Application of the Canadian Water Quality Index (CWQI) to PPWB Monitoring Program

Kevin J. Cash, National Water Research Institute
Karen A. Saffran, Alberta Environment
C. Ralph Wright, Wright Consulting

March, 2001

OBJECTIVES

As part of an ongoing assessment of its water quality monitoring program the PPWB's Committee on Water Quality (COWQ) has agreed to assess the utility of using indices in reporting general water quality. The objectives of this report are to: (1) briefly describe the background and development of the Canadian Water Quality Index (CWQI); (2) provide an Excel-based calculator of the CWQI; (3) apply the CWQI to a subset of PPWB monitoring data; and (4) provide recommendations as to utility of such an index to the PPWB. Detailed discussions of the development and application of the CWQI can be found in Neary et al. (2001) and Saffran et al. (2001).

DEVELOPMENT AND CALCULATION OF THE CWQI

An integral part of any environmental monitoring program is the reporting of results to both managers and the general public. This poses a particular problem in the case of water quality monitoring because of the complexity associated with analyzing a large number of measured variables. The traditional practice has been to produce reports describing trends and compliance with official guidelines or other objectives on a variable by variable basis. The advantage of this approach is that it provides a wealth of data and information; however, in many cases, managers and the general public have neither the inclination nor the training to study these reports in detail. Rather, they require statements concerning the general health or status of the river system of concern.

One possible solution to this problem is to reduce the multivariate nature of water quality data by employing an index that will mathematically combine all water quality measures and provide a general and readily understood description of water quality. In this way, the index can be used to assess water quality relative to its desirable state (as defined by water quality objectives) and to provide insight into the degree to which water quality is affected by human activity. An index is a useful tool for describing the state of the water column, sediments and aquatic life and for ranking the suitability of water for use by humans, aquatic life, and wildlife, *etc.*

An index can be used to reflect the overall and ongoing condition of the water. As with most monitoring programs, an index will not usually show the effect of spills, and other such random and transient events, unless these are relatively frequent or long lasting.

The CWQI was developed for the Canadian Council of Ministers of the Environment (CCME), Water Quality Task Group and is based on an index developed by the British Columbia Ministry of Environment, Lands and Parks (1995). This index has been adopted and modified for use by a number of provinces, including Manitoba (Manitoba Environment 1997) and Alberta (Wright et al. 1999).

The index is based on a combination of three factors:

1. the number of variables whose objectives are not met (**Scope**)

2. the frequency with which the objectives are not met, (**Frequency**) and

3. the amount by which the objectives are not met (**Amplitude**).

These are combined to produce a single value (between 0 and 100) that describes water quality. Once the CWQI value has been determined, water quality is ranked by relating it to one of the following categories:

Excellent: (CWQI Value 95-100) – water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels.

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

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

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

The assignment of CWQI values to these categories is termed "categorization" and represents a critical but somewhat subjective process. The categorization is based on the best available information, expert judgment, 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. Final categorization will also be a function of the uses of concern for a given local (e.g., water deemed excellent for recreational purposes may not be similarly categorized if an important use is drinking water quality).

Unlike some earlier indices, the CWQI formulation captures all key components of water quality, is easily calculated, and is sufficiently flexible that it can be applied in a variety of situations. The index can be very useful in tracking water quality changes at a given site over time and can also be used to compare directly among sites that employ the same variables and objectives. However, if the variables and objectives that feed into the index vary across sites, comparing among sites can be complicated. In these cases, it is best to compare sites only as to their ability to meet relevant objectives. For example, in calculating the index for a mountain stream and a prairie river, one might employ different nutrient objectives but the sites could still be compared as to their rank (*e.g.*, both sites are ranked as "Good" under the index).

After the body of water, the period of time, and the variables and objectives have been defined (see Saffran et al. 2001), each of the three factors that make up the index must be calculated. The calculation of F_1 and F_2 is relatively straightforward; F_3 requires some additional steps.

