Canadian Water Quality Guidelines for the Protection of Aquatic Life

CCME WATER QUALITY INDEX 1.0 Technical Report

Acknowledgements

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In addition to the authors of the report, there were several other people who contributed significantly to the development of the index. Dr. W. Hart, Centre for Water Resources, Memorial University, performed detailed evaluations of earlier index formulations. Ashok Lumb (Environment Canada), Earle Baddaloo (Alberta Environmental Protection), Jackie Shaw (Alberta Environmental Protection), Anne Kerr (Environment Canada), Kim Hallard (Saskatchewan Environment and Resource Management), Murray Hilderman (Saskatchewan Environment and Resource Management), Peter Rodgers (Environment Canada) and Karl Lauten (Saskatchewan Environment and Resource Management) contributed to discussions of the index. Ilze Reiss and Herb Vandermeulen of Environment Canada and Scott Tessier and Margaret Gibbs of CCME provided significant assistance during the course of the committee's work.

Introduction

The purpose of this report is to describe the development of a CCME Water Quality Index (CCME WQI). The CCME WQI is a tool for simplifying the reporting of water quality data. Traditional reports on water quality trends typically consisted of variable-by-variable, water-body-by-water-body statistical summaries. This type of reporting is of value to water quality experts and managers, but is often inaccessible to non-experts. It is hoped that the CCME WQI will fill a gap, providing meaningful summaries of overall water quality and trends, while producing output that is accessible to senior managers and non-technical lay people.

It is important when using indices to keep in mind their limitations. While a stock market index is a good indicator of the overall performance of the market, anyone with a stock portfolio will be interested in the performance of individual stocks, or stock sectors. An environmental index is similar. The CCME WQI is not intended to replace a detailed analysis of environmental monitoring data, nor should it be used as the only tool for management of water bodies. What it can do is provide a broad overview of environmental performance, and it was with this in mind that the CCME Water Quality Index was developed.

A number of attempts have been made to develop this type of index [1,2,3,4]. The advantages of indices include their ability to represent measurements of a variety of variables in a single number, the ability to combine various measurements in a variety of different measurement units in a single metric, and the facilitation of communication of the results. Disadvantages include the loss of information on single variables, the sensitivity of the results to the formulation of the index, the loss of information on interactions between variables, and the lack of portability of the index to different ecosystem types [5].

The CCME WQI is not intended to replace a detailed assessment of water quality conditions through conventional water quality assessment methods. It presupposes good analytical data on chemical water quality measurements relevant to the site(s) being assessed.

Background - Existing Canadian Indices and Index Evaluations

Prior to the development of the CCME Water Quality Index, there were a number of jurisdictions and institutions in Canada using some type of metric to assess water quality. The Water Quality Index Technical Subcommittee was formed by the Water Quality Guidelines Committee of the Canadian Council of Ministers of the Environment in 1997 to assess different approaches to index formulation and to develop an index that could be used to simplify water quality reporting in Canada. The different approaches in use in Canada are briefly described in this section of the report.

Centre St Laurent

The Centre St Laurent (CSL) is an Environment Canada office responsible for reporting on the St. Lawrence River. The WQI developed at CSL was

$$\text{WQI}=[\Sigma(\mathbf{A_i} \times \mathbf{F_i})]/\mathbf{n}$$

Where:

$\mathbf{A_i}$ is the mean level of exceedence for variable i for guideline i. When a variable value exceeds a guideline for that variable, the ratio "exceeding value/guideline value" is calculated. These ratios are summed and then divided by the number of times they occur.

$\mathbf{F_i}$ is the frequency of values that exceed a guideline for a variable relative to the total number of values obtained for that variable ($F_i = F_{exceed}/F_{total}$ for variable i).

n is the number of variables.

The CSL calculated a number of different water quality indices, depending on what water uses they were considering. For example, separate index calculations were made based on guidelines for protection of aquatic life, primary contact recreation, human consumption, and for saltwater areas of the St. Lawrence estuary, for shellfish harvesting.

Quebec

The Quebec index[6] was based on an approach originally developed in New Zealand[2] . This index was the minimum of a number of subindices, which are calculated for each of the water quality variables measured:

$$\text{WQI} = \mathbf{min}(\boldsymbol{I}\text{sub}_1, \boldsymbol{I}\text{sub}_2,\ldots,\boldsymbol{I}\text{sub}_n)$$

What made this approach different from others used in Canada was the use of 'Delphi curves' for the calculation of the subindices. Delphi curves are based on expert opinion as to the significance of a particular level of a water quality component. They are usually non-linear, and represent the aggregated opinion of what a particular level of a particular contaminant means in terms of the designated water use. The Quebec index represented the 'worst case impairment' of any of the variables measured.

British Columbia

The British Columbia approach to calculating a water quality index included a factor not considered in any of the other indices:

$$\text{WQI} = (\mathbf{F_1}^2+\mathbf{F_2}^2+\mathbf{F_3}^2)^{1/2}$$

Where:

$\mathbf{F_1}$ is the percentage of water quality guidelines exceeded.
$\mathbf{F_2}$ is the percentage of measurements in which one or more of the guidelines were exceeded.
$\mathbf{F_3}$ is the maximum (normalized to 100) by which any of the guidelines were exceeded.

