A SENSITIVITY ANALYSIS OF THE CANADIAN WATER QUALITY INDEX

A Report for CCME Prepared by:

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1. Introduction

A committee of water quality experts from across Canada developed the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (CWQI) in the late 1990's (CCME, 2001). The index is a guideline-driven tool that allows the user to distill large amounts of water quality data from a monitoring site into a single number, or index value. The index was developed after a review of water quality reporting in jurisdictions in Canada and elsewhere, and the final approach was based on work done in British Columbia (Rocchini and Swain, 1995, B.C. Ministry of Environment, Lands and Parks, 1996).

Forms of the index have been used for water quality reporting by several jurisdictions, including British Columbia, Alberta (Alberta Ministry of the Environment, 2001), the City of Edmonton (City of Edmonton, 2003), Newfoundland (Newfoundland Department of Environment, 2001), and the Toronto Region Conservation Authority (Forester, D.L. 2000). Recently, there has been an attempt at cross-jurisdictional application in Atlantic Canada (Environment Canada *et al.*, 2003) and Alberta (Glozer *et al.*, 2004).

In November 2003, a workshop was held in Halifax where users of the CWQI reviewed their experience with the index (Environment Canada, 2003). This workshop reviewed the usage of the index in Canada and concluded that the index was a valuable tool for communicating the results of large and complex water quality monitoring programs. However, there were some concerns raised about the formulation of the CWQI and the descriptive categories used to communicate the results of the Index.

As a follow-up to the recommendations from this workshop, the CCME commissioned this report, examining the sensitivity of the current index formulation, evaluating potential modifications to the index, and assessing the use of modified descriptive output categories for the CWQI.

1.1 Current Index Formulation

1.1.1 Conceptual Framework

The current formulation of the index is based on three measures of compliance or deviation from established water quality guidelines. The first component of the index is referred to as scope, and it measures the number of parameters out of compliance with objectives as a percentage of the total number of parameters measured. The second component is referred to as frequency, and measures how often a water quality objective is exceeded. The final component is referred to as magnitude, and measures by how much the objectives are exceeded. The three components are assembled into a unitless number scaled from 0 to 100. Higher index numbers reflect higher water quality, while lower numbers reflect poorer water quality.

There are three factors in the index, each of which has been scaled to range between 0 and 100. The values of the three measures of variance from selected objectives for water quality are combined to create a vector in an imaginary ‘objective exceedance’ 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.

1.1.2 Computational Framework

The CCME Water Quality Index takes the form:

$$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \qquad (1)$$

Where:

F_1 represents the percentage of variables that depart from their objectives at least once, relative to the total number of variables measured:

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) \times 100 \qquad (2)$$

F_2 represents the percentage of failed individual tests:

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \qquad (3)$$

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

$$F_3 = \left(\frac{nse}{0.01nse + 0.01} \right) \qquad (4)$$

The collective amount by which individual tests are out of compliance is calculated by summing the departures of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those departing from objectives). The *nse* variable is expressed as:

$$nse = \frac{\sum_{i=1}^{n} departure_i}{\#\ of\ \ tests} \qquad (5)$$

For the cases in which the test value must not exceed the objective:

$$departure_i = \left(\frac{FailedTest_i}{Objective_j} \right) - 1 \qquad (6)$$

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

$$departure_i = \left(\frac{Objective_j}{FailedTest_i} \right) - 1 \qquad (7)$$

For the cases in which the objective is zero

$$departure_i = FailedTest_i \qquad (8)$$

Departures are equivalent to the number of times by which a concentration is greater than (or less than) the objective.

2. Sensitivity Analysis

At its most basic, a sensitivity analysis is a study of the response of an output variable to variations in the input variables. In the case of the CWQI, there are a number of input variables whose influence on the output can be assessed. These are:

- The selection of inputs – both the number of the inputs and the actual parameters.
- The number of sampling occasions for the index period.
- The selection of the water quality objectives against which the index is being calculated.

An examination of the sensitivity of the CWQI to varying some of these inputs has been conducted on a large set of water quality data from Ontario (Painter and Waltho, 2003). Their major conclusions were:

- *"The Index computed with ten parameters provided more stable scores than with six parameters. Using nine parameters resulted in 14% of the Index scores ranked differently when compared to the Index with 10 parameters. If only 5 rather than 6 parameters had been used, then 30% of the scores were ranked differently. The Index was less likely to incorrectly rank a site when more variables were included in the calculation."*
- *"When the parameters tested were increased beyond 10 and included other water quality parameters that were still relevant to the sites but passed, the Index scores predictably improved. The scores improved when 21 parameters were tested and marginally improved when 32 were included."*
- *"Guideline selection influenced the results. Care needs to be exercised when making comparisons between sites that have used guidelines from various sources. The protection level and beneficial use of the guidelines should be equivalent for comparisons to be valid."*
- *"The stability of the Index improved when at least 3 years of data were included in the calculation. The inclusion of data from several years would ensure a more complete representation of the environmental condition. However, inclusion of too many years would dampen the responsiveness of the Index."*
- *"In this exercise, aquatic life protection guidelines were used so the dataset should reflect the environmental exposure or the risk associated with the guideline. For example, the interim PWQO phosphorus objective is designed to protect streams from excessive aquatic plant growth. Hence, the relevant dataset would be the spring, summer and fall growing season for that parameter."*
- *"Based on this sensitivity analysis, the performance of the Index was reasonable when at least 10 or more variables were included and at least 30 observations over a period of at least 3 years were used in the calculation."*

A number of these conclusions have limited relevance to many applications of the CWQI. There are few jurisdictions that routinely sample for as many as 32 parameters at water quality stations. Most water quality assessment programs have much smaller suites of chemical analyses available, so recommendations for inclusion of large numbers of parameters cannot be achieved in most jurisdictions.

2.1 Data Sets for Sensitivity Analysis

In order to assess the sensitivity of the CWQI to its inputs, several data sets were assembled for evaluation. One set was obtained from the Québec Ministère de l'Environnement, and consisted of 19,488 analytical results – 165 sampling stations analyzed for seven parameters. Each sampling station was sampled an average of six times a year over three years. This data set was evaluated using a set of guidelines supplied with the data. A second set of data was obtained from Environment Canada, and has been described in detail elsewhere (Glozier *et al.*, 2004). This was a large data set from the Banff and Jasper Parks area, and constituted data from a variety of sites gathered since the 1970's. To eliminated concerns associated with significant changes in analytical methodology, only data collected since 1990 were used in this report. This data set was evaluated using objectives recommended in Glozier *et al.*

2.1.1 Impact of the Number of Parameters on the CWQI

There is little uniformity on the approach of various jurisdictions to water quality sampling. Some monitoring agencies sample for a fairly uniform number of parameters at a wide variety of stations, while others focus on measuring water quality factors relevant to concerns at a specific site. Because of the formulation of the CWQI, it is generally recognized that it is possible to manipulate the outcome of the Water Quality Index by including large numbers of parameters for which there is no exceedance of guidelines.

To assess the impact of varying the number of parameters upon which the index is calculated, the Environment Canada data set (with 11 possible parameters) was evaluated. This analysis was performed twenty times (removing parameters in different sequences), and the results of two of these analyses are presented here to illustrate the difficulties with making definitive conclusions (see Table 1and Table 2).

Table 1. Sensitivity of CWQI to Number of Parameters. Trial 1 - Eleven Parameters

Number of Parameters	Calculated CWQI					
	Station 1	*Station 2*	*Station 3*	*Station 4*	*Station 5*	*Station 6*
11	56.1	45.5	76.2	54.2	38.1	54.8
10 (NH4 removed)	54.8	42.4	73.8	52.6	35.5	53.2
9 (NH4, Pb removed)	54.7	43.3	75.9	53.1	36.6	53.5
8 (NH4, Pb, DO removed)	53.3	44.1	73.1	53.1	37.5	51.8
7 (NH4, Pb, DO, pH removed)	51.8	44.8	69.5	51.6	34.1	49.8
6 (NH4,Pb,DO,pH,Cd removed)	100.0	59.1	88.4	100.0	43.3	90.3
5 (NH4,Pb,DO,Cd,As removed)	100.0	54.1	85.5	100.0	39.4	88.3
4 (NH4,Pb,DO,Cd,As,Mo removed)	100.0	47.1	85.5	100.0	31.7	85.4

Note: Order of removal is NH4, Pb, DO, pH, Cd, As, Mo, while Cu, Fe, Ni and Se are retained in all cases.

Table 2. Sensitivity of CWQI to Number of Parameters. Trial 2: Eleven Parameters.

Number of Parameters	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
11	56.1	45.5	76.2	54.2	38.1	54.8
10 (As removed)	54.8	42.1	73.8	52.6	36.1	53.2
9 (As,Mo removed)	53.3	38.1	73.8	50.8	32.8	51.3
8 (As,Mo,Se removed)	51.6	33.0	70.9	48.6	28.7	49.1
7 (As,Mo,Se,Cu removed)	49.6	34.0	73.1	46.0	30.0	49.9
6 (As,Mo,Se,Cu,pH removed)	47.2	34.0	69.5	42.6	24.2	47.5
5 (As,Mo,Se,Cu,pH,Ni removed)	44.1	25.8	64.7	38.0	23.0	44.3
4 (As,Mo,Se,Cu,pH,Ni,Fe removed)	39.5	30.9	57.7	31.0	26.8	39.8

Note: Order of removal is As, Mo, Se, Cu, pH, Ni, Fe, while NH4, Cd, Pb and DO are retained in all cases.

In both of these trials, and eighteen others not presented here but included in Appendix, two conclusions are fairly obvious – the specifics of which parameters are included or excluded from the index calculations have more influence on the output of the CWQI calculation than the number of parameters.

In Trial 1, the index values are relatively stable until Cadmium is removed from the parameter set (see Figure 1a). In this data set, Cadmium was the parameter with the most number of guideline exceedances. Its removal from the parameter list had a significant impact on the CWQI calculations. In Trial 2, the parameters with the most exceedances were retained in the Index, while those with no or very few exceedances were eliminated. The result is a significant trend in the CWQI values, declining steadily as the number of parameters decreases (see Figure 1b).

Figure 2 shows the results of all twenty trials. The CWQI plotted in this graph represents the average CWQI for all stations and all twenty combinations of parameters. Also shown is the standard deviation associated with each population of CWQI values. For this data set, there appears to be a break in the graph between seven and six parameters, suggesting that at least seven parameters should be retained in order to produce a relatively stable index calculation. As noted in the discussion above, however, the specifics of which parameters are retained in the index have more of an influence than the actual number of parameters.