F_1 (**Scope**) represents the percentage of variables that do not meet their objectives at least once during the time period under consideration ("failed variables"), relative to the total number of variables measured:

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

F_2 (**Frequency**) represents the percentage of individual tests that do not met objectives ("failed tests"):

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \qquad (2)$$

F_3 (**Amplitude**) represents the amount by which failed test values do not meet their objectives. F_3 is calculated in three steps.

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:

$$excursion_i = \left(\frac{FailedTestValue_i}{Objective_j} \right) - 1 \qquad (3a)$$

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

$$excursion_i = \left(\frac{Objective_j}{FailedTestValue_i} \right) - 1 \qquad (3b)$$

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:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{\#\ of\ tests} \qquad (4)$$

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.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01} \right) \qquad (5)$$

Once the factors have been obtained, the index itself can be calculated by summing the three factors as if they were vectors. The sum of the squares of each factor is therefore equal to the square of the index. This approach treats the index as a three-dimensional space defined by each factor along one axis. With this model, the index changes in direct proportion to changes in all three factors.

The Canadian Water Quality Index (CWQI):

$$CWQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \qquad (6)$$

The divisor 1.732 normalises the resultant values to a range between 0 and 100, where 0 represents the "worst" water quality and 100 represents the "best" water quality.

To illustrate the calculation of the CWQI the following simple example is provided. Consider a case in which ten variables will be considered in the index calculation (dissolved oxygen, pH, total phosphorus, total nitrogen, fecal coliform bacteria, arsenic, lead, mercury, 2,4-D, and lindane). The period to be examined is one year (2000). The sampling frequency at this site is monthly for most variables (note one missing mercury sample) and quarterly for pesticides.

River X - 2000

DATE	DO mg/L	pH	TP mg/L	TN mg/L	FC #/dL	As mg/L	Pb mg/L	Hg µg/L	2,4-D µg/L	Lindane µg/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:

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

Given the category ranges suggested in the document, the water quality at this river reach would be rated as “Good” based on 2000 data.

For presentation purposes, it is important that a narrative statement explaining the result accompany the calculated CWQI value. In this example, the statement might read, “The CWQI indicates that water quality in the River X was Good in 2000. Conditions at this site can be considered suitable for the protection of aquatic life. Measured total phosphorus and lead concentrations exceeded objectives on two occasions each; however, these excursions were fairly small and likely reflect natural events.”

APPLICATION OF THE CWQI TO PPWB MONITORING DATA

To assess the appropriateness of the CWQI for the PPWB monitoring data the index was applied to a subset of data collected at ten of the monitoring sites. For each site, monthly data collected over a ten-year period (1986-1996) were entered into the calculator. For illustrative purposes only a subset of variables collected at each site were used and the same objectives were applied across all sites (Table 1). Should the PPWB decide to use the index, decisions will be required as to the variables and objectives to include at each site. Such a decision is beyond the scope of the current exercise.

Table 1. Variables and objectives used in the application of the CWQI to PPWB data

Water Quality Variables	Objective
Dissolved Chloride	100 (mg/L)
Fecal Coliforms	100/100ml
Total Copper	.001 (mg/L)
Dissolved Iron	0.3 (mg/L)
Total Lead	0.02 (mg/L)
Dissolved Manganese	0.05 (mg/L)
NO2+NO3	10 (mg/L)
Dissolved Oxygen	6 (mg/L)
PH	6.5
Total Dissolved Phosphorus	0.015 (mg/L)
Sodium	100 (mg/L)
Sulphate	500 (mg/L)
Total Dissolved Solids	500 (mg/L)
Total Zinc	0.05 (mg/L)

Output from the CWQI for each of the reaches is provided in Figures 1-11. These figures plot the change in Index values over time and can be used to assess general water quality conditions and trends over time for a given site. The calculator itself also provides summaries of F1, F2, and F3 scores as well as a summary of all excursions (see attached Excel spreadsheet). While these outputs may be of less value in actual reporting, they provide insights as to the variables driving the observed condition and/or trend and are thus important in explaining the Index results. You may want two spaces after all figure numbers