The British Columbia index[7] had the longest and most extensive development and application. Two of its factors are analogous to components of other indices: $\mathbf{F_2}$ is similar to the Alberta index, while $\mathbf{F_3}$ is similar to the Centre St Laurent index. $\mathbf{F_1}$ was not found in any of the other indices. British Columbia had used its index to generate a provincial report focusing on water quality[8].

As with the other jurisdictions, British Columbia uses its index based on a variety of objectives. Each water body is assessed with respect to designated uses. British Columbia has different objectives for drinking, recreation, irrigation, livestock watering, wildlife, and aquatic life. Separate rankings were published based on each use relevant to the water body.

Manitoba

Manitoba adopted the British Columbia approach. Based on an evaluation of four years of data on eight sites in Manitoba, the province concluded that the British Columbia index appeared to give reasonable results for the Manitoba case. They had not made any attempts to modify the index. Manitoba used the index for their state of the environment report[9].

Alberta

Alberta used a 'performance indicator' for water quality in their state of the environment reporting. Their indicator for water quality was:

$$A = (n_{exceed}/n_{measure})*100$$

This was the percentage of the samples taken at a site where one or more of the variables exceed the objectives for a designated use. Common uses in Alberta include recreation, agriculture, and aquatic life.

Ontario

Ontario had made an evaluation of the British Columbia index, but had modified F_3 so that it represented the average normalized exceedence rather than the maximum. They had reported some problems with the third factor of the British Columbia index saturating when large exceedences of objectives occurred. There was no index being used routinely in Ontario.

Comparison of Indices

An analysis of the concepts behind the various indices and performance measures revealed that while there were computational differences in the indices, many of them were measuring the same attributes of deviation from objectives.

Each of the independent index approaches was a combination of one or more measures of three attributes of water quality, measured against objectives appropriate for the use of the water. These different approaches had been documented and summarised for the CCME in 1996[10].

Jurisdiction or Institution	Proportion of Objectives Exceeded	Frequency with which Objectives are Exceeded	Amplitude by which Objectives are Exceeded
British Columbia	F_1	F_2	F_3
CSL	-	Fi	Ai
Alberta	-	%Exc	-
Quebec	-	-	Delphi
Environment Canada	-	-	A

CCME Water Quality Index Development

Conceptual Model for the Index

The Water Quality Index Technical Subcommittee adopted the conceptual model from the British Columbia index. The ‘Delphi’ approach used in Quebec was seriously considered for incorporation in the index, but was discarded because of the time and logistics involved in developing ‘Delphi’ curves for large numbers of water chemistry variables.

There are three factors in the index, each of which has been scaled to range between 0 and 100. Figure 1 shows the conceptual model for the index. The values of the three measures of variance from selected objectives for water quality are combined to create a vector in an imaginary ‘objective exceedence’ space. The length of the vector is then scaled to range between zero and 100, and subtracted from 100 to produce an index which is 0 or close to 0 for very poor water quality, and close to 100 for excellent water quality. Since the index is designed to measure water quality, it was felt that the index should produce higher numbers for better water quality.

The Technical Subcommittee developed an earlier version of the index based on this conceptual model. This earlier version was evaluated on synthetic data sets[11], and data sets from British Columbia[12], and Newfoundland[13]. Along with evaluations in Alberta and Ontario, these evaluations revealed that significant problems arose due to the formulations for estimating frequency and amplitude.

As a result of these problems, Alberta Agriculture Food and Rural Development in association with Alberta Environmental Protection funded research into alternative formulations of the frequency and scope factors[14]. The Technical Subcommittee relied heavily on this work, and used it as the basis for the final formulation of the CCME WQI.

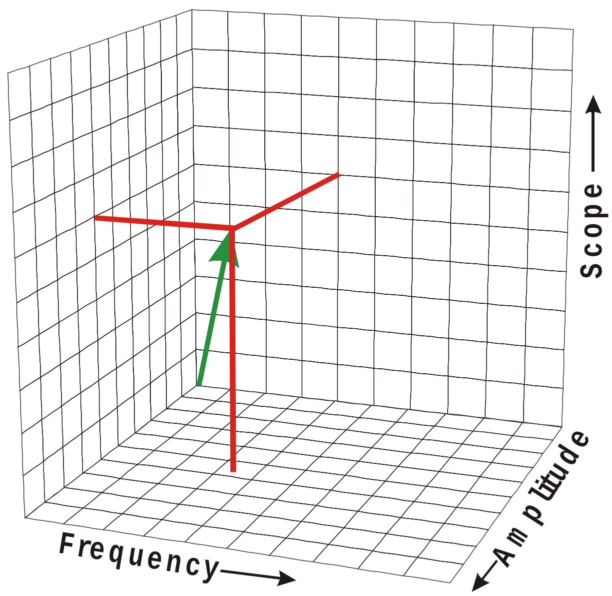

Figure 1. Conceptual Model of the Index

CCME Water Quality Index Formulation

The index consists of three factors:

Factor 1: Scope

F_1 (**Scope**) represents the extent of water quality guideline non-compliance over the time period of interest. It has been adopted directly from the British Columbia Index:

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) \times 100$$

Where **variables** indicates those water quality variables with objectives which were tested during the time period for the index calculation.

Factor 2: Frequency

F_2 (**Frequency**) represents the percentage of individual tests that do not meet objectives (“failed tests”):

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100$$

The formulation of this factor is drawn directly from the British Columbia Water Quality Index.

