Surface Source Water Receiving Chlorination Only

E. coli should not exceed 10 CFU/100mL

The British Columbia Ministry of the Environment recommends that *E. coli* not exceed 100 CFU/100mL in raw drinking water receiving partial treatment consisting of filtration or sedimentation, and disinfection. A guideline of 100 CFU/100mL assumes approximately 5 log removal, again a conservative estimate. This value is corresponds with many other literature guideline values (Warrington, 1998).

E. coli Target Value for Surface Source Water Receiving Slow Sand Filtration and Chlorination

E. coli should not exceed 100 CFU/100mL

5) Nitrate and Nitrite (as N)

Nitrate and nitrite are two of the major forms of nitrogen found in natural waters. Water quality guidelines frequently consider the concentrations of the 2 inorganic ions as a single unit in order to accommodate interconversion between the two forms (WHO, 2008). Considered alone, nitrite can increase chlorine demand as chlorine is consumed during the oxidation of nitrite to nitrate. If consumed, nitrite is generally converted to nitrate in the blood however residual nitrite can bind with haemoglobin to form methaemoglobin. Methaemoglobin binds oxygen and does not release thereby blocking oxygen transport and giving rise to methaemoglobinaemia. High levels of nitrate may be reduced to nitrite leading to methaemoglobinaemia. Infants are particularly susceptible to high levels of nitrate and nitrite in drinking water (WHO,2008). Published drinking water guidelines for nitrate as N consistently suggest that 10 mg/L is an acceptable level (Health Canada, 2008; WHO, 2008; USEPA, 2009). Similarly, little debate exists in regards to the consensus 1 mg/L nitrite (as N) guide limit (Health Canada, 2008; WHO, 2008; USEPA, 2009). Considered together, the WHO recommends that the sum of the ratios of nitrate and nitrite concentrations to their guideline values not exceed 1 (WHO, 2008). The Province of British Columbia sets a drinking water guideline of 10 mg/L nitrate + nitrite as N (BC MOE, 2010) which will be adopted for use in the CCME WQI.

Nitrate + Nitrite (as N) Target Value for Raw Water Receiving Chlorination Only or Slow Sand Filtration and Chlorination

Nitrate + Nitrite (as N) should not exceed 10 mg/L

6) Total coliforms

Total coliform bacteria include a variety of gram negative, non-spore forming bacilli able to grow in high concentrations of bile salts and identified based on their ability to ferment lactose within 24 hours at temperatures of 35-37°C (WHO, 2008). *E. coli* and thermotolerant (fecal coliforms) are included in this designation however total coliforms are not an indicator of fecal contamination. Measured total coliform concentrations include environmental bacteria able to survive and grow in natural waters. Therefore, total coliform measures do not indicate health risk. Instead high coliform levels can reduce treatment efficacy and contribute to aesthetic concerns. Coliform bacteria should be absent in treated drinking waters (Health Canada, 2008). Published source water quality guidelines for waters receiving basic treatment have been outlined by Warrington (1998)

For source waters receiving disinfection as the only means of treatment, a consensus recommended total coliform concentration is approximately 100 CFU/100mL. Increased treatment regimes tend to be accompanied by higher guideline values.. For use in conjunction with the CCME WQI to assess source water quality conditions, the consensus value of 100 CFU/100mL will be adopted as a conservative total coliform target concentration for source waters receiving chlorination alone or filtration and chlorination.

Total coliform Target Value for Surface Source Water Receiving Chlorination Only or Slow Sand Filtration and Chlorination

Total coliforms should not exceed 100 CFU/100mL

7) Iron

Iron is primarily an aesthetic parameter when considered in regards to drinking water quality. Though iron increases chlorine demand, recommended guidelines throughout the literature address the aesthetic concerns associated with high levels of the metal (WHO, 2008). Several quality agencies recommend that iron not exceed 0.3 mg/L in drinking water as concentrations less than 0.3 mg/L are not detectable by taste (Health Canada, 2008; USEPA, 2009). Therefore 0.3 mg/L iron will be adopted as a target value for use in the CCME WQI.

Iron Target Value for Raw Water Receiving Chlorination Only or Slow Sand Filtration and Chlorination

Iron should not exceed 0.3 mg/L

8) Temperature

Temperature is primarily an aesthetic parameter in regards to source water quality. Cooler water is more acceptable to consumers than is warm water. Despite the fact that chlorination is more effective at higher temperatures, warm waters can promote the growth of microorganisms and may increase taste, odour and colour (WHO,2008). Temperature guideline values for drinking water generally range from 12-15°C with some water quality standards allowing a maximum temperature of 28.3°C depending on the geographic location (British Columbia Ministry of Environment Land and Parks, 2001). The Guidelines for Canadian Drinking Water Quality set an aesthetic objective of less than or equal to 15°C (Health Canada, 2008) and will be accepted as a reasonable target value for raw water receiving either treatment.

Temperature Target Value for Raw Water Receiving Chlorination Only or Slow Sand Filtration and Chlorination

Temperature should not exceed 15°C

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