Figure 1a & 1b. Influence of Number of Parameters in Index Calculation

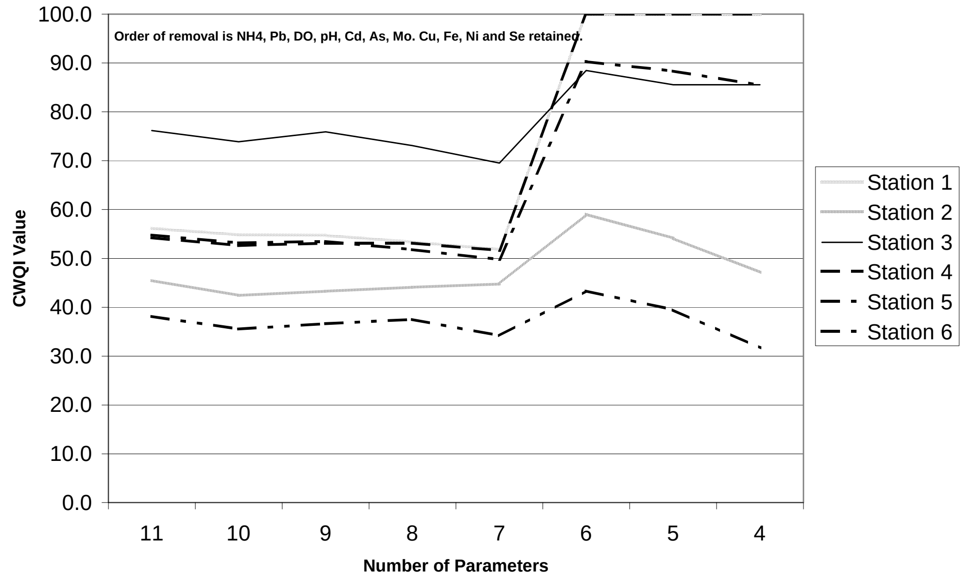


Figure 1a: Influence of Number of Parameters in Index Calculation

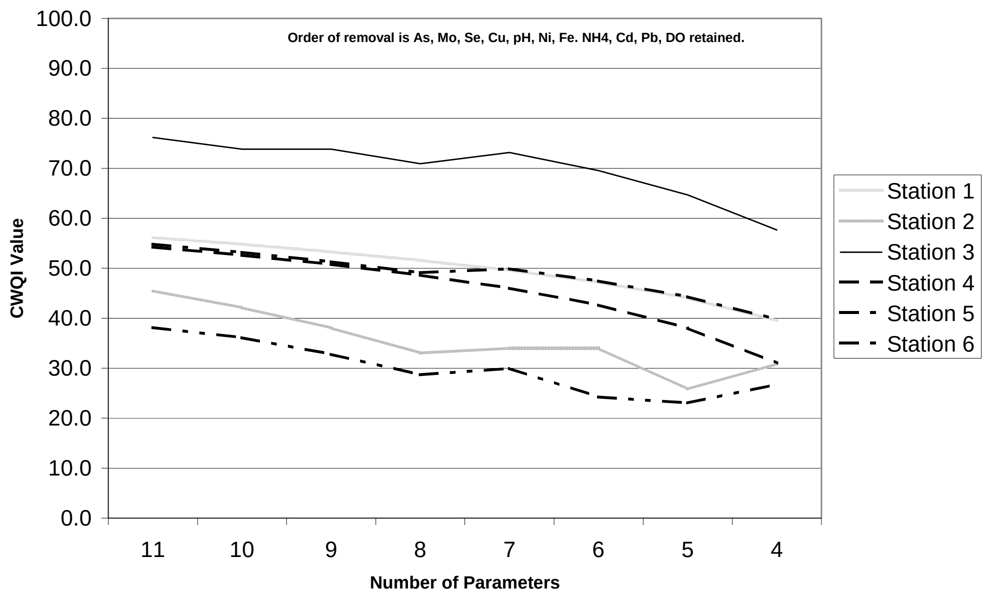
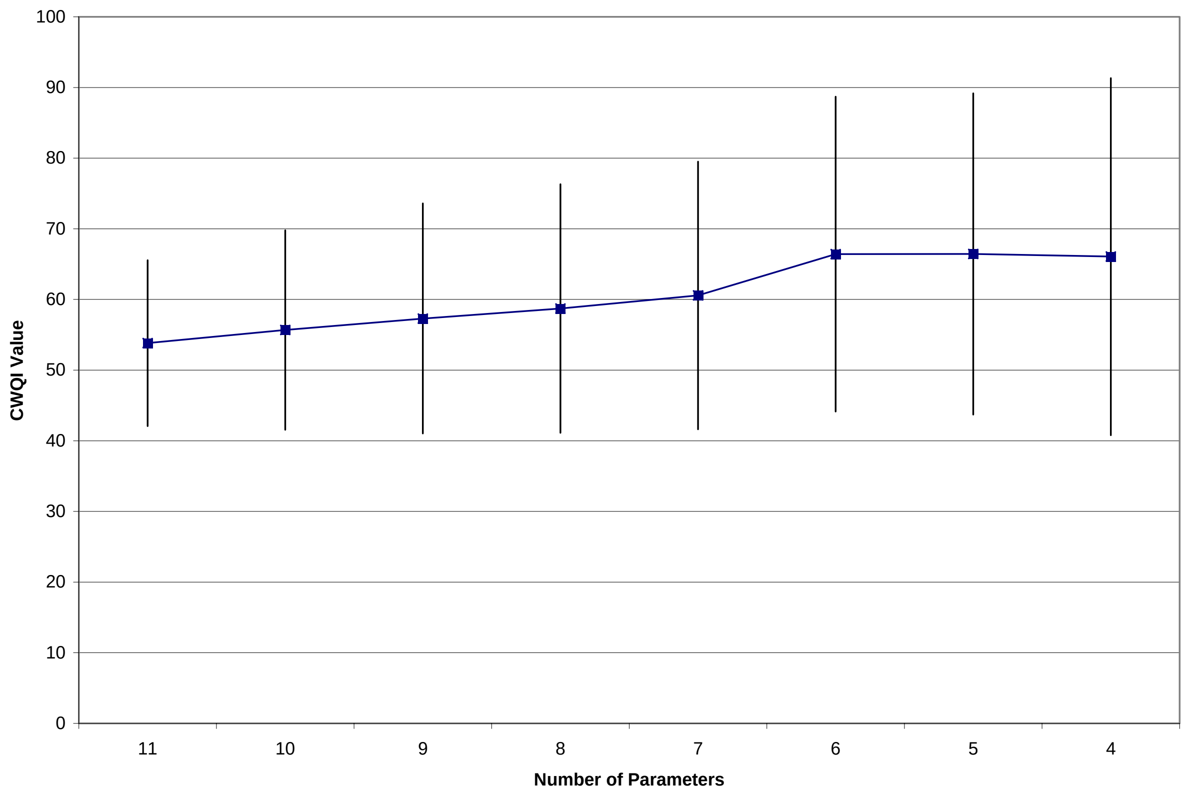


Figure 1b: Influence of Number of Parameters in Index Calculation

Figure 2. Influence of the Number of Parameters on the CWQI*



*Note: * Summary of the Results of Twenty Random Parameter Removal Trials on Six Stations.*

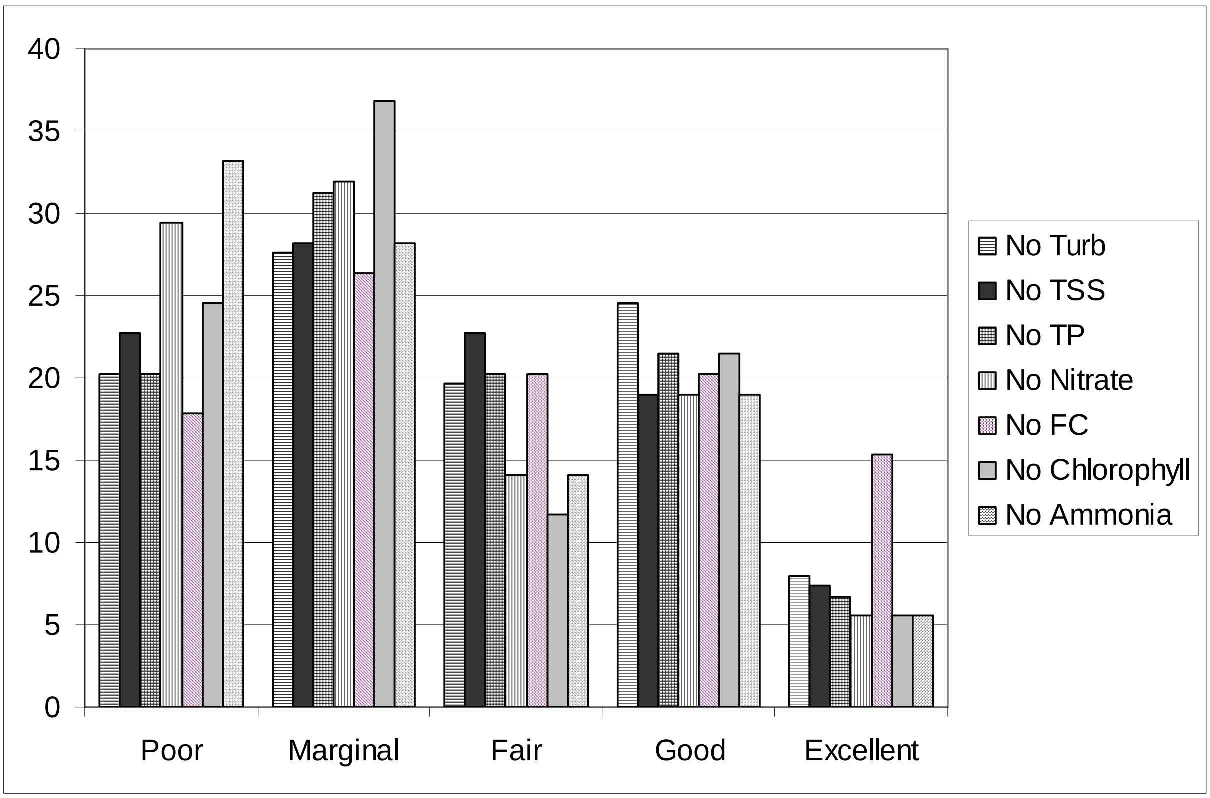
The users of the CWQI are typically water quality assessment professionals who have a good knowledge of the data upon which the index is being calculated. It is clear that the number of parameters can strongly influence the outcome of the index, a finding that was acknowledged in the CWQI Workshop (Environment Canada 2003). It is doubtful that an index being calculated from a number of factors can be independent of the selection of those factors, and that is clearly the case with the CWQI.