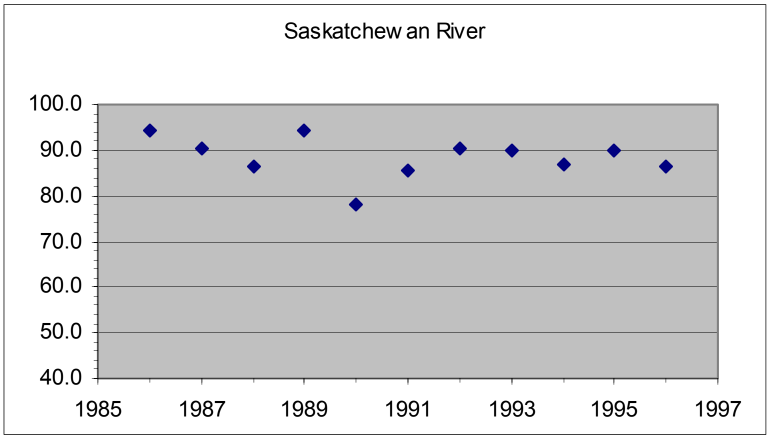

Figure 1. CWQI results for the Saskatchewan River (1986-1986).

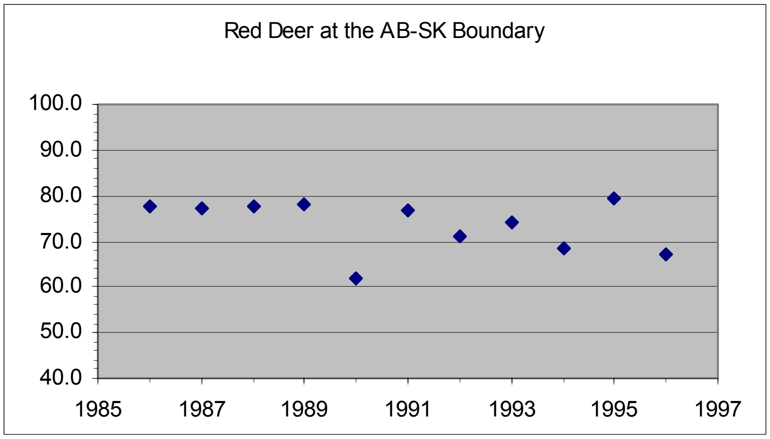

Figure 2. CWQI results for the Red Deer River at the Alberta-Saskatchewan Boundary (1986-1986).

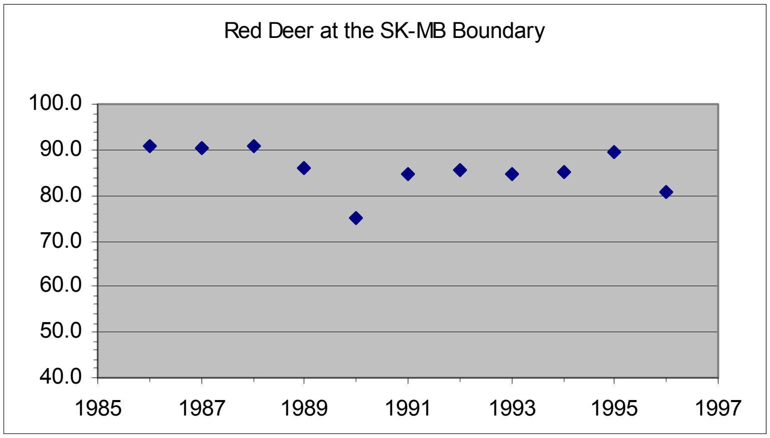

Figure 3. CWQI results for the Red Deer River at the Saskatchewan-Manitoba Boundary (1986-1986).

