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THE CANADIAN WATER QUALITY INDEX: A TOOL FOR WATER RESOURCES MANAGEMENT

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ABSTRACT

Since its development in 2001, the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (WQI) has established itself as a valuable tool for water resources management. The CCME WQI model consists of three measures of variance from selected water quality objectives (Scope; Frequency; Amplitude). These three factors combine to produce a value between 0 and 100 that represents the overall water quality. This value is converted into a ranking using an index categorization scheme that is based on expert opinion. Though the CCME WQI was developed for simplifying the reporting of water quality data it has evolved to become a multipurpose tool. This paper presents and discusses diverse examples of the CCME WQI being used as a water resources management tool. Case studies are presented of its use for drinking water quality data communications, ambient water quality data analysis, integrated watershed planning and management in the forestry sector and as a performance measurement tool to assess the effectiveness of best management practices.

INTRODUCTION

A critical component of Water Resources (WR) management is the collection, analysis, and distribution of water quality (WQ) data. Inherently technical WQ data often has to be communicated to diverse audiences. The communication of WQ data is especially challenging when the intended audience for the WQ data is the general public.

Most stakeholders such as the general public are not directly interested in WQ data. They are more interested in the information that the WQ data conveys and are even more interested in the knowledge that follows from the information. For example, a pH reading of 7 for a WQ sample collected from a lake does not mean much to most stakeholders. However when the data is converted into information that the pH is within acceptable WQ guidelines, this is of interest to stakeholders. If this information is further processed to convey the knowledge that meeting the WQ guidelines means that the WQ is suitable for aquatic life, the value of the data is increased immensely. Thus the process of communicating WQ data requires the processing of WQ data into information and then into knowledge.

The Canadian Council of Ministers of the Environment (CCME) Water Quality Index (WQI) was developed for simplifying the reporting of water quality data [1]. It is a tool for generating meaningful summaries of water quality data that are useful to technical and policy individuals, as well as the general public interested in water quality results. It provides a broad overview of water quality data and is not intended to be a substitute for detailed analysis of water quality data.

In Canada the province of British Columbia was the first to develop and apply a WQI. This was followed by a number of other jurisdictions and institutions applying some form of an index to WQ data prior to the development of the CCME WQI. In 1997, a CCME WQI technical sub-committee was formed to assess the various approaches already in use and subsequently formulate a CCME WQI that could be used nationally.

THE CCME WQI

The CCME WQI model consists of three measures of variance from selected water quality objectives (Scope; Frequency; Amplitude). These three measures of variance combine to produce a value between 0 and 100 that represents the overall water quality. The CCME WQI values are then converted into rankings by using the index categorization schema presented in Table 1.

Table 1. CCME WQI categorization schema [1]

Rank	**WQI Value**	**Description**
Excellent	95-100	Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels; these index values can only be obtained if all measurements are within objectives virtually all of the time
Good	80-94	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels
Fair	65-79	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels
Marginal	45-64	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels
Poor	0-44	Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels

Calculation of the CCME WQI

The detailed formulation of the WQI, as described in the Canadian Water Quality Index 1.0 – Technical Report [1], is as follows:

Scope, F_1

The measure for scope is F_1. This represents the extent of water quality guideline non-compliance over the time period of interest.

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}}\right) \text{X } 100 \quad [1] \qquad (1)$$

Frequency, F_2

The measure for frequency is F_2. This represents the percentage of individual tests that do not meet objectives ("failed tests").

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}}\right) \text{X } 100 \quad [1] \qquad (2)$$

Amplitude, F_3

The measure for amplitude is F_3. This represents the amount by which failed tests do not meet their objectives. This is calculated in three steps:

Step 1- Calculation of Excursion. Excursion is the number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective.

When the test value must not exceed the objective:

$$\text{excursion}_i = \left(\frac{\text{Failed Test Value}_i}{\text{Objective}_j}\right) - 1 \quad [1] \qquad (3)$$

When the test value must not fall below the objective:

$$\text{excursion}_i = \left(\frac{\text{Objective}_j}{\text{Failed Test Value}_i}\right) - 1 \quad [1] \qquad (4)$$

Step 2- Calculation of Normalized Sum of Excursions. The normalized sum of excursions, *nse*, is the collective amount by which individual tests are out of compliance. This is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those not meeting objectives).

$$nse = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{Number of tests}} \quad [1] \qquad (5)$$

Step 3-Calculation of F_3 . F_3 is calculated by an asymptotic function that scales the normalized sum of the excursions from objectives to yield a range from 0 to 100.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01} \right) \quad [1] \qquad (6)$$

The WQI is then calculated as:

$$\text{WQI} = 100 - \left(\frac{\sqrt{F_1^{\,2} + F_2^{\,2} + F_3^{\,2}}}{1.732} \right) \quad [1] \qquad (7)$$

The WQI values are then converted into rankings by using the categorization scheme presented in Table 1. By this process the CCME WQI converts raw WQ data into information (how many parameters exceeded the guidelines, how frequently and by what amplitude) and then into knowledge (the water is Excellent, Good, Fair or Poor for drinking water use etc.).