Factor 3: Amplitude

F_3 (**Amplitude**) represents the amount by which failed test values do not meet their objectives. F_3 is calculated in three steps. The formulation of the third factor is drawn from work done under the auspices of the Alberta Agriculture, Food and Rural Development[15].

(i) The number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective is termed an “excursion” and is expressed as follows. When the test value must not exceed the objective:

$$excursion_i = \left(\frac{FailedTestValue_i}{Objective_j} \right) - 1$$

For the cases in which the test value must not fall below the objective:

$$excursion_i = \left(\frac{Objective_j}{FailedTestValue_i} \right) - 1$$

ii) The collective amount by which individual tests are out of compliance 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). This variable, referred to as the normalized sum of excursions, or *nse*, is calculated as:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{\#\ of\ tests}$$

iii) F_3 is then calculated by an asymptotic function that scales the normalized sum of the excursions from objectives (*nse*) to yield a range between 0 and 100.

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

The CCME WQI is then calculated as:

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

The factor of 1.732 arises because each of the three individual index factors can range as high as 100. This means that the vector length can reach

$$\sqrt{100^2 + 100^2 + 100^2} = \sqrt{30000} = 173.2$$

as a maximum. Division by 1.732 brings the vector length down to 100 as a maximum.

Categorization of Index Values

The assignment of CCME WQI values to categories of water quality is termed "categorization" and represents a critical but somewhat subjective process. Categorization should be based on the best available information, expert judgement, and the general public's expectations of water quality. The categorization presented here is preliminary and will no doubt be modified as the index is tested further.

Because of the nature of the index, it is impossible to determine from an index range whether the ranking is due to extreme excursions in one variable, or frequent small excursions in one or more variables. The prototype Water Quality Index calculator, developed with support from Alberta Agriculture, Food and Rural Development allows users to determine the variables primarily responsible for the behaviour of the index.

Once the CCME WQI value has been determined, water quality can be ranked by relating it to one of the following categories:

Excellent: (CCME WQI Value 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: (CCME WQI Value 80-94) – water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.

Fair: (CCME WQI Value 65-79) – water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.

Marginal: (CCME WQI Value 45-64) – water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.

Poor: (CCME WQI Value 0-44) – water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

Index Application

The CCME WQI as described above has been applied to several data sets from across Canada. This section will give some examples.

Ontario

Most of Ontario's routine water quality monitoring data comes from an extensive network of regularly monitored stations in the Provincial Water Quality Monitoring Network (PWQMN). The CCME WQI has been tested on data from over eighty of these stations, and is currently being run on all data in the network gathered since 1980. The following example focuses on eight stations from the lower Trent River Watershed in southern Ontario (see Figure 2). The variables included in this data set are: aluminum, arsenic, cadmium, chromium, copper, dissolved oxygen, fecal coliform, nickel, pH, phenols, phosphorus, and zinc. Data are typically collected on a monthly basis.

The stations selected for these examples are representative of data collected at over 800 sites in Ontario between 1980 and 1995. The results are shown in Figure 3. There is good discrimination between sites on rivers flowing from primarily Canadian Shield based, non-agricultural areas (for example, station 17002100302) and sites where there are some impacts due to livestock rearing and low-intensity agriculture (for example, Station 17002104702). A full assessment of the utility of the index in reporting on Ontario water quality is in preparation.

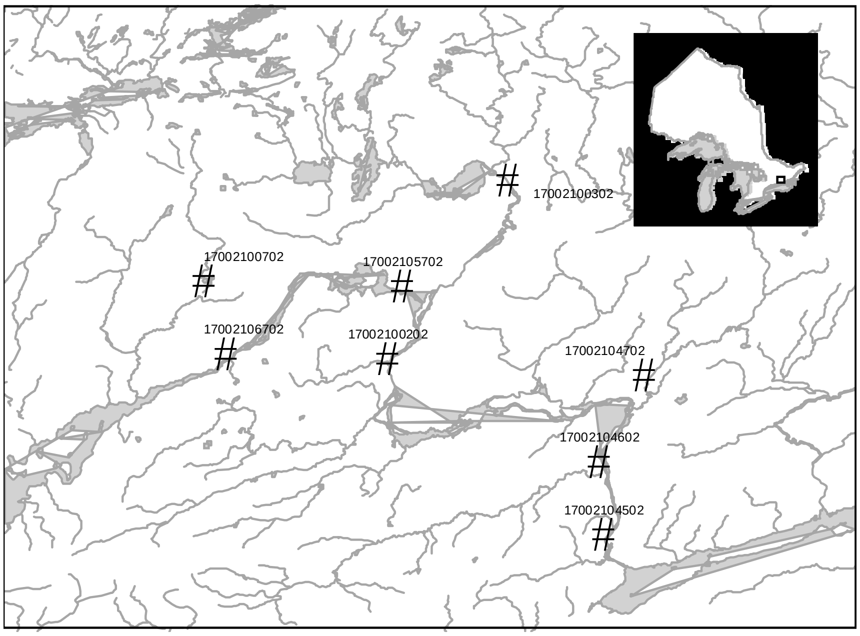

Figure 2. Location of Lower Trent River PWQMN Stations (Ontario)