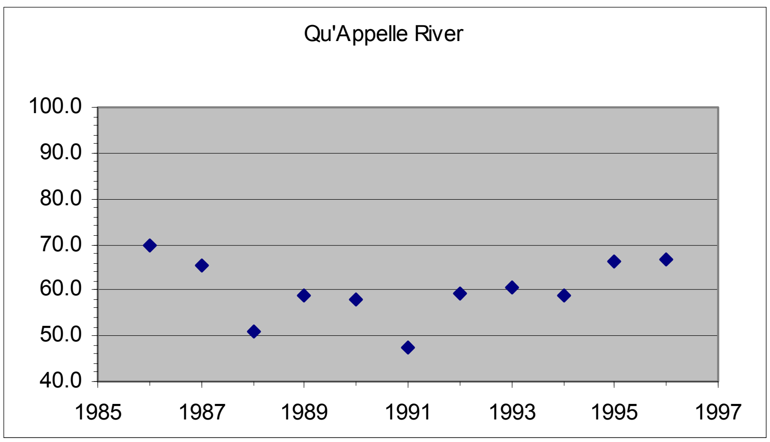

Figure 4. CWQI results for the Qu'Appelle River (1986-1986).

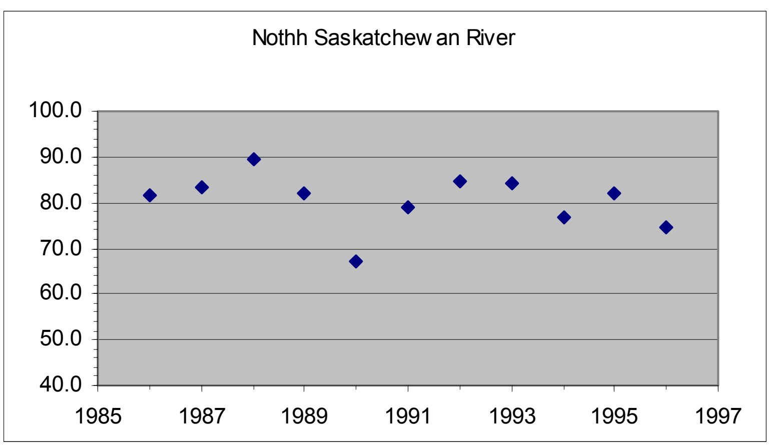

Figure 5. CWQI results for the North Saskatchewan River (1986-1986).

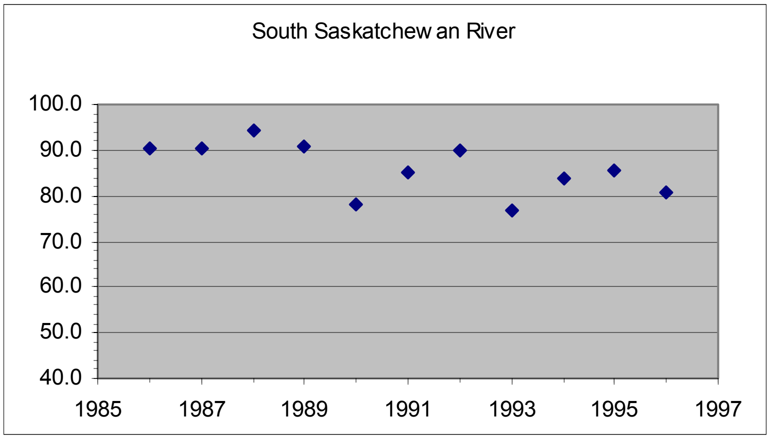

Figure 6. CWQI results for the South Saskatchewan River (1986-1986).