2.1.2 Impact of Parameter Selection on the CWQI

In this portion of the sensitivity analysis, we examined the impact of removal or inclusion of individual parameters on the output of the CWQI. For this portion of the analysis, we used the set of data from Québec. It had the benefit of representing large numbers of sampling stations with a smaller set of parameters.

In this data set, the parameters tested were Turbidity, Total Suspended Solids (TSS), Total Phosphorus (TP), Nitrate, Fecal Coliform (FC), Chlorophyll-a (Chl-a) and Ammonia. Each parameter was serially removed from the data set for CWQI calculation. The results are presented as the percentage of stations (out of 163) that fell within the various water quality categories presently recommended in the CWQI technical manual (CCME, 2001). The results are presented in Figure 3.

Figure 3. Influence of Parameters Selection on CWQI



As with the previous analysis, the specific parameter that was removed had a significant impact on the distribution of CWQI values. The exclusion of fecal coliform results had most influence on the distribution of CWQI values, reducing the number of index values in the ‘poor’ and ‘marginal’ categories, and significantly increasing the number of stations in the ‘excellent’ category.

Table 3 presents the results of this analysis in tabular form. The figures represent the percentage of the 163 stations that fell into each of the CWQI categories.

Table 3. Sensitivity of CWQI to Parameter Selection

CWQI Category	No Turbidity	No TSS	No TP	No Nitrate	No FC	No Chl-a	No Ammonia	Average	S.D.
Poor	20.2	22.7	20.2	29.4	17.8	24.5	33.1	24.0	5.5
Marginal	27.6	28.2	31.3	31.9	26.4	36.8	28.2	30.1	3.6
Fair	19.6	22.7	20.2	14.1	20.2	11.7	14.1	17.5	4.2
Good	24.5	19.0	21.5	19.0	20.2	21.5	19.0	20.7	2.0
Excellent	8.0	7.4	6.7	5.5	15.3	5.5	5.5	7.7	3.5

2.1.3 Impact of Number of Samples

The CWQI is based on a number of sampling occasions. Two of the parameters (F1 and F2) can be influenced by the number of sampling occasions. This section of the report looks at the influence of reducing the number of samples at a given site.

For this analysis, we used the data set provided by Environment Canada of water quality sites in the Prairies. In that data set, there were six sampling sites. The number of samples taken at each station is shown in Table 4.

Table 4. Sensitivity of CWQI to Number of Samples: Number of Samples Taken Per Year in Test Data Set

Station	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	Samples per Site
Site 1							10	12	12	8	42
Site 2		12		19		14		8		14	67
Site 3	8	11	12	12	11	12	12	12	12	6	108
Site 4							10	12	12	8	42
Site 5	6	9	8	6	8	4	6	7	7	7	68
Site 6							10	12	12	7	41
Samples per Year	14	32	20	37	19	30	48	63	55	50	368

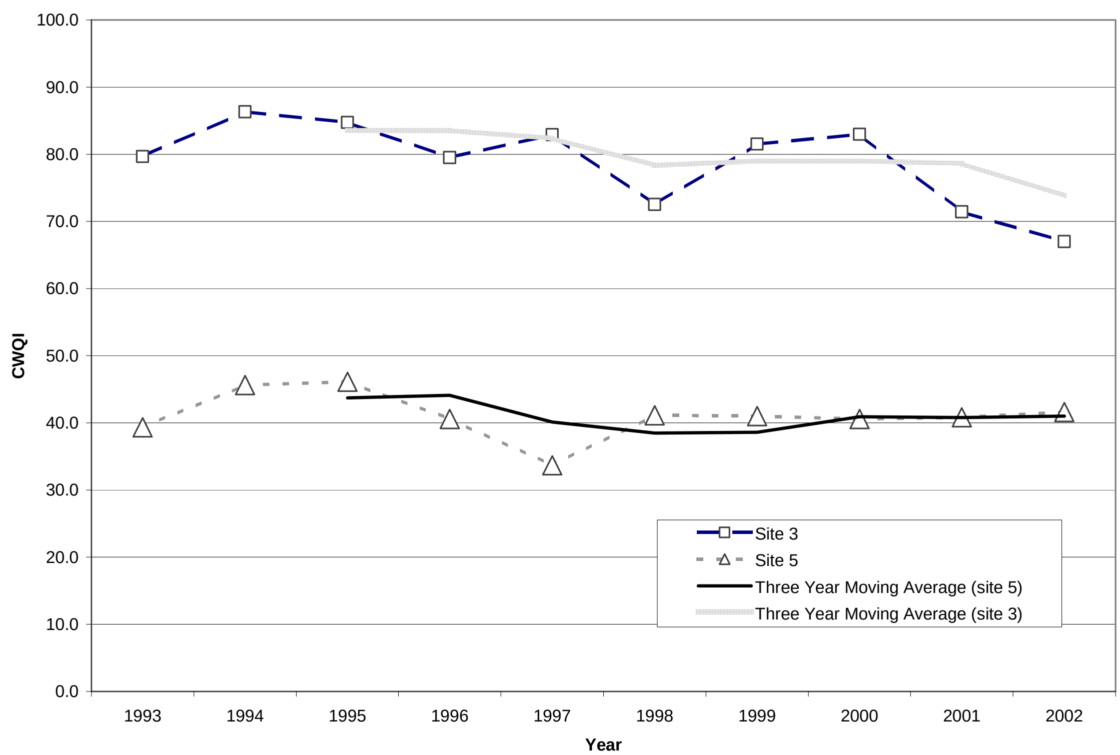
Two of the sites (3 and 5) had a minimum of six samples taken per year over a ten-year period. These sites were selected to examine the impact of the number of samples on the CWQI calculation.

Table 5 shows the CWQI calculated on a yearly basis compared to the CWQI calculated based on all the samples for each site. These data are shown graphically in Figure 4. Also shown in Figure 4 are three-year moving averages for each of the two sites.

Table 5. Yearly CWQI Values vs. Pooled CWQI

Year	Site 3	Site 5
1993	79.7	39.3
1994	86.3	45.6
1995	84.7	46.1
1996	79.5	40.6
1997	82.9	33.7
1998	72.5	41.1
1999	81.5	41.0
2000	83.0	40.6
2001	71.4	40.8
2002	67.0	41.6
Average	78.9	41.0
Std Dev.	6.39	3.41
CWQI on all data	73.8	38.8

Figure 4. CWQI Over Time at Two Monitoring Stations



This type of analysis is somewhat problematic with these data. One of the central assumptions associated with this type of analysis is that all of the measurements are from a population with a central tendency, whereas with water quality data, this may not be a valid assumption. There may be long-term water quality trends occurring, or there may be significant differences in hydrologic conditions or discharges from various contributing land uses or point discharges.

If the intent of the CWQI user is to perform a "one time" assessment of a number of sampling sites, there may be benefit to pooling several years of data. If, however, a trend-through-time analysis of water quality is desired, annual index values may provide a more realistic assessment of the variability in water quality associated with annual variability in pollutant inputs and hydrology.

2.1.4 Effect of Objective Selection on the CWQI

The CWQI is based on a comparison of measured water quality parameters against stated objectives. The effect of changing the objective against which the index is calculated was not tested quantitatively. The structure of the index makes it inevitable that there will be a strong and significant impact on the index if the objective is altered. It should be noted here that another recommendation of the CWQI workshop was to encourage the use of site-specific objectives for CWQI calculations. There are initiatives underway to assist CWQI users in the development of these site-specific objectives.

2.2 Effect of Index Formulation on the CWQI

Some of the criticisms of the CWQI 1.0 raised during the CWQI workshop, and identified during a questionnaire of CWQI users related to the formulation of the index. The most significant of these related to the first factor (F1) of the index.

2.2.1 Current F1 Formulation

As explained in Section 1.1.1 of this report, the F1 factor is intended to determine the **scope** of guideline exceedances. The F1 factor increases as the numbers of measured parameters exceed their water quality objectives during the index period.

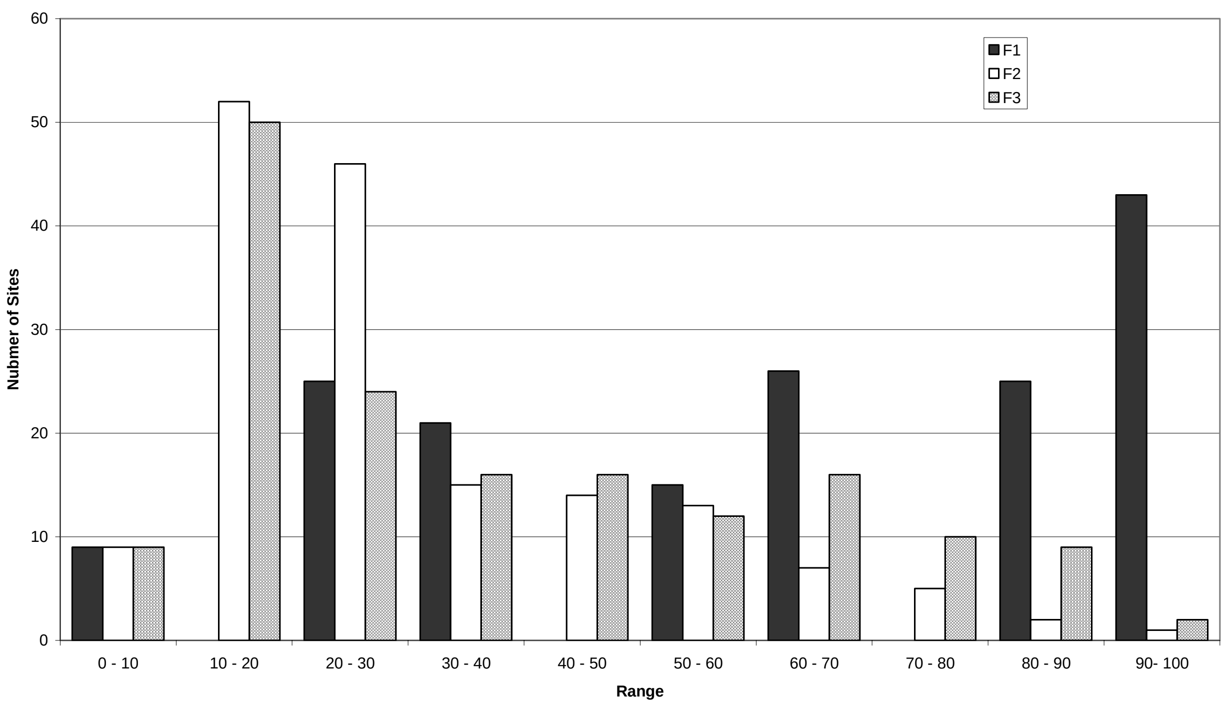
To assess the impact of the existing F1 formulation on the CWQI, a set of data from Québec was used (described in section 2.1). Table 6 shows the summary statistics from the CWQI analysis of the data set. There were a total of 163 sampling sites, each with seven parameters being measured.

