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Development of Source and Treated Water Quality Indicators For Drinking Water in Canada
From Conceptual Design to Methodological Development

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Development of Source and Treated Water Quality Indicators For Drinking Water in Canada

From Conceptual Design to Methodological Development

by

Laura D'Costa

A thesis submitted to the School of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of M.Sc. in Earth Sciences

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Canada

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ACRONYMS

ABC	Association of Boards of Certification
ANC	Australian and New Zealand
ARMC	Agriculture and Resource Management Council (ANC)
CCME	Canadian Council of Ministers of the Environment
CCME WQI	Canadian Council of Ministers of the Environment Water Quality Index
CDW	Committee on Drinking Water (Canada)
CESI	Canadian Environmental Sustainability Indicators
CWA	Clean Water Act (USEPA)
DISAE	Database of International Statistical Activities Europe
DWP	drinking water plant
ECa	Environment Canada
EC	European Council
ECC	Environment and Conservation Council (ANC)
EEC	European Economic Community
E.coli	*Escherichia coli*
ESR	Environmental Science and Research Ltd. (New Zealand)
FPT	federal/provincial-territorial
GCDWQ	Guidelines for Canadian Drinking Water Quality
GUDI	groundwater under the direct influence of surface water
GW	groundwater
HC	Health Canada
IWI	Index of Watershed Indicators (the United States)
MBA	multi-barrier approach (Canada)
M.Sc.	Masters in Earth Sciences
NL WRMD	Newfoundland and Labrador Water Resource Management Division
NRTEE	National Round Table on the Environment and Economy (Canada)
NSF WQI	National Sanitation Foundation Water Quality Index
NZMOE	New Zealand Ministry of the Environment
O&M	operation and maintenance
OWQI	Oregon Water Quality Index
SC	Statistics Canada
SDD WQI	Scottish Development Department Water Quality Index
SW	surface water
SWQI	Source Water Quality Indicator
TMDL	Total Maximum Daily Load (the United States)
TWQI	Treated Water Quality Indicator
UK	the United Kingdom
USEPA	United States Environmental Protection Agency
WACCB	Water, Air and Climate Change Bureau of Health Canada
WHO	World Health Organization
WISE	Water Information System for Europe

ABSTRACT

In September 2005, Health Canada took on the development of a Source Water Quality Indicator for Canada. The main objective was to develop a methodology by which source water quality could be linked to public health, the environment, society, and economy; and measured, tracked, and reported in the form of an indicator for decision making. A Treated Water Quality Indicator was also introduced to bridge the gap between source water quality and human health. With Federal/Provincial/Territorial and academic support, research into the approach and development of a conceptual design, parameter selection rationale, and two tools for the indicator calculations, along with recommendations for future work were completed.

The tools developed included a modified Canadian Council of Ministers of the Environment water quality index calculator, and a Treatability Ranking tool (that determined the complexity of treatment required to achieve safe drinking water). The results of this project are described herein.

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1 INTRODUCTION

This thesis outlines the development of a source and treated water quality indicator for Canada.

1.1 Setting the Stage

Canada's National Round Table on the Environment and Economy (NRTEE) reported in 2003 on the need to be able to account for assets necessary to sustain the economy, and the health of the environment and society for Canadians. The ability to measure, track and report on these types of capital, in the form of indicators, and to apply these measurements to decision making was considered essential to the development of a sustainable Canadian society. The types of capital were divided into two groups: human, and natural. Under the heading of natural capital five divisions were made: air quality, freshwater quality, greenhouse gas emissions, forest cover, and extent of wetlands. Further, under the freshwater quality heading, five indicators were identified: source water quality, aquatic life, recreation, agriculture and industry. (NRTEE, 2003)

In response to the NRTEE 2003 report, development of the natural capital indicators for air quality, freshwater quality and greenhouse gas emissions became a shared federal mandate between Environment Canada (ECa), Statistics Canada (SC) and Health Canada (HC). The project under this shared mandate was entitled 'Canadian Environmental Sustainability Indicators' (CESI) (see footnote[1] for CESI project report information).

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[1] For more information on the CESI project both a CESI Highlights and Feature report for the years 2005, 2006, and 2007 which report on ground-level ozone, greenhouse gas emissions, and freshwater quality for

HC plays a fundamental role in drinking water quality in Canada. The Water, Air and Climate Change Bureau of HC (WACCB) serves as secretariat to the Federal/Provincial/Territorial (FPT) Committee on Drinking Water (CDW). In this role, the WACCB provides scientific and technical expertise, and coordinates activities with the provinces and territories to develop the Guidelines for Canadian Drinking Water Quality (GCDWQ). The GCDWQ are utilized to evaluate treated water quality, and form the basis for most of the regulated drinking water quality standards in Canadian jurisdictions.

Based on HC's key leadership role in drinking water quality in Canada, HC was given the role of developing the source water quality indicator (SWQI) under the CESI project, and hired me to undertake this task. A treated water quality indicator (TWQI) was later introduced in order to bridge the gap between source water quality and human health. An overview of the NRTEE proposed indicators and federal responsibilities is illustrated in an organizational chart as Figure 1.

1.2 Project Role and Masters in Earth Sciences Contribution

With a background in Environmental Engineering and professional experience in engineering, hydrogeology and occupational health and safety, I was hired by HC as Project Lead. I also recognized this as an excellent opportunity to concurrently carry out a Masters in Earth Sciences (M.Sc.). Although my role did include several administrative

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aquatic life, can be found at the following web link: http://www.environmentandresources.ca/indicators/ (under the sub heading reports and documents) components, most importantly it comprised all the facets of the Masters in Earth Sciences (M.Sc.) requirements including the following contributions:

- I created a research plan and conducted research through review of the literature to further my knowledge in new areas to facilitate the project outcome outlined herein;
- I established the scientific objectives for the project in order to fulfill the given project mandate. To do this I gave specific consideration to the context in which it was important to measure, track and report on source and treated water quality; determined how links could be established between water quality and health, the environment, society and economy; and evaluated how this information needed to be used in decision making within an overall water management strategy;
- I developed the conceptual approach, methodology, and project process for the SWQI and TWQI. Determining what form of indicator could be used, what specific considerations regarding source and treated water quality needed to be incorporated, indicator limitations, and how these limitations could be addressed. I identified, how the indicators could be calculated, what were the required project components, and how these could be developed;
- In response to the above, I then developed technical guidance for a parameter selection rationale, to guide inputs into the indicator calculations;
- I oversaw the adaptation and development of tools to enable the implementation of the derived source and treated water quality indicator methodologies, and developed the associated technical guidance for their use. One of these tools, a customized Canadian Council of Ministers of the Environment Water Quality

Index (CCME WQI) calculator, was modified based on this research by the Government of Newfoundland and Labrador Water Resource Management Division (NL WRMD) with my input and direction; the second tool, the Treatability Ranking tool, was developed entirely by myself as part of this research, including the development of the business logic, and the direction of its development by a qualified programmer;

- I determined practical and beneficial applications for the SWQI and TWQI and illustrated these herein to guide the application of the indicators to decision making; and
- Finally I identified recommendations for further work in acknowledgement of the known limitations of the thesis results, and in an effort to advance the science of the SWQI and TWQI approach over time.

These tasks were carried out as part of this M.Sc. project, in consultation with, and with the help of, a number of individuals (as outlined in the Acknowledgements), including my supervisor at the University of Ottawa.

1.3 About This Thesis

This thesis is organized in the following manner:

Section 1 provides an introduction to the project mandate, the role of HC, and my project role with a focus on the elements that will be outlined in this thesis, a thesis breakdown by section for content navigation, and finally a thesis disclaimer.

Two literature reviews were undertaken to gain required knowledge in new thesis related areas, in order to advance this work. For the first, a literature review was conducted of international approaches to measuring, tracking and reporting on source water quality with an emphasis on researching any development of source water quality guidelines and or indices. Often when developing new tools in water quality management an overview of international approaches is undertaken to gain insight and possible direction. This literature review is described in Section 2.

For the second recommendation a more focused literature review was conducted of water quality indices developed and or applied. This second literature review is described in Section 3.

The results of these literature reviews provided useful insight and facilitated the development of the scientific objectives, methodology and project process by which the SWQI and TWQI were then developed. This is outlined in Section 4.

Section 4 identified the need to develop a parameter selection rationale, modified CCME WQI calculator tool and Treatability Ranking tool. Section 5 provides an overview and technical guidance regarding these three main project components.

Section 6 then outlines how the SWQI and TWQI can be applied on a site specific, watershed/aquifer and national scale for decision making. Finally Section 7 provides a general project summary, an outline to this works contribution to science, and recommendations for future work.

1.4 Disclaimer

The content of this thesis represents my point of view, and not the point of view of HC. HC assumes no responsibility for its content. An official report that will include elements of this work will be prepared by HC under separate cover.

This thesis has been written as an educational exercise in pursuit of a M.Sc. in Earth Sciences and should not be construed as professional advice.

2 INTERNATIONAL APPROACHES TO SOURCE WATER QUALITY

The following outlines the results of a review of international approaches to measuring, tracking and reporting on source water quality. The emphasis of the literature review was to search for any examples of source water quality guidelines and or indices developed and applied internationally as broad national policy or as a legislated requirement. Any international approach that was successfully applied would help support the credibility and feasibility of a similar approach for Canada, and potentially provide useful insight into development of the SWQI. The literature review focused on first world nations and included: New Zealand, Europe, the United States, and Australia. This section also includes some text clarifying an original recommendation that source water quality guidelines be developed in Canada, and a discussion on the feasibility/ appropriateness of adopting this and/or the other approaches. The next chapter also provides a literature review, but it focuses on the techniques themselves and the mathematical formulations.

It should be duly noted that many of Canada's provinces and territories have also developed guidance and/or legislation pertaining to source water protection. One of the most advanced examples is the Clean Water Act enacted in the province of Ontario. Canadian provincial and territorial representatives participated in the development of the SWQI and TWQI and helped guide the research direction. Although these Canadian examples provide useful insight at the provincial scale, it is known that no source water quality guidelines exist in Canada, and no source water quality indices are currently applied. For these reasons, Provincial and Territorial summaries were not included herein.

2.1 New Zealand

The following summary of work undertaken in New Zealand will describe their proposed monitoring, grading and reporting approach to source water quality, and then the actual direction they took.

In June of 2004 the New Zealand Ministry for the Environment (NZMOE) wrote a background paper proposing national environmental standards for source water (NZMOE, 2004). Similar to HC's main objective in developing a SWQI, New Zealand wanted to derive these standards to contribute to a multi-barrier approach to safe drinking water from source to tap (NZMOE, 2004). These standards proposed a grading, monitoring, and reporting framework to promote better water management; to facilitate cooperation amongst various stakeholders; and to provide information for decision making on source selection, treatment requirements (and associated costs), and appropriate activities in catchment areas (NZMOE, 2004).

Three levels of grading were proposed: one for each contaminant, one for each contaminant class, and an overall grade as follows:

- Step 1: a contaminant grade was assigned to each potential contaminant based on two considerations: a qualitative risk assessment of its potential impact to the suitability of a source as a drinking water supply, and its measured concentration in the source (NZMOE, 2004);

- Step 2: a grade was assigned to each of five contaminant classes: chemical contaminants (aesthetic), particles, chemical contaminants (health significant), microbes, and toxins; the grade assigned to each class was the worst scoring contaminant grade (as calculated in step 1) out of all the contaminants belonging to that class (NZMOE, 2004); and
- Step 3: an overall grade was assigned to the source water that represented the worst scoring contaminant class amongst the three health related classes: chemicals (health-significant), microbes, and toxins (NZMOE, 2004).

Grades were to be colour coded, and assigned a level of suitability and specific interpretation as outlined in Table 2.1. Although the overall grade assigned would not consider any non-health related parameters, an additional subscript to the colour grade was recommended indicating which classes (out of the five) required treatment to meet drinking water standards (Environmental Science and Research Ltd. (ESR), 2004).

For the monitoring component of the program, the NZMOE (2004a) proposed a core set of parameters be monitored including: chloride, calcium, magnesium, sodium, sulphate, iron, manganese, nitrate, arsenic, barium, fluoride, turbidity, A_{254} (ultraviolet light absorbance at the 254 nm wavelength) and *Escherichia coli (E.coli).* They also outlined minimum sampling requirements for microbiological contaminants (NZMOE, 2004) and recommended that cyanobacterial cell counts be collected when surface scum or algal growths were identified (ESR, 2004). This core set was based on selecting the most commonly occurring aesthetic contaminants of concern and naturally occurring health based contaminants that are difficult to identify in a catchment risk assessment (ESR, 2004). ESR also recommended that a source specific suite of contaminants, identified as moderate or high risk, be included (ESR, 2004).

In September of 2005 New Zealand proposed National Environmental Standards for source water quality that did not follow the approach outlined in the 2004 background paper as described above (NZMOE, 2005a). The 2005 standards were changed to a more qualitative approach promoting best management practices (NZMOE, 2005b). This change was based on feedback received from stakeholders and the community during public consultation (NZMOE, 2005b). The new standard did not propose any source water quality guidelines or use of a water quality index.

2.2 Europe

As outlined by the European Council (EC) and Database of International Statistical Activities Europe (DISAE) (2001), in the 1970's a set of legislative Directives were introduced relating to water quality standards and emission limit values. A second set of legislation was later introduced to address necessary improvements and gaps (EC & DISAE, 2001). The European Council (EC) currently has a comprehensive regulatory regime for water protection under the umbrella of the Water Framework Directive (2000/60/EC). Under the Water Framework Directive much of the older legislation is scheduled to be amended, replaced or repealed (EC & DISAE, 2001).

As further outlined by EC & DISAE (2001), the objectives of the Water Framework Directive include: integrated community policy for long term water use sustainability; expansion of the scope of water protection to include coastal waters and groundwater; maintaining or achieving good water quality; a watershed (river basin) approach to water management that continues to include emission limit values and water quality standards (as well as coordination provision for international river basin districts); charging for water use by taking into account cost recovery and application of the polluter pays principle; more public involvement; and integration/streamlining of legislation related to water quality management including other sectors.

Of interest in the Water Framework Directive is the approach to groundwater. Building on a premise that groundwater should not be polluted at all they are recommending that chemical standards not be set for groundwater (WISE, 2007). The concern with setting standards is the impression of allowable pollution versus the requirement to protect the source water (WISE, 2007).

Regarding source water quality guidelines, Europe had the only identified example entitled the Drinking Water Abstraction Directive (75/440/EEC as amended by Directives 79/869/EEC and 91/692/EEC). This legislation set guide (non-binding) and imperative (binding) water quality values, as well as monitoring requirements for surface water sources used to supply drinking water (EC & DISAE, 2001). Surface waters were first divided into one of three categories (A1, A2 and A3) based on the treatment in place. Based on these categories applicable water quality standards were determined, an action plan designed to ensure continual water quality improvements, and a monitoring program developed to verify compliance (EC & DISAE, 2001).

The following category descriptions have been copied herein from pg. 6 of Directive 75/440/EEC as amended (Office for Official Publications of the European Communities, 1975 as amended). These categories applied to source waters that were to be treated by the following:

- Category A1: "simple physical treatment and disinfection, e.g. rapid filtration and disinfection";
- Category A2: "normal physical treatment, chemical treatment and disinfection, e.g. pre-chlorination, coagulation, flocculation, decantation, filtration, disinfection (final chlorination);"
- Category A3: "intensive physical and chemical treatment, extended treatment and disinfection e.g. chlorination to break-point, coagulation, flocculation, decantation, filtration, adsorption (activated carbon), disinfection (ozone, final chlorination)".

Categories A1, A2 and A3 and their associated guidelines from Directive 75/440/EEC as amended can be reviewed at the website: http://rod.eionet.europa.eu (http://rod.eionet.europa.eu/show.jsv?id=202&mode=S). The basis for these guideline values could not be identified.

The Drinking Water Abstraction Directive falls under the category of legislation to be repealed (December of 2007) under the Water Framework Directive. To replace previous legislation, environmental objectives from existing legislation will be coordinated, and a new overall objective for 'good status' of all waters developed (WISE, 2007). Measures will be required to be implemented to achieve 'good status' (WISE, 2007).

2.3 The United States

In 2002, the USEPA proposed an Index of Watershed Indicators (IWI). The IWI was intended to provide a method for the characterization of the condition and vulnerability of water resources. The goals of this initiative also included: communication of this information to the public to inspire interest and stakeholder involvement; as a tool for water quality management professionals to enable them to make better decisions; and finally in order to establish national baseline conditions and measure change/progress towards healthy watersheds. The IWI was to consider fifteen indicators, seven related to the water quality condition and eight to vulnerability. To characterize the watershed the full set of indicators was not required, rather a minimum of four of the condition indicators and six of the vulnerability indicators were considered acceptable. This approach is not elaborated upon herein, since research in 2007 appears to indicate that this program has been superseded in favour of the total maximum daily load (TMDL) program.

The United States protects surface water quality through the Clean Water Act (CWA). The CWA is limited to a consideration of surface water in a watershed based approach, and does not directly consider groundwater or water quantity (US EPA, 2007).

In November of 2001, states were encouraged to integrate surface water quality reporting requirements (CWA Section 305b) with the requirement to identify impacted surface waters and their pollution control measures (CWA Section 303b) (US EPA, 2006b). Reporting of impaired surface waters takes place every two years (Jarrell, 1999).

Section 303 of the CWA includes both the development of water quality standards and the TMDL program (US EPA, 2007b). The US EPA describes a TMDL as the allowable discharge of a given pollutant while enabling water quality standards to be met for the designated use(s) (drinking water, recreation, aesthetics, irrigation, fishing and/or swimming) (US EPA, 2007b). Calculation of a TMDL considers the contributions from all point and non-point sources, a margin of safety, and the seasonal variation in water quality (US EPA, 2007b). TMDL discharge calculations for non-point sources are determined based on land use type (urban, agricultural, forestry) (Jarrell, 1999).

The initial requirements of the CWA emphasized control of point discharges through treatment solutions (Jarrell, 1999). TMDLs introduced a marked improvement to water quality by requiring consideration of the water body itself (on a watershed scale) and non-point discharges (Jarrell, 1999).

The USEPA also has a Source Water Assessment Program under the Safe Drinking Water Act. The program requires delineation of the area boundaries providing source water, an inventory of contamination sources within that area, susceptibility of water supplies to those contaminants, and reporting (US EPA, 2006a). Ground water protection programs are also encouraged through a grant program (US EPA, 2006a).

2.4 Australia

ESR (2004) summarized source water grading approaches in other jurisdictions including Australia. They identified that Australia does not have any of the following: standards in place for source water; national water quality requirements for abstraction; or a source water quality grading system (ESR, 2004). Determination of the level of protection to be applied to water resources in Australia in order to meet national guidelines is the responsibility of local stakeholders, State, Territory or regional governments (ANZ ECC ARMC, 2000).

As outlined in ESR (2004), the Sydney region manages their catchment by setting minimum water quality requirements at the DWP intake through bulk water supply agreements with water suppliers. These standards are based on historical source water quality, the design of the treatment system in place, and standards for treated water quality (ESR, 2004). A three level classification system for source waters was developed by the Water and Rivers Commission in Western Australia (ESR, 2004). This classification system assigns various levels of protection to catchment areas to ensure source waters are protected, and includes a land use planning component (ESR, 2004).

2.5 Environment Canada

In 2004, ECa retained Dillon Consulting Limited (Dillon) to draft a report on recommendations towards the derivation of source water quality guidelines in Canada. The Dillon report (2004) recommended that HC develop a grading system for water quality, similar to what was being proposed in New Zealand at that time (the grading, monitoring, and reporting framework). This recommendation was based on a literature review of water quality guidelines in other jurisdictions (Australia, New Zealand, USA, and Europe), which indicated that little guidance on how to develop source water protection guidelines was available, with the exception of New Zealand's proposed approach (Dillon, 2004).

Dillon's recommended approach included the following steps (Dillon, 2004):

- Evaluation of drinking water quality criteria;
- Assessment of maximum theoretical parameter concentration that can be handled by a treatment process;
- Finally, determination of criteria to represent the acceptable parameter concentration in source water for public health (considering the treatment process); i.e. source water quality guidelines.

ECa recommended that HC adopt the approach recommended by Dillon (2004) (ECa, 2005).

2.6 Discussion

In general, the various approaches internationally show a trend towards a watershed based management approach to protect source water quality. The examples of the various approaches for New Zealand, Europe, the United States and Australia provided some insight into this project's approach. The New Zealand proposed grading, monitoring, and reporting framework that was developed, but never adopted, is the closest example to what the SWQI is mandated to achieve. The New Zealand grading, monitoring and reporting framework provided some preliminary concepts to how source water quality could be graded and considerations in parameter selection. These were beneficial to the design of the SWQI approach.

The European Council's Drinking Water Abstraction Directive (75/440/EEC as amended by Directives 79/869/EEC and 91/692/EEC) provides the only example of source water quality guidelines developed and adopted. Unfortunately, four main reasons can be identified for why this approach would not be a suitable model for the SWQI. Firstly, this Directive was limited to a consideration of surface water. Secondly, the approach appears to be very rigid with respect to what treatment will be in place, and does not appear to have room for treatment design flexibility. Thirdly, the rationale for the derivation of these guideline values was not available (the technical background needed to understand their derivation). Lastly, the approach is currently being repealed and replaced within the broader Water Framework Directive. Details regarding its replacement could not be found. For these reasons, the Drinking Water Abstraction Directive approach could not be adapted for the Canadian context.

The approach of the United States is the TMDL. By integrating considerations of non-point source water quality impacts, this approach appears to be achieving better source water quality. However, two main reasons can be identified for why it is not appropriate for consideration in this project. Firstly, it does not consider groundwater. However, more importantly it can be interpreted as a framework under which pollution of source water is considered acceptable up to a certain point. This is counter to the concept of applying a source water protection barrier (adopted as a goal in this project as outlined in Section 4.1).

The Australian example was too limited in scope for consideration.

Finally, the following will address the recommendations made by ECa. It should be noted that the determination of the maximum theoretical parameter concentration that can be handled by a treatment process is not a trivial undertaking. In practice, determination of appropriate treatment is ascertained through a careful evaluation of site specific considerations by recognized professionals, who are qualified and have experience in this analysis. Not only do site specific source water characteristics influencing treatment performance need to be considered, but so do numerous site specific constraints (e.g. available footprint, costs, infrastructure, operation, maintenance, and operator skill requirements). As will be outlined further in this document in Section 5.3, the literature has laboratory, pilot and full scale examples of various removal efficiencies associated with treatment processes that can vary broadly. Causal relationships that determine the achieved removal efficiencies are not always easily ascertained, and are not limited to source water quality considerations. Deriving an acceptable concentration of a water quality parameter in source water, in consideration of the treatment process, is therefore not easily achieved since flexibility is required for site specific considerations.

Another consideration is the guideline development process itself. The GCDWQ are developed to apply to the evaluation of treated drinking water. For the GCDWQ, the CDW makes every effort to establish on average five to seven guidelines per year. The process from initiation of the guideline development process to publication however takes place on the order of several years. There are on the order of tens to hundreds of parameters that require consideration in source water quality. Too many to be evaluated and have guidelines developed within the two year SWQI project timeframe. Therefore for these additional reasons, development of source water quality guidelines became impractical.