The CCME WQI formulation has been automated in various spreadsheet programs. CCME WQI calculators are available from CCME (http://www.ccme.ca/initiatives/water.html?category_id=42) and the Newfoundland and Labrador Department of Environment and Conservation (NL DOEC) (http://www.gov.nf.ca/Env/env/waterres/Surfacewater/WQI/CanadianWQI.asp) web sites. The NL calculator uses the same formulation as the CCME calculator but it includes additional features and tools such as the ability to compute WQ indices for up to eight different water uses simultaneously, generation of Site Specific Guidelines for use in the WQI computations, parameter flagging, a customizable index categorization schema and other advanced sensitivity analysis options.

APPLICATIONS OF THE CCME WQI

Drinking Water Quality Data Reporting

With the current national emphasis in Canada on drinking water safety, the communication of drinking water quality (DWQ) to the general public is a national priority. In addition to communicating DWQ data, the communication of results to the public also requires communication of information on how well these results compare to DWQ guidelines or standards.

A similar priority was faced in NL, where the provincial government conducts DWQ monitoring of all public water supply systems and reports the results to all sampled communities on a quarterly basis. The traditional DWQ reports used consisted of raw DWQ data that did not convey any information or knowledge to the communities that received them.

To address this challenge the CCME WQI was adapted to not only convey information on how well the DWQ results of each quarter compared to DWQ guidelines but to also convey added knowledge on how well the community's DWQ ranked as per provincial expert opinion.

Khan et al. [2] describe this adaptation and implementation of the CCME WQI for DWQ data reporting in NL. The CCME WQI was selected as the communications tool for this task due to its ability to simplify DWQ data without compromising the integrity of the data. The CCME WQI simplifies DWQ data to a level that can be understood by the general public and in doing so it also compares, in a systematic manner, the compliance of the

DWQ data to DWQ guidelines. Another central reason for selecting the CCME WQI was that it allows one to integrate local expert opinion into the rankings through the CCME WQI index categorization schema.

The CCME WQI was initially applied to chemical drinking water quality data sets from 34 communities. These 34 communities represented a wide variation of water sources, treatment systems, and community sizes. The computed WQI scores and ranking were then compared against ranking that reflected provincial expert opinion. This comparison indicated that the CCME WQI ranking compared favorably with the provincial expert opinion based ranking. However a need was identified to introduce an additional level of differentiation within the CCME WQI “Good” ranking to account for DWQ datasets that were better than most of the datasets that fell within the “Good” categorization but were not as good as the datasets that fell within the CCME WQI “Excellent” ranking. Using DWQ datasets that were ranked by provincial experts as being “Very Good”, the CCME WQI index categorization schema was modified (from the schema shown in Table 1), as shown in Figure 1, by adding the new ranking category of “Very Good”.

Following on this the computation of the CCME WQI was implemented as an automated routine in the provincial DWQ database. As a result, WQI reports for each sampled community are now automatically generated at the end of each sampling period. The implementation schema is sophisticated enough to incorporate the complexities introduced by Boil Water Advisories (BWA), Trihalomethane (THM) exceedances and contaminant (parameter with health effects) exceedances.

The automated generation of WQI rankings is a practical means for dramatically improving the interpretation of DWQ results and the use of the CCME WQI throughout the province ensures that the rankings are computed in a consistent manner. This eliminates the personal subjectivity that was previously introduced by different regional DOEC officers when they interpreted DWQ results on the request of communities who could not understand their DWQ datasets.