Table 6. Summary Statistics of CWQI factors for 163 Stations

	F1	F2	F3	CWQI	Number of Samples
Average	52.6	19.7	26.6	62.6	17.0
Std.Dev	29.0	18.9	24.5	22.1	2.7
Median	57.1	14.0	19.5	62.7	17.0
Minimum	0.0	0.0	0.0	10.5	2.0
Maximum	100.0	84.7	82.7	100.0	27.0
Skewness	-0.2	1.2	0.6	0.0	-0.9
Kurtosis	-1.2	0.7	-0.9	-1.0	8.4

An examination of these data shows that F1 does "dominate" the factors that contribute to the CWQI. The F1 values were more than double those of F2 and F3. The distribution of these factors for this data set is shown in Figure 5.

Figure 5. Distribution of CWQI Factors for 163 Stations



A stepwise regression analysis was also performed on the Québec data set, and confirmed that F1 was driving the index for these data. Table 7 shows the result of this analysis, and for this data set, F1 alone accounted for almost 89% of the variance in the CWQI. The addition of F3 explained 99% of the variance, and F2 had little influence on the CWQI.

Table 7. Stepwise Regression Analysis 1: Response of CWQI on 3 Predictors, with N = 163

Step	1	2	3
A_0	100.31	99.29	98.56
F1	-0.7172	-0.5052	-0.4713
T-Value	-35.95	-63.27	-58.63
P-Value	0.000	0.000	0.000
F3		-0.3806	-0.3243
T-Value		-40.30	-30.19
P-Value		0.000	0.000
F2			-0.130
T-Value			-7.90
P-Value			0.000
R^2	88.86	99.00	99.28
R^2(adj)	88.80	98.98	99.26

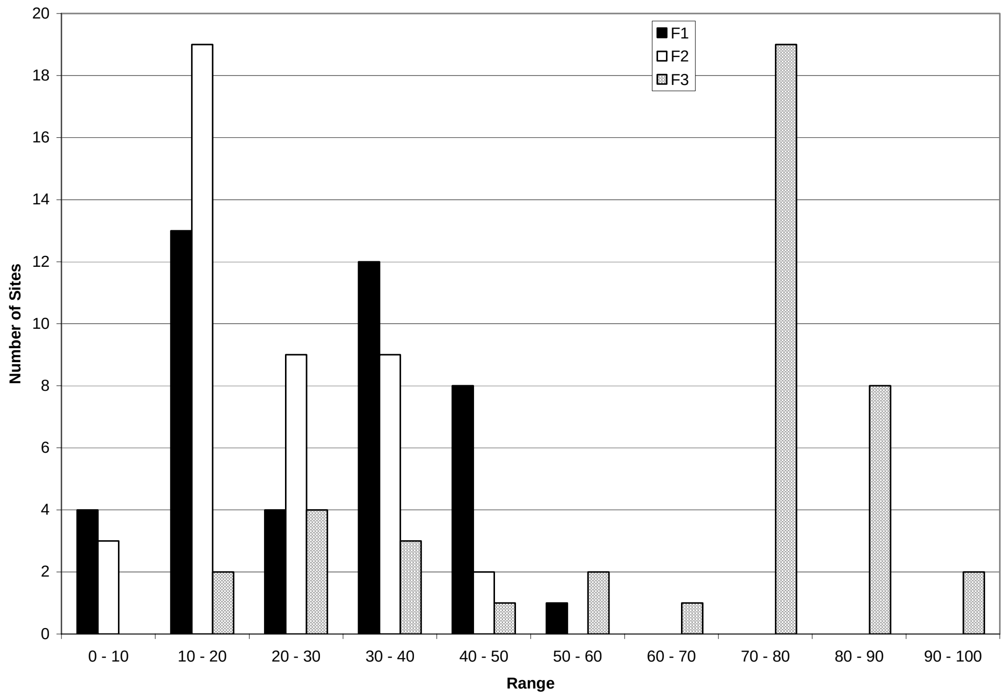
F1 does not always dominate the CWQI. In the second set of data (from stations in Western Canada), a similar analysis reveals a different pattern. Table 8 presents summary statistics from the Western Canada data set. In this case, there were fewer test parameters that exceeded guidelines, but those that did exceeded the guidelines by a significant amount. For this data set, F3 was the dominant factor in the CWQI.

Table 8. Summary Statistics of CWQI factors for 42 Stations

	F1	F2	F3	CWQI	Number of Samples
Average	29.5	20.9	65.5	56.1	8.8
Std.Dev	14.2	10.7	23.0	14.7	2.7
Median	31.7	13.6	74.0	55.1	8.5
Minimum	10.0	10.0	17.7	33.7	4.0
Maximum	55.6	40.6	92.7	86.3	12.0
Skewness	-0.1	0.4	-1.0	0.8	-0.2
Kurtosis	-1.5	-1.5	-0.4	-0.5	-1.2

Figure 6 shows the distribution of CWQI factors for this dataset:

Figure 6. Distribution of CWQI Factors for 42 Stations



A stepwise regression analysis confirmed that for this data set, F3 was the dominant factor in the CWQI. F3 alone in this instance accounted for 93% of the variance in CWQI, while F3 and F1 together accounted for 99.7% of the variance (see Table 9). Once again, F2 explained little of the variance.

Table 9. Stepwise Regression Analysis 2: Response of CWQI on 3 Predictors, with N = 42

Step	1	2	3
A_0	96.49	99.03	98.90
F3	-0.6172	-0.5172	-0.5123
T-Value	-23.63	-82.72	-106.7
P-Value	0.000	0.000	0.000
F1		-0.308	-0.230
T-Value		-30.41	-14.41
P-Value		0.000	0.000
F2			-0.119
T-Value			-5.553
P-Value			0.000
R^2	93.32	99.73	99.85
R^2(adj)	93.15	99.72	99.84

2.3 Alternative F1 Formulations

2.3.1 Alternative F1 Scenario 1

At the suggestion of the CCME, an alternative formulation of the first factor of the CWQI was tested. The suggested formulation was:

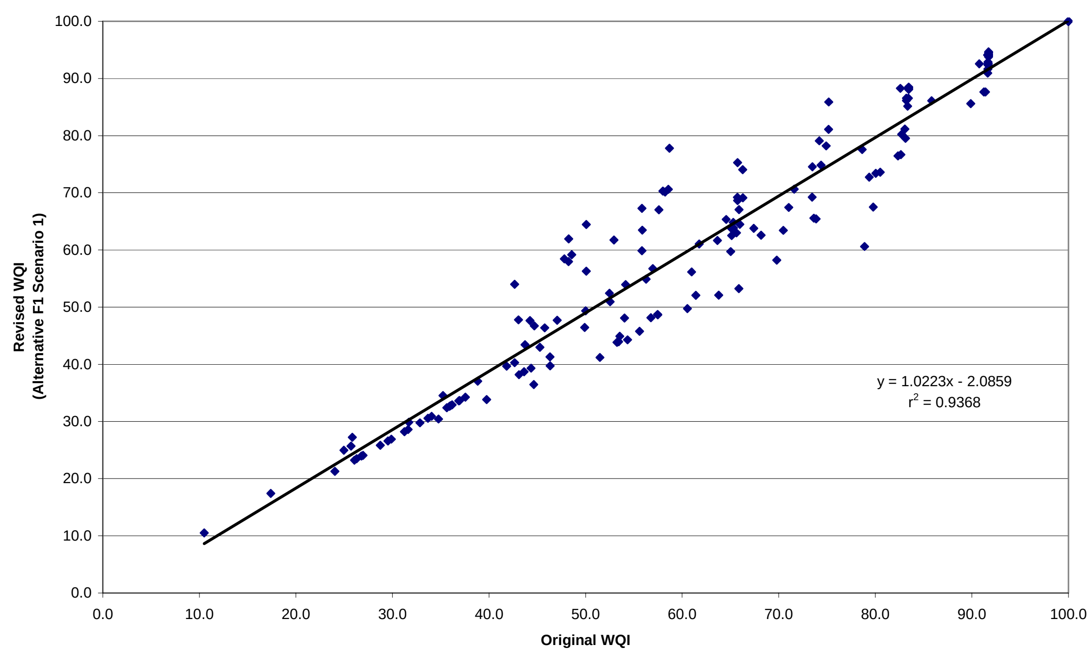
$$F1 = (F1a+F1b)/2$$

Where: *F1a* = (number of failed variables/total number of variables) x 100 (same as the current formulation of F1).

F1b = (number of samples showing values that exceed guidelines or objectives/total number of samples) x 100.

In order to examine the effect of the alternative F1 formulation, the data set from Québec (described in Section 2.1) were used. Figure 7 shows the comparison between the original CWQI and the CWQI recalculated with this revised F1 formulation for 163 sampling sets. As can be seen from Figure 5, there was not a statistically significant difference between the original CWQI and the index calculated with this alternative to the F1 factor.

Figure 7. Comparison between existing CWQI and CWQI calculated with Alternative F1 Scenario 1



For these 163 data series, the revised CWQI was slightly lower than the original CWQI (a mean of 61.89) for the revised CWQI compared to 62.58 for the original CWQI. The medians for the two populations were virtually identical (62.75 for the original CWQI versus 62.80 for the revised formulation. A Wilcoxon Signed Rank Test determined that the two formulations were not significantly different ($p<0.01$), but there **was** a significant difference at a lower probability ($p = 0.033$).

2.3.2 Alternative F1 Scenario 2

In a typical sampling program for which the CWQI is designed for use, samples are taken monthly for all or part of a year. Occasionally, there are samples taken where several guidelines are exceeded simultaneously. This may be due to ambient conditions, poor sampling technique, or sample contamination. One of the criticisms of the current CWQI formulation (Environment Canada, 2004) was that too much weight was given to occasional guideline exceedance.

A second alternative to F1 was evaluated, one that intentionally discounted infrequent (less than 10%) exceedances of guidelines. This formulation was

$$F1 = F1a*(F2>0.1)+0.5*F1a*(F2<=0.1)$$

Where: F1a = (number of failed variables/total number of variables) x 100 (same as the current formulation of F1).