3 WATER QUALITY INDICES

This section presents a scientific overview of water quality indices identified in the literature as developed for various purposes and scales. Although the international approaches to measuring, tracking and reporting on source water quality presented in Section 2 can be reviewed to support the credibility and feasibility of a National approach, it was possible that they were not based on the best available science or a comprehensive overview of available index options. The research presented in this section was undertaken to understand from a scientific perspective: the strengths and weaknesses of different index approaches, water quality index formulations, factors to consider in successful index application, and to form a basis of comparison for evaluating the CCME WQI being applied in Canada.

3.1 General Index Considerations

Indices are often developed in order to assimilate, interpret, and communicate relevant findings from a large collection of data to users with less technical knowledge, including the general public and governmental and legislative decision makers (Ott, 1978; Smith, 1990; Hébert, 1996; CCME, 2001). It is important to understand that indices are ordinal-scale information that is often a "simplification" or categorization of real data from interval or ratio scales; and that the categorization process produces a loss of information (Ott, 1978; Smith, 1989; Hébert, 1996). An index should be designed to answer a well defined question (Ott, 1978). If the index is well designed and applied as is intended, the missing data should not seriously distort from the answer that the index is designed to represent (Ott, 1978). However, misapplication of the index may result in erroneous conclusions and unsuitable decisions (Ott, 1978; CCME, 2001).

This review will be limited to water quality index development, for which the literature demonstrates countless examples. In 1982, Beron estimated through his own literature review, that over one hundred scientists had been involved in developing approaches for water quality indexing (Smith, 1990). This number has continued to increase over the years as demonstrated by the following literature review. Despite these efforts however, there are a limited number of success stories that demonstrate sustained water quality index application (Smith, 1990).

Controversy surrounding index use is based on several factors. These include:

- the loss of technical data either through lack of inclusion or from being hidden by the aggregation (Ott, 1978; Dunnette, 1979; Smith, 1990; CCME, 2001);
- the potential for index misapplication (Ott, 1978; Dunnette, 1979);
- the lack of agreement on index design among scientists (Dunnette, 1979);
- local modifications which lead to a loss of consistency and comparability among regions, as well as the potential for introducing bias (Ott, 1978); and
- Both anthropogenic activities and natural environmental conditions can influence the results of a water quality index value, complicating its interpretation (Ott, 1978; Hébert, 1996).

Despite the controversy surrounding index use, there are numerous advantages outlined in the literature in support of water quality index use. Firstly, it must be considered that a water quality index is not intended to replace a detailed analysis of water quality data (CCME, 2001). It should be remembered that even though there will be a loss of some water quality information in the index itself, the raw data can still be reviewed as required (House and Ellis, 1980). With this in mind, far from information losses, indices can in fact provide additional information on water quality (House, 1989) offering several operational and managerial advantages (House and Ellis, 1980). The following beneficial applications of water quality indices have been outlined in the literature:

- To reduce large amounts of water quality data to a single number (Ott, 1978; House and Ellis, 1980; Cude, 2001; CCME, 2001a,b), "in an objective and reproducible manner" (House and Ellis, 1980);
- To better enable communication of water quality information to the general public and governmental and legislative decision makers (Ott, 1978; House and Ellis, 1980; Cude, 2001; CCME, 2001a,b) that promotes a better understanding of operational decisions (House and Ellis, 1980) and lends support to improvement efforts (Cude, 2001; Bordalo et al 2006);
- to evaluate performance of an existing practice that may impact on water quality (Ott, 1978; House, 1989; Cude, 2001);
- to evaluate trends (Ott, 1978; House and Ellis, 1980; CCME, 2001a), "even at low concentrations in a timely and efficient manner" (House, 1989);
- to highlight specific conditions (Ott, 1978; Cude, 2001);

- to guide decision making (Ott, 1978; House and Ellis, 1980) and lead to better/more effective management practice (House and Ellis, 1980; Said et al, 2004) e.g. determine monitoring frequencies (Cude, 2001);
- to make comparisons temporally at a specified location (Ott, 1978; House and Ellis, 1980; Cude, 2001; CCME, 2001b);
- to make comparisons geographically between locations (Ott, 1978; House and Ellis, 1980; House, 1989; Cude, 2001; CCME, 2001b) in addition to being used to "pin-point" river reaches contributing to an impact, and flag those that need to be investigated in greater detail (House and Ellis, 1980);
- to prioritize the allocation of resources (Ott, 1978);
- to assess water quality relative to its desirable state (in comparison to regulatory standards) (Ott, 1978; House & Ellis, 1989; Smith, 1990; Hébert, 1996; CCME, 2001b) and the degree to which water quality is being impacted by human activity (CCME, 2001b);
- To provide economic information (gains or losses from water quality improvements or deteriorations) (House and Ellis, 1987; Said et al, 2004), and suitability for specific uses (House & Ellis, 1989; Smith, 1990; Hébert, 1996; CCME, 2001b); and finally
- To show water quality gradations within a class (House 1989; Cude, 2001) and illustrate when class thresholds are being approached (House, 1989).

To circumvent local water quality index tailoring, Ott (1978) recommends that the Federal government be responsible for recommending a standardized index method to be applied locally. This is the approach undertaken in this project. Further, to ensure a water quality index stands up well to scientific scrutiny, the following recommendation as outlined by Ott (1978), is also adopted herein: "the best way to proceed with indices is to test them by use, and continue to refine them based on experience" (Coate & Mason in Ott 1978). There are numerous examples of the success of this approach in the literature, where indices have seen sustained application including application of the CCME WQI, the Oregon water quality index (OWQI) and the Scottish Development Department Water Quality Index (SDD WQI).

The following text will include:

- an outline of commonly used terms associated with indices;
- general mathematical index structures (with several variations of the generic structures in actual application);
- an overview of some of the more interesting water quality indices developed, with emphasis on the ones most commonly referred to in the literature and currently being applied; and
- Relevant information that has been gleaned from this review, and applied to the SWQI and TWQI.

3.2 Commonly Used Terms Associated with Indices

There are various terms that need to be defined to understand an explanation of index structure. These include a parameter, indicator, index, increasing scale, decreasing scale, ambiguity and eclipsing. Descriptions of these terms included herein have been modified from Ott (1978), and where indicated further expanded upon from other sources.

Parameter (or determinand)

In water quality monitoring, physical, biological, chemical and radiological parameters are monitored to measure a water quality condition. Parameters are defined by numerical values that are on interval or ratio scales. Examples of these parameters include pH (interval), total coliform counts (ratio), nitrates (ratio), and radium 226 (ratio). A useful definition of a parameter is found from Hartmut Willmitzer (2000): a parameter is "a variable, measurable property whose value is a determinant of the characteristics of a system." Parameters are also often referred to in the literature as 'determinands' (Smith, 1990; House & Ellis, 1987).

Indicator

An indicator is a value on an interval or ordinal scale derived from only one parameter, and is often referred to as a sub-index (Smith, 1990; Ott, 1978). The derivation is often from either an implicit or explicit mathematical function or rating curve (Smith, 1990; Ott, 1978), where a rating curve is a graph that provides an indicator value in correspondence with a given parameter concentration. A sub-index is calculated in order to transform all parameters into common units and scale to enable their aggregation into an index (Dunnette, 1979; House and Ellis, 1980; Cude, 2001; Liou et. al, 2004; Sarkar & Abbasi, 2006; Sanchez et. al, 2006). Swamee and Tyagi (2000) further subdivide indicators into the categories of absolute (independent of water quality guidelines) and relative (dependent on water quality guidelines).

Index

An index is a single number on an ordinal scale derived from the mathematical aggregation of two or more indicators and is derived from more than one parameter[2] (Smith, 1990; Ott, 1978).

Decreasing and Increasing Scale Indices

As outlined in Ott (1978), there are both decreasing and increasing scale indices. A decreasing scale index has a decreasing index value as a measured negative impact increases. Therefore in a decreasing scale index rated from 0 to 100, a value of 0 is the worst case. An increasing scale index has an increasing index value as a measured negative impact increases. Therefore in an increasing scale index rated from 0 to 100, a value of 0 would be the best case.

With respect to water quality indices almost every single example in the literature (with negligible exception) is of the decreasing scale form. Increasing scale indices will therefore not be covered herein.

Ambiguity

Ambiguity exists when the index result "can report poor environmental quality when none of the sub-indices report poor environmental quality" (Ott, 1978, pg. 91).

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[2] The terminology 'source water quality indicator' was provided as part of the project mandate. From this, the natural extension was to use the terminology 'treated water quality indicator'. In the true sense of the terms 'index' and 'indicator', since both the source and treated water quality 'indicators' consider more than one parameter, they should be correctly termed 'indices'.

Ambiguity tends to increase as more indicators are added to an index calculation. Ambiguity thereby exaggerates a problem (Ott, 1978).

Eclipsing

Eclipsing occurs when “extremely poor environmental quality exists for at least one pollutant variable, but the overall index does not reflect this” (Ott, 1978, pg. 70). Eclipsing underestimates a problem (Ott, 1978) or overestimates water quality (House and Ellis, 1980). Smith (1990) describes eclipsing as a problem where the index result masks the parameter responsible for limiting that water’s suitability for use, and the degree by which it does this. Eclipsing problems generally worsen as the number of parameters increases (Swamee and Tyagi, 2000).

3.3 General Mathematical Index Structures

There are many mathematical functions used to derive both indicators and indices. The following paragraphs will briefly describe the general structure of these. In index development, modifications of these general structures are sometimes seen. It should be noted that calculation of an index is a two step process. First the sub-indices (indicators) are calculated to transform all parameters into common units and scale (interval or ordinal), following which the index is calculated based on an aggregation of the sub-index values into an ordinal scale (Ott, 1978; Smith, 1990; Hébert, 1996). Ambiguity and eclipsing are problems associated with certain types of the index calculations, but generally at least one, the other, or both, are possible in the various aggregations.

In Ott's review (1978) of indicators, a linear, segmented linear, non-linear and segmented non-linear function, were commonly identified, and the following features of these various aggregations were pointed out. In the linear function, a change in a parameter value is directly proportional to the sub-index value. The linear function is a very straightforward, simple approach. Incorporating more flexibility is the segmented linear function, which consists of two or more straight line functions with different slopes. In a segmented linear function, a change in effect results from an exceedance of a certain threshold value. The various non-linear functions account for many variable curves including, for instance, parabolic or exponential functions. The non-linear functions can include both mathematical formulas and implicit values that can only be read from graphs. Non-linear functions can also include unimodal functions with either one minimum or maximum value. Finally there are the segmented non-linear functions, with various equations associated with different parameter ranges, with at least one function being non-linear. As can be seen, there appear to be almost as many methods for the calculation of sub-indices as there are mathematical functions. Due to the extent of these possibilities they are not outlined further herein.

Many of the indicator development models utilize implicit rating curves. As outlined in the definition for an indicator, a rating curve is a graph that assigns an indicator value to a given parameter concentration. A concern identified with implicit rating curves should be noted. Water quality data can sometimes be measured outside of the range of a given implicit rating curve (Smith, 1990). In that event, it would be impossible to identify the related sub-index value, and the index could not be calculated.

Despite the large number of functions that are used to derive indicators, it has been noted in the literature by O'Connor (Ott, 1978) and Ott (1978), through a comparative review of various indices that the actual shape of the rating curve does not matter as much as the parameters selected. O'Connor created straight line approximations of each sub-index curve and examined the correlation between these and the original index results. To his surprise the correlations were quite high (Ott, 1978). Ott (1978) did a comparative analysis of the rating curves for specific parameters for several of the indices he evaluated and found that the parameter rating curves were generally quite similar to each other in shape or generally fell within the 80% confidence intervals of one of the more common indices at the time (the NSF WQI). This is not a surprising conclusion if the indicator functions were relative to the accepted water quality guidelines at that time.

Generic structures of index functions as encountered in the literature are presented in Table 3.1, titled 'Characteristics of the Various Water Quality Index Aggregation Functions'. This table also includes a description of the advantages and disadvantages of the various aggregations, and developers from the literature that applied them (or a variation of them). Index functions include aggregation by summation, multiplication, or representation by the minimum operator of the various sub-indices (indicators) as briefly described below.

As further outlined by Ott (1978), the simplest aggregation of the sub-indices is addition, for which there are non-weighted, weighted and root-sum-power (or root-mean-square) forms. Ott (1978) further outlined the following observations with these aggregations. In the non-weighted additive aggregation, sub-index values are simply summed. The weighted additive aggregation (weighted linear sum) assigns variable weights that are multiplied to each indicator value before they are summed. The root-sum-power form is a non-linear function that minimizes the eclipsing and ambiguity encountered in the other additive options. There is also the root-mean-square option, similar to the root-sum-power except the arithmetic mean of the square is calculated before the square root is taken. Generally, these indices are not well suited for decreasing scale sub-indices due to the scale of the eclipsing problem.

The multiplicative form is most popularly applied to water quality indices that use a decreasing scale (Ott, 1978; Smith 1990; Liou et al., 2004). The multiplicative form allows for the overall index score to reflect poor environmental quality if any one sub-index displays it, thereby eliminating the eclipsing problem in all but the most subtle cases (Ott, 1978). For the multiplicative form, ten (10) sub-indices are recommended with the weights adding to unity, allowing for each weight to be relatively small, but not too small (Ott, 1978). When the weights are too small non-linearity is introduced into the process making the results less reliable (Ott, 1978).

As also outlined in Ott (1978), the minimum operator is the limit of the root-sum-power method as the power (p) approaches infinity. In the minimum operator, the index value takes on the value of the worst water quality of any of the sub-indices (Ott, 1978). The advantage of the minimum operator is that an exceedance of a given threshold will be reported; therefore, it is a good alternative when an exceedance needs to be known (Ott, 1978). The minimum operator method is only applied to decreasing scale sub-indices (Ott, 1978). Please refer to Ott (1978) for more subtleties and details related to these aforementioned various alternatives.

As outlined in Table 3.1, the various index aggregation functions have limitations with respect to their propensity to exhibit ambiguity and or eclipsing. More refinements to index aggregation methodologies are demonstrated to have evolved over time, most often to try to circumvent the eclipsing or ambiguity problems of previous aggregation methods. This includes application of the minimum operator method, explored by Smith (1990), and Hébert (1996). The minimum operator method, though identified by Ott (1978), had not previously been applied to water quality indexing. Similarly other aggregation functions have been developed including the unweighted harmonic mean square by Dojlido (1994), arithmetic Solway weighted formulation described by House and Ellis (1980, 1987, 1989), and finally the apparent ambiguity and eclipsicity-free aggregation developed by Swamee and Tyagi (2000) (though this approach has never been applied).

Outside of these aforementioned index aggregation approaches, there are statistical methods being applied as well as fuzzy logic. Examples of fuzzy logic in the literature include Ocampo-Duque et al. (2006), Mpimpas et al. (2001), Chang et al. (2001), and Silvert (2000). Although these approaches appear quite interesting, their descriptions are overly technical and aggregations overly complex for the scope of this thesis. An outline of some of the statistical methods (Harkins) can be found in Ott (1978) and references for fuzzy logic have been included in the reference section for further exploration by the more technical reader.

3.4 Overview of Some of the Water Quality Indices in the Literature

An overview of some of the more interesting water quality indices developed is given in this section, with emphasis on those most commonly referred to in the literature and applied in practice. A comparative analysis of the various water quality indices developed up until the mid to late 1970's is outlined by Ott (1978). The summary of water quality related indices up until 1978 described herein is based on Ott's review, and the original references were not consulted. Appendix 1 provides the list of references Ott relied upon that have been included in this review, and the authors are referred to herein by their last names. Since Ott, other water quality indices have been developed, and similarly some of the more interesting of these are briefly outlined.

As will be seen in the index descriptions, water quality indices are divided between general and specific use categories. There are various opinions in the literature regarding the appropriateness of applying one index to describe multiple water uses. The argument for various water quality indices, depending on use, stems from the fact that the value of a parameter may have a different effect (positive or negative) depending on the proposed use, influencing not only it's relevance for inclusion in an index, but also its impact on overall index scoring (e.g. shape of indicator curve, and weighting (where weights are considered)) (Ott, 1978). The concept that indicators should be developed for a specific use appears reasonable, and is espoused herein.

To accompany the following text, two tables have also been created. Table 3.2 provides an illustrative comparison of the formulations for the described water quality indices and any included consideration for toxic substances; and Table 3.3 provides an illustrative comparison of the parameters included in the described water quality indices and associated weights where available. The information in Tables 3.2 and 3.3 is not described in detail in the following text, and is meant to stand alone and provide additional information for the curious reader.

3.4.1 General Use Water Quality Indices

The text included in this section 3.4.1 outlines general use water quality indices. All of the information outlined in this section (3.4.1) used Ott (1978) as a reference.

Horton's Quality Index - Horton (1965)

In 1965 the first water quality index based on a numerical scale was developed by Robert K. Horton. Horton believed that water quality indices needed to be able to show varying gradations of a water quality condition, to allow for temporal and geographical comparisons. His criteria for parameter selection included: limited in number, significant in most parts of the country and reflective of available data. Horton had hoped that his approach would bring in national consistency for rating a water body. No information on the actual application of this index is included in the literature reviewed. However, Horton's approach utilizing a numerical scale had a tremendous influence on later index design.

The National Sanitation Foundation Water Quality Index (NSF WQI) - Brown, McClelland, Deininger & Tozer (1970)

A very interesting index, which took a unique development approach, is the National Sanitation Foundation's Water Quality Index (NSF WQI) developed by Brown, McClelland, Deininger and Tozer in 1970. The NSF WQI was developed based on a technique called 'Rand Corporation's Delphi Technique', which amalgamates the opinions of a large body of experts. In the NSF WQI, one hundred and forty two (142) persons with expertise in water quality management were sent a questionnaire asking them to rate thirty five (35) parameters for inclusion in a water quality index, with the flexibility of adding parameters as they saw fit. Each parameter recommended for inclusion was to be rated based on its contribution to overall water quality. A second questionnaire was sent in an attempt to gain greater convergence, enabling the respondent to modify his original rankings in comparison to the amalgamated response of the entire group. A third questionnaire with the final parameter list, asked the respondents to draw a graph (implicit function) of how water quality was impacted on a scale of zero (0) to one hundred (100) as the parameter in question increased. The curves were averaged using an arithmetic mean, and eighty percent (80%) confidence limits were drawn. Weights were also derived for each parameter based on the significance ratings of the respondents. This index included the concept of a colour rating system from red for very bad water quality, through orange, yellow, green and blue for excellent water quality. Please see Table 3.4, titled' Water Quality Index Category Descriptions' for a description of categories.

The NSF WQI became the most widely applied index in the United States by late 1977 with local modifications made by users depending on data availability. Concerns with the NSF WQI as expressed by Harkin (1974) were that the approach was not objective since any index result could be challenged by another body of experts.

Dinius' Social Accounting system – (Dinius 1972)

In 1972, Dinius proposed a water quality index that treated water as natural capital. The index was modeled after accounting balance sheets for tracking assets and liabilities. The index was intended as a tool to identify the amount and location of pollution, as well as the money and community effort expended for pollution control efforts. In this index pure water quality was assigned a value of 100%, and pollution was treated as a liability subtracted from this value to equal the overall remaining capital. The capital was then weighted by the overall length of all streams. What is also interesting is the language used by Dinius in her categories for public water supply. From 90% to 100% her category is described as 'purification not necessary', from 80% to 90% 'minor purification required', from 50% to 80% ' necessary treatment becoming more expensive', from 40% to 50% the category is 'doubtful' and below this ' not acceptable'. It does not appear that this index was ever applied. Please see Table 3.4 for a more detailed description of categories.

3.4.2 Specific Use Water Quality Indices

The indices described above are general water quality indices. The text included in this section 3.4.2 outlines some examples of specific use water quality indices found in the literature with emphasis on those developed for public water supply. All of the information outlined in this section (3.4.2) used Ott (1978) as a reference.

Public Water Supply (PWS) Index - O'Connor (1972)

O'Connor developed a specific use index to describe how surface water quality affected public water supplies. This index was developed using something similar to the Delphi technique as described for the NSF WQI above, however on a much smaller scale relying on only eight experts. One interesting part of the calculation of this index is the addition of a factor for the occurrence of pesticides or toxic substances. This factor causes the index result to automatically become zero if any pesticide or toxic substance parameter included in the calculation exceeds its threshold limit.

Index for Dual Water Uses – Public Water Supply Index - Stoner (1978)

In Stoner's Public Water Supply Index, pollutants (toxic substances, Type I) and variables with health or aesthetic characteristics (Type II) are included. One of the interesting aspects to Stoner's approach was the inclusion of one parameter (methylene blue active substances) because of its link to aesthetic concerns, and potential for interfering with the proper functioning of the coagulation, sedimentation and/or filtration treatment barriers. The index is designed such that one hundred (100) is the best possible score, however as water quality worsens in comparison to a limit, the index value becomes increasingly negative. The developer suggests that the negative values can be used as a surrogate for water treatment costs.

3.4.3 Discussion of the Indices Outlined in Ott (1978)

What is interesting about all of the general and specific use water quality indices described in Ott (1978) is that they only consider surface water. The number of variables included ranged from 8 to 31; almost all had decreasing scales; and a fixed range of 0 to 100. The most common parameters included, among those described in Ott (1978), in the categories of chemical, physical and biological parameters respectively were dissolved oxygen, pH, and fecal coliforms. All of the indices described herein included coliforms (either fecal or total) as a parameter. In general many of the indices had a lot of commonality in parameter selection. The following text will now describe other water quality indices in the literature.

3.4.4 Other Water Quality Indices in the Literature

New Zealand Water Quality Indexing System - Smith (1990)

The most popular approach by which indicators were aggregated into indices (identified by Smith (1990) through his review) was the weighted product multiplicative function. The main concern with this function is the potential eclipsing for moderately poor water quality, and or nonlinearity (distortion) if the weights are too small (as outlined in Table 3.1).

To get around the problem of eclipsing, Ott (1978) had proposed that a minimum operator approach could be applied to a decreasing scale index. This type of indexing system, using the minimum operator, was recommended for implementation by Smith (1990) in New Zealand. Several reasons for this choice were: it was felt a waters' suitability for use would be governed by its worst parameter; there was no restriction on the number of indicators that could be included; new indicators could easily be added to the index; weightings were not required; and eclipsing was avoided (Smith, 1990).

The index proposed by Smith (1990) was developed using the Delphi Method as described in the development of the NSF WQI. In this case the development relied on eighteen (18) water quality experts, and implicit curves were forced through fixed points (the limits of the proposed water quality criteria) (Smith, 1990). At the time of Smith's article (1990) this approach was being applied as a planning and communication tool by some water authorities in New Zealand.

Oregon Water Quality Index - Dunnette (1979) & Cude (2001)

Dunnette (1979) developed an index for application in Oregon. In this index, Dunnette developed a unique approach to parameter selection. He first reviewed other water quality indices, evaluated parameters against a rejection rationale, conducted a staff survey using a modified Delphi approach, and finally evaluated the panel list of parameters against water impairment categories (Dunnette, 1979).