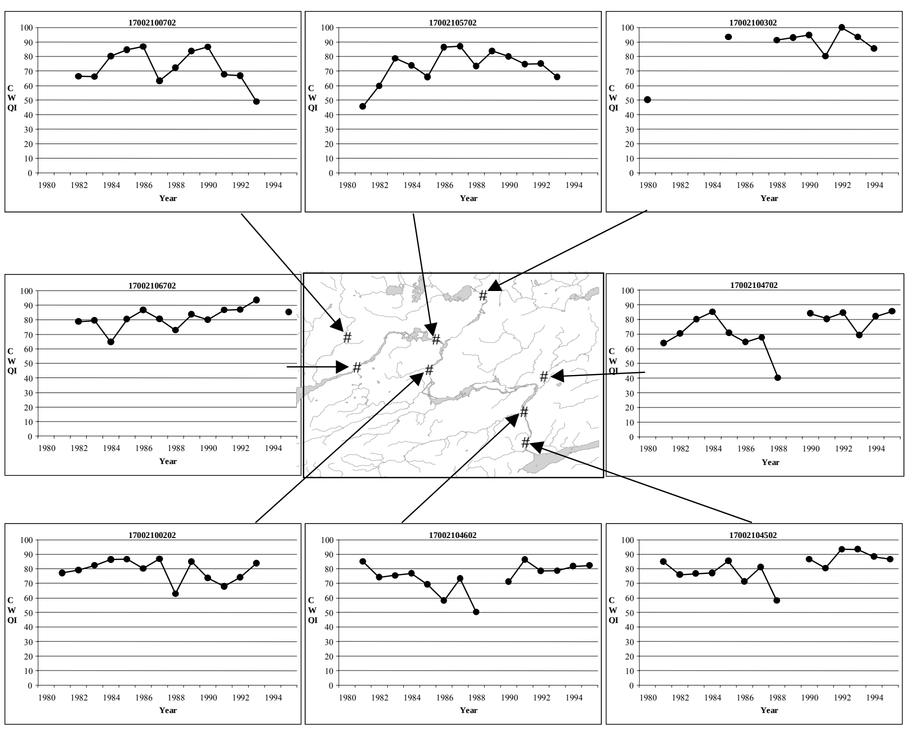

Figure 3. CCME WQI Trends in the Lower Trent River

Newfoundland

The CCME WQI was applied to three selected watersheds in Newfoundland. Water quality data from 1986 to 1994, collected under Federal-Provincial Water Quality Agreement, for twelve stations located in the Humber Watershed, the Exploits Watershed and the Quidi Vidi Watershed were used in the analysis (see Figure 4). Variables included in the index calculation were conductivity, turbidity, dissolved oxygen, pH, dissolved organic carbon, aluminum, arsenic, cadmium, chromium, copper, iron, manganese, lead, nickel, phosphorus and zinc.

The CCME WQI trend at eight of these sites is shown in Figure 5. An assessment of the application of the CCME WQI to these watersheds[15] concluded that there was good discrimination between pristine sites (for example, Lloyds River - YN0001) compared to sites impacted by urbanization or past mining activities (YO0017, YO0001).

