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APPLICATION OF CCME WATER QUALITY INDEX TO MONITOR WATER QUALITY: A CASE OF THE MACKENZIE RIVER BASIN, CANADA

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Abstract. All six ecosystem initiatives evolved from many years of federal, provincial, First Nation, local government and community attention to the stresses on sensitive habitats and species, air and water quality, and the consequent threats to community livability. This paper assesses water quality aspect for the ecosystem initiatives and employs newly developed Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) which provides a convenient mean of summarizing complex water quality data that can be easily understood by the public, water distributors, planners, managers and policy makers. The CCME WQI incorporates three elements: *Scope* – the number of water quality parameters (variables) not meeting water quality objectives (F_1); *Frequency* – the number of times the objectives are not met (F_2); and *Amplitude*. the extent to which the objectives are not met (F_3). The index produces a number between 0 (worst) to 100 (best) to reflect the water quality. This study evaluates water quality of the Mackenzie – Great Bear sub-basin by employing two modes of objective functions (threshold values): one based on the CCME water quality guidelines and the other based on site-specific values that were determined by the statistical analysis of the historical data base. Results suggest that the water quality of the Mackenzie-Great Bear sub-basin is impacted by high turbidity and total (mostly particulate) trace metals due to high suspended sediment loads during the open water season. Comments are also provided on water quality and human health issues in the Mackenzie basin based on the findings and the usefulness of CCME water quality guidelines and site specific values.

Keywords: aquatic life, CCME water quality index, ecosystem health, ecosystem initiatives, Mackenzie River basin, metals, protocols, site specific guidelines, water quality guidelines

1. Introduction

Environment Canada's (EC) six large ecosystem initiatives are Georgia Basin Ecosystem, Northern Rivers Ecosystem, Northern Ecosystem, Great Lakes Action Plan, St. Lawrence Action Vision 2000 and Atlantic Coastal Action Program and their common goals are set towards the improvement of air, water quality and protection of important habitats and species through partnerships between different levels of government, industry, universities and communities. Through ecosystem initiatives, EC is able to address priority areas and issues of concern, ensuring that

Canadians have clean air and water, protecting and conserving nature, and taking action on climate change. This paper deals with one of the very important objective of the ecosystem initiatives and it assesses the water quality in different water bodies of Canada's Northern River Ecosystem.

In the spring of 2000, the National Round Table on the Environment and the Economy (NRTEE), in collaboration with Statistics Canada and Environment Canada launched the Environment and Sustainable Development Indicators (ESDI) Initiative. This ESDI Initiative was built on the need to take account of assets that are necessary to sustain a dynamic economy and a healthy society and environment for Canadians (NRTEE, 2003). Fresh Water Quality is one of the six national-level environmental indicators that were deemed appropriate as indicators that would be reported annually. It provides a national measure of the overall state of water quality as measured against major objectives (CCME, 2003) for water use in Canada. Since its inception and endorsement by the CCME for use in Canadian jurisdictions, the Water Quality Index (WQI) has been implemented in British Columbia, Alberta, Saskatchewan, Manitoba, the Mackenzie River basin and the Atlantic Provinces. A similar WQI has been applied in Quebec. From this experience with CCME WQI implementation, both strengths and challenges of the WQI have come to light, including issues related to monitoring, communication and public expectation, inputs, interpretation of the CCME WQI, and the long-term feasibility studies of the quality aspects of water resources and financial commitment by governments.

In order to assess the suitability of water for diverse uses, there is a need to devolve an index similar to the air quality model that will categorize the quality of water. This index should integrate the significant physico-chemical and biological constituents of water and present them in a simple, yet scientifically defensible manner. Attempts to categorize water according to its degree of purity date back to the mid-twentieth century (Horton, 1965; Landwehr, 1974), however, Ott (1978) and Steinhart *et al.* (1981) reviewed more than 20 water quality indices being used till late seventies. Steinhart *et al.* (1982) applied a new environmental quality index to summarize technical information on the status of, and trends in Great Lakes Ecosystem. In Canada, the water quality index was introduced in mid-90's (Rocchini and Swain, 1995; Dunn, 1995; Hebert, 1996) by Water Quality Guidelines Task Group of the Canadian Council of Ministers of the Environment. This Task Group created the Water Quality Index Technical sub-committee that in turn modified the original British Columbia Water Quality Index into the CCME Water Quality Index (WQI), which was endorsed by the CCME (CCME, 2001). This newly developed CCME WQI has been employed by various provinces and Ecosystems all across Canada to assess water quality (CCME, 2001a,b; Cash *et al.*, 2001; Husain, 2001; Sharma, 2002; Lumb *et al.*, 2002; Khan *et al.*, 2003; Paterson *et al.*, 2003).