Rating curves were developed for the selected parameters to determine indicator values. The rating curves were designed to reflect more impact at lower than high concentrations for an equal change, and negative exponential curves were developed for parameters that varied inversely with water quality (Dunnette, 1979). The curves were also fit to reflect water quality observed in the river in question (Dunnette, 1979).

In 2001, Cude wrote a paper on the 1995 re-development of the Oregon Water Quality Index (OWQI) in consultation with Dunnette. Dunnette's OWQI appears to have been applied in Oregon for reporting purposes up until 1983, when it was discontinued due to the resource requirements in its calculation (Cude, 2001). At the time of the OWQI redevelopment (1995) the understanding of the science behind water quality and index development, as well as computer technology for index calculation, had evolved allowing for design improvements and easier computation (Cude, 2001). What is interesting about this article is the evidence of how the index evolved over time. The parameters temperature and phosphorous were added to the original parameter list, rating curves were adapted to reflect the evolving science, and the index aggregation was changed from a weighted arithmetic mean function to an unweighted harmonic square mean formula (suggested as an improvement by 'Dojlido et al., 1994') (Cude, 2001).

United Kingdom (UK) Water Quality Index for River Management - House & Ellis (1980, 1987) and House (1989)

House and Ellis re-developed a water quality index (1987) to replace the Scottish Development Department (SDD) (1976) water quality index developed for application in the United Kingdom (UK) for general surface water use. The European Council Directive (Drinking Water Abstraction Directive (75/440/EEC as amended by Directives 79/869/EEC and 91/692/EEC)) being implemented at that time, required Water Authorities to relate effluent discharges to the expected use of the receiving waters. Refer to Section 2.2 for a brief outline of this Directive. A general water quality classification system had been adopted (National Water Council (NWC) classification) for the management of surface water quality; however, House and Ellis (1980) felt that this assessment was rather subjective, and that a water quality index was necessary in order to quantify water quality within the classes in a standardized and reproducible manner.

House and Ellis (1980) evaluated the SDD index and determined that it underestimated water quality at the poor end of the scale and needed to include toxic substances (House and Ellis, 1987). Both the SDD 1976, and the new indices produced by House and Ellis (1987) were developed adopting an approach similar to Brown et al. (for the NSF WQI). House and Ellis (1987) further adopted the impairment categories and rejection rationale technique developed by Dunnette (1979) in the parameter selection process.

Apart from this, House and Ellis (1987) included four water use categories. These water use categories included general use, potable water supply, aquatic toxicity and potable sapidity. The potable water supply index evaluates surface water quality for suitability for abstraction as a drinking water supply (House and Ellis, 1987). The other two indices evaluate toxic parameters of water quality with respect to suitability for fish and wildlife and potable supply, respectively (House and Ellis, 1987). Sapidity appears to be defined as "having flavor" (Merriam-Webster, 2007-2008). In this context it is expected that the term implies aesthetically pleasing. These four water quality classes and the parameters included in them are further outlined in Table 3.3.

The index results are then placed within a relative scale for the cost to treat the water for that use (as outlined in Table 3.4) (House and Ellis, 1987). What is interesting about this classification system is that House and Ellis were able to test their index on over 2000 data sets covering more than 200 river tributaries, with data covering a period of three to ten years (House, 1989).

The Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) – CCME (2001)

This index is described in detail in Section 5.2 of this thesis, so it is not elaborated upon in this section.

3.5 Discussion - Considerations in Index Development

In general, index development seems to have evolved by adapting historical approaches for geographical and legislative relevant applications, with the introduction of improved aggregations over time. The most commonly utilized technique in index development appears to be the Delphi technique. The Delphi technique was utilized in one form or another in the water quality indices developed by: Brown, McClelland, Deininger & Tozer (1970), O'Connor (1972), Dunnette (1979), House and Ellis (1987), and Smith (1990).

Through the literature it is apparent that numerous attempts to devise water quality indices have been undertaken over the last quarter of a century. Although not described in detail in the above sections, the literature review revealed a broad geographical extent of water quality index application (or intended application), with examples of water quality indices being applied in various countries. Not all of these are detailed herein; however they were identified in the literature:

- Canada (Inhaber 1975; Hebert 1996; and the CCME WQI, 2001);
- the United States (Brown, McClelland, Deininger & Tozer ,1970; Nemerow and Sumitomo, 1970; Dinius, 1972; McDuffie and Haney, 1973; Walski and Parker, 1974; Stoner, 1978; Dunnette, 1979; Cude, 2001; Said et al.,2004);
- the United Kingdom (House & Ellis,1980 and 1987; and House, 1989);
- New Zealand (Smith, 1990);
- Italy (Prati, Pavanello & Pesarin 1971);
- Taiwan (Liou et al., 2004; Chang et al., 1998; and Chang et al., 1999);
- Africa (Egborge and Benka-Coker, 1986);
- India (Sargaonkar and Deshpande, 2003; Bhargava, 1983);
- Spain (Sanchez et al., 2006; Bordalo et al., 2006); and
- Portugal (Bordalo et al., 2006).

For the development of the SWQI and TWQI, the review identified considerations regarding controversy surrounding index use and ways to circumvent this, beneficial index applications, index terminology, and strengths and weaknesses of various aggregation methodologies.

It is evident from a review of the literature and as outlined in Table 3.1, that all index formulations have their strengths and shortcomings, and not one can be considered perfect for the given application. A few indices however, have seen extended use including the approaches adopted in Oregon and the UK. The success of these approaches is believed to be due largely to their long term application and refinements over time (as recommended in Ott (1978)).

The approach that will be adopted in development of the SWQI and TWQI includes the expectation of long term application and dynamic refinements based on experience to address application concerns and ensure proper result interpretation. Additionally, the Federal government will be responsible for recommending a standardized approach for local, watershed and national application. Both of these strategies were recommended by Ott (1978) to circumvent several of the controversies surrounding water quality index use. Numerous benefits have been identified with the use of water quality indices, and it is hoped that many of these will be realized with the SWQI and TWQI approaches.

4 SCIENTIFIC OBJECTIVES, METHODOLOGY AND PROJECT PROCESS

Critical steps in the project were development of the scientific objectives, methodology, and project process for the SWQI and TWQI.

To define the project scientific objectives, and frame the project methodology and work requirements, a series of questions needed to be answered. These questions are as follows, and are outlined in the following sections:

- Section 4.1 scientific objectives: What scientific objectives needed to be derived to achieve the project mandate and to ensure the indicators served a beneficial purpose in an overall water quality management framework?;
- Section 4.2 indicator result derivation: What methodology would be applied to the data to derive indicator results?; What specific considerations regarding source and treated water quality needed to be incorporated?; What were the indicator limitations and how could these limitations be addressed?; What tools would be needed to enable data manipulation and consistent generation of results?; What technical guidance would be required to ensure credible, consistent application and interpretation?; and
- Section 4.3 data requirements: What data and parameters are relevant, and how would users be guided to select the relevant data to include?; How would the data be collected?

This thesis does not include a consideration of water quantity or vulnerability. It is appreciated that both will have an impact on water quality, however other Federal Departments are addressing water quantity and vulnerability indicators, and they were therefore considered outside the scope of this work.

4.1 Scientific Objectives

As a reminder, the overall mandate for this project as outlined by NRTEE (2003) was to account for source water quality as an asset necessary to sustain the health of the environment, society, and economy for Canadians; and to create an indicator to measure, track and report on source water quality, for decision making.

In order to accomplish this, specific considerations needed to be given to source water quality in the context of how it is defined, why it is important to measure, track and report on it, and for what purpose/benefit could an indicator be used within an overall water quality management framework.

The considerations that enabled forming links between water quality and human health, the environment, society and the economy are outlined in the following Section 4.1.1. The scientific objectives developed to address measuring, tracking, and reporting on the indicator results are outlined in Section 4.1.2. Finally, overall scientific objectives determined for the project are outlined in Section 4.1.3.

4.1.1 Links to Human Health, the Environment, Society and Economy

The first scientific objective for the water quality indicator in order to achieve the project mandate is to:

- Establish a link (to the extent possible) between water quality and human health, the environment, society and economics.

First let us address human health. Source water is defined as "water in its natural or raw state, prior to being withdrawn for treatment and distribution as a drinking water supply" (CDW & CCME pg. 235, 2004), and as such, it is only indirectly linked to human health due to the treatment and distribution it receives. In more general terms, since we don't drink the source water directly, it cannot be directly linked to human health. In order to form a direct link between water quality and human health, a treated water quality indicator (TWQI) that represents the quality of water that we drink, is required. For this reason the project scope was broadened to include a TWQI.

In the context of overall water quality management, it is recommended that a source to tap multi-barrier approach (MBA) be followed. The MBA utilises the concept of multiple barriers from source to tap and contains three main elements: the source water (watershed/aquifer), the drinking water treatment plant, and the distribution system (CDW & CCME, 2004). Barriers are put in place to reduce or prevent contamination to the drinking water supply to better protect public health (CDW & CCME, 2004). The barriers are an integrated system of procedures, processes and tools to be applied to these three elements (CDW & CCME, 2004). Processes and procedures can include physical barriers such as robust, affordable treatment technology, development of a source water protection plan, operator training, operation and maintenance of a treatment system, development of appropriate standards, appropriate water treatment plant design, water quality monitoring, and others. Tools can include guidelines, standards and objectives to compare water quality results against, methodologies such as sampling protocols, good practice guides for the effective operation of a treatment system, research and development of new treatment technologies (R&D), operator training programs, and others including the SWQI and TWQI. The MBA fits into the framework of a water safety plan. An illustration of the MBA with an outline of other procedures, processes and tools is provided as Figure 2.

Ideal multi-barrier systems compensate for the limitations or failures of one or more barriers by the effective operation of the remaining barriers (World Health Organization (WHO), 2004). This compensation minimizes the likelihood of contaminants passing through the entire system and being present in sufficient amounts to cause illness to consumers (WHO, 2004).

Two key elements of a MBA that serve a critical support function with respect to the environment and society are source water protection (SWP) and effective operation of a treatment system.

SWP minimizes impacts to the source water quality reducing our reliance on other barriers within the MBA. It can result in limiting treatment requirements and the linked cost, operation, and maintenance related considerations. This further eases operation and management risks, a burden placed on water treatment plant operators. Other environmental and societal advantages to source water protection include that it promotes a proactive verses reactive ethic of responsibility; ameliorates the state of our environment improving water quality, ecology, and our enjoyment of water resources; it secures water resources for future generations; and provides a clean source for other applications (including industry, agriculture, and other support functions including economic).

Effective operation of a treatment system is integral to a safe water supply, since it ensures the treatment system in place is performing its intended function. The treatment system requires adjustments in response to source water quality changes and operational parameters, performance of operation and maintenance related functions, and validation testing to ensure proper functioning. A safe drinking water supply is of course beneficial to society, whose access to such a resource has a strong impact on quality of life.

Therefore the following three scientific objectives can be outlined for the water quality indicators to form a link with the environment and society. They will serve to:

- Help identify the presence of gaps in the multi-barrier approach;
- Help identify parameters of concern in the source & treated water, track changes, and identify trends; and

- Help evaluate the effectiveness of source water protection initiatives/mitigation strategies and help guide source water protection planning and effective treatment plant operation.

With respect to economics, cost considerations associated with both source and treated water quality, are numerous. Some examples of associated costs include the following. There are the capital, operation, and maintenance costs associated with the treatment barriers in place for drinking water supplies; costs associated with infrastructure and energy requirements for water takings from a specified source; costs associated with an adverse impact to the treated water quality (these costs can include the loss of human lives, long term impacts on human health and the health care system, and all other associated costs related to the inquiry, remedial actions, and regaining of public trust); there are the costs to mitigate impacts from point and non-point discharges; as well as costs to develop and implement appropriate source water protection plans. Ultimately, economic considerations would have to consider the true costs, benefits, and related risks of various approaches in any decision making process. The limited timeframe and budget of this project made incorporation of all these economic considerations, into the SWQI/TWQI approach, unattainable at this time. However, guidance on one way in which an economic link to water quality can be achieved, utilizing the capital, operation and maintenance cost of treatment, is outlined in the recommendation section of this report (Section 7).

4.1.2 Measuring, Tracking and Reporting

The results of this work are intended to be applied across Canada and shared with the Canadian public. In consideration of this responsibility, it is critical that this work be scientifically defensible, and credible. Additionally, since the SWQI/TWQI results are intended to represent information from across Canada in national reporting, it is important that the approach used to evaluate, compile and report on the results be as consistent as possible. Consistency is important to enable geographic and temporal comparisons, to minimize bias introduction, and so that the results can be easily interpreted and communicated. A consistent approach with broad application and buy in also helps to ensure credibility.

Across Canada there is expected to be a lot of variability regarding important considerations in source and treated water quality indicator design. Variability is expected in the types of sources used to supply water treatment systems, the types of water quality parameters of concern, water treatment system sizes (small to large), water quality monitoring programs, applications of water treatment technologies, and legislated framework for the scale at which the indicators will be applied. This variability requires the indices to remain general enough to be applicable nationally, and yet specific enough to be locally beneficial. This balance between generality and specificity was one of the important considerations taken into account in the development of the indices presented in this thesis.

Therefore two other scientific objectives for the indicators are to:

- Provide a consistent, scientifically defensible means of compiling, evaluating and reporting on source & treated water quality; and
- Be designed to be beneficially applicable across Canada (to the extent possible).

4.1.3 Overall Scientific Objectives

In summary the overall scientific objectives of this thesis are to develop water quality indicators that:

- Link to health, the environment, society and economics (to the extent possible);
- Help identify the presence of gaps in the multi-barrier approach;
- Help identify parameters of concern in the source & treated water, track changes, and identify trends;
- Help evaluate the effectiveness of source water protection initiatives/ mitigation strategies and help guide source water protection planning and effective treatment plant operation;
- Provide a consistent scientifically defensible means of compiling, evaluating and reporting on source and treated water quality; and
- Can be beneficially applicable across Canada (to the extent possible).

4.2 Indicator Result Derivation

The indicators required a methodology to enable the generation of a representative ranking or score. Section 4.2.1 addresses the methodology to be applied in deriving indicator results and Section 4.2.2 describes the project components required in order to manipulate data to derive consistent results.

4.2.1 Methodology for the Derivation of Indicator Results

In review of the various indices and their associated aggregations, it was observed that all of the aggregations are prone to one concern or another (Section 3). Looking at a few examples (please refer to Tables 3.1 and 3.2) it is noted that the CCME WQI, which is a root mean square formula, is prone to eclipsing. The approach adopted in the UK (the arithmetic Solway weighted formulation) underestimates water quality at the lower end of the scale. The approach in Oregon (the unweighted harmonic mean square) is prone to ambiguity. The minimum operator (recommended for use in New Zealand) is not a true aggregation and does not represent a composite picture of water quality.

Another concern associated with some of the aggregations used in application is that they are tailored to jurisdictional specific considerations. For instance the approach in the UK has been fine tuned to fit within their water classification system. The approach in Oregon is based on explicit values and parameters derived for one specific surface water source.

Keeping in mind that all forms of aggregation have concerns, to achieve the objective of a scientifically defensible approach, it becomes important to select an index aggregation that has been tested in practice, whose limitations are well known so that these can be addressed, and which can accommodate considerations of relevance to source and treated water quality data in the Canadian context.

4.2.2 Source and Treated Water Quality Considerations Associated with the CCME WQI

The original CCME WQI approach is described in detail in Section 5.2. Outside of its known limitations identified in the literature, the following additional limitations were identified as part of this thesis with respect to applications to source and treated water quality. The original CCME WQI approach:

- Requires that water quality data be compared to a set of guidelines. There are, however, no guidelines for source water quality;
- Has no mechanism to accommodate the representation of water quality parameters monitored at significantly different frequencies as you would expect to encounter in source and treated water quality monitoring programs across Canada;
- Has unrealistic data requirements for systems that rely on groundwater as a source given regulated monitoring requirements in Canada;
- Has no mechanism to accommodate considerations associated with bacteriological water quality data (of fundamental importance to source and treated water quality due to their link to human health);
- Has a categorization scheme that fails to account for natural sources of impact, describing excellent scores as very close to natural conditions; and
- Presumes that the guideline value represents the toxicological significance of a parameter, which is not true of the GCDWQ.

The advantage of the original CCME WQI formulation, over all the other formulations evaluated, is that it includes consideration of not only an exceedance of a guideline value, but also the frequency and severity of an exceedance. These factors are critical to a water quality index (as outlined by Ott (1978)). The other advantages to the original CCME WQI includes that it has been used extensively in the Canadian context, and it has been applied successfully to treated water quality using the Canadian guidelines (in one special case described in Section 6.2.1).

Given the outlined advantages to the original CCME WQI approach, it was decided in this thesis that if the above identified limitations specific to source and treated water quality in Canada, could be accommodated with slight modifications to the original CCME WQI formula or to how it was applied, a modified form of the CCME WQI would be adopted. Based on the research undertaken as part of this work, this was determined to be the case. A modified CCME Water Quality Index (CCME WQI) (to be described in Section 5.2) will be utilized for the initial evaluation of source water quality and the only evaluation of treated water quality in this project.

With respect to the first limitation outlined above. The GCDWQ define an acceptable quality of Canadian drinking water and therefore become the best guidelines against which to compare source water quality. In order to evaluate the implications of source water quality with respect to drinking water supply, it is however important to consider how changes to source water quality affect the complexity of treatment required to achieve treated water of an acceptable drinking water quality ('treatability'). With this in mind, although a modified CCME WQI can be utilized to initially evaluate source water quality, a second step was developed as part of this thesis, to enable the determination of a treatability ranking (described in Section 5.3). Please note, distribution related considerations were considered outside the scope of this thesis.

The means by which the other identified original CCME WQI formulation limitations (as outlined above) were addressed are outlined in Section 5.2.

A depiction of the calculation for both the SWQI and TWQI is presented as Figure 3. For the SWQI two steps will be undertaken, both a modified CCME WQI score as well as a treatability ranking will be calculated. For source water quality, a parameter value failing a GCDWQ (resulting in a score of less than 100 in the original and modified CCME WQI) only reflects that treatment is required. To be able to evaluate the significance of the treatment required to achieve safe drinking water, the second step will be to determine a treatability ranking. For the TWQI, it is appropriate to compare treated water quality to the GCDWQ. Therefore utilization of the modified CCME WQI to represent treated water quality is the only step in this calculation.

4.2.3 Tools

As outlined in Section 4.1.3, a scientifically defensible, consistent approach for evaluating and compiling source and treated water quality was an important project objective. To ensure consistency three main project components were developed, a parameter selection rationale, a modified CCME WQI calculator and a treatability ranking tool.

Another scientific objective was to ensure beneficial applicability of the SWQI and TWQI across Canada. For this reason the three main project components were designed to accommodate considerations for the following anticipated variability:

- Use of groundwater, surface water and/or groundwater under the direct influence of surface water (GUDI) as raw water sources;
- A broad range of water quality parameters that may pose a concern in either source or treated water including physical, microbiological, chemical (organic/inorganic, volatile organic compounds (VOCs), pesticides), and radiological parameters.
- Monitoring frequencies anticipated for various source types and water treatment plant sizes;
- A range of water treatment technologies in the categories of disinfection, filtration and advanced treatment believed to be conventionally applied across Canada in response to the various water quality parameters of concern and specific to a range of water treatment plant sizes (from small to large); and
- Three scales (site specific, watershed, and national) at which the indicators could be applied depending on existing legislated water quality reporting frameworks.

To help guide parameter selection for use in the two tools, a parameter selection rationale has been developed, and is outlined in Section 5.1. This parameter selection rationale defines a parameter of concern, outlines a core set of parameters, and a series of questions to guide the selection of site specific parameters of concern in acknowledgment of the inherent variability in water quality concerns across Canada. This variability occurs due to a range of considerations tied to geologic formations, land use activities (agriculture, commercial/industrial, residential), atmospheric deposition and other environmental factors.

The two tools developed are a modified CCME WQI calculator and a Treatability Ranking tool. An original CCME WQI calculator was developed by the Government of Newfoundland and Labrador Water Resource Management Division (NL WRMD), and adapted for this project to include the considerations of the modified CCME WQI approach described herein. The Treatability Ranking tool was researched and formulated as part of this project. The Treatability Ranking tool utilizes a point rating system modified from the Association of Boards of Certification (ABC) 'Operator Certification Program Standards' Water Treatment Plant Point Rating System (used across Canada to classify water treatment plants for the determination of operator skill requirements).

The two tools can accommodate any of the three source types described, a range of water quality parameters, a minimum monitoring frequency (to be described), and various application scales. The treatability ranking tool then includes considerations for variability in system size, and treatment system requirements. The two tools are outlined in more detail in Section 5.2 and 5.3 respectively, along with technical guidance on the manipulation of data for input into these tools, and interpretation of results generated by these tools.

4.3 Data Requirements

In order to be able to utilize the SWQI and TWQI and report on them nationally, data are required that address several questions discussed in this section. Section 4.3.1 identifies decisions made on the most appropriate location for the collection of monitoring data and how users would be guided to select the relevant data to include; and section 4.3.2 addresses how the data will be collected.

4.3.1 Data Relevance & User Guidance

The best location for representative source water quality data was identified as the raw water sampling port (or location used to sample raw water as it enters the treatment plant). In the absence of raw water quality data, use of ambient water quality data was considered. However, the use of ambient surrogate water quality data is not recommended for the following two reasons. Firstly, source water quality intakes or wells are often located in order to obtain the best water quality from a particular source. This is not usually true of ambient monitoring locations which are often located to monitor for a known or potential impact. Additionally, ambient surrogate locations would not necessarily monitor for the parameters of relevance to source water considerations.

For treated water quality data, consideration was given to measuring treated water quality data immediately post treatment and prior to distribution. The advantage to this approach is that the TWQI could confirm a source waters' predicted treatability. However, as outlined in this section, the purpose of these indicators also includes relating treated water quality to public health and measuring the quality of water people drink. The TWQI will also be applied to assess the presence of gaps in a source to tap multi-barrier approach. With these goals in mind, treated water quality data should be measured at the most appropriate location (for adequate representation of risks); anywhere from post treatment to the consumer's tap.

Data requirements are further dictated by the two tools used to generate SWQI and TWQI scores. These are the CCME WQI calculator tool, and the Treatability Ranking tool. These tools require a certain minimum amount of data, and consistent input variables, in conformity with their formulations and in order to adequately represent the water quality in question. Other data requirements for these tools are further outlined in Section 5.2 and 5.3, respectively.

4.3.2 Data Collection

A challenge identified early on in the project was the collection of data for national reporting. With respect to source water quality data, a review of legislated requirements in Canada revealed that reporting of source water quality data is infrequently legislated, since the focus is usually on verification of treated water quality. To collect water quality data for the purpose of national reporting on the SWQI and TWQI, SC undertook the development of a national Drinking Water Plant (DWP) Survey in order to access data collected at a DWP level that may not necessarily be reported on. To facilitate this process technical guidance on the SWQI and TWQI data requirements and survey content was provided.