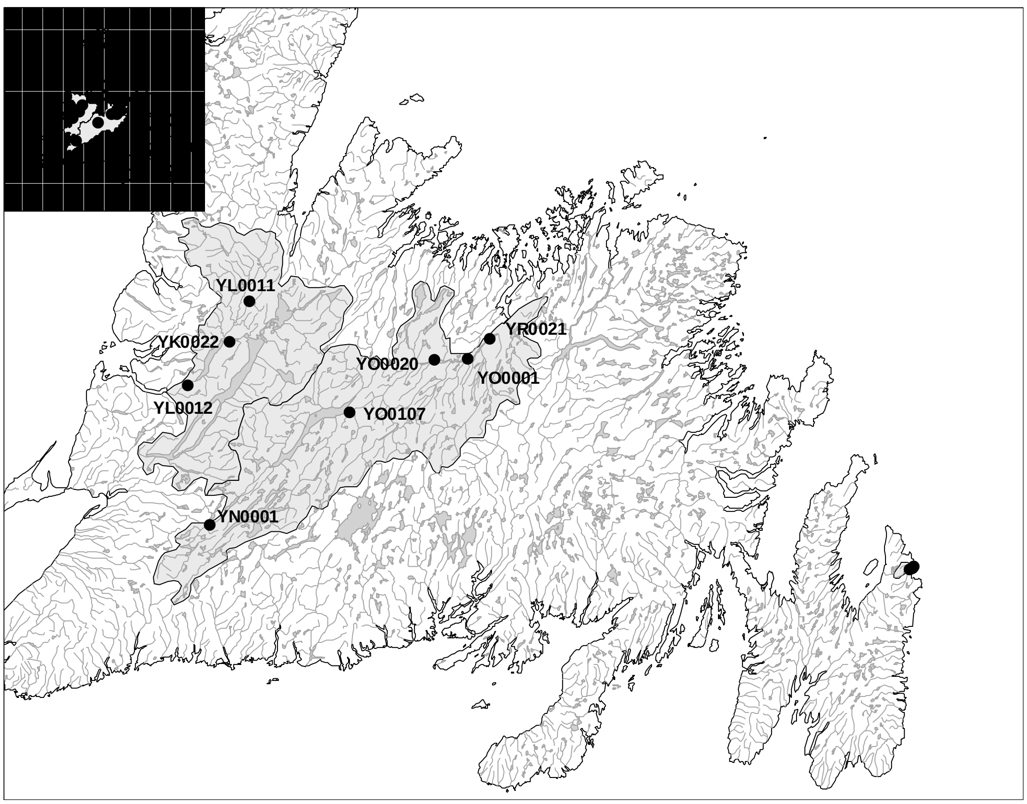

Figure 4. Water Quality Index Sites in Newfoundland

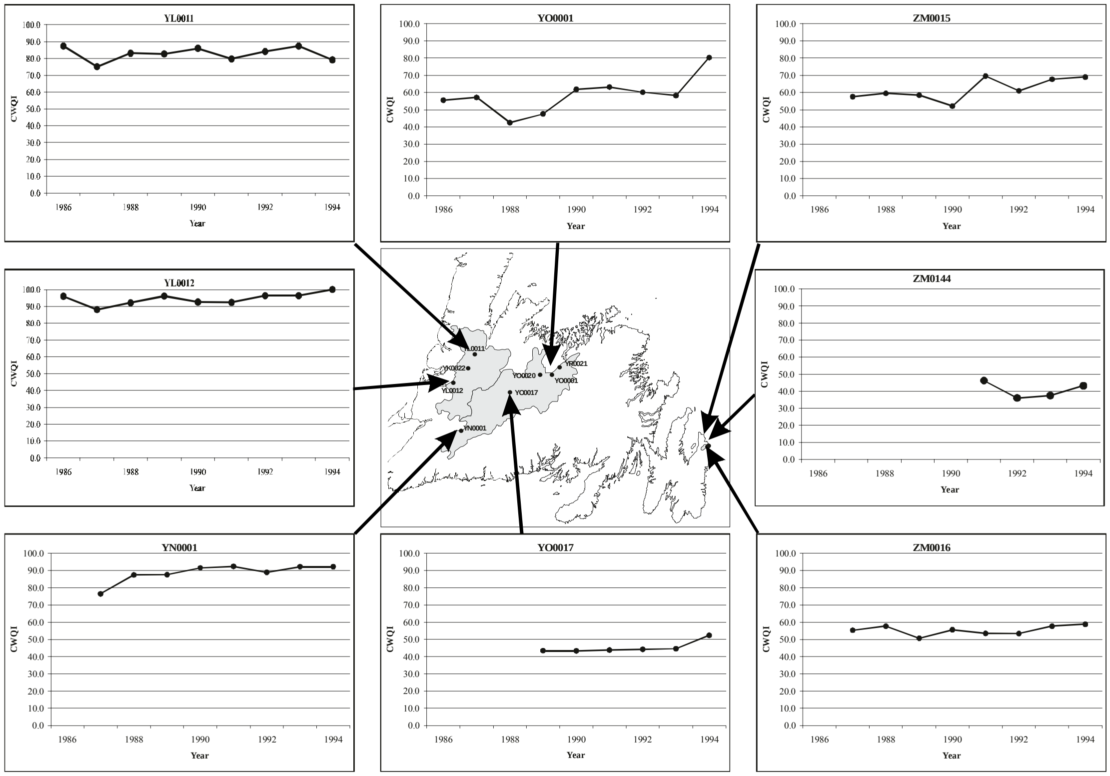

Figure 5. CCME WQI trends at selected sites in Newfoundland

Saskatchewan

The data for the Saskatchewan application were obtained from the Prairie Provinces Water Board (PPWB). The PPWB was established in the 1930s and represents an agreement among the three Prairie Provinces and the Federal government. Originally, the PPWB was concerned only with water quantity (transfers across provincial boundaries) but the interests broadened over time and led to the inclusion of a water quality program starting in 1968. Currently the PPWB monitors water quality at twelve sites (six along the Alberta Saskatchewan boundary and six along the Saskatchewan-Manitoba boundary – see Figure 6).

Figure 7 shows the results when the CCME WQI is applied to eight of these reaches. Variables included in this example are: chloride, cooper, fecal coliform, iron, lead, manganese, $NO_2 + NO_3$, sodium, sulphate, zinc, phosphorus, dissolved oxygen, total dissolved solids and pH. Data were typically collected on a monthly basis.

As can be seen in Figure 7 overall water quality ranges from marginal to excellent, depending on the river reach and sample year. As expected, the Churchill River, the least impacted in the sampling network, consistently shows the highest CCME WQI values. In contrast, the Carrot River, which is subject to both agricultural and forestry activity, has a water quality which is typically "fair", largely as a consequence of excursions to the phosphorous objective. As with a recent PPWB analysis, the CCME WQI does not suggest a significant trend in water quality for any of these sites. A more complete assessment of the CCME WQI in these rivers is currently in progress.