The present study (Sharma, 2002; Lumb *et al.*, 2002) describes the application of the CCME Water Quality Index to monitor the changes in water quality

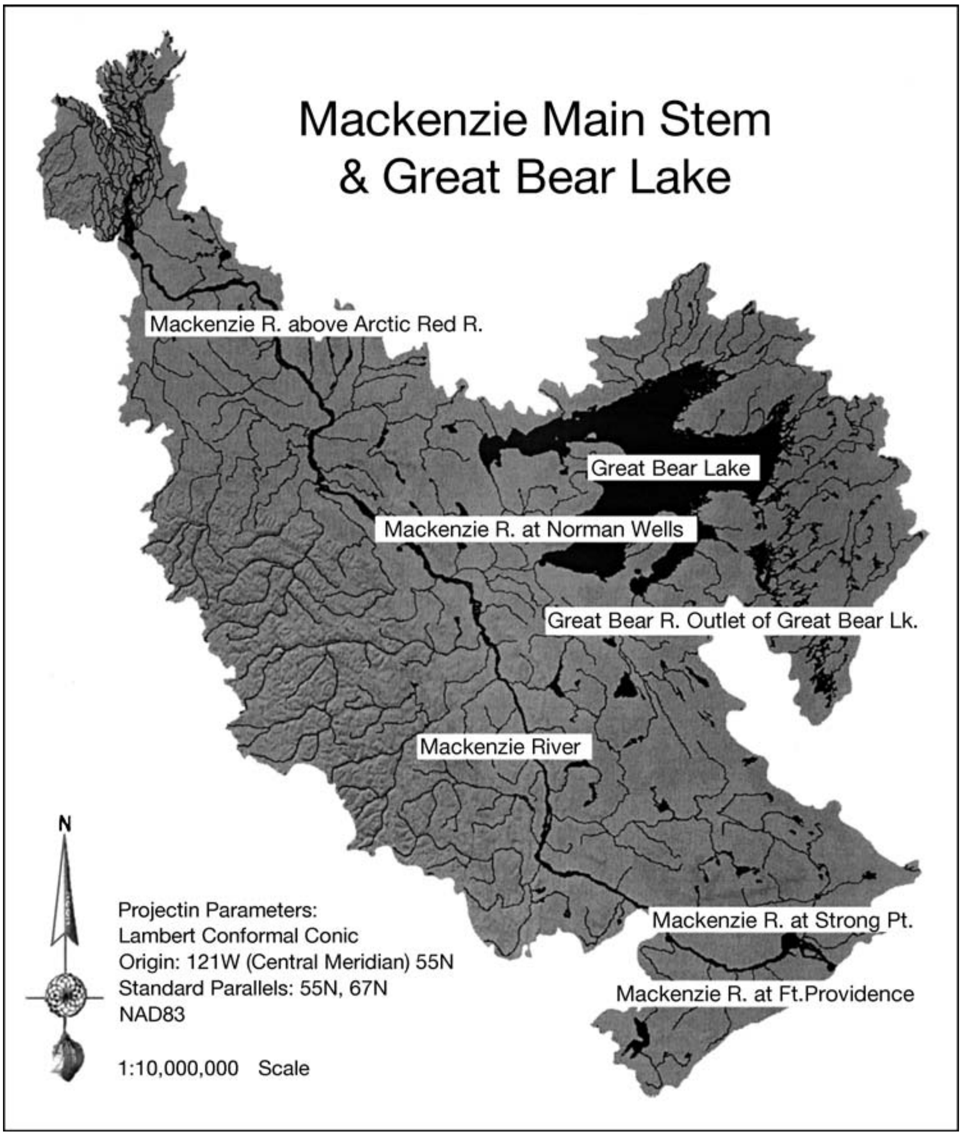

Figure 1. Mackenzie River basin 5 water quality sites.

at the following five sites in the Mackenzie-Great Bear sub-basin which is the largest of the six sub-basins within the Mackenzie River basin, NT, Canada (Figure 1).