Completion of the survey will be mandatory under the Statistics Canada Act, and will include detailed information concerning the quality and quantity of source and treated water, the treatment processes in place, and associated costs. The survey will cover a three year reporting period from 2005 to 2007. SC hopes to send out the DWP Survey in spring or early summer 2008.

5 SCIENTIFIC DEVELOPMENT OF THE MAIN PROJECT COMPONENTS

Consistency is very important to enable comparability (geographical and temporal) for the given beneficial applications of the indicators (outlined in Section 3.1) and also for generating defensible results within the technical limitations of the methodology, finally to minimize the introduction of bias, and maintain credibility.

In order to ensure a consistent approach to indicator calculation and interpretation the following three tasks have been undertaken as part of this project: development of a parameter selection rationale, tools for the SWQI and TWQI calculation, and technical guidance. These are outlined in further detail herein.

It should be noted that the target audience for the use and interpretation of the three main project components (described in the sections 5.1, 5.2 and 5.3) are recognized professionals with experience and qualifications in both water quality risk assessment and treatment plant operation.

5.1 Parameter Selection

To facilitate consistency in the decision process for selecting parameters to be input into the SWQI and TWQI, a parameter selection rationale was developed. This parameter selection rationale is outlined in Section 5.1.1. A particular challenge relating to parameter selection is then described in Section 5.1.2.

5.1.1 Parameter Selection Rationale

A parameter selection rationale was developed for both the SWQI and TWQI to help guide the user on the appropriate parameters to input into the tools. For consistency, a core set of parameters was designated that is required to be selected by the user should that data be available. In acknowledgement of the inherent variability in water quality concerns across Canada, a site-specific parameter selection rationale was also included that will guide the inclusion of a minimum of three site-specific parameters. Ten parameters are considered the minimum number to be able to use the tools. Ten parameters are also considered the optimum number of parameters to minimize the potential for eclipsing in the CCME WQI formulation, where this number can adequately represent risks. However, evaluation on a case by case basis may result in the requirement to include more parameters for risk representation.

A parameter of concern to both source and treated water quality is defined as one that poses or contributes to one of the following two possibilities:

- A risk to human health; and/or
- A significant impact on the aesthetics (taste/odour/appearance) of the drinking water.

Though parameters that could pose or contribute to a risk to human health are by far more critical than those with an impact on the aesthetics of the drinking water, aesthetics were included based on the following considerations. Handling of taste and odour related parameters continues to be the biggest challenge posed in water treatment (DNH&W, 1993). Taste and odour causing compounds are the major source of consumer complaints, and drive public acceptance of the treated water (Lalezary et al., 1986; DNH&W, 1993).

The core set of parameters was determined to be those that meet all of the following criteria:

1. Are identified as parameters of concern (as defined above);
2. Commonly occurred across Canada in association with both groundwater and surface water sources;
3. Are commonly monitored in Canada; and
4. Are important considerations in treatment system design.

The core set of parameters for source water are:

1. *Escherichia coli.;*
2. total coliforms;
3. turbidity;
4. nitrate/nitrite;
5. total organic carbon;
6. iron; and
7. manganese.

The core set of parameters for treated water[3] are:

1. *Escherichia coli.;*
2. total coliforms;
3. turbidity;
4. nitrate/nitrite;
5. disinfection byproduct(s) (DBP(s)) (dependent on the source water quality and treatment processes in place); The appropriate DBPs to monitor should be selected from this list which includes DBPs with a GCDWQ or for which a GCDWQ is in preparation:
   a. Trihalomethanes – total (THMs);
   b. Bromodichloromethane (BDCM);
   c. Haloacetic Acids – total (HAAs);
   d. Chlorate/chlorite; and or
   e. Bromate;
6. iron;
7. manganese; and
8. disinfection residual (dependant on disinfectant added to process);
   a. free chlorine residual; or
   b. combined chlorine residual.

Table 5.1 outlines some more background information on the core parameters and helps provide additional material supporting their selection. Table 5.1 includes an outline for each core parameter of their constraints in drinking water, common composition and

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[3] samples collected post treatment and/or in distribution system and/or at the tap

from where they originate, treatment related considerations, effect on human health and common treatment strategies used for their removal.

The following decision matrices outline questions to be used for selecting the minimum three site-specific parameters. Selection of any parameter should be based on a site-specific risk assessment from source to tap. All parameters selected should meet the definition of 'parameter of concern' as defined above.

In acknowledgement of the fact that there could be very large data sets, users are encouraged to preferentially select parameters:

- Exceeding or approaching a guideline/standard or site specific target (Please note: parameters do not need to have a GCDWQ to be included); or
- Detected above the detection limit.

Site-specific parameters to select in the source water include those that:

- Have been identified as a parameter of concern specifically for the source water in question;
- Could interfere with the proper functioning of a barrier in place (e.g. turbidity);
- Require adjustment for operational considerations (e.g. pH); and/or
- Could act as a precursor to the formation of a disinfection by-product (e.g. total organic carbon).

Site-specific parameters to select in the treated water include those that:

- Have been identified as a concern specifically for the source water in question;
- Must be controlled to protect public health (e.g. disinfectant residual);
- Could be created or introduced as a result of the treatment process (e.g. chlorate, or chlorite); and/or
- Could be introduced from the distribution or domestic plumbing systems (e.g. lead).

5.1.2 A Data Requirement Challenge

The data requirements as outlined in the parameter selection rationale above and for the two tools (Section 5.2 and 5.3) are necessary to conform with the technical limitations of the tool scoring derivations, and in order to adequately represent source and treated water quality. In a review of legislated water quality monitoring undertaken in Canada, it was identified that the monitoring and reporting of treated water quality is more heavily regulated than source water quality. Additionally, sites that utilize groundwater as their source waters, and smaller treatment systems, typically have less comprehensive monitoring programs, and are not monitored as regularly as surface water sources or larger treatment systems.

Regularly monitoring core sets of parameters related to health, aesthetic and/or operational considerations in the source water, is a good management practice. It is an important practice to ensure that the water quality (condition) that the treatment system design was based on has not changed; that the source water protection barriers in place are effective; and that the treatment system is adequately designed and operated to handle the influent water quality.

5.2 The CCME WQI Calculator Tool

The Original Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) – CCME (2001)

The CCME developed a water quality index (WQI) in 2001 for aquatic systems. The CCME WQI adopted the approach used in British Columbia (as modified by Alberta Environment (CCME 2001b)), based on its extended use and broad application (CCME, 2001a). The original CCME WQI aggregates three factors, F1 (scope), F2 (frequency) and F3 (amplitude) from only measured (and not probabilistic) values over a given time period (CCME, 2001a). F1 represents the percentage of parameters (out of the total number of measured parameters) having failed to meet their guideline at least once during the time period under consideration; F2 represents the percentage of individual tests (out of the total number of tests taken) where a parameter failure is reported; and F3 accounts for the amount by which parameters fail their guidelines (CCME, 2001a,b). Ott (1978) also outlined the importance of including both frequency and severity of an exceedance in an indicator. The CCME WQI is a decreasing scale index ranging from 0 to 100, where a high score indicates good quality (CCME, 2001b). The formulae are given below:

CCME WQI F_1 (Scope): $$F_1 = \left(\frac{\text{\# of failed parameters}}{\text{total \# of parameters}} \right) \times 100$$

CCME WQI F2 (Frequency): $F_2 = \left(\frac{\text{\# of failed tests}}{\text{total \# of tests}} \right) \times 100$

CCME WQI F3 (Amplitude): $F_3 = \left(\frac{nse}{0.01\, nse + 0.01} \right)$

Where *nse* is the normalized sum of "excursions", given by:

$$nse = \left(\frac{\sum_{i=1}^{n} excursion_i}{\text{total \# of tests}} \right)$$

Where *n* is the number of failed tests and an excursion represents the amount by which a maximum guideline (objective) is exceeded in a given failed test *i* (or a minimum guideline is not reached), and is calculated as follows:

$$excursion_i = \left(\frac{Failed\ Test\ Value_{\ i}}{Objective_{\ i}} \right)^{a} - 1$$

Where a is equal to 1 when the guideline is a maximum not to be exceeded by the test value and a is equal to negative 1 when the guideline is a minimum that must be achieved.

The F3 formula produces an asymptotic function that scales the result to fall between the range of 0 and 100. The range of 0 to 100 is necessary to have an equal scale for each of the F1, F2, and F3 sub-indices. The asymptotic function depicted in Figure 4 is on a logarithmic scale that minimizes the relevance of small excursions and maximizes the relevance of large excursions in the F3 result. As depicted any nse that is less than 0.1 falls in the range of 0 to 10. A nse value of 1 gives a F3 value of 50 and any nse over 10 has an F3 value from 90 to 100.

Finally, the CCME index is calculated based on 100 minus the quadratic average (root mean square) of the three factors as follows:

CCME WQI: $CCME\ WQI = 100 - \sqrt{\left(F_1^2 + F_2^2 + F_3^2\right)/3}$

In this formula, F1, F2, and F3 are given an equal weighting of importance. The quadratic average of the three factors is then subtracted from the ideal score (100) in order to have a decreasing scale. The root mean square formulation is often utilized in index development and is prone to eclipsing (refer to Table 3.1 and the discussion in Section 3.3). A feature of this formulation is that differences in F1, F2 or F3 values are amplified by the fact that they are squared.

The above formulae and aspects of the description are copied and paraphrased from (CCMEb, 2001). An example of an original CCME WQI calculation is provided in Appendix 2. The CCME WQI score from 0 to 100 is subdivided into five categories as outlined in Table 3.4.

The following known concerns were identified in the literature with respect to the original CCME WQI formulation:

- It is highly sensitive to sample design and parameter selection (CCME, 2001b; Zandbergen and Hall, 1998); a characteristic that is not unique to the CCME WQI formulation: House (1989) also identified this concern with the UK water quality index;
- It is important to point out that for a given system, although the probability of measuring an exceedance is constant (relative frequency of observations), the number of observed exceedances increases (absolute frequency of observations) as the number of measurements increases. For this reason a large data set holds a disadvantage for the F1 factor (Mercier and Léger, 2005a; Zandbergen and Hall, 1998) which can saturate with too many variables (CCME, 2004); The F3 factor can also saturate where very large exceedances in comparison to the guideline value are measured for frequently monitored parameters. This is particularly problematic for bacteriological factors, a topic that is discussed in more detail under the heading of 'Bacteriological Data' in Section 5.2.1 below;
- The momentary failure of many variables is scored much more severely than the repeated failure of one variable based on the F1 factor. This may not hold true from a toxicological standpoint (Mercier and Léger, 2005a);
- It does not give warning of worsening water quality until guidelines are exceeded; (Zandbergen and Hall, 1998);
- Often in practice, the frequency of water quality monitoring is spaced out over time. For instance samples can be collected seasonally (once every three months).

In this event the CCME WQI score is unlikely to reflect transient or short term events (e.g. storms, chemical spills, or pesticide run-off). This can result in the WQI score categorizing water quality as good or excellent, when on a day to day basis (for instance) it may not be (CCME, 2004). This is particularly important in surface water quality, where conditions are said to be at their worst during storm events, which can account for 60-95% of annual loadings of pollutants in urban areas (Bellevue 1995; Macdonald et al. 1997 as outlined in Zandbergen and Hall, 1998). The inability to reflect short-term events is a communication challenge for local water quality (Mercier and Léger, 2005a); and

- It does not show the key indicators driving the CCME WQI score (CCME, 2004).

Any application of the CCME WQI needs to give due consideration upfront regarding the formulations' identified limitations (Mercier and Léger, 2005a). Some of these concerns have been addressed in the development of the modified CCME WQI calculator for the SWQI and TWQI, with technical guidance provided for proper application and result interpretation.

Restrictions on how the CCME WQI should be applied as outlined in the literature include:

- Comparisons should only be made when the same guidelines are being used (CCME, 2001a);
- Comparisons should only be made when the same parameters are being used (CCME, 2001a);

- Care is required with older data sets tested using different analytical methods (CCME, 2001a);
- The parameters included should be relevant to the water body being represented (CCME, 2001a) and at least four parameters should be included (CCME, 2001b); and
- Minimal data sets (with less than four monitoring events in a given year) should not be used (CCME, 2001a) and a minimum of three years of data are required (CCME, 2004). The result should be accompanied by a statement explaining its significance (CCME, 2001b).

These recommendations have been adopted in this thesis with the exception of the following two. Firstly, a minimum of 10 parameters will be required for the SWQI and TWQI as described in Section 5.1.1, to minimize eclipsing in the CCME WQI formulation. Secondly an exception has been made to the minimum data set for groundwater sources only, allowing two monitoring events a year, based on the consideration that groundwater will be more stable than surface water sources. This second exception is further described in the following section.

5.2.1 Application of the CCME WQI to the SWQI and TWQI

As part of this project, the Government of Newfoundland and Labrador Water Resources Management Division (NL WRMD) was asked to evaluate the feasibility of applying the CCME Water Quality Index (CCME WQI) to specific considerations associated with the SWQI and TWQI (identified in Section 4.2.2). The following text outlines the results of the work performed by NL WRMD as outlined in their report (NL WRMD, 2007), that have been adopted herein. Additional recommendations are also included that have been derived as a result of this project.

Temporal Roll Up

It was identified that in source and treated water quality monitoring programs, there would be inconsistency in the frequency by which the various parameters would be sampled at each given site. This frequency was estimated to range anywhere from continuous monitoring to once every five years. When combining data into the CCME WQI for calculation, care would be required to give each parameter reasonable representation with respect to each other, and to ensure proper application of the CCME WQI mathematical formulation. In order to do this a methodology was required to enable the temporal roll up of frequently monitored parameters.

Temporal roll up can be explained as a way to represent multiple monitoring results for a given parameter, over a given time period, as one value. Roll-up methods considered included a mean, median, maximum or a percentile. The following itemized text presents the recommendations put forth in collaboration with the NL WRMD (NL WRMD, 2007) that have been adopted here.

1. Parameters should be rolled up temporally when there is a significant disparity between parameter monitoring frequencies. An example includes one parameter monitored daily, and other parameters monitored as a suite on a quarterly basis to

represent the same site. The reason for the temporal roll-up is that significant temporal variation results in a loss of representation of the less frequently monitored parameters for Factor F2 in the CCME WQI calculation. Although the calculator can manage large temporal data gaps for computational purposes, it is being recommended that data sets with large temporal variation utilize a roll-up method to avoid the loss of representation of the less frequently monitored parameters. Roll-up also helps to counter the effects of temporal autocorrelation when sampling is at a relatively high frequency, in which case, the time series has to be re-sampled at fewer, randomized time intervals.

2. For application of the CCME WQI, a minimum of six sampling events will be required to be included for groundwater sites, equating to two sampling events a year over a three year period. This minimum monitoring frequency is somewhat arbitrary and has been selected in order to enable the inclusion of more groundwater (GW) sites which are anticipated to be monitored on a less frequent basis than surface water (SW) sites. Four sampling events a year, for a total of twelve monitoring events will be required as an absolute minimum for surface water sites. The three year period has been adopted for consistency with the use of the CCME WQI in the CESI project. Despite this minimum allowance for groundwater, it is however strongly recommended that at a minimum four annual sampling events to represent seasonal fluctuations in water quality be collected (as a best management practice) and included for the three years of data. For both surface water and groundwater, it is recommended that sampling take place randomly within these seasonal time scales for the laws of probability to apply and to capture various water quality events. The temporal period to be represented by a rolled-up value for each

parameter at a site should be based on the size of the treatment plant. Although there are no standard parameters and monitoring frequencies across the National jurisdictions, generally similar trends in monitoring frequencies were observed. The following recommendations are being made:

- large systems that conduct monitoring on a monthly or more frequent basis should roll up monitoring data into monthly values;
- Medium sized systems that conduct monitoring on a quarterly or more frequent basis should roll up monitoring data into quarterly values;
- Small sized systems that conduct monitoring on a less frequent sampling schedule require at least two sampling events a year in order to be able to apply the CCME WQI calculator. Monitoring data in these cases should be rolled up to biannual values; and
- In all cases, monitoring should be rolled up to the largest possible frequency (i.e. choose monthly over quarterly, and quarterly over biannually where possible).

3. Professional judgment must be used in selecting the value used to represent a temporal period. Data should be screened carefully to ensure the value selected is representative of the overall water quality and any potential risks represented by that water quality. In general, the maximum value measured of a parameter should be used over a given temporal period to represent that parameter during that temporal period. In some cases a maximum may not be appropriate. An example includes where a parameter has an optimum range (e.g. for pH where a low value may be undesirable).

4. The NL WRMD further recommended that the CCME WQI only be calculated using measured values when rolling up data. The maximum value was recommended since it is the most conservative and would capture any adverse water quality results.

Bacteriological Data

Bacteriological data are of fundamental importance to drinking water quality considerations. The formulation of the CCME WQI was not designed to handle bacteriological data. With respect to surface water quality, bacteriological data can range considerably in amplitude. For this reason, bacteriological data saturate the CCME WQI with respect to the amplitude by which the two core parameters, *E.coli* and total coliforms, exceed their zero guideline (zero guidelines pose a difficulty in the F3 criterion through the excursion calculation) for surface water sources. As an alternative to the zero GCDWQ, for surface water sites a threshold target value of 100 coliform-forming units (cfu)/100 mL can be used in the CCME WQI calculator for source water (NL WRMD, 2007) if the treatment in place can achieve greater than a 5 log removal (reducing the raw concentration of 100 cfu/100 mL to an effluent concentration of <0.001 cfu/100 mL which approximates zero) (NL WRMD, 2007). It is recognized that this is not the ideal solution because it relies inherently on the treatment barrier in the multi-barrier approach. Where a 5 log removal is not anticipated, only a treatability ranking should be calculated.

Several Modifications Being Proposed For Piloting

An alternative to both the utilization of a temporal roll up and bacteriological threshold value that requires further evaluation is the feasibility and mathematical appropriateness of calculating the F1, F2 and F3 factors on a parameter by parameter basis, utilizing all of the available data and existing guidelines. The new formula would be:

$$\text{CCME WQI Modified:} = 100 - \sqrt{(\sum_{i=1}^{n}(F_{1i}^{2} + F_{2i}^{2} + F_{3i}^{2})/3n}$$

Where n is the number of parameters. In this formulation, all parameters are given an equal weight in the quadratic mean.

Another unique challenge is posed by bacteriological data in treated water. Instead of measuring cfu/100 mL, many sites monitor for presence or absence of *E.coli* and total coliforms, since any exceedance is a failure of the GCDWQ. Since a numerical value is required for the calculation of the CCME WQI result in the calculator, it is proposed here that a positive presence test be approximated. In the absence of any risk assessment information, a value of 10 cfu/100 mL could be utilized. However a better approximation should be made using professional judgment where risk assessment information is available. The 10 cfu/100 mL is an arbitrary number, and requires pilot testing to ensure that this value adequately captures this risk in the resulting modified CCME WQI score. Absence would be entered as a value of 0 cfu/100 mL.

Another alternative that could be applied would be to calculate the probability of failing the test. That is of having one or more cfu/100 mL in a single test, given μ, the average measured number of cfu/100 mL. This probability is obtained from the Poisson distribution as follows:

$$\Pr(\text{result} \geq 1 \text{ cfu/100 mL in a single test}) = 1 - \exp(\mu)$$

This probability could then be used to produce an excursion number in the calculation of F3. (This probability calculation could be applied to any discrete parameters in the SWQI and TWQI calculations).

One technical concern with the CCME WQI, addressed for the first time in this thesis, is the presumption of the toxicological significance of guideline values. The CCME claim that "the index avoids the problem of weighting different variables that exceed an objective or guideline by treating all variables that are retained with equal importance. Since the relative impacts of different chemicals such as copper or PCBs are addressed during the development of water quality objectives, further weighting is not warranted" (CCME FAQS website, 2005).

This presumption that the relative toxicity of a parameter is accounted for by the guideline value is not true of the GCDWQ. For the GCDWQ, guideline values are determined in consideration of toxicology, uncertainty factors, treatment achievability, and the capability of analytical methods to accurately detect the parameter at the guideline value. Therefore GCDWQ values cannot be used as a basis for establishing the relative toxicological significance of one parameter over another, and care must be taken to not misconstrue it as such.

An alternative that requires evaluation to account for the significance of parameters relative to others would be to include a parameter weighting. Utilizing the previously proposed CCME WQI modified formula above, a weighting function could be introduced for each parameter as outlined below.

CCME WQI Modified with weighting:

$$= 100 - \sqrt{\sum_{i=1}^{n} w_i(F_{1i}^2 + F_{2i}^2 + F_{3i}^2) \, /(3 * \sum_{i=1}^{n} w_i)}$$

In this example each parameter is assigned a unique weight w_i, and n is equal to the number of parameters. The formula is divided by the sum of all weights. This approach would require a careful evaluation of the potential impact of each parameter on a water quality's suitability to assign a scientifically defensible weight.

The recommended approaches to be adopted, and alternatives being recommended for consideration, will all require pilot testing. Based on pilot testing results, the modified CCME WQI methodology should be further refined.

Calculator Development

The calculator developed in collaboration with the NL WRMD not only calculates a modified CCME WQI score for the SWQI and TWQI, it also includes sensitivity analysis, parameter flagging, and grouping subset functions. The sensitivity analysis function enables a user to identify worsening water quality trends before an exceedance of a guideline occurs. (This was a shortcoming identified in the literature with the original CCME WQI calculation). This is done by modeling the CCME WQI result as parameter concentrations are arbitrarily increased by user defined percentages. The parameter flagging function enables a user to identify when a parameter has exceeded a user defined threshold value. In this function a user can enter a threshold value that is lower than the guideline value, and the parameter will be flagged in the calculator output if this threshold value is reached. The grouping subset function is valuable as it enables the selection of a labeled series of data (for instance all results collected within a given three year period) out of a more comprehensive data set. Other advantages to the modified CCME WQI calculator design are outlined in its application described in Section 6.

5.3 Treatability

The Treatability Ranking tool has been created to rank source water quality with respect to the complexity of treatment required to meet the GCDWQ. The tool is basically a calculator that generates points based on a pre-defined point rating system in response to user inputs. In development of this tool, a range of treatment processes conventionally applied in Canada was selected. A point rating system which forms the basis for determination of a Treatability Ranking underlies the entire application. This point rating system has been modified for this application from the ABC 'Operator Certification Program Standards' Water Treatment Plant Point Rating System (used across Canada to class water treatment plants for the determination of operator skill requirements). Modifications to the ABC classification system in this application were made based on application specific considerations and professional judgment. The point rating system and the treatment processes included are presented in Table 5.2.

5.3.1 Point Rating System

Inputs to the rating system consist of source water type, treatment plant capacity, responses to questions regarding source water quality concerns, source raw water quality concentrations, and treated water quality target concentrations. For each input, there is either a simple, moderate or complex point rating calculation as outlined in Table 5.2. The simple point rating is determined by a user selecting between more than one alternative, with each alternative having a pre-defined score. The moderate point rating is still relatively simple; however, it requires either a calculation or a little more logic to be performed by the application to derive a score: it compares whether parameter concentration(s) is/are less than, greater than, or equal to its/their guideline value(s). The complex point rating system involves the program evaluating the raw water concentrations against the treatment targets entered by the user for each specific parameter. The evaluation utilizes a predefined logic consisting of constraints and constants to select an overall treatment outcome from a pre-defined set of treatment alternatives. The total sum of points at the end of the program places the source water into one of five treatability categories.