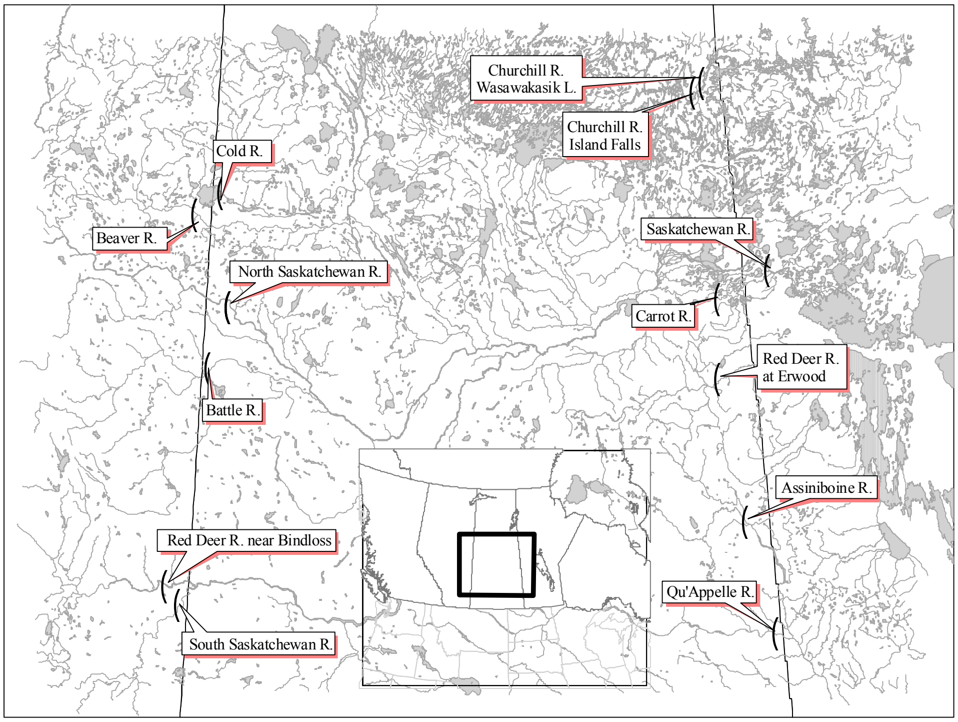

Figure 6. Prairie Provinces Water Board Sampling Sites

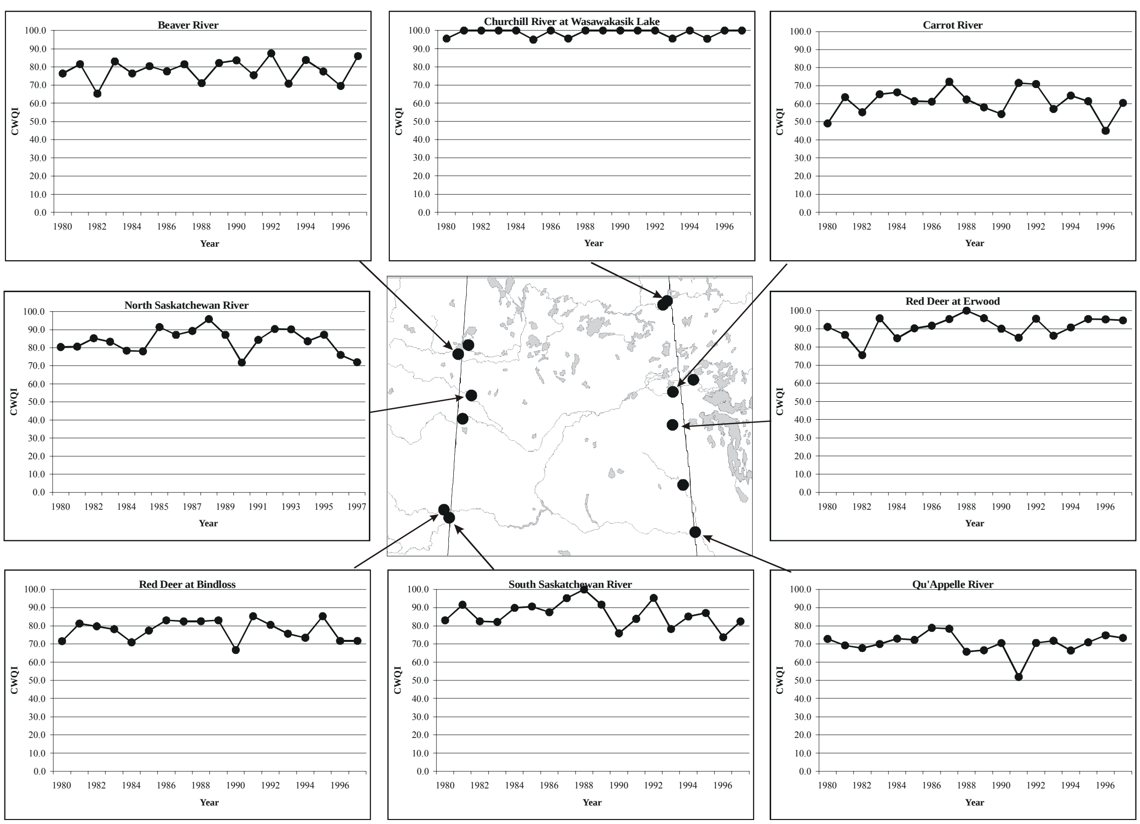

Figure 7. CCME WQI trends at Prairie Provinces Water Board Stations

Alberta

Alberta Environment maintains about twenty long-term water quality sampling sites in the province's major rivers (the long-term river network, LTRN). Most variables are measured at these sites on a monthly basis, but some are tested quarterly. The example illustrates the application of the CCME WQI to three sites in the Bow River: at Cochrane, upstream of Calgary; at Carseland, downstream of Calgary, and at Ronalane, near the confluence with the Oldman River (see Figure 8). The variables included in the calculation of the index are: cyanide, fluoride, pH, dissolved oxygen, aluminum, arsenic, boron, cadmium, copper, nickel, lead, mercury, selenium, zinc, total phosphorus, total nitrogen, ammonia, nitrite, and fecal coliform bacteria. Alberta is continuing to test the index and plans to revise the list of variables used, including the addition of pesticide data.