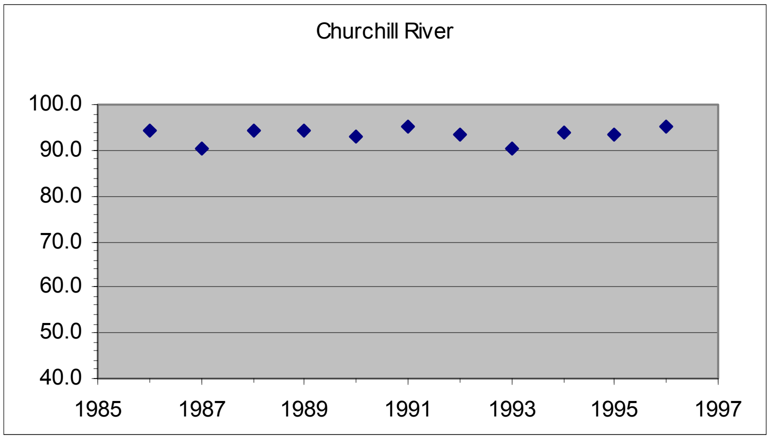

Figure 7. CWQI results for the Churchill River (1986-1986).

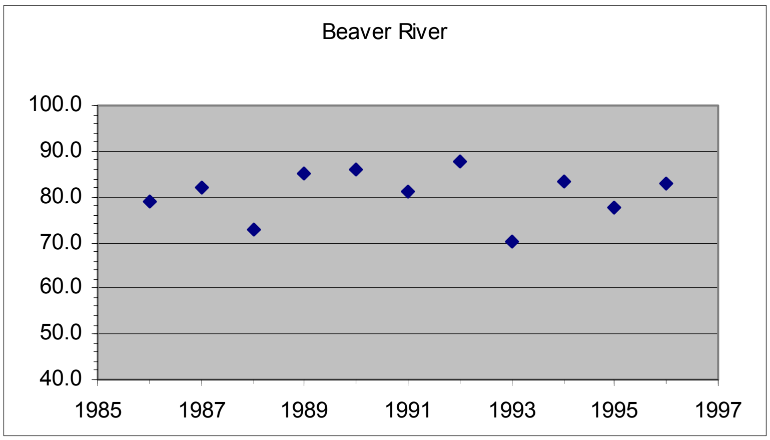

Figure 8. CWQI results for the Beaver River (1986-1986).

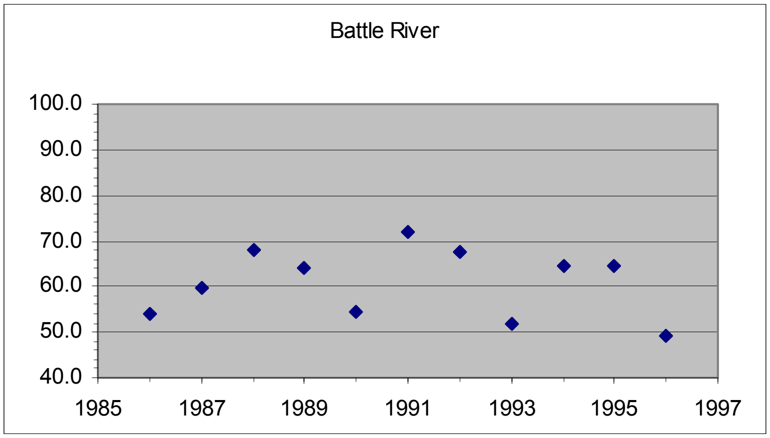

Figure 9. CWQI results for the Battle River (1986-1986).