5.3.2 Data Entry Requirements and Treatability Ranking Tool Logic

The Treatability Ranking tool functions in the following manner:

1. The first data entry requirement is a selection between groundwater (GW) and surface water (SW) or ground water under the direct influence of surface water (GUDI). For the purpose of this application GUDI is considered equivalent to SW. Points are assigned to the selection (see Table 5.2) and additionally this selection determines the initial available list of unit treatment processes based on source type (appropriate unit treatment processes based on source type were determined from a literature review). A constraint within the application requires that all results include disinfection; and the SW/GUDI selection makes the addition of filtration mandatory;

2. The next data entry requirement is plant capacity. Points are assigned to the plant capacity (see Table 5.2), and additionally this value categorizes the simulation into a small, medium or large water treatment plant, further limiting the viable unit treatment processes (appropriate unit treatment processes based on plant capacity were determined from a literature review);

3. Next, a yes or no response is entered for questions pertaining to the source water quality concerns of algal blooms and taste/and odour for which only points are assigned (Table 5.2);

4. Next, parameter data entry takes place. There are eight parameter tables included in the Treatability Ranking tool in the following categories: Core Parameters (from the Parameter Selection Rationale); Operational Parameters; and Site Specific Parameters (6 tables): microbiological, related to algal blooms, radiological characteristics, inorganics, organics, and pesticides. As outlined in Table 5.2, depending on the concentration entered for several of these parameters (iron, manganese and colour), additional points will be generated.

As outlined in the parameter selection rationale, users are required to enter a raw water concentration for ten parameters (seven core and a minimum of three site specific). Users are also encouraged to enter source water concentration data for operational parameters (pH, alkalinity, ammonia, bromide, colour, and hardness) where the data are available (these can count towards the site specific parameter requirements). These operational parameters impact the selection of appropriate unit treatment processes as part of the constraint logic.

The source water concentration entered by the user should represent the maximum value reported for that parameter over the same three year period utilized to determine representative CCME WQI values. The only exception to this is for the microbiological parameters. Where more than ten source water quality monitoring events took place for the microbiological data, users are encouraged to use a 95th percentile to represent the microbiological data. Where ten monitoring events have not taken place, then the maximum value over the three year period should be used.

It is duly noted that the core set outlined may not form part of a given utilities data set. In that event, utilizing the parameter selection rationale, the parameters of most relevance (minimum of ten) should be included. Due to the uniqueness of parameters selected in this scenario, it would not be possible to make geographical comparisons utilizing this data set and another that used the recommended core and site specific parameter approach.

The user is also expected to enter 'Treated Water User Defined Targets'. The GCDWQ are included as default targets where available, and other proposed targets are included from the literature where GCDWQ are not available.

5. The program then takes the 'Raw Water User Defined Maximum Concentration' (e.g. 100) & 'Treated Water User Defined Targets' (e.g. 0.001) values entered to calculate the required removal and to make the final selection of a treatment process.

   Eq: $|\log_{10}$ of (treated target/raw concentration)$|$ = required log removal

   e.g. $|\log_{10}(0.001/100)| = |-5| = 5$

The required log removal calculated above was then compared to estimated removal efficiencies included in the Treatability Ranking tool. Log math allows for the removals of unit treatment processes to be summed, to mimic the removal effect of treatment processes in series. The application then selects unit treatment processes for all the inputs that generate the least number of points (see Table 5.2), while achieving the required removal.

The unit treatment process removals included in the Treatability Ranking tool were estimated based on the results of laboratory, pilot and full scale studies found in a review of the literature. It should be further noted that these removal efficiencies were at times quite broad in range for the same parameter and treatment process. At other times only one value was identified. Where only one value was available it was often included in an effort to make the tool as complete as possible. Every attempt was made to make the ballpark estimates in the Treatability Ranking tool representative of an average removal. All of the removal efficiency values included will require further validation as more technical data become available.

A few additional constraints were incorporated into the tool based on a very limited consideration of some known generic factors that could interfere with the proper operation of a treatment process. These included: inclusion of an additional unit treatment process to reduce a concentration before another unit treatment process would be effective (e.g. reducing hardness for ultraviolet light to be effective); and disallowing the consideration of a unit treatment process if a parameter concentration was too high (e.g. turbidity would need to be below a certain value to consider direct filtration). These constraints further limited the viable unit treatment processes that could be considered in the final result.

6. A tally of all points as outlined in Table 5.2 is made after the entire calculation is complete. The total points rank the source water quality into a category from easy to treat to hard to treat. This division into categories is currently quite arbitrary and will require further piloting.

An example Treatability Ranking calculation for GW is included as part of Appendix 2.

5.3.3 Other Treatability Approaches

In October of 2005, the USEPA Office of Research and Development undertook a five year project for the creation of a treatability database. The initial USEPA project scope was estimated to include removal efficiency information for up to thirty unit treatment processes and 250 parameters (PennWell, 2007).

The Treatability Database (USEPA) will be a web-based database containing comprehensive summaries of treatment removal information for given parameters from laboratory, pilot and full scale studies described in the literature (Speth and Miltner, 2007).

At the present time, only nine parameters of relevance to the Treatability Ranking tool were scheduled to be completed in the USEPA Treatability database (Miltner et al., 2007). Time constraints did not enable the Treatability Ranking tool to be validated and updated with this information. It is however, very strongly recommended that this excellent resource be used to update and refine the Treatability Ranking tool as the USEPA information becomes available. This will be considerably important in ensuring a scientifically defensible approach, since the removal efficiency values currently included in the Treatability Ranking tool are based on only limited references.

5.4 Categorization & Result Interpretation

The following section will outline the approach adopted for result categorization and some considerations in this and result interpretation.

5.4.1 Categorization of the CCME WQI Score

The determination of the values that fit into the CCME WQI categories (Table 3.4) was based on a critical yet subjective process (CCME, 2001a). The categorization system is described as based on the best available information, expert input and expectation of what water quality should be. In originally deriving the categories, they expected that they would be modified over time based on use and experience (CCME, 2001a).

A modification to the CCME WQI categories was made as described in Khan et al., (2004) to introduce a 'very good' category between 'good' and 'excellent' when evaluating treated water quality. Adoption of this modified version of the CCME WQI categorization is recommended herein for the TWQI. This change is described in Section 6 of this thesis.

For the SWQI, as noted in Section 4.2, application of the GCDWQ to evaluate source water quality is not really appropriate, since source water is not expected to be consumed, but rather treated and distributed before consumption. Through a Drinking Water Plant survey being conducted by Statistics Canada, to be able to pilot the SWQI and TWQI and report on them nationally, considerable water quality data will become available. Through this work, modified CCME WQI scores and treatability rankings will be developed for a considerable number of water quality data sets. An interesting exercise that should be undertaken is to compare the modified CCME WQI score derived for source water quality to see if it correlates well with the treatability ranking. If a good correlation can be determined, then it may be possible to amalgamate the two approaches into a new classification system that reflects both water quality and treatability, similar to the categories (Table 3.4) assigned by House (1989) for application in the UK.

5.4.2 Categorization of the Treatability Ranking

At this time there are five arbitrary treatability ranking categories. They are currently titled: easy to treat, moderately easy to treat, moderately hard to treat, hard to treat and exceptionally hard to treat. These categories have been arbitrarily assigned the range of scores from 0 to 15, 16 to 40, 41 to 70, 71 to 100 and anything greater than 100. These ordinal scores will need to be refined as data become available to test the tool, and user input can be considered. The expectation with these categories is that they will reflect an increasing treatment complexity as the source water quality worsens. Those source waters only requiring disinfection will fall into the easy to treat category. Those requiring disinfection and filtration will fall into the next category, and so on until the breadth of possible treatments in the Treatability Ranking tool is considered.

5.4.3 Qualifying Indicator Results

The most critical consideration in interpreting the SWQI and TWQI results is the potential implications for public health. It has been recommended in Section 6 that any site-specific reporting of the SWQI and TWQI be done in real time. It has been further recommended that the methodology utilized by the Government of Newfoundland and Labrador be adopted.

Further to this, both the CCME WQI calculator and Treatability Ranking tool enable a distinction between health and non-health based parameters. In the CCME WQI calculator, users are encouraged when entering GCDWQ and/or target values to enter a column of values for health and non-health based considerations. The calculation can then distinguish between the two types of guideline values and when reporting the results flag if a health based guideline has been exceeded.

For the Treatability Ranking tool, where both aesthetic and health based targets exist for the same parameter, simulations of the Treatability Ranking can first be run utilizing only health based targets and secondly utilizing only aesthetic based targets. This functionality can be used to ascertain which of these are driving the treatment complexity.

6 INDICATOR APPLICATIONS FOR DECISION MAKING

This section will address how the indicators can be applied in decision making. It will include a discussion on water treatment system size and source water type; the various scales to which the indicators can be applied, including site specific, watershed/aquifer, and national; how the indicator(s) can be used in trend analysis; and finally other potential beneficial applications for the indicators.

6.1 Water Treatment System Size and Source Water Type

The data requirements of the SWQI and TWQI methodology will determine the appropriateness of these tools for different sizes of water supply systems. Every effort has been made to incorporate considerations for the range of small to large water treatment plants, while respecting that a minimum amount of data are required to generate an indicator that will adequately represent water quality conditions. Constraints have been built into the Treatability Ranking tool (discussed in Section 5.3) to screen treatment processes for appropriateness based on the designed plant capacity.

With respect to source water used for drinking water supplies across Canada, inclusion of groundwater and GUDI, and surface water was considered essential. This decision is supported by the following conclusions.

From a tabulation of 1996 Provincial and Territorial data on groundwater and surface water use in Canada, approximately twenty five percent (25%) of the Canadian population relies on groundwater as the source for their drinking water. Approximately two thirds of these groundwater supplies are located in rural areas, and the remaining predominantly in smaller municipalities. Nationally, groundwater accounts for the primary source of drinking water in some provinces including Prince Edward Island (100%), New Brunswick (60%) and Yukon (60%) (HC, 2003).

Additionally, although surface water supplies account for the supply to the remaining seventy five percent (75%) of the Canadian population, these supplies are predominantly located in Canada's large urban centres. The smaller water systems, mostly groundwater, account for the majority of water supply systems in Canada and, due to their predominant rural and remote applications (HC, draft 2007), are important to National coverage and representation. It should be further noted that due to the limited resources (including economic and trained personnel) often associated with the smaller water supply systems, the multi-barrier systems in place at these locations are typically not as robust as the larger systems, and therefore are at greater risk with respect to public health concerns (Ford et al., 2005).

Groundwater therefore represents an important amount of Canadian source water, and is integral to a broad geographical representation, and to adequately represent the range of water treatment plant sizes and their associated health risks.

6.2 Applications at Scale

The following outlines how the indicators can be applied at various scales for decision making.

Illustrations of the recommended site specific, watershed/aquifer and national applications are depicted as Figures 5, 6 and 7 respectively, and should be viewed concurrently with the following descriptions.

6.2.1 Site Specific (Figure 5)

Figure 5 illustrates use of the SWQI and TWQI at a site specific scale in relation to the MBA. On the right hand side of the figure the three elements of the MBA (source, treatment and distribution) are shown, leading to the tap (drinking water). On a site specific scale by calculating the SWQI and TWQI and monitoring for parameters identified in the parameter selection rationale, risks can be identified in the source and treated water, and by this mechanism help to identify gaps in the MBA.

Other additional applications at the site specific scale include the following. The CCME WQI calculator tool, described in Section 5.2, will enable individual parameter tracking in comparison to the GCDWQ, sensitivity analysis to evaluate if a parameter is approaching a guideline value, and parameter flagging for evaluating parameter concentrations against a user defined artificial target. Utilizing the functionality of the CCME WQI calculator tool, the indicators can be used to identify parameters of concern in both the source and treated water quality.

The parameter selection rationale (outlined in Section 5.1) for instance, will stimulate thought into what risks might be present. This thought process may lead to decisions in optimizing the monitoring programs in place to better capture the identified risks.

Where parameters of concern are identified in either the source water or treated water, a risk assessment and an evaluation to determine a causal relationship, should be undertaken where appropriate. The Treatability Ranking tool (outlined in Section 5.3) can also be utilized to model the implications of various water quality scenarios on treatment complexity. This can help guide where a SWP strategy may be most effective, targeting parameters that may be hard to treat and/or for which a treatment barrier is not in place or identify the need for an additional treatment barrier.

With respect to tracking, if water quality data are consistently collected and evaluated over time, a deteriorating, improving, or stable water quality condition can be identified. If the water quality remains stable or improves, then it may be possible to link that outcome to the source water protection strategies implemented and decide to continue investing in them. If the water quality condition deteriorates, then the results may be beneficial in helping to guide decisions into better source water protection planning. Similarly, for the treated water quality, if it remains stable or improves over time, then it may be possible to link that outcome with treatment plant operation strategies, or perhaps to the source water quality. In this way, identification of a deteriorating treated water quality may help guide either or both source water protection planning and treatment plant operation.

It is important to note that in some cases there will be source water quality parameters that no source water protection measure could alter. This can be the case when there are natural parameters of concern. These parameters of natural origin may also contribute to the complexity of required treatment, ultimately negatively influencing the SWQI and/or TWQI result.

Based on the results of the overall evaluation, suitable procedures, processes and tools within the multi-barrier approach can then be decided upon for application.

An indicator is meant to serve the role of simplifying complex data for communication to the public. For site specific reporting on the SWQI and TWQI the following is recommended. Site specific reporting requires a far more careful communication approach, since the public may use the results to make decisions regarding the safety of their drinking water. The first recommendation is that this type of reporting be made in real time (utilizing one comprehensive monitoring event and not three years of data), and that both the SWQI and TWQI results be reported together with interpretative text outlining their significance from a human health perspective. For reporting on the TWQI, the approach that has been implemented by the Government of Newfoundland and Labrador is an excellent example. This approach is outlined below. It is also possible that more recommendations may be available from the Government of Newfoundland and Labrador on this approach based on their further experience.

Application of the CCME WQI to Treated Water Quality Data

In 2004 the Government of Newfoundland and Labrador Water Resource Management Division (NL WRMD) published a paper on their work in applying the CCME WQI to the communication of drinking water quality data (Khan et al, 2004). NL WRMD undertook some testing, asking officers their expert opinion on the CCME WQI classification of water quality results. The general finding was that a further categorization was required between 'good' and 'excellent' for 'very good' water quality. A 'very good' category was determined to fall in the point range of 89 to 94.

NL WRMD decided that since the public relies on their reports to ascertain the quality and safety of their drinking water, instead of a CCME WQI score, if a contaminant of human health concern is detected in the most recent sample, the report will direct them to contact their health authority for guidance, listing the parameter(s) that exceeded its (their) guideline(s) and a cautionary qualifier(s) (Khan et al, 2004).These qualifiers can be in the form of a boil water advisory (BWA) where appropriate (Khan et al, 2004).

6.2.2 Watershed/Aquifer (Figure 6)

As illustrated in Figure 6, the SWQI and TWQI can be applied on a watershed scale. In the Figure if you picture points A, B, C and D as communities within a watershed, with all tributaries moving downstream towards community D, the following exercise can be undertaken.

The indicators can be calculated for each water treatment plant within the watershed. In Figure 6, SWQI scores decrease with respect to source water treatability as the water quality moves downstream from community A to D, showing a negative water quality impact from contributing tributaries. Despite the increased degradation of source water quality however, the various treatment plants (based on their effective operation) are however still able to achieve a reasonably good treated water quality with modified CCME WQI scores of 85 or 90.

Applications at the watershed scale include the following. Water quality can be tracked along the watershed and utilized to guide source water protection and/or treatment plant operation. The SWQI may provide insight into tributaries (and their respective water capture areas) contributing to an identified water quality concern. This will narrow the evaluation into the origin of the identified concern, and provide insight into the most effective location(s) to apply source water protection efforts. The Treatability Ranking tool and TWQI will help identify what source water quality parameters are most challenging to handle at the treatment plant, and help guide the most appropriate source water protection measures.

Source water quality tracking along a watershed may also guide the identification of potential water quality concerns that could make their way downstream. This could help create awareness for water treatment plant operators, help guide response planning, and stimulate a communication network between water treatment plants. With respect to water treatment plant operation, this may also provide the necessary warning to have the appropriate barrier in place to handle any imminent concerns identified.

These benefits are equally applicable within aquifers where groundwater wells are known to be instrumented within the same water tables, and the hydrogeology including direction of groundwater flow is well understood.

National (Figure 7)

As depicted in Figure 7, the modified CCME WQI score for the TWQI is on the Y axis, and the SWQI treatability ranking is on the X access. By placing a point within the corresponding XY scatter plot, that represents both the original source water treatability and ultimate treated water quality, a national picture of water quality across the country can be created.

Looking at a summation of points by column and row, this scatter plot can be analysed to determine the number of water systems nationally, falling into categories ranging from easy to treat to hard to treat for source water quality and poor to excellent for treated water quality. The scatter plot enables a comparison between the source water quality to be handled by the treatment process and the treatment outcome. Knowing that ideally a good to excellent treated water quality is desired, this enables an evaluation of whether application of that treatment to the source water was successful. These results can be computed to determine various statistics of national interest. For instance, what percentage of source waters rated as hard to treat, were treated to a level of excellent water quality (based on the number of points in the top left box, divided by the total number of points)? Further evaluation can look at specific cases for statistical derivation, such as: how do groundwater and surface water sites compare overall for water quality? And how do small, medium and large size systems compare? These types of evaluations may identify where the largest challenges are faced in terms of achieving good to excellent treated water quality, and help guide appropriate resource allocation, and/or help direct programs for safe drinking water.

One of the main advantages to this national reporting approach is that site specific information is protected. This is important in order to limit the risk of result misinterpretation.

6.2.3 Trend Analysis

It is generally recommended that at least ten years of data be used for trend analysis (Cude, 2001).

The properties of measurement scales (nominal, ordinal, interval and ratio) determine what can be done with them. The transformation of water quality data from a number scale (interval or ratio) to an ordinal scale (index) leads to a loss of information. Due to this, trend analysis utilizing an index (equally applicable to the SWQI and TWQI) requires careful evaluation. A certain level of consistency will be required to be maintained including: the parameters included, sampling location, analytical method utilized for parameter analysis, guideline value, index/indicator calculation, and possibly other components. Guidance on trend analysis utilizing an index is anticipated to be provided at a future time by SC and/or ECa under separate cover.

For the time being for trend analysis, it is recommended to evaluate trends in parameter concentrations in both the source and treated water quality on a parameter by parameter basis (in the interval or ratio scale). Consistency is however still required in this analysis including: the same sampling location, analytical method for concentration determination, and comparison to the same guideline or target value.

6.2.4 Other Potential Indicator Applications

Beneficial applications identified for water quality indices are outlined in Section 3.1. All of these beneficial applications are equally applicable to the SWQI and TWQI and are encouraged within the limitations of the given approach.

As long as consistency is maintained, and GW and SW compared on an equal footing as identified in this approach, the SWQI and TWQI can be utilized as tools for use in the comparison of various source waters to help in the determination of the most suitable supply among various options. This type of evaluation should not be limited to an evaluation of the SWQI and TWQI results as there will be numerous other factors to consider (including but not limited to: source water vulnerability, land use activities and land use planning, available infrastructure, costs, and available resources).

Other potential beneficial applications identified by the working group include use of the SWQI and/or TWQI as tools to:

- Identify how the ecosystem is responding to pressures;
- Help support watershed/aquifer management, and the economics of source water protection;
- Support funding requests for required water treatment technology or infrastructure upgrades;
- Identify relevant source water quality data from existing monitoring programs and networks, and to identify critical data gaps;
- Link the SWQI/TWQI with economic decision making;
- Improve partnerships among all levels of government and non governmental organizations (NGO's);
- Determine potential links between environmental risks and health effects as a basis for informing policy-makers;
- Deal with emerging water quality issues on a pro-active basis and, avoid a crisis situation;

7 SUMMARY AND RECOMMENDATIONS

The following sections presents a thesis summary, recommendations towards future work, and outlines the overall contribution to science achieved by this thesis

7.1 Summary

In 2003 the National Round Table on the Environment and Economy (2003) identified the need to account for natural capital as an asset necessary to sustain the health of the environment, society, and economy for Canadians; and to create an indicator to measure, track and report on this capital for decision making. This was considered essential to a sustainable Canadian society. In September 2005, I was hired by Health Canada as the project lead to develop the source water quality indicator. A treated water quality indicator was later introduced to bridge the gap between source water quality and human health.

My role included the following M.Sc. contributions:

- Developing and implementing a research plan;
- Deriving scientific objectives to fulfill the project mandate within an overall water management framework;
- Developing the conceptual approach, methodology, and project process (determining what indicator could be used, its associated limitations, and how these could be addressed, how the indicators could be calculated and what project components were required and how these could be developed);
- Developing technical guidance in the form of a parameter selection rationale;

- Creating a Treatability ranking tool; Providing direction to the modification of a CCME WQI calculator tool; and developing the associated technical guidance for their application to the derivation of a SWQI and TWQI;
- Determining practical and beneficial applications for the SWQI and TWQI at various scales for applicability across Canada; and
- Identifying recommendations for further work in acknowledgement of the known limitations of the thesis results and in an effort to advance the science of the SWQI and TWQI approach over time.

These tasks were carried out as part of this M.Sc. project, in consultation with, and with the help of, a number of individuals.

As part of the research undertaken, a review of source water quality guidelines in developed countries, revealed that out of New Zealand, Europe, the United States and Australia, only New Zealand had attempted to create an indicator similar to the requirements of the source water quality indicator. This monitoring, grading and reporting approach, was never implemented, however, it did reveal important concepts for the design of the source water quality indicator.

A review of historical and international water quality indices revealed numerous attempts at water quality index development, with all index formulations having various strengths and weaknesses. To circumvent controversy surrounding index use, it was suggested that indices should be tested and refined through use over time, and developed by a lead federal government agency to minimize controversy. Limited examples of sustained index use were identified in Canada, the United Kingdom and Oregon that adopted this outlined approach.

Scientific objectives were determined for the project to achieve the given project mandate and to ensure the indicators fit into an overall water quality management framework. To form the link between water quality and public health, a treated water quality indicator is necessary. To form the link between water quality and the environment and society, the source and treated water quality indicators need to serve as tools for use within the multi-barrier approach to safe drinking water, including promoting the effective operation of the water treatment plant and source water protection. Several considerations for linking source water quality to economics have been outlined, however, an in-depth review was considered outside the scope of this thesis.

To ensure a consistent and scientifically defensible approach to the indicator calculation and interpretation, a parameter selection rationale, tools for the source and treated water quality indicator calculation, and technical guidance were developed. These were developed in consideration of factors that would vary across Canada, including source type, a range of parameters of concern, types of treatment, system sizes, monitoring programs and legislated reporting scales, to ensure national applicability.