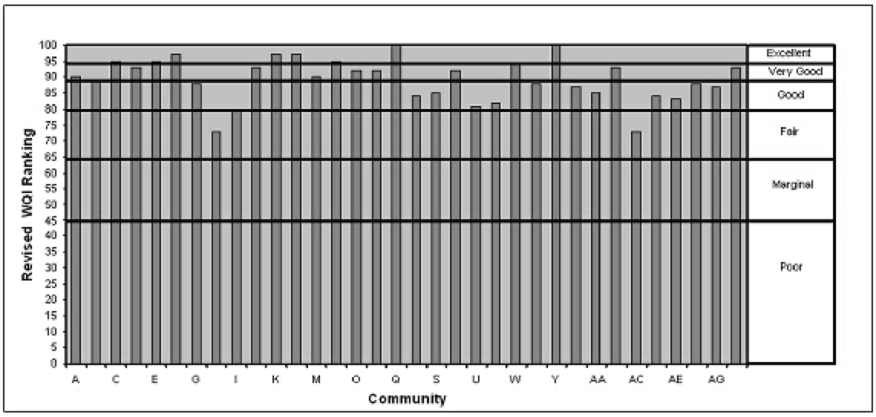


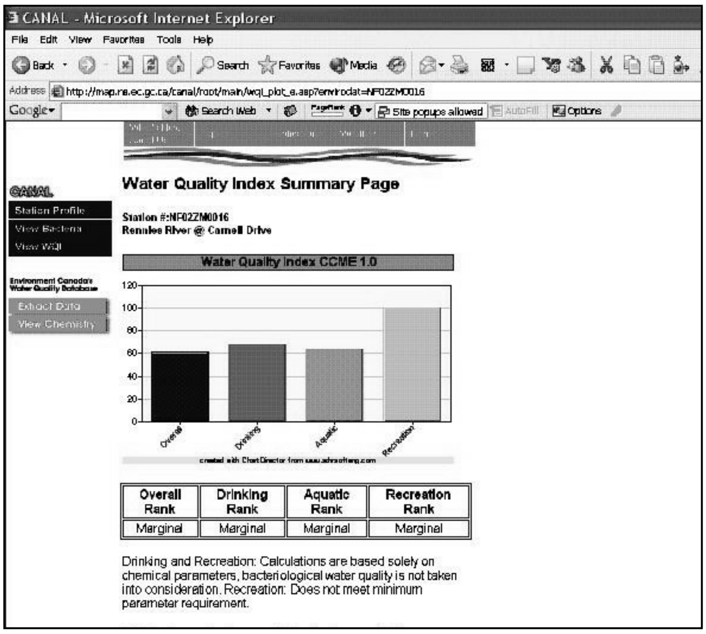
Figure 1. Distribution of water quality using revised WQI rankings (Reproduced with permission from Water Quality Research Journal of Canada 39, 285 293 (2004), copyright CAWQ, Burlington, Ontario, Canada.)

Ambient Water Quality Data Analysis

In an innovative application the CCME WQI is being utilized in conjunction with WQ data web services to deliver ambient WQ data to Canadians through a GIS web site called the Canada-Newfoundland/Labrador Aqua Link (CANAL). The CANAL web site is available at: http://map.ns.ec.gc.ca/canal/root/main/.

The ambient WQ data is collected from a Federal–Provincial network consisting of 109 sites throughout NL. The sampling frequency at these sites varies from between one time per year to twelve times per year. Collected water quality samples are analyzed for 38 WQ parameters and the data obtained is then stored in an Environment Canada database called ENVIRODAT. The data collected in ENVIRODAT is used by both federal and provincial agencies and is used to support; water resources management programs, pollution control regulations, water quality guidelines and objectives development, water quality modeling (simulation and prediction), environmental assessment studies, legislative formulations and federal, provincial and international agreements and commitments.

The CANAL website was developed to provide the general public and various other stakeholders increased access to this wealth of WQ information on ambient water bodies in NL. The website provides users direct access to WQ data in ENVIRODAT through a WQ data web service. It also uses data web services to provide detailed site profiles for each sampling site. The distinguishing feature of CANAL is that it uses the CCME WQI to summarize and interpret the WQ data for various water uses (Figure 2). This immensely increases the utility of the WQ data being served through the CANAL website.



Water Quality Index Summary Page

Station #:NF02ZM0016
Rennies River @ Carnell Drive

Overall Rank	Drinking Rank	Aquatic Rank	Recreation Rank
Marginal	Marginal	Marginal	Marginal

Drinking and Recreation: Calculations are based solely on chemical parameters, bacteriological water quality is not taken into consideration. Recreation: Does not meet minimum parameter requirement.

Figure 2. Screen shot of WQI page from CANAL.

In addition to being a communications and summarizing tool the CCME WQI has also proven to be very useful for analysis and communication of ambient water quality data. This stems from its ability to convert raw WQ data into insightful and meaningful information. When analyzing any WQ dataset the usual analysis requires understanding which parameters exceeded guidelines, how frequently and by how much. This information is captured in the F1, F2, and F3 factors of the CCME WQI and a review of F1, F2, and F3 values for any dataset provides valuable insights into issues with the dataset.

The CCME WQI can be used to compare upstream and downstream WQ data sets. Table 2 presents F1, F2, and F3, and WQI scores from two sampling sites on the South Brook in NL. Site A is located upstream of site B. A comparison of the F1, F2, and F3 values indicates that the number of parameters failing the guidelines (F1) increases as one moves downstream. It's effect however, on the overall WQI score is countered by a decreasing frequency (F2) and amplitude (F3). This type of analysis using the WQI F1, F2, and F3 values and scores helps summarize the essential differences between the two sites and is a very useful first step in the detailed comparison of the two sites.