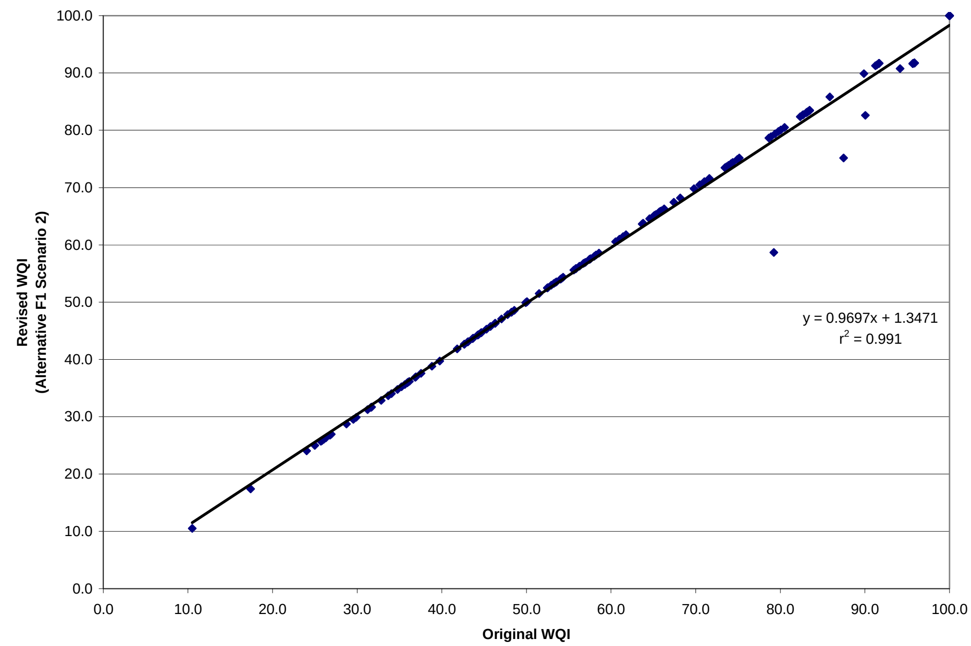
F2 = (total number of failed tests/total number of tests) x 100 (same as the current formulation of F2).

Basically, this formulation of F1 “discounts” occasional exceedances of guidelines. If the frequency of exceedance within the index calculation period is less than or equal to 10%, the current F1 formulation is divided by 2.

A comparison of the CWQI calculated with this second F1 reformulation against the original CWQI is shown in Figure 8, again using the 163 data series provided by the Québec Ministère de l’Environnement. For the majority of the cases (147 out of 163), the output of the two formulations is identical. In the case of the other 17 sites, the exceedance of guidelines occurred less than 10% of the time, and the CWQI calculated with this revised F1 resulted in higher CWQI values.

A Wilcoxon Signed-Rank Test revealed that there was a significant difference between the two data sets ($p<0.001$), with the revised CWQI producing slightly higher results (mean of 63.14, median 63.75) than the original formulation of the CWQI (mean of 62.58, median 62.80). This reformulation improved CWQI rankings for stations where occasional (less than 10%) of the samples exceeded guidelines.

Figure 8. Comparison between Existing CWQI and CWQI Calculated with Alternative F1 Scenario 2



For this data set, revising the F1 formulation did not change the fact that F1 "drove" the index (although note that F1 does not always dominate the CWQI – see Section 2.2.1). Table 10 shows the results of a stepwise regression analysis for this data set:

Table 10. Stepwise Regression Analysis 3: Response of CWQI on 3 Predictors, with N = 163. Revised F1 formulation

Step	1	2	3
A_0	100.06	99.41	98.76
F1	-0.7154	-0.5051	-0.4713
T-Value	-37.36	-65.04	-60.80
P-Value	0.000	0.000	0.000
F3		-0.3833	-0.3272
T-Value		-40.37	-30.97
P-Value		0.000	0.000
F2			-0.132
T-Value			-8.14
P-Value			0.000
R^2	89.60	99.07	99.34
R^2(adj)	89.54	99.05	99.33

The results of the stepwise regression are very similar to those obtained from the original CWQI formulation (compare to Table 7).

2.4 Examination of Different Formulations with Synthetic Data

Another alternative to the examination of the behaviour of different formulations of the CWQI is the examination of the index with a synthetic set of index factors (F1, F2 and F3). The two alternative F1 formulations, along with the current CWQI formulation were examined using this set of synthetic scenarios. The synthetic data, along with the original CWQI and the WQI calculated with the two alternative F1 formulations are presented in Table 11. Basically, the synthetic data set consisted of varying the percentage of the number of parameters with exceedances and the percentage of samples with exceedances. The influence of the third factor in the index (the magnitude of exceedance) was also varied in these scenarios to range from minor to fairly major amounts of guideline exceedance.

Table 11. Alternative F1 Formulations Tested on Synthetic Factor Data

% of Parameters with Exceedances	% of Samples with Exceedances	F1 (original)	F1 (Alternative 1)	F1 (Alternative 2)	F2	F3	WQI (original)	WQI (Alternative 1)	WQI (Alternative 2)	Ranking with Original WQI	Ranking with Alternative 1	Ranking with Alternative 2
10	5	10	7.5	5	0.5	0.50	94	96	97	Good	Excellent	Excellent
10	10	10	10	5	1	0.99	94	94	97	Good	Good	Excellent
10	25	10	17.5	5	2.5	2.44	94	90	96	Good	Good	Excellent
10	50	10	30	5	5	4.76	93	82	95	Good	Good	Excellent
10	75	10	42.5	5	7.5	6.98	92	75	93	Good	Fair	Good
10	100	10	55	5	10	9.09	90	67	91	Good	Fair	Good
25	5	25	15	12.5	1.25	1.23	86	91	92	Good	Good	Good
25	10	25	17.5	12.5	2.5	2.44	85	90	92	Good	Good	Good
25	25	25	25	12.5	6.25	5.88	85	85	90	Good	Good	Good
25	50	25	37.5	25	12.5	11.11	83	76	83	Good	Fair	Good
25	75	25	50	25	18.8	15.79	80	68	80	Good	Fair	Good
25	100	25	62.5	25	25	20.00	77	59	77	Fair	Marginal	Fair
50	5	50	27.5	25	2.5	2.44	71	84	84	Fair	Good	Good
50	10	50	30	25	5	4.76	71	82	84	Fair	Good	Good
50	25	50	37.5	50	12.5	11.11	70	76	70	Fair	Fair	Fair
50	50	50	50	50	25	20.00	66	66	66	Fair	Fair	Fair
50	75	50	62.5	50	37.5	27.27	61	55	61	Marginal	Marginal	Marginal
50	100	50	75	50	50	33.33	55	45	55	Marginal	Marginal	Marginal
75	5	75	40	37.5	3.75	3.61	57	77	76	Marginal	Fair	Fair
75	10	75	42.5	37.5	7.5	6.98	56	75	75	Marginal	Fair	Fair
75	25	75	50	75	18.8	15.79	54	68	54	Marginal	Fair	Marginal
75	50	75	62.5	75	37.5	27.27	49	55	49	Marginal	Marginal	Marginal
75	75	75	75	75	56.3	36.00	42	42	42	Poor	Poor	Poor
75	100	75	87.5	75	75	42.86	34	29	34	Poor	Poor	Poor
100	5	100	52.5	50	5	4.76	42	69	68	Poor	Fair	Fair
100	10	100	55	50	10	9.09	42	67	67	Poor	Fair	Fair
100	25	100	62.5	100	25	20.00	39	59	39	Poor	Marginal	Poor
100	50	100	75	100	50	33.33	33	45	33	Poor	Marginal	Poor
100	75	100	87.5	100	75	42.86	24	29	24	Poor	Poor	Poor
100	100	100	100	100	100	50.00	13	13	13	Poor	Poor	Poor

Table 12 presents the correlation of each of the index factors on the resulting WQI. For this set of factors, the current formulation of the CWQI is highly correlated with F1, and much less so with F2 and F3. The first alternative formulation of F1 (see Section 2.3.1) resulted in the modified WQI being correlated much more equally with all three factors. The second alternative formulation of F1 (see Section 2.3.2) resulted in correlations indicating a more even distribution of influence among the three factors. For this second alternative, however, the correlations were not as evenly distributed as the first alternative F1.

Table 12. Correlation of Different Formulations of WQI Factors on Resulting Index

Description	Correlation Coefficient
Correlation of F1 (original) vs. Original CWQI	-0.956
Correlation of F2 vs. Original CWQI	-0.777
Correlation of F3 vs. Original CWQI	-0.776
Correlation of F1 (Alternative 1) vs. CWQI (Alternative 1)	-0.982
Correlation of F2 vs. CWQI (Alternative 1)	-0.962
Correlation of F3 vs. CWQI (Alternative 1)	-0.971
Correlation of F1 (Alternative 2) vs. CWQI (Alternative 2)	-0.973
Correlation of F2 vs. CWQI (Alternative 2)	-0.902
Correlation of F3 vs. CWQI (Alternative 2)	-0.915

Regardless of formulation of F1, it had the highest impact on the resulting Index value (confirmed by stepwise regression). For this set of synthetic factors, F1 explained 91 to 97% of the variance in the index value, regardless of which formulation was considered.

In terms of the ranking of index output, there were differences in the frequency of categorical rankings among the different F1 formulations. Table 13 shows the number of scenarios in each of the existing CWQI categories for the three F1 (existing and two alternative) formulations. The existing CWQI formulation placed none of the scenarios in the "excellent" category, and eight of the scenarios in the "poor" water quality category. The first alternative F1 formulation placed only four scenarios in the "poor" category, but placed eleven scenarios in the "fair" category. The second alternative F1 alternative placed the most (thirteen) scenarios in the "excellent" and "good" categories.

Table 13. Comparison of Categorical Rankings with Differing WQI Formulations using Synthetic Data

	Ranking with original WQI	Ranking with F1 Alternative 1	Ranking with F1 Alternative 2
Excellent	0	1	4
Good	11	8	9
Fair	5	11	7
Marginal	6	6	4
Poor	8	4	6

3. CWQI Ranking System

3.1 Existing Ranking System

The CWQI was designed to yield a numeric output ranging from 0 for extremely poor water quality through 100 for excellent water quality. In addition to the numeric results, the Technical Committee that created the CWQI developed a series of descriptors for various ranges of CWQI output. The current descriptive ranges are:

Descriptor	Numeric Range of CWQI
Excellent	95 – 100
Good	80 – 94
Fair	65 – 79
Marginal	45 - 64
Poor	0 - 44

The ranges were selected and described based on a subjective evaluation of a number of data sets from across Canada (CCME, 2001).