The parameter selection rationale includes core parameters and guidance for the selection of parameters relevant to specific sites to account for site variability. It is anticipated that all water quality data required for utilizing the SWQI and TWQI will not always be available, especially for small treatment systems, and those sites that rely on groundwater versus surface water sources.

The modified Canadian Council of Ministers of the Environment water quality index calculator, developed by the Government of Newfoundland and Labrador Water Resources Management Division as part of this project, incorporates new guidance to address source and treated water quality specific considerations as follows. The calculator will generate a score from 0 to 100 for water quality based on three factors, and categorize the water quality from poor to excellent. Data requirements for utilizing the calculator include: a minimum of ten parameters, a sampling frequency of twice a year for groundwater, four times a year for surface water, and three years worth of data. To accommodate parameters monitored at various frequencies a temporal rollup utilizing the maximum value is recommended, with the temporal period determined by plant size. Further technical considerations related to bacteriological data and parameter weighting are also outlined. The proposed approach along with other proposed alternatives and modified formulations require pilot testing.

The Treatability Ranking tool ranks source water quality with respect to the complexity of treatment required to meet the Guidelines for Canadian Drinking Water Quality. The ranking is based on a modification of the Association of Boards of Certification 'Operator Certification Program Standards' Water Treatment Plant Point Rating System. The tool will generate the least complex treatment associated with the entered information based on an evaluation of a series of treatment related constraints and ballpark parameter specific removal efficiencies. From this the source water quality will be categorized from easy to hard to treat. Parameter data requirements are similar to those for the CCME WQI calculator with the exception that only one value is entered for each parameter (the maximum over three years of data) or the 95th percentile for microbiological data where ten monitoring events took place over the three year period.

Additional considerations in source and treated water quality indicator categorizations include whether the category was driven by a health or non-health related concern. This distinction has been enabled within the two tools. Further recommendations regarding categorization have also been outlined.

For application of the indicators all water treatment plant sizes and source water types have been considered and accommodated to the extent possible within the methodology. Possible applications of the source and treated water quality indicators have been described for three scales: a site specific, watershed (or aquifer), and national scale; with reporting on a national scale being the only project requirement. Trend analysis for the indicators themselves needs to wait until further guidance from Federal Government Departments is provided. For the time being water quality tracking is recommended on a parameter specific basis, utilizing ten years of data, and the required consistency for comparability over time. Additional beneficial applications of the indicators have been identified.

The types of decisions that can be made utilizing the source and treated water quality indicators can be summarized as follows for the various scales.

On a site specific and watershed scale, the indicators can be used to identify parameters of concern in both the source and treated water quality. On a watershed scale, the SWQI may provide insight into tributaries (and their respective water capture areas) contributing to an identified water quality concern and warning of identified parameters of concern can be provided to treatment plants downstream (or downgradient). This can serve to:

- Help guide decisions in optimizing the monitoring programs in place to better capture identified risks;
- Help target source water protection (e.g. narrow an evaluation into the origin of the identified concern, and provide insight into the most effective location(s) to apply source water protection efforts) or treatment plant operation measures (e.g. in response to water quality degradation events making their way downstream or downgradient);

The Treatability Ranking tool can be utilized to model the implications of various water quality scenarios on treatment complexity.

- This can help guide where a source water protection strategy may be most effective, targeting parameters that may be hard to treat and/or for which a treatment barrier is not in place, and/or identify the need for an additional treatment barrier;

With respect to tracking, if water quality data is consistently collected and evaluated over time, a deteriorating, improving, or stable water quality condition can be identified.

- This can be used to determine whether source water protection or treatment operation strategies are effective, or if they are needed;

Overall for site and watershed specific applications:

- Decisions can be made regarding suitable procedures, processes and tools to implement to achieve an effective multi-barrier approach;
- The source and treated water quality indicators can be utilized as tools for use in the comparison of various source waters to help in the determination of the most suitable supply among various options;
- The source water protection can possibly help support funding requests for required water treatment technology or infrastructure upgrades;

On a national scale, the modified Canadian Council Ministers of the Environment Water Quality Index score for the treated water quality indicator and source water quality indicator treatability ranking will be plotted in an XY scatter plot, that represents both the original source water treatability and ultimate treated water quality to create a national picture of water quality across the country. The indicators can then identify where the largest challenges are faced in terms of achieving good to excellent treated water quality. A statistical analysis of the scatter plot correlating points to geographic location and or system size can be used to help:

- Decide the most appropriate geographic locations or system size to target resource allocation, and /or help direct programs for safe drinking water to target audiences.

Data collection for national reporting on the indicators will be done through a national drinking water plant survey.

7.2 Recommendations for Future Work

The following recommendations are offered to address the long term needs of this project and continued scientific defensibility of the source and treated water quality indicator approach.

1. Once the water quality data are collected through the drinking water plant survey, the categories applied to the source water quality indicator should be evaluated and further refined. An interesting exercise that should be undertaken is to compare the modified Canadian Council of Ministers of the Environment water quality index score to see if it correlates well with the treatability ranking for source water quality. If good correlation is found, then it may be possible to amalgamate the two approaches into a new classification system that reflects both water quality and treatability, similar to the approach undertaken in the United Kingdom.
2. This thesis describes several existing water quality index formulations, and proposes two alternative formulations for the modified Canadian Council of Ministers of the Environment water quality index. Two of the more promising existing formulations are methods proposed by Dojlido et al. (1994) (the unweighted harmonic mean square), and the method proposed by House and Ellis (1980, 1987, and 1989) (the arithmetic Solway weighted formulation). Both

existing and modified alternative approaches proposed herein should be evaluated in more detail and pilot tested utilizing the water quality data generated by the Canadian drinking water plant survey. Any further identified improvements to the modified Canadian Council of Ministers of the Environment water quality index formulation from this exercise should then be considered for adoption in the source and treated water quality indicator calculations.

3. Recommendations on how economics can be considered are outlined only briefly. An approach to seriously consider would be to include ballpark capital, operation and maintenance and lifecycle costs associated with each unit treatment process in the Treatability Ranking tool. When the Treatability Ranking tool generates a treatment process, these ballpark costs would also be generated in a consistent manner. The United States Environment Protection Agency is developing these types of ballpark costing curves, and these could be evaluated for suitability to the Canadian context. This economic link to source water quality would serve to illustrate the cost implications of poor source water quality and help promote source water protection. Other approaches to forming an economic link utilizing the indicators should be further explored by a qualified economist.
4. The core set of parameters included in the parameter selection rationale should be revisited once data from the drinking water plant survey are available. Considerations in the core set of parameters should include a sensitivity analysis of parameter concentrations on the treatability ranking. Knowledge of sensitivity to parameter concentration could be incorporated into the modified (weighted) CCME WQI formula proposed herein. Another consideration in the weighting is

the effect of a parameter's concentration on the waters source or treated suitability.

5. The parameters of concern identified by drinking water plant survey respondents along with the associated reported concentration ranges should be evaluated against the core set of parameters included in the parameter selection rationale. They should also be used to help refine the list of parameters included in the Treatability Ranking tool.
6. The technical information currently included in the development of the Treatability Ranking tool was limited. For the Treatability Ranking tool, the United States Environmental Protection Agency is developing a comprehensive Treatability database, which can serve as an excellent resource for technically improving the removal efficiencies that form the predominant basis for the ranking score.
7. The methodology outlined in this text as well as the tools developed have only been vetted conceptually. They require thorough testing through piloting. This piloting may include utilizing data from the drinking water plant survey results when they become available, or by providing the methodology to targeted members of the Canadian population for piloting and provision of feedback.
8. Based on piloting, future availability of technical information, and user feedback, the methodology and tools in calculating the source and treated water quality indicators will need to be continually refined and updated.
9. The review of water quality index aggregation formulations did not include statistical methods or fuzzy logic. A worthwhile exercise would be to further

explore these, including any developments that were based on probabilities of exceedance.

10. Consideration should also be given in the future to incorporating distribution related considerations into the methodology, and turbidity exemption allowances for filtration into the Treatability Ranking tool.

7.3 Contribution to Science

The work conducted as part of this thesis constitutes the following contributions to science:

- Creation of a consistent methodology to measure, track and report on source water quality, in the form of an indicator for the first time ever in Canada, with links to the environment and society;
- Creation of a consistent new methodology to measure, track and report on treated water quality, in the form of an indicator with links to human health, the environment, and society;
- Development of a modified CCME WQI that enables source and treated water quality considerations to be addressed;
- Creation of a parameter selection rationale for determining parameters of relevance to both source and treated water quality;
- Design of a strategy and application to evaluate the complexity of treatment associated with a given source water quality (Treatability Ranking Tool);

- Illustration of beneficial applications to decision making of the source and treated water quality indicators and associated tools for site specific, watershed and national scales;
- Provision of recommendations for ongoing work to improve upon the scientific defensibility of the given approach based on piloting, evolving science, and resource availability.

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TABLES

Table 2.1 New Zealand - Proposed Monitoring Grading and Reporting Framework Source Water Quality Categorization Scheme

Grade	Level of Suitability	Interpretation
Green	Very good	No treatment required (meets the maximum acceptable values of the Drinking Water Standards for New Zealand
Yellow	Good	Reliance on treatment to remove low levels of microbes to make the water safe; or chemicals or caynobacteria present but no treatment required
Orange	Fair	Reliance on treatment to remove moderate levels of microbes to make the water safe
Red	Poor	Reliance on treatment to remove high levels of microbes, or chemicals or toxins, to make the water safe
Black	Very poor	Heavy reliance on treatment to remove high levels of chemicals, toxins or microbes

Copied from Table 3 (NZMOE, 2004a)

Table 3.1 Characteristics of the Various Water Quality Index Aggregation Functions

Aggregation Function	Mathematical Formulation	Decreasing Scale Index Attributes	Application
Additive Forms			
Linear sum or weighted sum	$I = \sum_{i=1}^{n} I_i$ $I = \sum_{i=1}^{n} w_i * I_i \quad \sum_{i=1}^{n} w_i = 1$	eclipsing (overestimates water quality) [(Ott, 1978), (House and Ellis, 1980), (Swamee and Tyagi 2000); no ambiguity (Ott, 1978);	Prati et al. (1971), McDuffie and Haney (1973), Horton (1965), Brown et al. (1970), Dinius (1972), O'Connor (1972), Deninger and Landwehr (1971), Stoner (1978)
Root-sum-power or Root-mean-square (p = 2)	$I = \left(\sum_{i=1}^{n} I_i^{\,p}\right)^{\frac{1}{p}}$ $I = \left(\frac{1}{n}\sum_{i=1}^{n} I_i^{\,p}\right)^{\frac{1}{p}}$	eclipsing; no ambiguity (Ott, 1978,)	Nemerow and Sumitomo (1970), Inhaber (1975), CCME WQI (2001)
arithmetic Solway Weighted Formulation	$I = \frac{1}{100}\left[\sum_{i=1}^{n} w_i I_i\right]^2$	underestimates water quality at the lower end of the quality scale (House and Ellis, 1980)	House and Ellis (1980, 1987, 1989)
unweighted harmonic mean square	$I = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{I_i^2}}}$	low subindex values unlikely to be eclipsed (Smith et al., 2002); ambiguity (Swamee and Tyagi, 2000)	Cude (2001), (Dojlido et al., 1994)
Ambiguity and eclipsicity-free aggregation	$I = \left(1 - n + \sum_{i=1}^{n} I_i^{\frac{-1}{p}}\right)^{-p}$	suggested to be free from ambiguity and eclipsing when p = 0.4 (Swamee and Tyagi, 2000)	Swamee and Tyagi (2000)

Table 3.1 Characteristics of the Various Water Quality Index Aggregation Functions (continued)

Aggregation Function	Mathematical Formulation	Decreasing Scale Index Attributes	Application
Multiplicative Forms			
Weighted product	$I = \prod_{i=1}^{n} I_i^{w_i}$	may eclipse subindices that show moderately poor quality but not extremely poor quality; exhibits non-linearity (and potentially considerable distortion) when weights are small (Ott, 1978); may be eclipsed if a near zero weight applied to a low subindex (Swamee and Tyagi, 2000)	Brown et al (1970), Deininger and Landwehr (1971), Walski and Parker (1974), Bhargava (1983)
Other			
Minimum operator	$I = min\{I_1, I_2, \ldots I_i, \ldots I_n\}$	No eclipsing; no ambiguity (Ott, 1978); does not provide a composite picture (Swamee and Tyagi, 2000)	Smith (1989,1990), Hebert (1996)

Notes:

I_i = subindex for parameter i

n = number of parameters

w_i weight for parameter i

p = power

Table 3.2 Formulation Comparison for the Described Water Quality Indices

Index Name & Year	Author(s)	Treatment of pesticides and toxic substances	Index Formula	Formula notes
Horton's Quality Index (1965)	Horton*	Not included since they were not considered acceptable under any circumstances	$QI = \frac{\sum_{i=1}^{n} w_i I_i}{\sum_{i=1}^{n} w_i} M_1 \ M_2$	Ii = subindex for parameter i n – number of parameters wi = weight for parameter I M1 = for temperature M2 = for obvious pollution M1, M2 = 1(acceptable) or ½ (unacceptable)
National Sanitation Foundation (NSF) Water Quality Index (WQI) (1970)	Brown, McClellard, Deininger, Tozer*	NSF WQI automatically set to 0 if exceeded a set limit (either published drinking water standard or 0.1 mg/L)	$NSF\ WQI = \sum_{i=1}^{n} w_i I_i \ or \ = \prod_{i=1}^{n} I_i^{w_i}$	note the authors later introduced the multiplicative form to remedy eclipsing Ii = subindex for parameter i n – number of parameters wi = weight for parameter i
Dinius' Social Accounting system (1972)	Dinius*	Not included	$I = \frac{1}{21} \sum_{i=1}^{11} w_i I_i$	Ii = subindex for parameter i wi – weight for parameter i
Public Water Supply Index (1972)	O'Connor*	If any toxic substance exceeded it's threshold value the overall index would equal zero	$PWS = \delta \sum_{i=1}^{11} w_i I_i$	δ= 0 if pesticides or toxic substances > limits δ= 1 if otherwise Ii = subindex for parameter i wi – weight for parameter i
Index for Dual Water Uses (1978)	Stoner*	Includes toxic variables (eg. lead, chlordane, radium 226)	$I = \sum_{i=1}^{n} T_i + \sum_{j=1}^{m} w_j I_j$	Ti = subindex for Type I parameter i n = number of Type I parameters wj = weight for Type II parameter j Ij– subindex for Type II parameter j m – number of Type II parameters

Table 3.2 Formulation Comparison for the Described Water Quality Indices (continued)

Index Name & Year	Author(s)	Treatment of pesticides and toxic substances	Index Formula	Formula notes
New Zealand Water Quality Indexing System (1989/1990)	Smith D.G. (1989 & 1990)	Not included due to limited relevance to New Zealand waters.	$I = min\{I_1, I_2, \ldots I_i, \ldots I_n\}$	Ii = subindex for parameter i n = number of parameters
Oregon Water Quality Index (1995)	Cude (2001) as modified from Dunnette (1979)	Not included	$WQI = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{SI_i^2}}}$	SIi = subindex i n = number of parameters
United Kingdom (UK) Water Quality Index for River Management (1980, 1987, & 1989)	House and Ellis (1980, 1987 & 1989)	Included in specific use categories only	$WQI = \frac{1}{100}\left[\sum_{i=1}^{n} w_i q_i\right]^2$	qi = Water Quality Rating for the ith parameter wi = weighting for the ith parameter n = number of parameters
Canadian CCME WQI (2001)	Canadian Council of Ministers of the Environment (2001)	Enabled. Any parameters relevant to the water body being tested can be included.	$CCME\ WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$ $F_1 = \left(\frac{\#\ of\ failed\ parameters}{Total\ \#\ of\ parameters}\right) \times 100$ $F_2 = \left(\frac{\#\ of\ failed\ tests}{Total\ \#\ of\ tests}\right) \times 100$ $F_3 = \left(\frac{nse}{0.01nse + 0.01}\right), nse = \frac{\sum_{i=1}^{n} excursion_i}{\#\ of\ tests}$ $excursion_i = \left(\frac{failed\ test\ value_i}{guideline_j}\right) - 1$	F1 = scope, F2=frequency, F3 = amplitude nse= normalized sum of excursions excursion i= when a test value does not meet its guideline (please note the formula shown is for when a test value must not exceed a guideline, when a test value must not fall below a guideline the numerator and denominator are reversed) divisor 1.732 – square root of 3

Table 3.3: Parameter Comparison for the Described Water Quality Indices

Index Name	Horton's Quality Index		National Sanitation Foundation (NSF) Water Quality Index (WQI)		Dinius' Social Accounting system		O'Connors Public Water Supply Index	
Water Use Category	General		General		General		Public Water Supply (PWS)	
Parameters Incorporated (name, number of, and weight)	10	weights	9	weights	11	weights	13	weights
alkalinity	X	1			X	0.5	x	0.058
ammonia								
arsenic								
Biochemical Oxygen Demand (5 day)			X	0.1	X	2		
cadmium								
carbon chloroform extract	X	1						
chloride	X	1			X	0.5	X	0.06
chromium								
coliforms (total)	X	2			X	3		
coliforms (fecal)			X	0.15	X	4	X	0.171
colour					X	1	X	0.054
copper								
cyanide								
Dissolved Oxygen (DO)	X	4	X	0.17	X	5	X	0.056
fluorides							X	0.079
hardness					X	1	X	0.077
hydrocarbons (total)								
iron								
lead								
manganese								
mercury								
Methylene Blue Active								
nitrates			X	0.1			X	0.07
nitrite								
nitrogen								
obvious pollution	X	0.5 or 1						
PAHs (polyaromatic								
pesticides (total)								
pH	X	4	X	0.12	X	1	X	0.079
phenols							X	0.104
phosphates			X	0.1				
phosphorous (total)								
sewage treatment (% of	X	4						
solids (dissolved)							X	0.084
solids (suspended)								
solids (Total)			X	0.08				
specific conductance	X	1			X	1		
sulfates							X	0.05
temperature	X	0.5 or 1	X	0.1	X	2		
turbidity			X	0.08			X	0.058
zinc								

notes:

na: not applicable

x: indicates that a particular parameter was included in the index

***: Type I parameters not shown**

Table 3.3: Parameter Comparison for the Described Water Quality Indices Continued

Index Name	**Stoner's Index for Dual Water Uses**	**New Zealand Water Quality Indexing System**	**Oregon Water Quality Index**	**United Kingdom (UK) Water Quality Index for River Management**			
Water Use Category	Public water supply	Water Supply	General Water Quality	General Use	PWSI (potable water supply	ATI (Aquatic Toxicity Index)	PSI (Potable Sapidity Index)
Parameters Incorporated (name, number of, and weight)	**13 Type II***	**9**	**8**	**9**	**13**	**9**	**12**
alkalinity							
ammonia	x	x		x	x		
arsenic						x	x
Biochemical Oxygen Demand (5 day)		x	x	x	x		
cadmium						x	x
carbon chloroform extract							
chloride	x			x	x		
chromium						x	x
coliforms (total)				x	x		
coliforms (fecal)	x	x	x				
colour	x				x		
copper	x					x	x
cyanide						x	x
Dissolved Oxygen (DO)		x	x	x	x		
fluorides	x				x		
hardness							
hydrocarbons (total)							x
iron	x				x		
lead						x	x
manganese							
mercury						x	x
Methylene Blue Active	x						
nitrates				x	x		
nitrite	x						
nitrogen			x				
obvious pollution							
PAHs (polyaromatic							x
pesticides (total)							x
pH	x	x	x	x	x		
phenols	x					x	x
phosphates							
phosphorous (total)			x				
sewage treatment (% of							
solids (dissolved)							
solids (suspended)		x		x	x		
solids (Total)			x				
specific conductance							
sulfates	x				x		
temperature		x	x	x	x		
turbidity		x					
zinc	x					x	x

notes:

na: not applicable

x: indicates that a particular parameter was included in the index

***: Type I parameters not shown**

Table 3.4 Water Quality Index Category Descriptions

Scoring	Brown et al 1970 (NSF WQI)	Dinius (1972) Public Water Supply Index	House & Ellis (1989) - General Water Use Index	CCME WQI (2001a)
90-100	(91-100) Excellent - Blue	(90-100) Purification not necessary	(71-100) indicates water of high quality suitable for all high value uses including Potable Water Supply, game fisheries, contact recreation and high quality industrial abstractions at low cost	(95-100) Excellent: water quality is protected with a virtual absence of threat or impairment; conditions very close to **natural or pristine levels**.
80-90	(71-90) Good - Green	(80-90) Minor purification required		(80-94) Good: water quality is protected with only a minor degre of threat or impairment; conditions rarely depart from natural or desirable levels.
70-80		(50-80) Necessary treatment becoming more expensive		(65-79) Fair: water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.
60-70	(51-70) Medium - Yellow		(51-70) indicates waters of reasonable quality suitable for high values uses including PWS after conventional treatment, good coarse fisheries, indirect contact sports and most industrial abstractions at moderate costs	(45-64) Marginal: water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.
50-60				
40-50	(26-50) Bad - orange	(40-50) Doubtful	(31-50) indicates polluted waters with generally moderate value uses including PWS after advanced treatment, indirect contact sports, reasonable to sporadic coarse fish populations and some industrial abstractions at high treatment costs	(0-44) Poor: water quality is almost alwayls threatened or impaired; conditions usually depart from natural or desirable levels.
30-40		(0-40) Not acceptable		
20-30			(10-30) indicates badly polluted waters of low economic value requiring substantial investment in treatment facilities if it is to be upgraded. Use generally restricted to non-contact recreational uses, sewage transport and navigation.	
10-20	(0-25) very bad - Red			
0-10				

Table 5.1 Core Parameter Background Information

	Constraints in Drinking Water					
Parameter Name	Health	Aesthetic/ Operational	**Common composition & where it originates**	**Treatment related considerations**	**Effect on Human Health**	**Treatment**
Escherichia coli (EC)	0 (cfu/100mL)		"Escherichia coli is a member of the coliform group, part of the family Enterobacteriaceae, and is described as a facultative anaerobic, Gram-negative, non-spore-forming, rod-shaped bacterium." "E. coli is found exclusively in the faeces of humans and other animals." (HC, EC 2006) Sources may include: human sewage or animal (e.g. cattle) faeces.	"Its presence in water indicates not only recent faecal contamination of the water but also the possible presence of intestinal disease causing bacteria, viruses, and protozoa." (HC, EC, 2006)	" While most strains of E. coli are nonpathogenic, some can cause serious diarrhoeal infections in humans... One enterohaemorrhagic strain, E.coli O157:H7, has been implicated in many foodborne and a few waterborne outbreaks...E. coli serotype O157:H7 causes abdominal pain, bloody diarrhoea, and haemolytic uraemic syndrome (HUS). (HC, 2006b)	disinfection and filtration
Total Coliforms (TC)	0 (cfu/100mL)		"While E. coli is the only member of the total coliform group that is found exclusively in faeces, other members of the group are found naturally in water, soil, and vegetation, as well as in faeces... Total coliforms belong within the family Enterobacteriaceae. " (HC, TC, 2006)	"their presence in water leaving a drinking water treatment plant indicates a serious treatment failure. The presence of total coliform bacteria in water in the distribution system indicates that the distribution system may be vulnerable to contamination or may simply be experiencing bacterial regrowth... The presence of total coliforms in non-disinfected wells indicates that the well is either prone to surface water infiltration and therefore at risk of faecal contamination or that bacterial regrowth is occurring within the well." (HC, TC, 2006)	"It should be noted that, in the absence of E. coli, the presence of total coliforms in the distribution system is of no immediate public health significance. However, their presence should prompt further actions." (HC, TC, 2006)	disinfection and filtration