1. Mackenzie River near Fort Providence
2. Mackenzie River at Strong Point
3. Mackenzie River at Norman Wells

4. Mackenzie River above Arctic Red River (Tsiighetchic)
5. Great Bear River at Outlet of Great Bear Lake

The 4241 km long Mackenzie River is the second largest river in North America and it drains into the Arctic Ocean. The Mackenzie-Great Bear sub-basin lies north of 60° and has a limited number of floral and faunal species due to its northern location, though the Mackenzie River's microclimate results in more biodiversity than other areas at the same latitude. The Western Canadian Mainland Sedimentary basin portion of the Mackenzie River basin is underlain by vast reserves of oil and natural gas. It was developed for the production and transportation via the Canol pipeline from Norman Wells to Whitehorse, Yukon during World War II. The Norman Wells (still partially producing) oil field currently produces eleven to twelve million barrels of crude oil per year. Natural gas with an estimated reserve of 66 trillion cubic feet, is producing only minor portion to date (i.e. 2000 onwards production at Ikhil Gas Field near Inuvik). Mackenzie Gas Project (MGP) should be fully operational by 2010. The eastern Canadian Shield portion of the Mackenzie-Great Bear sub-basin and upstream Great Slave, Liard and Peel sub-basins, are also known for uranium, gold, diamond, lead, zinc, tungsten, copper and silver reserves. The current population of the Mackenzie-Great Bear sub-basin is about 10 000, the greatest concentration of which is in Inuvik, followed by Fort Simpson. Hunting, trapping, fishing and tourism remain important to the local economy.

2. Conceptual Framework of CCME Water Quality Index

The CCME WQI was originally developed as the Canadian Water Quality Index (CWQI). It comprises of three factors and is well documented (CCME, 2001a).

Factor 1 : F_1 (Scope)

Scope assesses the extent of water quality guideline non-compliance over the time period of interest, which means the number of parameters whose objective limits are not met. It has been adopted directly from the British Columbia Water Quality Index:

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

Where, the **variables** indicate those water quality parameters whose objective values (threshold limits) are specified and observed values at the sampling sites are available for the index calculation.

Factor 2 : F_2 (Frequency)

The frequency (i.e. how many occasions the tested or observed value was off the acceptable limits) with which the objectives are not met, which represents the percentage of individual tests that do not meet the objectives ("failed tests"):

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

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

$$\text{Factor 3}: \ F3\,(\text{Amplitude})$$

The amount by which the objectives are not met (amplitude) that represents the amount by which the failed test values do not meet their objectives, and is calculated in three steps.

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:

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

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

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

The collective amount, by which the individual tests are out of compliance, is calculated summing the excursions of individual tests from their objectives and then dividing the sum by the total number of tests. This variable, referred to as the normalized sum of excursions (*nse*) is calculated as:

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{number of tests}}$$

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

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

The CWQI is finally calculated as:

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

The factor of 1.732 has been introduced to scale the index from 0 to 100. Since the individual index factors can range as high as 100, it means that the vector length can reach a maximum of 173.2 as shown below:

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

The above formulation produces a value between 0 and 100 and gives a numerical value to the state of water quality. Note a zero (0) value signifies very poor water quality, whereas a value close to 100 signifies excellent water quality. The assignment of CCME WQI values to different categories is somewhat subjective process and also demands expert judgment and public's expectations of water quality. The water quality is ranked in the following 5 categories:

1. Excellent: (CCME WQI values 95–100)
2. Good: (CCME WQI values 80–94)
3. Fair: (CCME WQI values 60–79)
4. Marginal: (CCME WQI values 45–59).
5. Poor: (CCME WQI values 0–44)

The CCME has prepared software in Visual Basic, which is implemented in Microsoft Excel for computing the WQI. The macro is quite flexible in that it can take a large number of data sets on the large number of water quality variables for computing the indices. The choice of variables, depending on the availability of data, can be manipulated easily. The detailed instructions on the implementation of the macro are well described in the Calculator Version 1.0 (CCME, 2001). The output is available in the form of a table displaying the values of F_1, F_2, F_3, WQI, number of samples, number of variables tested, total number of variables, total tests, failed tests, passed tests and tests below detection level. It also gives a frequency histogram of F_1, F_2 and F_3. The macro is user-friendly but requires input data in a given tabular format. It should be noted that F_2 essentially is the ratio of number of failed tests divided by the total number of tests expressed as percentage.