Of the three sites, the best quality is observed, as expected, at the Cochrane site (see Figure 9). The impact of Calgary is seen at the Carseland site downstream of the city. The Ronalane site shows some recovery and is somewhere between the other two in quality. The apparent improvement at the Carseland site in the early 1980s could be interpreted as showing the effect of wastewater treatment upgrades in Calgary in 1982 (phosphorus removal). This interpretation is clouded, however, by the fact that the full suite of variables was not collected at this site until 1987 (see *Applying the Index*).

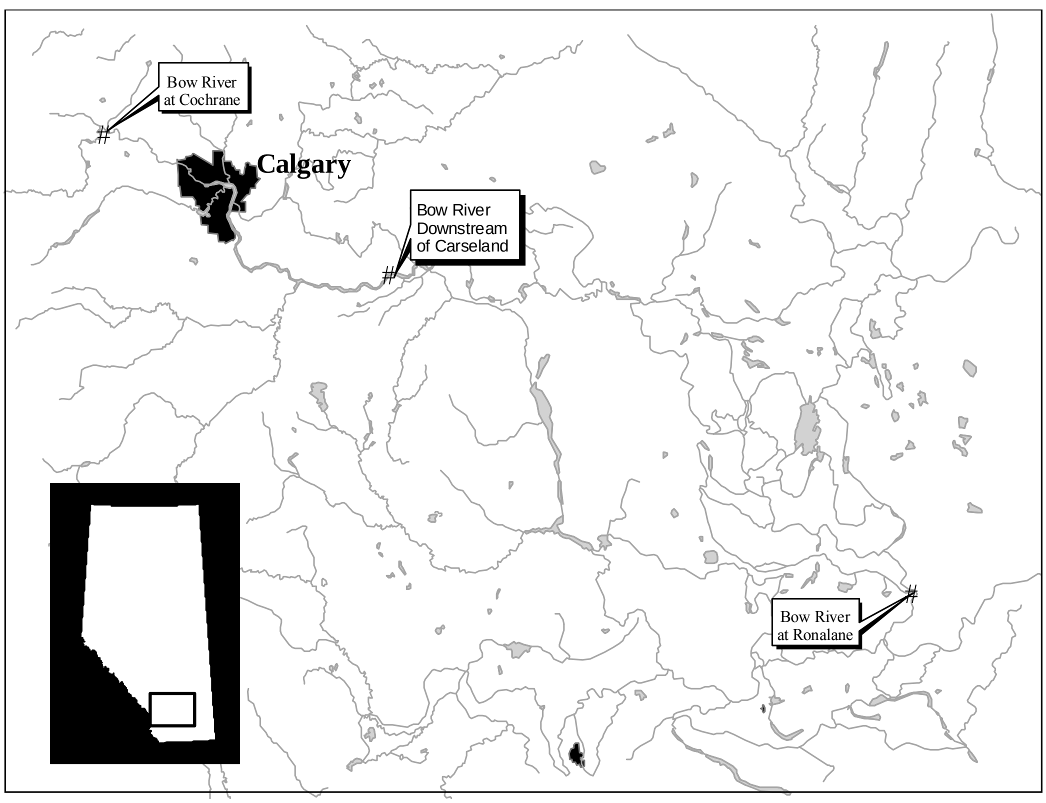

Figure 8. Bow River Sites (Alberta)