Table 5.1 Core Parameter Background Information

	Constraints in Drinking Water					
Parameter Name	Health	Aesthetic/ Operational	**Common composition & where it originates**	**Treatment related considerations**	**Effect on Human Health**	**Treatment**
Nitrate/ Nitrite (as nitrogen)	10 (mg/L) as N		Both are naturally occurring ions that are ubiquitous in the environment. Both are products of the oxidation of nitrogen by microorganisms. Nitrate is the more stable form but can be reduced by microbial action to nitrite. Nitrates are used as fertilizers, in explosives, as oxidizing agents & as food preservatives. Most nitrogenous materials in environment tend to be converted to nitrates. Sources of nitrates in water include decaying plant or animal material, agricultural fertilizers, manure, domestic sewage or geological formations. Nitrate is highly mobile in soil and migrates readily to the water table when present in excess amounts...Nitrate levels are often higher in groundwater than surface water." (HC, Nitrate/Nitrite, 1987)	" Nitrites may be produced from excess ammonia in drinking water distribution systems that use chloramines, formed in situ from chlorine and ammonia as a disinfectant." (HC, Nitrate/Nitrite, 1987); "...nitrite may accelerate the decomposition of monochloramine and interfere with chlorine residual measurements."(HC, Chloramines, 1995)	Methaemoglobinaemia, the most commonly reported toxic effect of the ingestion of nitrate-contaminated drinking water, is a condition resulting in an inability to release oxygen to body tissues... Symptoms are cyanosis, asphyxia and death. Infants < 3 months of age are more susceptible than older infants, children or most adults, with the exception of pregnant women and persons with genetically controlled deficiencies of certain enzymes. Other potential health effects include: probable carcinogens in humans, mutagenicity, congenital malformations and behavioral effects, and slowed motor reflexes.(HC, Nitrate/Nitrite, 1987)	" Treatment technologies for removing nitrates and nitrites from drinking water include ion exchange and reverse osmosis.. Other treatment methods such as biological denitrification and electrodialysis have also been suggested. " (HC, Nitrate/Nitrite, 1987)
Nitrate/ Nitrite (as the species)	45 (mg/L) as NO3					

Table 5.1 Core Parameter Background Information

	Constraints in Drinking Water					
Parameter Name	Health	Aesthetic/ Operational	**Common composition & where it originates**	**Treatment related considerations**	**Effect on Human Health**	**Treatment**
Iron		0.3 (mg/L)	The concentration of iron in well-aerated waters is seldom high. Under reducing conditions, which may exist in some groundwaters, lakes or reservoirs, and in the absence of sulphide and carbonate, high concentrations of soluble Fe(II) may be found....The presence of iron in natural waters can be attributed to the weathering of rocks and minerals, acidic mine water drainage, landfill leachates, sewage effluents and iron-related industries (HC, Iron, 1978)	At concentrations above 0.3 mg/L, iron can stain laundry and plumbing fixtures and produce undesirable tastes in beverages. The precipitation of excessive iron imparts an objectionable reddish-brown colour to water. Iron may also promote the growth of certain micro-organisms, leading to the deposition of a slimy coating in water distribution pipes. Generally, only a small percentage of the population will be able to taste iron in drinking water at concentrations below 0.3 mg/L...(HC Iron, 1978)."	"Iron, is an essential element in human nutrition...The ingestion of large quantities of iron results in haemochromatosis, a condition in which normal regulatory mechanisms do not operate effectively, leading to tissue damage as a result of the accumulation of iron. This condition rarely develops from simple dietary overloading." (HC, Iron, 1978)	oxidation followed by filtration, manganese greensand filtration (ion exchange, reverse osmosis may be effective for low concentrations in dissolved form)
Manganese		0.05 (mg/L)	"The element manganese is present in over 100 common salts and mineral complexes that are widely distributed in rocks, in soils and on the floors of lakes and oceans... In Canada, manganese is primarily employed in the steel industry. Manganese is also used in the manufacture of dry cell batteries and as an oxidizing agent... Manganese is more prevalent in groundwater supplies than in surface water supplies owing to the reducing conditions that exist underground. High concentrations of manganese are also found in some lakes and reservoirs as a result of acidic pollution" (HC Manganese,1987 as updated)	"The presence of manganese in drinking water supplies may be objectionable for a number of reasons. At concentrations above 0.15 mg/L, manganese stains plumbing fixtures and laundry and produces undesirable tastes in beverages. Even at concentrations as low as 0.02 mg/L, problems may be encountered. As with iron, the presence of manganese in water may lead to the accumulation of microbial growths in the distribution system. Even at concentrations below 0.05 mg/L, manganese may form coatings on water distribution pipes that may slough off as black precipitates" (HC Manganese,1987 as updated)	"Manganese is an essential element in humans. Manganese is regarded as one of the least toxic elements. Except for one isolated incident, manganese intoxication due to drinking water has not been documented." (HC, Manganese, 1987 as updated)	

Table 5.1 Core Parameter Background Information

	Constraints in Drinking Water					
Parameter Name	Health	Aesthetic/ Operational	**Common composition & where it originates**	**Treatment related considerations**	**Effect on Human Health**	**Treatment**
Bromate	0.01 (mg/L)		"The concentration of bromide in raw water is a major factor in the formation of bromate. The major natural sources of bromide in groundwater are saltwater intrusion and bromide dissolution from sedimentary rocks. Sewage and industrial effluent as well as road and agricultural runoff may also contribute to elevated bromide levels in surface waters." (HC, Bromate, 1998)	"Bromate is not a natural component of water but may be formed during the disinfection of drinking water using ozone or a combination of ozone and hydrogen peroxide." (HC, Bromate, 1998) "Water treatment grade sodium hypochlorite solutions may contain bromate as a contaminant." (HC, Bromate, 1998)	" Bromate is a highly toxic substance that has caused irreversible renal failure, deafness and death subsequent to accidental poisoning." "Bromate has been classified as being probably carcinogenic to humans" (HC, Bromate, 1998)	"There are no practical methods currently available to remove bromate from water. Bromate in ozonated drinking water supplies is best controlled by limiting its formation, which is influenced by the bromide concentration, the source and concentration of organic precursors, pH, temperature, alkalinity and ozone dose."HC, Bromate, 1998)
Chlorate/ Chlorite	1.0 (mg/L)		" Chlorite and chlorate are disinfection by-products that are found in drinking water when chlorine dioxide is used as a disinfectant... The majority of chlorine dioxide added to drinking water will eventually form chlorite. Chlorate can also be formed when hypochlorite solutions do not meet quality specifications and are not stored and/or used appropriately." (HC, Chlorite & Chlorate public consultation document, 2007)	" If chlorine dioxide and chlorite ion are not removed prior to post-chlorine disinfection, they will react with free chlorine to form chlorate ion. Once chlorate ion is present in water, it is very persistent and very difficult to remove. It is therefore recommended that municipal treatment plants control the production of chlorate ion. (HC, Chlorite & Chlorate public consultation document, 2007)	"Studies on chlorite, chlorate and chlorine dioxide do not provide sufficient information to assess their potential as carcinogens...Animal studies on chlorate suggest an increase in the utilization or metabolism of thyroid hormones. Chlorine dioxide can affect the neurobehavioural and neurological development of rats exposed before birth at levels that are significantly higher than those that could exist in drinking water." (HC. Chlorite & Chlorate public consultation document, 2007)	Operators must ensure that the hypochlorite solution they use meets quality specifications and is stored and used appropriately. The formation of chlorate can be reduced by tuning the chlorine dioxide generator .and removing any chlorite ion with activated carbon, iron-reducing agents or sulphur reducing agents before adding a chlorine residual." (HC, Chlorite & Chlorate public consultation document, 2007)

Table 5.1 Core Parameter Background Information

Parameter Name	Constraints in Drinking Water		Common composition & where it originates	Treatment related considerations	Effect on Human Health	Treatment
	Health	Aesthetic/ Operational				
Haloacetic Acids (HAAs)	0.08 (mg/L)		"Haloacetic acids are a group of compounds that can form when the chlorine used to disinfect drinking water reacts with naturally occuring organic matter (e.g., decaying leaves and vegetation)...The haloacetic acids most commonly found in drinking water are monochloroacetic acid (MCA), dichloroacetic acid (DCA), trichloroacetic acid (TCA), monobromoacetic acid (MBA) and dibromoacetic acid (DBA). (HC, HAAs for public consultation, 2006)	" Trihalomethanes and haloacetic acids are the two major groups of disinfection byproducts found in drinking water and generally at the highest levels. Together, these two groups can be used as indicators for the presence of all disinfection by-products in drinking water supplies, and their control is expected to reduce the levels of all disinfection by-products and the corresponding risks to health." (HC, Trihalomethanes, 2006)	"The health effects associated with exposure to" HAAs "will vary with the specific compound." DCA & TCA are considered to be probable and possible carcinogens to humans respectively. Other possible health effects associated with specific HAAs include: developmental effects (heart defects); and male reproductive effects (at levels significantly higher than those found in drinking water). Further studies are required to confirm these effects as well as their long-term significance to human health. (HC, HAAs for public consultation, 2006)	"The approach to reduce exposure to" trihalomethanes and haloacetic acids "is generally focussed on reducing the formation of chlorinated disinfection by-products. The concentrations of "trihalomethanes, haloacetic acids" and other chlorinated disinfection by-products in drinking water can be reduced at the treatment plant by removing the organic matter from the water before chlorine is added, by optimizing the disinfection process or using alternative disinfection strategies, or by using a different water source." (HC, Trihalomethanes, 2006 & HAAs public consultation document 2006)
Trihalo methanes (THMs)	0.1 (mg/L) (average based on min 4 samples)		" Trihalomethanes are a group of compounds that can form when the chlorine used to disinfect drinking water reacts with naturally occurring organic matter (e.g., decaying leaves and vegetation)..The trihalomethanes most commonly found in drinking water are chloroform, bromodichloromethane (BDCM), dibromochloromethane (DBCM) and bromoform.(HC, Trihalomethanes, 2006)		"Chloroform is considered to be a possible carcinogen in humans. Human studies also suggest a link between reproductive effects and exposure to high levels of THMs.. "Preliminary animal studies indicate that BDCM and other" THMs "that contain bromine may be more toxic than chlorinated" THMs "such as chloroform... BDCM is considered to be a probable carcinogen in humans... Exposure to BDCM at levels higher than the guideline value has also been linked to a possible increase in reproductive effects (increased risk for spontaneous abortion or stillbirth) above what can normally be expected. Further studies are required to confirm these effects." (HC, Trihalomethanes, 2006)	
Bromodichloro methane (BDCM)	0.016 (mg/L)					

Table 5.1 Core Parameter Background Information

Parameter Name	Constraints in Drinking Water		Common composition & where it originates	Treatment related considerations	Effect on Human Health	Treatment
	Health	Aesthetic/ Operational				
chlorine residual (free chlorine)	detectable (mg/L) (min)		" Most drinking water treatment plants in Canada use chlorine as a disinfectant. The use of chlorine in the treatment of drinking water has virtually eliminated waterborne diseases, because chlorine can kill or inactivate most microorganisms commonly found in water. Free chlorine in Canadian drinking water distribution systems ranges from 0.04 to 0.8 mg/L." (HC, Chlorine public consultation document, 2007)	"It is important that the use of chlorine include strategies that reduce the formation of chlorinated disinfection byproducts (CDBPs), without compromising the effectiveness of disinfection...An optimal operational range for chlorine in drinking water is between a detectable level and 5 mg/L. A minimum free chlorine residual of 0.2 mg/L at all points in the distribution system is considered desirable to prevent bacterial regrowth. (HC, Chlorine public consultation document, 2007)	"Health Canada has classified chlorine as unlikely to be carcinogenic to humans. Studies in laboratory animals and humans indicate that chlorine exhibits low toxicity, regardless of the route of exposure (i.e., ingestion, inhalation, dermal). Studies in animals have not been able to identify a concentration of chlorine associated with adverse health effects, in part because of aversion to its taste and odour. No adverse health effects have been observed in humans from consuming water with high chlorine levels (up to 50 mg/L) over a short period of time." (HC, Chlorine public consultation document, 2007)	"As chlorine is added to drinking water as a disinfectant and to maintain a residual concentration in the distribution system, treatment of the water for chlorine removal is generally not required. " (HC, Chlorine public consultation document, 2007)
Chloramines (combined chlorine)	3.0 (mg/L)		Monochloramine is produced from the reaction of chlorine and ammonia. "The production of monochloramine, dichloramine (NHCl2) and trichloramine (NCl3) is highly dependent upon pH, the ratio of chlorine to ammonia-nitrogen and, to a lesser extent, temperature and contact time. (HC, Chloramines, 1995)	"Chloramine is considered to have moderate biocidal activity against bacteria and low biocidal activity against viruses and protozoan cysts...Inactivation of organisms using monochloramine requires larger concentrations and a longer contact time than chlorine disinfection." The use of monochloramine as a secondary disinfectant in the treatment of drinking water may yield advantages such as increased residual activity in the distribution system, reduction of the formation of THMs and other by-products associated with chlorine use, possible control of bacterial biofilm regrowth in the distribution systems and, in some circumstances, reduction of taste and odour problems associated with chlorination.." (HC, Chloramines, 1995)	"Monochloramine is classified as being possibly carcinogenic to humans.." "No treatment-related developmental or reproductive effects have been observed in rats exposed to monochloramine in drinking water in limited studies. Some possible immunologic effects have been reported. Nevertheless, the biological significance of these effects is not clear, and no other studies report these effects. " (HC, Chloramine, 1995)	"Monochloramine hydrolyses slowly in aqueous solutions. Aeration and boiling of water are not effective for the removal of monochloramine; Ultraviolet light depletes only free chlorine, whereas chloramines seem to be quite stable in sunlight. Pure chloramines can be removed by granular activated carbon." (HC, chloramines, 1995)

Table 5.1 Core Parameter Background Information

Parameter Name	Constraints in Drinking Water		Common composition & where it originates	Treatment related considerations	Effect on Human Health	Treatment
	Health	Aesthetic/ Operational				
Turbidity	0.1 (NTU) ideally*		"Turbidity is caused by matter such as clay, silt, fine organic and inorganic matter, plankton, and other microscopic organisms, which is suspended within the water." Concerns are most likely to result from a spike in the level of turbidity, due either to an increase in the amount of particulate matter in the source water (e.g., from heavy rains) or to a breakdown in the treatment process (e.g., inadequate coagulation, a ruptured filter).(HC, EC, 2000)	"The performance of the drinking water filtration system is usually assessed by monitoring the levels of turbidity...Suspended matter can protect pathogenic microorganisms from chemical and ultraviolet (UV) light disinfection." (HC, EC, 2006); The most important consideration when dealing with turbidity is to make sure the levels remain low and fairly constant over time. (HC, Turbidity, 2003)	"It is important to control turbidity in public water supplies for both health and aesthetic reasons. Suspended matter can contain toxins such as heavy metals and biocides and can also harbour microorganisms, protecting them from disinfection. Recent research has correlated turbidity levels with treated water supplies being contaminated with Giardia and Cryptosporidium. "(HC, Turbidity, 2003)	clarification, filtration
Total Organic Carbon (TOC)		2-4 (mg/l)	"a measure of the concentration of organic carbon in water, determined by oxidation of the organic matter into carbon dioxide (CO2). Total organic carbon includes all the carbon atoms covalently bonded in organic molecules. In natural waters, total organic carbon is composed primarily of nonspecific humic materials." (Symons et. al., 2000)	"The purpose of the treatment technique for DBP precursor removal is to reduce the formation of DBPs. NOM reacts with disinfectants to form DBPs; therefore, lowering the concentration of NOM (as measured by TOC) can reduce DBP formation." TOC removal is generally more difficult in higher alkalinity waters, and source water with low TOC levels." (USEPA, 1999)	TOC can contribute to the formation of disinfection byproducts. See THMs and HAAs.	best available technologies include: enhanced coagulation, enhanced softening, granular activated carbon, nanofiltration (USEPA 2006)

Acronym Legend

BDCM		NOM	natural organic matter
DBP		TC	total coliforms
EC		THMs	Trihalomethanes
HAAs		TOC	total organic carbon
HC			

* Where this is not achievable, the treated water turbidity levels from individual filters (NTU) shall be less than or equal to: chemically assisted filtration: ≤0.3 95% of time, always ≤1.0;

Table 5.2 Treatability Ranking Tool Point Rating System

Point Category	Associated Variables	Complexity of Point Rating	Scoring Alternatives	Maximum possible Score	Notes
Source Water Type	Groundwater Surface Water	Simple	0 (groundwater) OR 10 (surface water or GUDI)	10	
Design Plant Capacity	Design Plant Capacity	Moderate	An integer from 1 to 20 is calculated by the program	20	The program converts the ML/day entered by the user to MGD; 1 point is assigned for every 0.5 MGD (rounded up to an integer value). The maximum value is 20, therefore any calculated value over 20 defaults to 20.
Source Water Quality Concerns	Taste and/or odour (T&O) Algal growths (AG)	Simple	0 (no) OR 2 (yes) T&O 0 (no) OR 3 (yes) AG	5	Yes or No are selected by the user in response to the following questions: 'Are facility processes installed, or specifically adjusted on at least a weekly basis for at least two months in a year, due to algae? and 'Are processes installed, or adjusted at least seasonally, to address taste/odour?
	Iron (Fe) Manganese (Mn)	Moderate	0 (Fe & Mn <= GCDWQ) 2 (Fe > & Mn <= GCDWQ) OR 3 (Mn > & Fe > or <= GCDWQ)	3	
	Colour	Moderate	0 (colour <= GCDWQ) OR 3 (colour > GCDWQ)	3	

Table 5.2 Treatability Ranking Tool Point Rating System (continued)

Treatment		Complex (Unit			All point results in this category depend on unit processes selected based on logic. Treatment selection in logic is based on user entered Raw Water and Treatment targets for 7 core + a minimum of 3 site specific parameters (Operational or other)
Disinfection (7 options, only one selected)	• Chlorine		7	15	
	• UV + Chlorine		9		
	• Chlorine+ chloramine		11		
	• UV + Chloramine		12		
	• chlorine dioxide + Chlorine		13		
	• Ozone + Chlorine		14		
	• Ozone + Chloramine		15		
Filtration (6 options)	• No filtration		0	24	
	• Cartridge or bag		5		
	• Slow sand		5		
	• MF or UF		10 or 15 depending on pre-or post treatment		
	• Direct		18		
	• Conventional		24		
Pre/Post treatment (4 options)	• None		0	23	
	• pH/alkalinity adjustment		8		
	• coagulation/flocculation and/or clarification		15		
	• both		23		
Advanced Processes (8 options & any combination)	• PAC		2	77	
	• GAC		5		
	• Ion Exchange		5		
	• Aeration/air stripping		5		
	• Activated alumina		10		
	• Greensand		10		
	• RO or NF		20 or 25 depending on pre-or		
	• Lime softening		20		

FIGURES

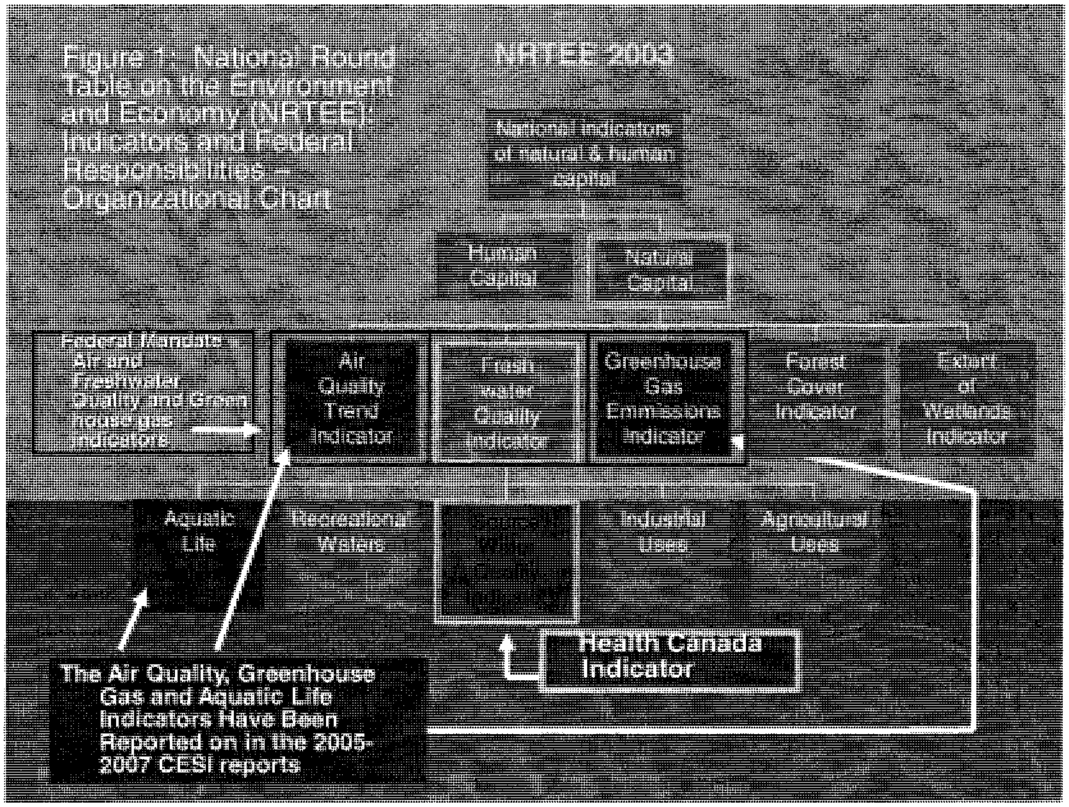

Figure 1: National Round Table on the Environment and Economy (NRTEE): Indicators and Federal Responsibilities – Organizational Chart

NRTEE 2003

National indicators of natural & human capital

Human Capital

Natural Capital

Federal Mandate – Air and Freshwater Quality and Green house gas indicators

Air Quality Trend Indicator

Fresh water Quality Indicator

Greenhouse Gas Emmissions Indicator

Forest Cover Indicator

Extent of Wetlands Indicator

Aquatic Life

Recreational Waters

Source Water Quality Indicator

Industrial Uses

Agricultural Uses

Health Canada Indicator

The Air Quality, Greenhouse Gas and Aquatic Life Indicators Have Been Reported on in the 2005-2007 CESI reports