3. Methodology

CCME WQIs were computed for the five sites in the Mackenzie-Great Bear subbasin of the Mackenzie River basin using two sets of threshold values. The first set was based on the recommended CCME guidelines and the second set on the statistics of the data sequence of the variable in question. The CCME recommended Canadian Water Quality Guidelines (CWQGs)-based objectives were applied to categorize the water primarily for overall use, for use as raw drinking water for use as boiled/filtered drinking water (simulated scenario by removing some variables) and for freshwater aquatic life. The same CCME CWQGs-based objectives were also applied to identify the role of physical variables, major ions, nutrients and total trace metals in determining the water quality. The water quality indices have been determined by combining variables of interest for a particular use or application, named herein, as protocols or subgroups. The term overall implies that all sampled variables have been used in the assessment of WQI. The site-specific sets of regulatory values for each water quality variable were also applied to evaluate the overall water quality. These statistics were combined in three forms of thresholds:

a. mean + 2 sd (standard deviation) of the whole data series of a given variable
b. 90th range (not rank) percentile of the whole data series of the variable
c. mean + 2 sd of the data series during the freshet period (when stream flows are highest following spring snowmelt and rain storms) which is typical during the months of May and June or just June of the given variable.

The evaluation of CCME WQIs for agricultural use was not considered because agriculture (a land use) not practiced in the sub-basin.

Thus, for each site and water use, different sets (subgroups or protocols) of water quality variables have been used depending upon the availability of data and also regulatory standards. All the variables that have been used in the present study are listed in Table I. The indices have been worked out for 11 protocols (CCME based regulatory values applied on eight subgroups, and three sets of values based on the data statistics applied only one subgroup named overall), which are relevant for the settings of the Mackenzie basin. The following protocols were organized in following format for WQI calculations.

4. Organization of Protocols

4.1. CCME BASED REGULATORY VALUES APPLIED ON VARIOUS WATER USES

1. Overall use-based on the variables: temperature, pH, true color, turbidity, ammonia, nitrates, nitrites, total dissolved solids, chloride, sulphate, fluoride, cyanide, arsenic, selenium, aluminium, barium, beryllium, cadmium, copper, iron, lithium, lead, manganese, molybdenum, nickel, vanadium, zinc, calcium, sodium and silver.
2. Category-based on the variables used for overall use (shown above in protocol 1) but physical variables (temperature, color, turbidity) and 3 metals (aluminium, copper and iron) removed from the analysis. This represents a simulated scenario tantamount to treated (by boiling and/or filtering) water for drinking applications.
3. Category for drinking use based on the variables: temperature, pH, ammonia, nitrate and nitrite, true colour, turbidity, total dissolved solids (TDS), chlorides, sulphate, aluminium, copper, lead, and zinc. Technically, only treated, finished

TABLE I

Water quality standards for different water uses (based on CCME, 1999) adopted for NT and site specific statistics (Norman Wells)

Water quality variable	Unit	CCME standards			Site specific standards-overall		
		Overall	Drinking	Aquatic	Mean	Sd	90th range per.
PH	Max.	8.5	8.5	9	7.7*	0.71*	8.1
	Min.	6.5	6.5	5	–	–	6.3
Temperature	(°C)	15	15	15	5.2	5.6	14
Ammonia	(mg/L)	1.37	1.37	1.37	0.09	0.15	0.21
Nitrate and nitrite	(mg/L)	NA	48.2	NA	0.11	0.11	0.18
Color	(TCU)	15	15	15	23.0	35.4	50.0
Conductivity	(uS/cm)	Na	Na	Na	210.0	59.0	260.0
Total dissolved solids	(mg/L)	500	500	500	140.0	43.0	163.0
Total suspended solids	(mg/L)	25	NA	NA	94.0	243.0	253.0
Turbidity	(NTU)	5	5	5	47.0	118.0	120.0
Chloride (Cl)	(mg/L)	100	250	250	9.0	3.8	11.7
Fluoride (F)	(mg/L)	1	1.5	NA	0.11	0.07	0.15
Sulfate (SO_4)	(mg/L)	500	500	500	24.7	5.2	29.2
Aluminum (Al)	(mg/L)	0.005	0.005	0.005	0.75	1.00	2.20
Arsenic (As)	(mg/L)	0.025	NA	NA	0.0001	0.07	0.0004
Barium (Ba)	(mg/L)	1	NA	NA	0.06	0.09	0.10
Beryllium (Be)	(mg/L)	0.1	NA	NA	0.06	0.12	0.15
Cadmium (Cd)	(mg/L)	0.0018	NA	NA	0.0003	0.076	0.0006
Calcium (Ca)	(mg/L)	1000	NA	NA	26.5	36.0	30.0
Copper (Cu)	(mg/L)	0.004	1	1	0.005	0.076	0.0073
Cyanide (CN)	(mg/L)	0.005	NA	NA	NA	NA	NA
Iron (Fe)	(mg/L)	0.3	Na	Na	1.72	2.53	5.45
Lead(Pb)	(mg/L)	0.007	0.01	0.01	0.001	0.076	0.0034
Lithium (Li)	(mg/L)	2.5	NA	NA	0.01	0.11	0.011
Manganese (Mn)	(mg/L)	0.05	NA	NA	0.03	0.11	0.086
Molybdenum (Mo)	(mg/L)	0.05	NA	NA	0.0005	0.11	0.001
Nickel (Ni)	(mg/L)	0.15	NA	NA	0.0036	0.077	0.0067
Selenium (Se)	(mg/L)	0.001	NA	NA	0.0002	0.07	0.0004
Silver (Ag)	(mg/L)	0.0001	NA	NA	0.0001	0.17	0.00018
Sodium (Na)	(mg/L)	200	NA	NA	5.9	1.6	7.8
Vanadium (V)	(mg/L)	0.1	NA	NA	0.003	0.076	0.0054
Zinc (Zn)	(mg/L)	0.03	5	5	0.01	0.08	0.024