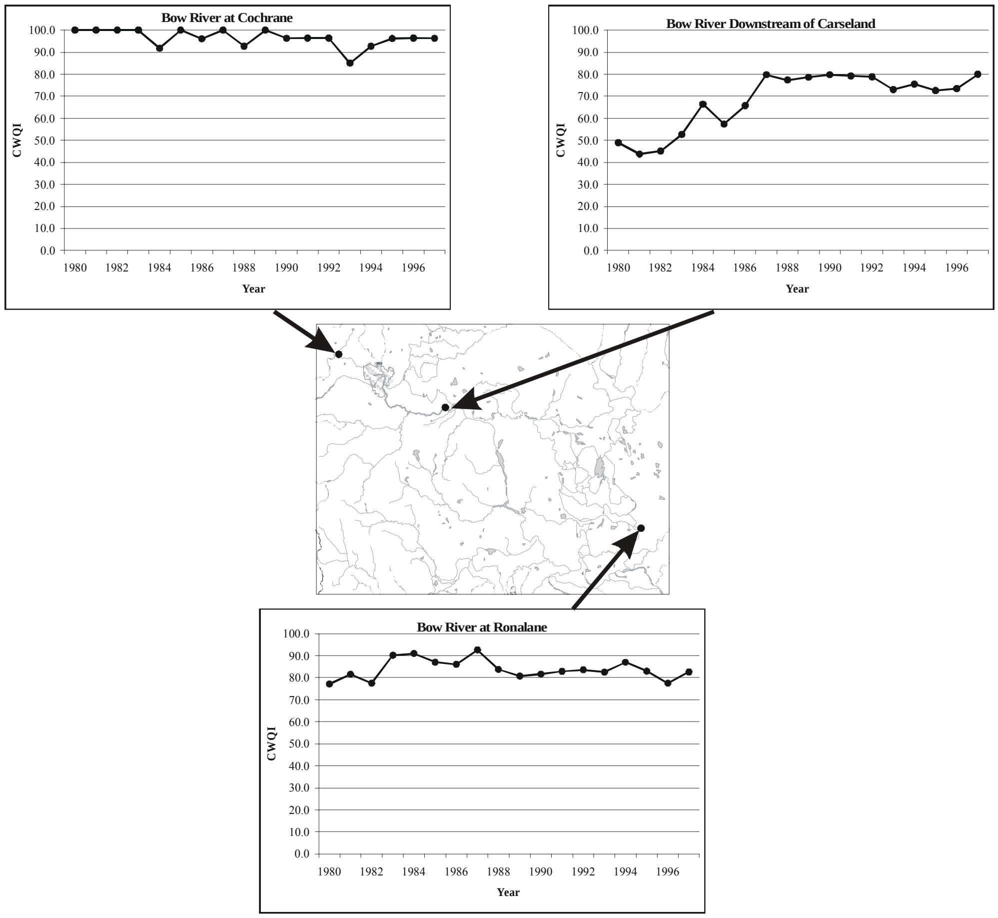

Figure 9. CCME WQI Trends in the Bow River (Alberta)

Discussion

The examples presented above show the capability for the index to identify differences between sites of varying water quality, and identify trends in water quality associated with improvement or degradation of a stretch of river. A quantitative assessment of the validity of the index was not possible, because there are no existing accepted metrics against which to compare it.

Of the many problems inherent in the development of this index, two required most attention: the varying scale of measurements, and the range of exceedence. Differing scales of measurement are characteristic of water quality analyses. Some parameters, such as pesticides, may be environmentally significant at $ng \cdot L^{-1}$ ranges, while others are significant at the $mg \cdot L^{-1}$ range. Adopting the objective-oriented approach developed in British Columbia allows these types of data to be assembled in the same multivariate index formulation, since the metric of interest is the comparison of the measured data relative to its objective.

The objective-oriented BC WQI also avoided the problem of weighting parameters. There were discussions of how to deal with objective exceedence for a parameter such as phosphorus relative to a parameter with more toxic associations such as PCBs. The Subcommittee felt that since the relative toxicities of different chemicals were addressed during the development of water quality objectives, further weighting was not warranted.

Another problem frequently encountered in reporting on water quality data is results below the analytical detection limit. It is problematic to deal with these numbers statistically, but the problem is avoided with the CCME WQI approach. 'Less than' values are used in the index as observations which are within the objectives, so the results are counted, but all the statistical problems associated with how to deal with them are circumvented.

Applying the Index

Applying this index to water quality data sets must be done with due regard to how the index is formulated. Experience with the British Columbia index has shown that misapplication, or use of the index for purposes for which it was not designed, can lead to erroneous conclusions. There are several rules for application that should be taken into consideration:

a) **Index comparisons should only be made when the same sets of objectives are being applied.** The CCME WQI allows the index user to select the objective set on which to compare measured water quality. This is a design feature that increases the versatility of the index considerably but allows for misuse. Different jurisdictions in Canada use different objectives for water quality, and there are usually different objectives for different water uses. Objectives designed for the protection of water used for irrigation or livestock watering will be different from those designed to protect sensitive aquatic life. If an index value is calculated on one set of objectives and compared to an index value based on a completely different set of objectives, any conclusions drawn will be wrong.

b) **Index comparisons should only be made using the same sets of parameters**. This is common sense "apples to apples" reasoning. Comparing a site where most of the measured parameters are pesticides to a site where most of the measured parameters are metals will yield information of limited value. It is possible to obtain index values under these conditions, but comparison of these types of sites will only tell the user how each site is doing relative to those objectives. There is no way the index can replace a detailed site assessment of different types of pollutants. Similarly, if a trend-through-time index series is calculated for a specific site and the number and type of water quality parameters change significantly during the course of the time series, meaningless conclusions may be drawn.

c) **Care should be taken with older data.** Many data sets can go back to times when the sensitivity of analytical methodology was considerably less than with more modern methods. This is of particular concern in cases where there are older results that appear to be just above the detection limit. For example, metals data generated in the 1970's may have been obtained using colorimetric methods with detection limits significantly above current water quality objectives. All analytical methods are capable of producing 'false positive' results and incorporation of these into the index can provide misleading conclusions. For example, if older cadmium data was derived from a method with a detection limit of 0.01 $mg{\cdot}L^{-1}$ there will probably be results at (or slightly above) the detection limit. These may or may not be valid. If these data are run in the index against an objective of 0.0002 $mg{\cdot}L^{-1}$ false positives will represent very large excursions over the objective and questionable index values will result.

d) **The index should be run on parameter sets relevant to the water body being tested.** Several jurisdictions, including Ontario and Québec have older data sets where large suites of parameters were tested. The CCME WQI should only include 'relevant' parameters in the calculation. Because of the way the index is calculated, the inclusion of many parameters (for example, all pesticides in a 'scan') may result in unrealistically low index values. For example, gas chromatographic – mass spectrometer scans will often provide large amounts of data on many chemicals simultaneously. Including all of these data in index calculations will artificially depress the index value. This will be of particular concern in trend-through-time index evaluations when the number of tested parameters varies significantly, or in situations where comparisons between sites is desired.

e) **Minimal data sets should not be used.** The CCME WQI was not designed to replace proper evaluation of water quality conditions through thorough assessment of water quality chemicals of concern. The CCME WQI should not be run with less than four parameters and four sampling visits per year.

Despite these restrictions on its use, the CCME WQI has been successfully applied in several Canadian jurisdictions and has produced values that contain valuable information with regard to trends through time and spatial discrimination of impacted and non-impacted sites. The committee feels that it has application as a management and communication tool if applied appropriately.

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