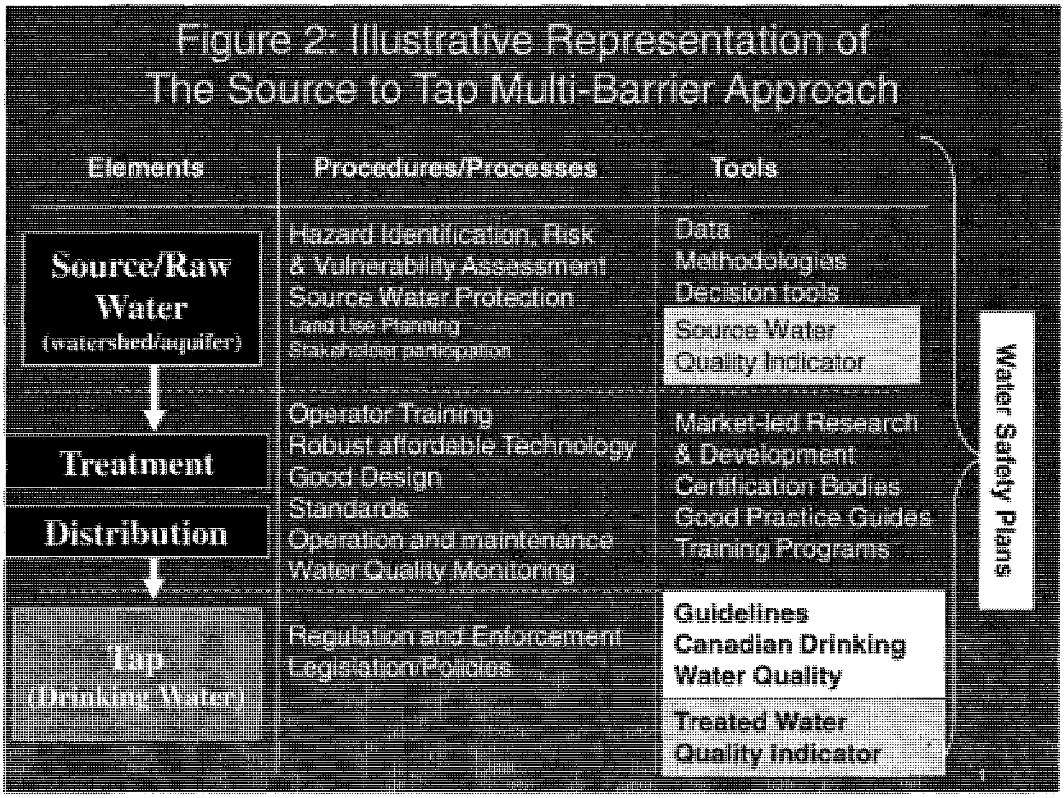

Figure 2: Illustrative Representation of The Source to Tap Multi-Barrier Approach

Elements	Procedures/Processes	Tools
Source/Raw Water (watershed/aquifer)	Hazard Identification, Risk & Vulnerability Assessment Source Water Protection Land Use Planning Stakeholder participation	Data Methodologies Decision tools Source Water Quality Indicator
Treatment **Distribution**	Operator Training Robust affordable Technology Good Design Standards Operation and maintenance Water Quality Monitoring	Market-led Research & Development Certification Bodies Good Practice Guides Training Programs
Tap (Drinking Water)	Regulation and Enforcement Legislation/Policies	**Guidelines Canadian Drinking Water Quality** **Treated Water Quality Indicator**

Water Safety Plans

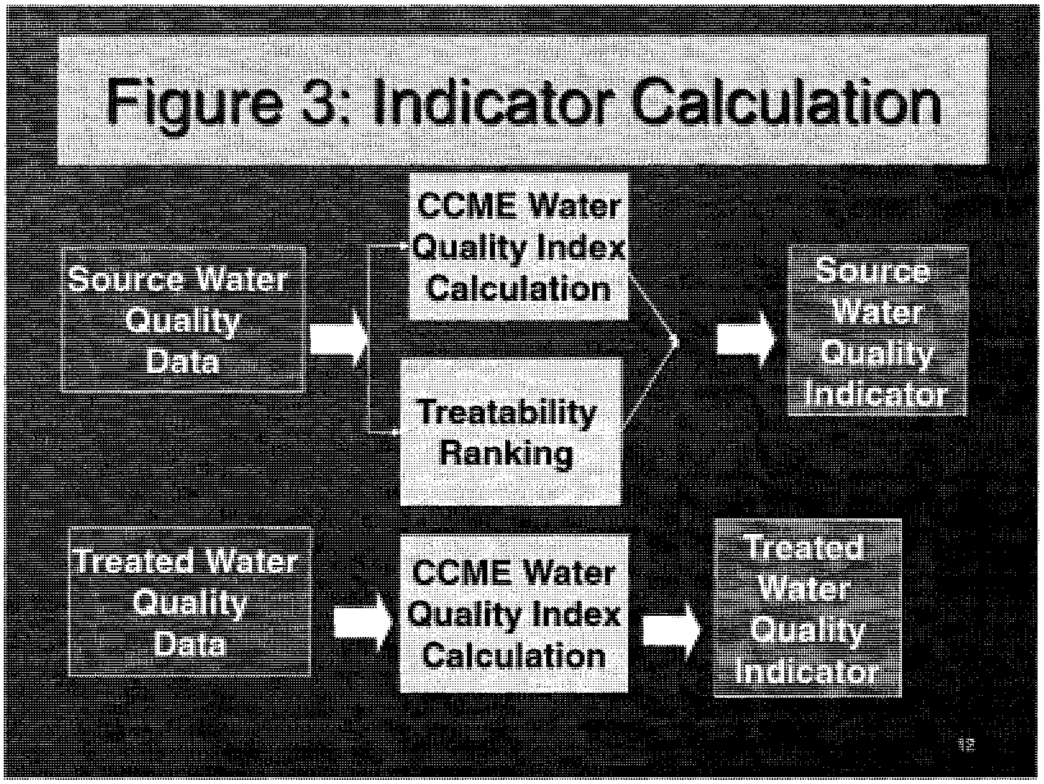

Figure 3: Indicator Calculation

Source Water Quality Data

CCME Water Quality Index Calculation

Treatability Ranking

Source Water Quality Indicator

Treated Water Quality Data

CCME Water Quality Index Calculation

Treated Water Quality Indicator

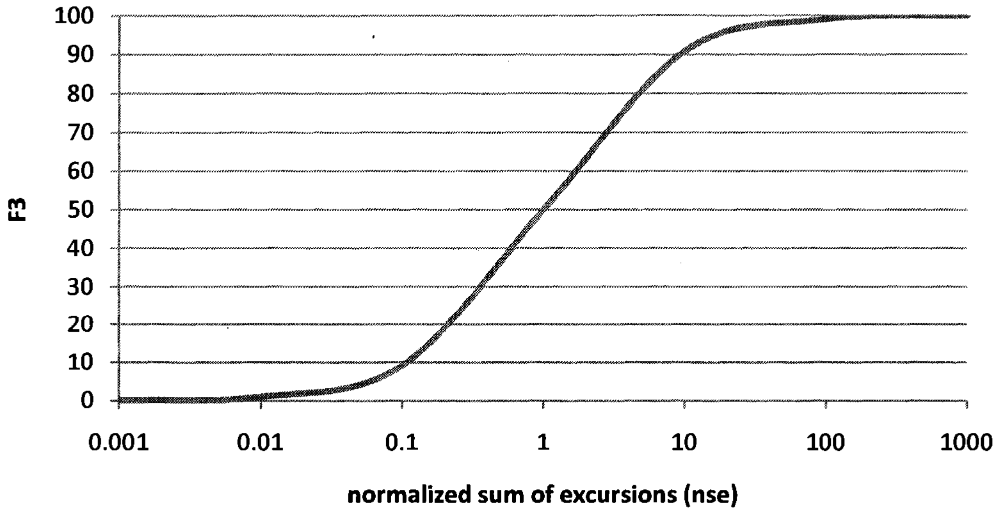

Figure 4: CCME WQI F3 Formula - Asymptotic Function

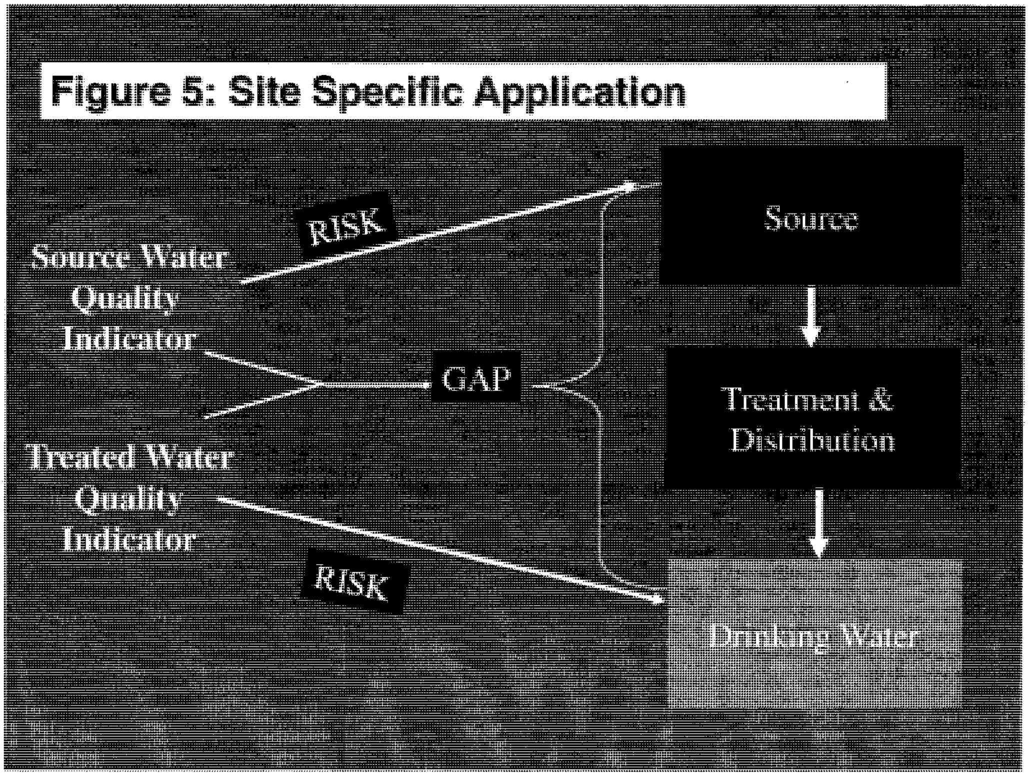

Figure 5: Site Specific Application

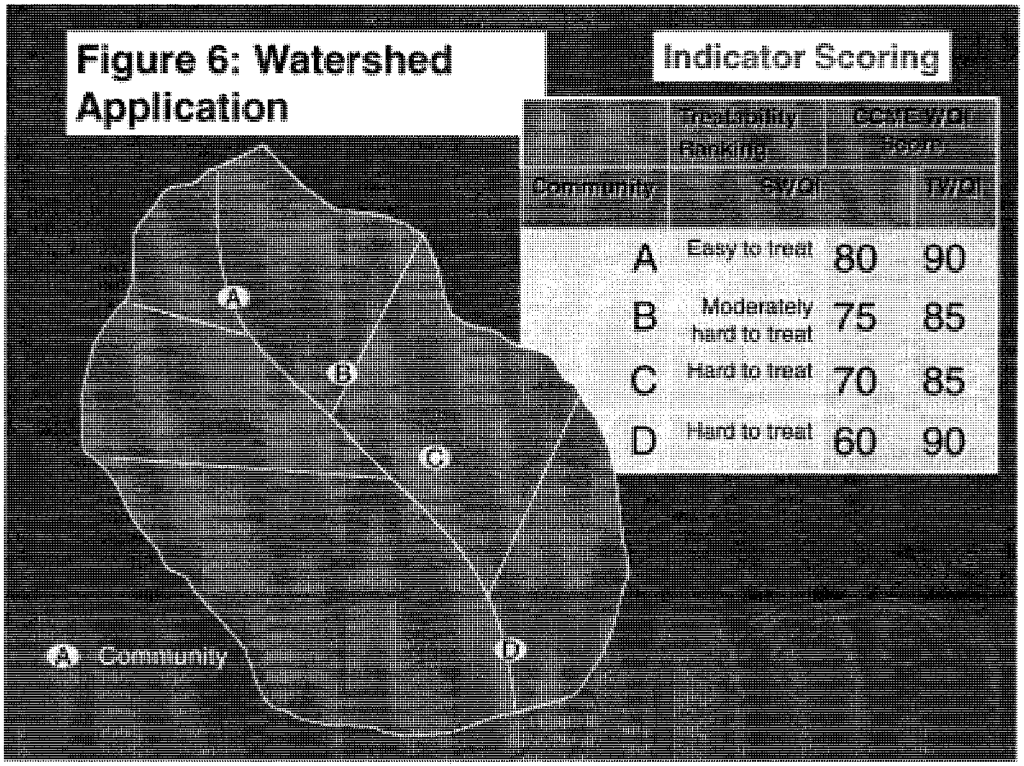

Figure 6: Watershed Application

Indicator Scoring

	Treatability Ranking	CCME WQI Score	
Community		SWQI	TWQI
A	Easy to treat	80	90
B	Moderately hard to treat	75	85
C	Hard to treat	70	85
D	Hard to treat	60	90

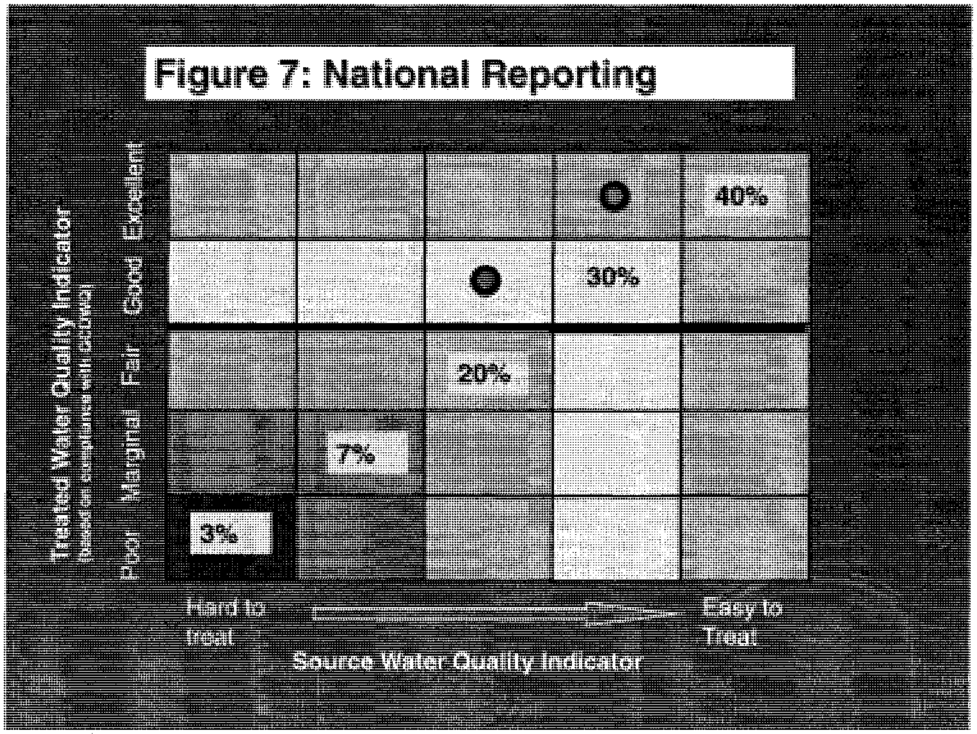

Figure 7: National Reporting

Appendix 1
Summary of Literature References from Ott (1978)

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Nemerow, Nelson L., and Hisashi Sumitomo. "Benefits of Water Quality Enhancement," Syracuse University, Syracuse, NY, Report No. 16110 DAJ, prepared for the U.S. Environmental Protection Agency (December 1970).

O'Connor, Michael Fredrick. "The Application of Multi-Attribute Scaling Procedures to the Development of Indices of Water Quality," Ph.D. Dissertation, University of Michigan, University Microfilms No. 72-29,161 (1972).

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Appendix 2
Sample CCME WQI and Treatability Ranking Calculations

Example 1: CCME WQI Sample Calculation

The following example has been copied from reference (CCME, 2001b). This example does not conform with the data requirements outlined for the SWQI and TWQI however is included to illustrate how the CCME WQI formulation is calculated for a given water quality data set.

North Saskatchewan River at Devon - 1997

DATE	DO Mg/L	pH	TP mg/L	TN mg/L	FC #/dL	As mg/L	Pb Mg/L	Hg g/L	2,4-D g/L	Lindane g/L
7-Jan-97	11.4	8.0	0.006	0.160	4	0.0002	0.0004	L0.05	L0.005	L0.005
4-Feb-97	11.0	7.9	0.005	0.170	L4[2]	L0.0002	**0.0094**	L0.05		
4-Mar-97	11.5	7.9	0.006	0.132	4	L0.0002	L0.0003	L0.05		
8-Apr-97	12.5	7.9	**0.058**[1]	0.428	L4	L0.0002	0.0008	L0.05	0.004	L0.005
6-May-97	10.4	8.1	0.042	0.250	L4	0.0002	0.0008	L0.05		
3-Jun-97	8.9	8.2	**0.108**	0.707	26	0.0006	0.0013	L0.05		
8-Jul-97	8.5	8.3	0.017	0.153	9	0.0002	0.0004			
5-Aug-97	7.5	8.2	0.008	0.153	8	L0.0002	L0.0003	L0.05	L0.005	L0.005
2-Sep-97	9.2	8.2	0.006	0.130	12	0.0003	0.0018	L0.05		
7-Oct-97	11.0	8.1	0.008	0.093	12	L0.0002	0.0011	L0.05	L0.005	L0.005
4-Nov-97	12.1	8.0	0.006	0.296	8	L0.0002	**0.0051**	L0.05		
1-Dec-97	13.3	8.0	0.004	0.054	4	L0.0002	L0.0003	L0.05		
OBJECTIVE:	*5*	*6.5 - 9.0*	*0.05*	*1*	*400*	*0.05*	*0.004*	*0.1*	*4*	*0.01*

[1] Bolded values do not meet the objective

[2] L = less than

The number of variables not meeting objectives is 2 (TP, Pb). The total number of variables is 10. Therefore:

$$F_1 = \left(\frac{2}{10}\right) \times 100 = \mathbf{20}$$

The number of tests not meeting objectives is 4, and the total number of tests is 103. Note that there are missing data in the mercury and pesticide columns. In this case:

$$F_2 = \left(\frac{4}{103}\right) \times 100 = \mathbf{3.9}$$

The excursions, their normalized sum, and F_3 are calculated as follows:

$$excursion = \left(\frac{0.058}{0.05}\right) - 1 = 0.16, \text{ etc.}$$

$$nse = \frac{(0.16+1.16+1.35+0.275)}{103} = 0.029$$

$$F_3 = \left(\frac{0.029}{0.01(0.029)+0.01}\right) = \mathbf{2.8}$$

With the three factors now obtained, the index value can be calculated:

$$CCMEWQI = 100 - \left(\frac{\sqrt{20^2+3.9^2+2.8^2}}{1.732}\right) = \mathbf{88}$$

Given the category ranges suggested in the document, the water quality at this river reach would be rated as "Good" based on 1997 data.

Example 2: Treatability Ranking – Groundwater Calculation

The following example has been created for illustrative purposes. The inputs are included as outlined in Section 5.3, and the points have been assigned as outlined in Table 5.2.

Source Type, Plant Capacity & Water Quality Concerns Point Rating

Input Categories	Response Options	Point or category Options	User Input	Application Calculation/ Determination	Points Generated by Application
Source Water Type	GW/SW	0,10	GW		0
Design Plant Capacity	ML/day	1-20	0.2	0.11	1
		small:0-0.25 *medium: 0.25-25* *large:>25 ML/day*		small	
Source Water Quality Concerns					
Taste and/or odour	Yes/No	2,0	Yes		2
algal growths	Yes/No	3,0	No		0
Iron (GCDWQ = 0.30 mg/L)	<, > or = GCDWQ	(0,2,3)	0.1	Fe & Mn <= GCDWQ	0
Manganese (GCDWQ = 0.05 mg/L)	<, > or = GCDWQ		0.05		
Colour (GCDWQ = 15 TCU)	<, > or = GCDWQ		5	colour <= GCDWQ	0
				point summary	3

Parameter Inputs and Required Removals

Parameters	Raw Water Concentration	Treated Water Quality Target *(note values cannot = 0)*	Required Removal in logs (Application Calculation)
Core			
1. *Escherichia coli (cfu/100 mL)*	0	0.0001	na
2. Total Coliforms (cfu/100 mL)	0	0.0001	na
3. Turbidity (NTU)	1	5	na
4. Nitrates & nitrites (mg/L)	30	45	na
5. Total Organic Carbon TOC (mg/L)	0	4	na
6. Iron (mg/L)	0.1	0.30	na
7. Manganese (mg/L)	0.05	0.05	na
enteric viruses (always presumed in GW)			4
Operational			
1. alkalinity (mg/L)	not measured	100	
2. pH	7	6.5-8.5	no adjustment
3. ammonia (mg/L)	2	1	0.30
4. bromide (mg/L)	0	0	na
5. colour (TCU	5	15	na
6. hardness mg/L	120	100	0.08
Site Specific			
1. sulphide	4	1	0.60

Unit Treatment Process Derivation

General Treatment Category			**1) Disinfection**						**3) Additional Pre or Post Treatment**						
Sub Categories			**Primary & Secondary Disinfection (or Oxidation) Alternatives**				**2) Filtration**			**4) Advanced Processes**					
Unit Treatment Process			Chlorine (both primary &/or secondary)	UV (primary) + Chlorine (secondary)	Chlorine (primary)+ chloramine (secondary)	UV (primary) + Chloramine (secondary)	cartridge or bag	MF Or UF	pH/ alkalinity adjustment	GAC	ion exchange	aeration or air stripping	activated alumina	greensand + potassium permanganate	RO or NF
ABC scoring			7	9	11	12	5	10	8	5	6	6	10	10	20
		GW Small Viable Processes √	√	√	√	√	√	√	√	√	√	√	√	√	√
Parameters	units	Removal Required (logs)	**Estimated Average Log Removals for Unit Treatment Processes**												
Escherichia coli	(logs)	na													
Total Coliforms	(logs)	na													
Turbidity (NTU = End Result not removal, logs = removal)	(NTU or logs)	na													
Enteric Viruses	(logs)	**4**	4	4	4	4	0	4							4
Nitrates & nitrites (combined)	log removal	na													
Total Organic Carbon (TOC)	log removal	na													
Iron	log removal	na													
Manganese	log removal	na													
ammonia	log removal	**0.30**			1.00	1.00					1.30				0.92
bromide	log removal	na													
Colour	log removal	na													
Hardness (as CaCO3)	log removal	**0.08**									0.87				1.52
Sulphide (as H2S)	log removal	**0.60**	2.00		2.00									2.00	
selected unit treatment processes			√								√				
point tally			7								5				

Treatment Solution & Associated Points

Treatment Solution		**Points**
Disinfection	Chlorine (both primary &/or	5
Filtration	na	
Pre-Post Treatment	na	
Advanced	ion exchange	7
		12

Final Result

Overall Points From Program	**15**
Category	**Easy to Treat**