3.2 Alternative Ranking System

The terms of reference for this project proposed an alternative set of ranges for the water quality descriptors. These are:

Descriptor	Numeric Range of CWQI
Excellent	90 – 100
Good	75 – 89
Fair	60 - 74
Marginal	45 - 64
Poor	0 - 44

Basically, the ranges of values for the “excellent”, “good” and “fair” categories have been dropped by 5.

3.3 Evaluating the Ranking Systems

In order to evaluate the alternative ranking systems, the set of analytical results provided by Environment Canada was sent to two experienced water quality experts. The experts were given data from seven sites over ten years (not all sites had data for all the years). There were a total of 52 station-years worth of data. The water quality experts were not told the source of the data, but were given the objectives against which to judge each of the water quality parameters. The experts were instructed to rank the water quality based exclusively on the data into the appropriate water quality categories. The breakdown of the experts' assessment is shown in Table 14.

Table 14. CWQI and Expert Evaluation of 52 Station-years of Data

Category	Expert 1	Expert 2	Current CWQI Category	Revised CWQI Category
Excellent	31	21	5	17
Good	13	8	31	25
Fair	7	4	13	10
Marginal	0	5	3	0
Poor	1	14	0	0

It is apparent that there was not good agreement between the assessments by the two experts. One of them (who also has considerable experience in fisheries) tended to rank stations with even minor oxygen deficits as "poor" or "marginal", while the other did not.

Figure 9 shows the average CWQI score for each of the categories as ranked by the two experts. There are clear differences in the evaluation by the two. Expert 1 appeared to rank sites as having higher water quality than Expert 2. As noted above, Expert 2 appeared to weight oxygen data more highly, and ranked station-years of data with lower oxygen as being marginal or poor water quality.

Figure 10 shows how the two experts ranked the 52 data series, compared to both the existing and the proposed revision of the CWQI ranking system. It is apparent that there was little consensus between the two experts, and that both experts ranked water quality in a descriptive way differently than the CWQI. It should be noted that both of the experts' assessment of "excellent" water quality conformed to CWQI scores lower than the current CWQI range (95 – 100). Both experts included stations with CWQI scores significantly lower than 95 in their "excellent" category, so there may be some merit in relaxing the standard for this category of CWQI scores.

Figure 9. Average WQI Scores for Water Quality Categories as Ranked by Two Experts

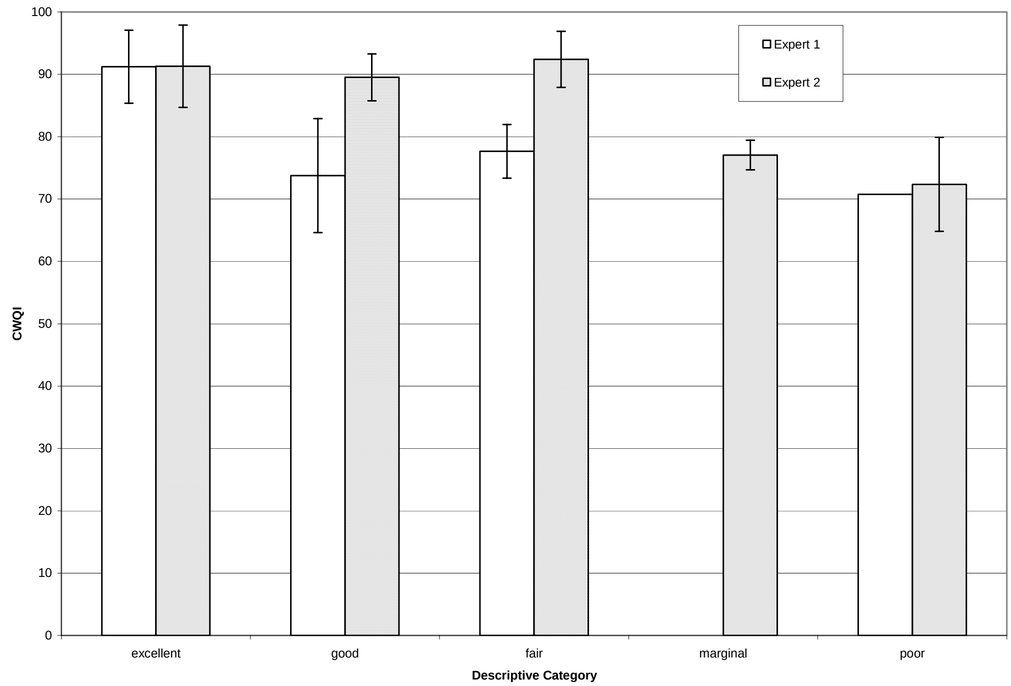
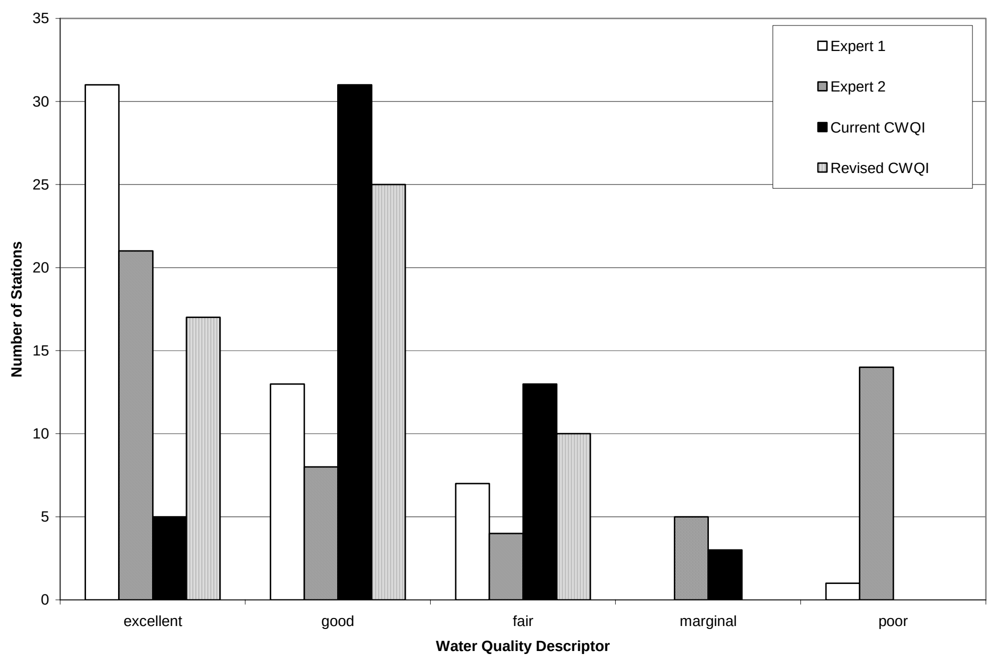


Figure 10. Comparison of Expert Opinion of Descriptive Water Quality Categories and Two Ranking Systems for CWQI



4. Discussion

An index can be defined as a device that serves to indicate a value or quantity. Any index is inherently related to its inputs, and the CWQI is no exception. The analogy that the developers of the CWQI used was that of a stock index (CCME, 2001). A stock index is an aggregate of several stock prices that serves to indicate the general trend of the stock market. That analogy is apt for the CWQI – it is an aggregate of several measures of compliance to water quality objectives, and appears to adequately reflect the degree of compliance.

The purpose of this study was to quantitatively assess the sensitivity of the CWQI to the manipulation of the data that are fed into the index.

4.1 Sensitivity to the Number of Parameters

The first variable to be evaluated was the number of parameters that are fed into the index. This evaluation was conducted on the Environment Canada data set from Alberta. There were eleven variables available for index calculation, and there were twenty assessments of the impact of parameter removal. In the two cases presented in detail, parameters were removed in a different order. The CWQI output stayed relatively stable (within 5 – 10% of the value calculated with all parameters) in both instances until the parameters dropped below 7. Based on this assessment, and an examination of the mean CWQI calculated on the twenty parameter removal trials, it would appear that 7 or more parameters are required in order to use the CWQI. In a separate assessment of the CWQI, ten or more parameters were recommended for CWQI calculation (Painter and Waltho, 2003). However, it is not just the number of parameters that influences the CWQI – it is the **selection** of parameters (see discussion in Section 4.2). In the Alberta data set used for this evaluation, nutrients are the water quality parameters of most concern, and the parameters for which most exceedances were observed. Removing or retaining those parameters and cadmium (a metal with relatively frequent guideline exceedances) had more of an impact than removing or selecting metals that had fewer exceedances.

4.2 Sensitivity to Parameter Selection

The CWQI is intrinsically sensitive to which parameters are selected. This somewhat confounds the observations made above regarding the number of parameters used to calculate the index. It is also difficult to formulate recommendations regarding the parameters to select, because they will be highly dependent on the site at which the CWQI will be calculated. In the evaluation conducted in this study, the CWQI output was measured by the number of sites in various water quality ranges as a function of selectively removing specific parameters. In the Quebec data set used, fecal coliform was the parameter that had most influence on the index value. Removal of that parameter had a significant impact on the distribution of index values, while the index somewhat more stable to the inclusion or exclusion of the other parameters.

If the index is to be used to assess the impact of mine drainage on a Boreal Shield site, then parameters associated with that water quality impact should be included. Adding large numbers of parameters related to organochlorine pesticides and eutrophication related parameters will "dilute" the index and artificially increase the CWQI values. Similarly, an evaluation of agricultural runoff should include nutrients, dissolved oxygen, and microbial parameters as index inputs. Adding large numbers of metals or acidification-related parameters will necessarily increase index values.

Painter and Waltho (2003) made similar conclusions by adding 30 or more parameters to the index calculation. The CWQI will produce output indicating improved water quality if the index is "diluted" by adding parameters that are not relevant to the water quality issues at the site. It is difficult to formulate a "rule of thumb" that encapsulates these observations. Basically, the user of the CWQI should select parameters that are relevant to the water quality issues that are perceived to be a problem at a given site.

The impact of parameter selection can also be seen in the data presented in Section 2.1.1. In the data set considered for that exercise, cadmium was the parameter with most impact on the Water Quality Index. Selective removal of that parameter had a significant impact on the overall CWQI for the stations, whereas the removal of other parameters had less of an impact.

4.3 Sensitivity to the Number of Measurements

The sensitivity of the index to the number of measurements was evaluated by examining two sites for which there were ten-year water quality data sets. The CWQI values measured by averaging yearly data (calculated on 6-12 samples per year) were compared to CWQI values measured on all samples (70 – 110 samples. In general, the results were similar for the sites considered. The average of the annual measurements were within 5 – 10% of the CWQI values calculated based on all measurements.

Of course, annual measurements can be expected to vary based on differences in hydrologic factors and pollutant inputs. Calculating the index based on longer-term data sets will dampen these effects. Painter and Waltho (2003) recommended three or more years of monthly measurements to produce a relatively stable index value. This may be a reasonable recommendation if the user wants to produce a single index value for a site.