Table 2. F1, F2, and F3 for Two Sites on the South Brook

South Brook At Site A				**South Brook At Site B**			
F_1	**F_2**	**F_3**	**WQI Score**	**F_1**	**F_2**	**F_3**	**WQI Score**
33	26	65	55	57	21	55	53

The CCME WQI can also be used to gain insight into temporal variations in WQ at a given site. Table 3 presents F1, F2, and F3, and WQI scores from three different months from a pond in NL. A comparison of the F1, F2, and F3 values provides a synopsis of how the WQ varied from month to month.

Table 3. Temporal variation of F1, F2, F3 and WQI Scores

Month	**F_1**	**F_2**	**F_3**	**WQI Score**
June	33	21	54	61
August	29	22	38	70
October	21	17	58	63

Integrated Watershed Planning and Management in the Forestry Sector

The CCME WQI is also an excellent tool for integrated watershed planning and management in the forestry sector. A sensitivity analysis option in the NL WQI calculator allows the user to change the values of all or a selected set of WQ parameters to help understand the potential impacts of WQ changes. This sensitivity analysis option can be used to evaluate the impact of potential forestry activity if it is known from previous studies what the potential effects on WQ would be. Following on this, Table 4 presents the results of an evaluation of the potential impact of increased forestry activity in the watershed upstream of a pond in Lewisporte. WQ indices for the site are presented for current WQ conditions and for the expected WQ after the forestry activity has taken place. The expected post forestry WQ was generated from current WQ data by increasing all turbidity, potassium, phosphorous, nitrogen and dissolved organic carbon readings by factors of 2.19, 1.25, 1.36, 1.80 and 1.49 respectively. These multiplication factors were computed from an analysis of changes between pre and post forestry WQ in an adjoining watershed. The pre and post forestry WQ indices presented in Table 4 indicate that the forestry activity will only slightly increase the frequency (F2) of WQ exceedances. As a result the overall WQI score will decrease by only one WQI point and the ranking of the WQ will not change. Thus the WQI provides information and knowledge on the potential impact of the proposed forestry activity that can be easily communicated to stakeholders.

Table 4. Sensitivity Comparison for Stanhope Pond (Lewisporte)

Current Conditions					After Anticipated Forestry				
F1	F2	F3	WQI Score	WQI Rank	F1	F2	F3	WQI Score	WQI Rank
45	17	49	61	Marginal	45	19	49	60	Marginal

Performance Measurement Tool to Assess the Effectiveness of Best Management Practices

Best Management Practices (BMPs), such as no development zones along water bodies and no development within sensitive areas, are often implemented in watersheds with multiple land use activities and those that are under pressure from development. The implementation of BMPs is done with the intention of achieving a balance between protecting environmental health and encouraging local economic growth through resource development. The application of the CCME WQI as a performance measurement tool for BMPs was assessed through analysis of historical WQ data from the Lewisporte protected public water supply area in NL. The implementation of BMPs in the Lewisporte protected public water supply area began in approximately 1997. Data from 25 WQ samples collected from 1993 to 2002 was used for the analysis. The data was split into a pre BMP and post BMP period but since the effect of BMPs is not immediate, a rolling window was used to assess when the effect of BMPs was being reflected in the WQ. The use of a rolling window resulted in four sets of pre BMP and post BMP data as shown in Table 5. The WQI score was calculated for the pre BMP and post BMP data for each set and compared. Starting from the second data set the post BMP WQI scores started showing an improvement over the pre BMP WQI scores. From examining the WQI scores for sets two to four, it seems that the effect of the BMPs was being reflected in the WQ from 1998 onwards.

Table 5. Pre and Post BMP WQI Scores for Stanhope Pond (Lewisporte)

Datasets	Period	Time Frame	Number of Parameters	Number of Samples	CCME WQI Value
1	Pre BMP Period	1993-1996	16	8	63
	Post BMP Period	1997-2002	16	17	59
2	Pre BMP Period	1993-1997	16	10	60
	Post BMP Period	1998-2002	16	15	61
3	Pre BMP Period	1993-1998	16	13	58
	Post BMP Period	1999-2002	16	12	64
4	Pre BMP Period	1993-1999	16	17	58
	Post BMP Period	2000-2002	16	8	64

CONCLUSIONS AND POTENTIAL APPLICATIONS

As demonstrated from the case studies presented in this paper, the CCME WQI's application is not limited to just ambient water quality data communication. The NL DOEC has also used the CCME WQI for various other WR applications such as aquaculture, relative ranking of water bodies, communication of real time water quality data and trend studies. It has been demonstrated to be a multi-faceted water resources management tool that has many potential applications. Potentially it can be used in any situation where data is being compared against corresponding guidelines or standards.

ACKNOWLEDGEMENTS

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