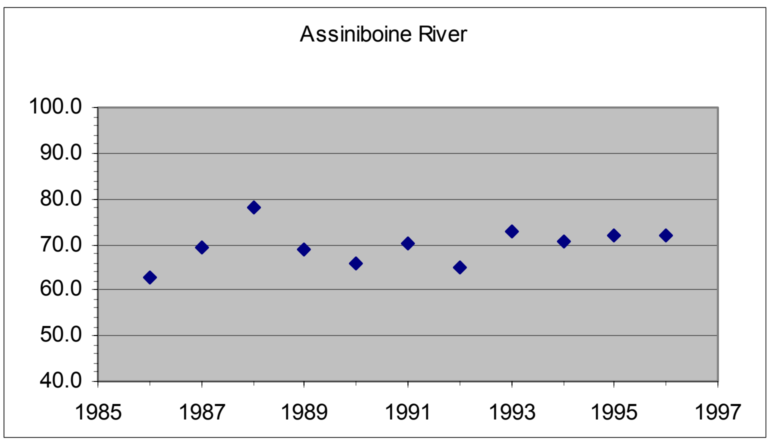

Figure 10. CWQI results for the Assiniboine River (1986-1986).

The CWQI indicates that water quality in the North Saskatchewan, South Saskatchewan, Saskatchewan, Churchill, Beaver and Red Deer (at the Saskatchewan-Manitoba boundary) rivers is consistently good to excellent. Water quality in the Red Deer (at the Alberta-Saskatchewan Boundary) and Assiniboine rivers is typically ranked as fair, while water quality in the Battle, and Qu'Appelle rivers is often ranked as marginal.

It is important to note that in this case the Index was run on a limited set of variables. In the case of the Battle and Qu'Appelle rivers, these variables include total phosphorous, TDS, manganese and sodium all of whose objectives are commonly exceeded and serve to drive the index value downward.

Overall, the patterns produced by the Index are consistent with previous trend analyses performed by the PPWB (Dunn 1995a,b). All the rivers demonstrate year to year variability in water quality but none show a consistent trend. Rivers such as the

Churchill and Saskatchewan show the highest overall water quality while frequent excursions in the Qu'Appelle and Battle rivers serve to reduce their overall water quality in these reaches.

Within a given year, output from the calculator (see attached Excel sheet) can also be used to explore the underlying causes of the resulting Index value. However, the utility of the Index will ultimately depend on the selection of an appropriate set of water quality variables and the development of relevant objectives for each of those variables. Any decision by the PPWB to adopt the CWQI should include a commitment to review current objectives and, where necessary, establish interim objectives to ensure all relevant variables are included in the Index calculation

In conclusion, the CWQI is an efficient way to report the results of PPWB monitoring activities to managers and the public. Versions of this index are already employed by Alberta and Manitoba and are being considered by Saskatchewan. Adoption of the CWQI by the PPWB would compliment these efforts and improve our ability to report on general water quality in the Prairie Provinces. As discussed above, the index is most valuable in describing changes in water quality in one location over time and should not be used for comparisons among sites unless variables and objectives are standardized.

REFERENCES

British Columbia Ministry of Environment, Lands and Parks. 1995. The British Columbia Water Quality Index. Prepared for the Water Quality Branch. Victoria, B.C. 13 pp.

Dunn, G.W. 1995a. Trends in water quality variables at the Alberta/Saskatchewan boundary. Prepared for the Committee on Water Quality, March 1995.

Dunn, G.W. 1995b. Trends in water quality variables at the Saskatchewan/Manitoba boundary. Prepared for the Committee on Water Quality, March 1995.

Manitoba Environment. 1997. State of the Environment Report for Manitoba 1997. Winnipeg, MB. 174 pp.

Neary, B. et al. 2001. The Canadian Water Quality Index: Technical Report (in press).

Saffran, K.A., K.J. Cash and K. Hallard. 2001. The Canadian Water Quality Index (CWQI) 1.0: A User's Manual

Wright, C.R., K.A. Saffran, A.-M. Anderson, R.D. Neilson, N.D. MacAlpine, and S.E. Cooke. 1999. A Water Quality Index for Agricultural Streams in Alberta: The Alberta Agricultural Water Quality Index (AAWQI). Prepared for the Alberta Environmentally Sustainable Agriculture Program (AESA). Published by Alberta Agriculture, Food and Rural Development. Edmonton, AB. 35 pp.