It is generally recognized that water quality may vary significantly from year to year, and within the year from season to season. Climatic variables like sunlight and rainfall may have significant impacts on water quality, and can be reflected either in annual or seasonal variation. The design of normal monitoring programs should not have to be altered to fit the requirements of the CWQI.

From a strictly computational standpoint, the index values were reasonably stable when calculated with 6 to 12 measurements. Since many provincial or federal water quality monitoring programs are designed with monthly samples taken, this appears to be adequate for CWQI calculation.

4.4 Sensitivity to Objective Selection

Since the CWQI is based on the frequency, scope, and amplitude of objectives exceedance, its sensitivity to the selection of different objectives is inevitable. This aspect of index sensitivity was not evaluated quantitatively. As noted above, CWQI users are encouraged to select objectives relevant to the site being evaluated.

4.5 Alternative Formulations of F1

One complaint about the existing formulation of the CWQI that was raised at the recent Water Quality Index workshop was that the F1 factor in the index was given too much weight (Environment Canada, 2003). Two fairly large data sets were evaluated using stepwise regression. It was shown that for data sets where several parameters were likely to exceed guidelines, F1 did indeed “drive” the index, accounting for almost 89% of the index variation. However, in a second data set where only one of the parameters exceeded guidelines with any frequency, F3 “drove” the index.

Two alternative formulations of F1 were evaluated in an attempt to reduce the impact of F1 on the CWQI. For the data set considered, the first reformulation of F1 (suggested by the CCME technical committee and described in Section 2.3.1) produced WQI values that were not significantly different at p=0.01, but were different at a lower probability (p=0.05). A second alternative F1 formulation (described in Section 2.3.2) that devalued infrequent guideline exceedances produced WQI results different from the existing CWQI formulation when examined on a large number of stations (p=0.01). In instances where infrequent objective exceedance is deemed a problematic for CWQI output, it may provide some redress.

The same two alternative formulations of F1 were tested on a synthetic data set data, where 30 different scenarios of varying percentages of parameter exceedances and samples exceedances were examined. Descriptive statistics for the index values calculated on this data set are presented in Table 15. The current formulation of the CWQI is highly correlated with F1, and much less so with the other two factors in the index. The other two formulations of F1 yielded index values where the resulting index values were more evenly correlated with the input factors, with the first alternative F1 formulation producing the most evenly balanced correlations.

Table 15. Descriptive Statistics of Index Values Calculated on Synthetic Exceedance Data with Alternative F1 Formulations

Index Version	Mean	Median	Std. Dev.
CWQI (original formulation)	64.33	67.64	23.42
CWQI (first alternative F1 formulation)	66.98	68.64	20.71
CWQI (second alternative F1 formulation)	69.16	75.73	23.90

Comparing the original CWQI with the CWQI calculated with the first alternative F1 for this set of synthetic data indicated that the two sets of indices were not significantly different ($p = 0.264$). A paired-t test was used after testing the population of differences for normality with the Kolmogorov-Smirnov and Anderson-Darling Normality tests and finding that it was not significantly different from normal ($p<0.01$).

A similar comparison of the original CWQI and the CWQI calculated with the second alternative F1 for this set of synthetic data indicated that the second reformulation of the CWQI produced values that were significantly higher ($p=0.002$) than the original. Again, a paired-t test was used after testing the population of differences for normality with the Kolmogorov-Smirnov and Anderson-Darling Normality tests and finding that it was not significantly different from normal ($p<0.01$).

4.6 Descriptive Categories of Water Quality

Two experienced water quality experts were sent 52 station-years of data for a “blind” classification of the water quality into the descriptive categories used by the CWQI (see Section 3.3). There was little agreement between the two experts, and it is apparent that if such an approach is desired to rationalize the categories into which CWQI results are place, a much larger panel of experts will be required. There is obviously some subjectivity associated with such categorical evaluations, and consensus is unlikely.

Ranking water quality according to expert opinion has been done in France and is the basis of the water quality ranking system used in Québec (the IQBP – see Hébert in Environment Canada 2003). This so-called “Delphi” approach was considered by the committee that developed the CWQI, but was abandoned as being two unwieldy to implement. The results of this small experiment indicate that a much larger panel of expertise will be required to evaluate the current categories of CWQI output.

Despite the lack of agreement between the two experts for many of the data series, both experts ranked stations with CWQI lower than 95 as having “excellent” water quality. There appears to be some support for changing the range of this category, at least.

5. Conclusions

Based on this study, several "rules of thumb" for the routine application of the CWQI to water quality monitoring data sets can be derived:

1. Based on random parameter removal trials on a water quality data set involving eleven parameters, it is suggested that the CWQI should be calculated with a minimum of seven parameters for a given site. Index values can be expected to vary depending on the exact selection of parameters relative to the water quality issues being experienced at the site. Parameter selection will have more impact on CWQI values than the number of parameters included. Including many parameters with few exceedances of guidelines will increase the CWQI value for a site.

2. A minimum of six samples should be included for each index period. Larger sample sizes or longer index periods will produce a more stable index value, but may dampen yearly variation that is of interest.

3. Parameter selection should be based on measurements of water quality relevant to the site. There appears to be no simple "rule of thumb" for selecting an optimal parameter set.

4. The proposed F1 reformulation produced CWQI results that were different from the current index formulation at $p=0.05$, but not at $p=0.01$. A second alternative F1 formulation was evaluated that ranked data series with infrequent guideline exceedances as having better water quality, and produced results that were significantly higher ($p<0.01$) than the current CWQI formulation.

5. Using a synthetic set of data, the current CWQI formulation produced output that is highly correlated with only one of the factors. The two alternative F1 formulations produced index values that were more evenly correlated with all three factors. The F1 formulation proposed by the CCME produced the index most evenly correlated with all factors, while the second alternative F1 formulation tended to produce the highest WQI values and rankings. The proposed reformulation of F1 produced index values that were not significantly different from the current CWQI, while the second reformulation of F1 produced results that were significantly higher than the current formulation.

6. The two alternate F1 formulations produce index values different from the current CWQI. Both appear to reduce the dominance of F1 on the index output for the synthetic data set. Testing the reformulated index output with a panel of experts and a real data set may provide a method for evaluating the relative merits of the two.

7. Expert opinion on the qualitative description of water quality can be variable. Some support was found for relaxing the CWQI score range for the "excellent" water quality category, but a full evaluation of the descriptive ranges of water quality will take a larger panel of water quality experts.

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Appendix A

Details of the Sensitivity Analysis

Appendix A

Details of the Sensitivity Analysis

This appendix describes the details of the sensitivity analysis to determine response of the CWQI from manipulating the number of parameters included in the index calculation. The data set used was from Alberta (see Glozier *et al.*, 2004 for a more complete description of the data set). There were six stations considered, each of which had been well sampled for eleven parameters over several years. All data for each station were pooled. Table A-1 shows the number of samples taken at each site.

Table A-1. Number of Samples Taken per Station for Parameter Number Sensitivity

Station	Number of Samples
Station 1	42
Station 2	67
Station 3	108
Station 4	42
Station 5	68
Station 6	41

There were twenty parameter removal trials conducted. The order of parameter removal was determined through a random number generator in Excel. Each of the eleven parameters were assigned a number between 1 and 11, then removed in the order suggested by the random number generator. In cases where duplicate random numbers were generated for the same trial, the lowest unselected number between 1 and 11 was substituted for the duplicate.

Table A-2 contains the details of parameter removal sequence for each of the twenty trials. The parameters were removed in the order suggested in the matrix, ranging from 1 through 7. Parameters numbered 8 through 11 were retained in the index calculation.

The results of this parameter removal analysis are presented in Table A-3. Each table entry represents the CWQI calculated at the specified station with the given number of parameters. Reference to Table A-2 for the appropriate trial number will allow the interested reader to determine which parameters were retained or excluded for each calculation.

Table A-2. Parameter Removal Sequence for Twenty Trials

Parameter	Trial																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Ammonia	8	1	1	9	10	2	3	1	9	4	9	3	2	3	5	5	10	5	11	10
Arsenic	1	6	11	5	6	6	6	2	5	1	11	2	8	11	2	10	7	9	3	1
Cadmium	11	5	3	8	11	5	5	6	8	8	8	5	3	1	1	4	4	10	2	2
Copper	4	11	4	10	1	7	1	10	1	3	2	8	10	10	9	1	1	11	7	5
Iron	7	10	9	4	8	1	7	8	3	2	6	1	1	6	3	6	8	1	1	8
Lead	9	2	7	1	2	8	4	3	10	7	1	4	9	5	10	7	5	2	5	9
Molybdenum	2	7	6	2	5	9	11	4	2	6	3	7	5	2	7	3	11	3	8	7
Nickel	6	9	8	11	9	11	9	7	6	9	4	10	6	9	6	11	6	6	6	4
Dissolved Oxygen	10	3	5	6	3	4	8	5	4	10	5	6	4	8	8	9	3	8	4	11
PH	5	4	10	7	4	10	2	9	11	5	7	11	7	4	11	8	2	4	10	3
Selenium	3	8	2	3	7	3	10	11	7	11	10	9	11	7	4	2	9	7	9	6

Table A-3. CWQI Calculated for Twenty Parameter Removal Trials

Trial	Station	Number of Parameters							
		11	**10**	**9**	**8**	**7**	**6**	**5**	**4**
1	Station 1	56.1	54.8	93.6	92.8	91.7	100.0	100.0	100.0
1	Station 2	45.5	42.1	38.1	33	34	34	25.8	30.9
1	Station 3	76.2	73.8	73.8	70.9	73.1	69.5	64.7	57.7
1	Station 4	54.2	52.6	50.8	48.6	46	42.6	38	31
1	Station 5	38.1	36.1	32.8	28.7	30	24.2	23	26.8
1	Station 6	54.8	53.2	51.3	49.1	49.9	47.5	44.3	39.8
2	Station 1	56.1	54.8	54.7	53.3	51.8	100	100	100
2	Station 2	45.5	42.4	43.3	44.1	44.8	59.1	54.1	47.1
2	Station 3	76.2	73.8	75.9	73.1	69.5	88.4	85.5	85.5
2	Station 4	54.2	52.6	53.1	53.1	51.6	100	100	100
2	Station 5	38.1	35.5	36.6	37.5	34.1	43.3	39.4	31.7
2	Station 6	54.8	53.2	53.5	51.8	49.8	90.3	88.3	85.4
3	Station 1	56.1	54.8	53.3	92.8	91.7	90.4	88.4	100.0
3	Station 2	45.5	42.4	38.4	49.4	52.1	53.6	47.1	49.7
3	Station 3	76.2	73.8	71.0	83.5	90.4	88.5	88.5	100.0
3	Station 4	54.2	52.6	50.8	85.4	83.3	89.9	87.9	100.0
3	Station 5	38.1	35.5	32.2	40.6	42.9	44.0	38.5	41.0
3	Station 6	54.8	53.2	51.3	85.5	91.7	90.4	88.4	100.0
4	Station 1	56.1	56.0	54.7	53.3	51.8	50.0	47.9	45.1
4	Station 2	45.5	46.4	42.9	38.7	43.9	38.3	39.2	40.0
4	Station 3	76.2	78.1	78.1	75.9	73.0	69.4	64.5	57.5
4	Station 4	54.2	54.6	53.1	51.5	49.5	47.1	47.8	45.0
4	Station 5	38.1	39.2	36.4	33.0	36.8	33.2	34.4	27.5
4	Station 6	54.8	55.0	53.5	51.8	49.8	47.3	44.1	39.5
5	Station 1	56.1	54.8	54.7	53.3	51.8	50.0	47.9	45.1
5	Station 2	45.5	46.8	47.9	48.8	49.5	46.2	41.7	35.2
5	Station 3	76.2	78.2	79.5	77.3	74.6	74.6	71.0	66.0
5	Station 4	54.2	52.6	53.1	53.1	51.6	49.9	47.8	45.0

Table A-3. CWQI Calculated for Twenty Parameter Removal Trials

Trial	Station	Number of Parameters							
		11	10	9	8	7	6	5	4
5	Station 5	38.1	39.5	40.8	41.8	39.4	36.0	32.5	25.3
5	Station 6	54.8	55.1	55.0	53.6	52.0	50.2	48.1	45.3
6	Station 1	56.1	54.8	53.3	51.6	49.7	90.4	88.4	85.5
6	Station 2	45.5	50.4	47.3	43.1	44.1	66.4	59.9	68.4
6	Station 3	76.2	73.8	71.0	67.3	62.6	76.9	71.1	80.8
6	Station 4	54.2	52.6	50.8	48.6	49.3	89.9	87.9	84.8
6	Station 5	38.1	41.7	39.0	35.6	36.5	59.1	54.1	65.7
6	Station 6	54.8	53.2	51.3	49.1	46.4	80.7	76.8	85.6
7	Station 1	56.1	54.8	53.3	51.6	51.8	100.0	100.0	100.0
7	Station 2	45.5	46.8	47.5	44.4	45.6	61.0	56.1	84.6
7	Station 3	76.2	78.2	76.0	73.2	74.7	100.0	100.0	100.0
7	Station 4	54.2	52.6	50.8	48.6	49.5	90.4	88.4	85.6
7	Station 5	38.1	39.5	36.9	33.7	35.0	45.0	41.1	70.9
7	Station 6	54.8	55.1	53.6	51.9	52.0	100.0	100.0	100.0
8	Station 1	56.1	54.8	53.3	53.3	51.8	50.0	100.0	100.0
8	Station 2	45.5	42.4	38.4	39.1	33.7	34.1	46.2	36.3
8	Station 3	76.2	73.8	71.0	73.1	73.1	69.5	88.4	85.5
8	Station 4	54.2	52.6	50.8	51.5	49.5	49.9	100.0	100.0
8	Station 5	38.1	35.5	33.0	34.1	29.7	30.4	39.1	39.4
8	Station 6	54.8	53.2	51.3	51.8	49.8	47.3	88.3	85.4
9	Station 1	56.1	54.8	53.3	51.6	49.6	47.2	44.1	39.5
9	Station 2	45.5	46.8	43.4	48.8	49.9	45.8	40.0	31.5
9	Station 3	76.2	78.2	78.2	76.0	73.2	69.5	64.6	57.6
9	Station 4	54.2	52.6	50.8	48.6	49.3	46.9	43.7	39.1
9	Station 5	38.1	39.5	36.8	40.6	41.7	39.4	40.2	35.5
9	Station 6	54.8	55.1	53.6	51.9	49.9	47.5	44.3	39.8
10	Station 1	56.1	54.8	53.3	51.6	49.7	47.2	44.1	45.2
10	Station 2	45.5	42.1	47.0	48.8	44.9	39.5	31.9	32.4
10	Station 3	76.2	73.8	70.9	73.1	69.6	64.7	64.7	66.0
10	Station 4	54.2	52.6	50.8	48.6	46.0	42.6	38.0	39.5
10	Station 5	38.1	36.1	39.6	41.4	38.2	33.8	27.4	28.9
10	Station 6	54.8	53.2	51.3	51.9	49.9	47.5	44.3	45.3
11	Station 1	56.1	56.0	54.7	53.3	51.8	50.0	47.9	45.1
11	Station 2	45.5	46.4	47.9	44.4	40.0	41.0	47.4	48.7
11	Station 3	76.2	78.1	79.5	79.5	77.3	74.6	70.9	66.0
11	Station 4	54.2	54.6	53.1	51.5	49.5	49.9	47.8	45.0
11	Station 5	38.1	39.2	40.8	38.1	38.4	39.4	44.0	41.3
11	Station 6	54.8	55.0	55.0	53.6	52.0	50.2	48.1	45.3
12	Station 1	56.1	54.8	53.3	51.6	51.8	100.0	100.0	100.0
12	Station 2	45.5	50.4	47.0	43.1	44.3	68.3	73.8	67.3
12	Station 3	76.2	73.8	70.9	67.3	69.4	88.4	85.5	85.5
12	Station 4	54.2	52.6	50.8	48.6	49.5	90.4	100.0	100.0
12	Station 5	38.1	41.7	39.6	36.4	37.8	64.3	67.7	61.0
12	Station 6	54.8	53.2	51.3	49.1	49.8	90.3	88.3	85.4
13	Station 1	56.1	54.8	53.3	92.8	91.7	90.4	88.4	85.5
13	Station 2	45.5	50.4	47.3	67.4	71.0	66.3	59.8	63.3
13	Station 3	76.2	73.8	71.0	83.5	80.7	80.7	76.9	71.1
13	Station 4	54.2	52.6	50.8	85.4	91.3	89.9	87.9	84.8

Table A-3. CWQI Calculated for Twenty Parameter Removal Trials

Trial	Station	Number of Parameters							
		11	10	9	8	7	6	5	4
13	Station 5	38.1	41.7	39.0	62.0	64.0	59.0	59.7	52.6
13	Station 6	54.8	53.2	51.3	85.5	83.4	80.7	76.8	71.0
14	Station 1	56.1	94.2	93.6	92.8	91.7	100.0	100.0	100.0
14	Station 2	45.5	57.4	53.6	49.4	50.2	52.4	72.7	66.1
14	Station 3	76.2	87.2	87.2	85.6	83.5	90.4	88.4	85.5
14	Station 4	54.2	88.3	87.0	85.4	83.3	90.4	88.4	85.6
14	Station 5	38.1	47.6	44.3	40.5	35.6	37.0	56.7	47.0
14	Station 6	54.8	88.4	87.1	85.5	83.4	90.3	88.3	85.4
15	Station 1	56.1	94.2	93.6	92.8	91.7	90.4	88.4	85.5
15	Station 2	45.5	57.4	53.7	67.2	62.6	56.8	48.3	35.7
15	Station 3	76.2	87.2	85.6	83.5	80.7	76.9	71.1	71.1
15	Station 4	54.2	88.3	87.0	85.4	83.3	80.5	76.6	70.7
15	Station 5	38.1	47.6	45.2	62.7	58.1	52.3	53.0	43.3
15	Station 6	54.8	88.4	87.1	85.5	83.4	80.7	76.8	71.0
16	Station 1	56.1	54.8	53.3	51.6	91.7	90.4	88.4	100.0
16	Station 2	45.5	46.8	43.5	39.3	51.6	45.9	62.9	70.5
16	Station 3	76.2	78.2	76.0	76.0	91.8	90.4	88.5	100.0
16	Station 4	54.2	52.6	50.8	48.6	83.3	80.5	76.6	85.6
16	Station 5	38.1	39.5	36.9	33.4	42.6	37.6	60.3	70.8
16	Station 6	54.8	55.1	53.6	51.9	91.7	90.4	88.4	100.0
17	Station 1	56.1	54.8	53.3	51.6	91.7	100.0	100.0	100.0
17	Station 2	45.5	46.8	47.5	48.4	63.1	65.5	61.8	57.0
17	Station 3	76.2	78.2	76.0	73.2	90.4	100.0	100.0	100.0
17	Station 4	54.2	52.6	50.8	51.3	91.3	100.0	100.0	100.0
17	Station 5	38.1	39.5	36.9	37.9	47.9	49.9	50.0	48.3
17	Station 6	54.8	55.1	53.6	51.9	91.7	100.0	100.0	100.0
18	Station 1	56.1	54.8	54.7	53.3	51.8	50.0	47.9	45.2
18	Station 2	45.5	50.4	51.8	48.3	49.2	45.2	39.2	30.4
18	Station 3	76.2	73.8	75.9	75.9	73.1	69.5	64.6	57.6
18	Station 4	54.2	52.6	53.1	51.5	49.5	47.1	44.0	39.5
18	Station 5	38.1	41.7	42.9	40.2	36.9	32.4	32.1	23.9
18	Station 6	54.8	53.2	53.5	51.8	49.8	47.3	44.1	39.5
19	Station 1	56.1	54.8	93.6	92.8	91.7	100.0	100.0	100.0
19	Station 1	56.1	54.8	53.3	51.6	49.6	47.2	44.1	39.5
19	Station 2	45.5	50.4	70.8	67.2	70.8	77.9	73.5	85.6
19	Station 3	76.2	73.8	85.6	83.5	80.7	88.4	85.5	100.0
19	Station 4	54.2	52.6	87.0	85.4	91.3	100.0	100.0	100.0
19	Station 5	38.1	41.7	65.6	62.7	64.9	72.1	74.3	100.0
19	Station 6	54.8	53.2	87.1	85.5	83.4	90.3	88.3	100.0
20	Station 1	56.1	54.8	93.6	92.8	91.7	90.4	88.4	85.5
20	Station 2	45.5	42.1	53.7	54.6	49.7	52.7	46.0	36.2
20	Station 3	76.2	73.8	85.6	83.5	80.7	88.5	85.6	85.6
20	Station 4	54.2	52.6	87.0	85.4	83.3	80.5	76.6	70.7
20	Station 5	38.1	36.1	45.2	41.5	41.7	44.3	39.1	31.0
20	Station 6	54.8	53.2	87.1	85.5	83.4	90.4	88.4	85.6