NA; not applicable or available.

*The maximum value or the upper limit for pH is mean + 2.sd and minimum or the lower limit is mean −2.sd.

Note. Trace metal CCME Canadian Water Quality Guidelines shown are for hard water (i.e Total Hardness >60 mg/L of calcium carbonate) since all 5 sites have hard water.

Also note that for other protocols i.e. 2, 5, 6, 7 and 8, the CCME threshold under overall category were used for evaluation of WQIs. Note statistics reported above pertain to the entire data set, that is, freshet is part of that. It should also be recognised that only one water use designated as "overall" was examined for WQI calculation using site-specific regulatory values.

water quality values should be compared to Canadian Drinking Water Quality Guidelines (CDWQGs, CCME CEQG, 1999).
4. Category for aquatic use based on the variables indicated in protocol 3 but without nitrate and nitrite ions.
5. Category based on physical variables: temperature, pH, colour, turbidity and TDS.
6. Category based on nutrients using the variables: ammonia, nitrate and nitrite, TDS and total suspended solids (TSS).
7. Category based on major ions using the variables: chloride, fluoride, sulphate, calcium, magnesium, sodium, and potassium.
8. Category based on total trace metals using the variables: pH, cyanide, arsenic, selenium, aluminium, barium, beryllium, cadmium, copper, iron, lithium, manganese, molybdenum, nickel, lead, vanadium, zinc, and silver.

4.2. Site specific regulatory standards applied for overall use

9. Category for overall use based on variables in protocol 1 above but the threshold of variables taken as mean + 2 standard deviation of the sampled data series.
10. Category for overall use indicated in protocol 9 but threshold of variables (mean + 2 sd) taken from freshet data (months of May & June or June) only. Since the flood reaches the Arctic Red River Station in June, therefore the freshet period for this station is June.
11. Category for overall use based on variables in protocol 1 but the threshold of variables taken as 90th range percentile of the data series.

The water quality data sets were abstracted from Eco Atlas (Eco Atlas, 2003) and after careful editing, subjected to analysis. Variables, for which there are no regulatory standards available, have been ignored in the CCME WQI analysis in the case of protocols 1–8. Furthermore, only sets of data that had a minimum of four variables, sampled at least four times, were used in the analysis as is the recommendation in CCME WQI calculator. The threshold values based on the CCME recommendations for various applications are shown in Table I. The objective functions based on the statistics of the data vary within the sampling sites but a typical set has been shown in Table I, which represents the Norman Wells site.

5. Results of Water Quality Analysis

5.1. Mackenzie river near fort providence (site #1) and strong point (site #2)

The sites are located beyond the outlet of the Great Slave Lake with the data available from 1960 to 1997 for Fort Providence but only from 1993 to 2002 for

Strong Point. Values of CCME WQIs (range from 66 to 75) indicate that water quality for overall, drinking and aquatic uses can be rated as **fair** until the 1980s. The calculated CCME WQI value decreased to **marginal** level (range 48 to 56) in the 1990s both for Fort Providence and Strong Point. The CCME WQI calculated on the basis of three physical variables (temperature, color, turbidity) consistently showed mostly **poor** quality (range 36 to 53, but majority values less than 45) throughout the four decades. The WQI values (range 50 to 53) based on the trace metals in the 1990s put the water in the **marginal** category, though these values were high (80 to 100, **good** to **excellent**) until the 1980s. The high values prior to the 1980s are largely attributed to the fact that only a few trace metals were sampled during these decades (only one in the 1960s three in the 1970s and nine in the 1980s whereas 17 variables were sampled in the 1990s). The low values in the 1990s may be an artifact of the larger number of samples collected in that decade, improving the probability of at least one failed test for each variable and a CCME WQI value dominated by Factor F1 (Scope). To discern the role of metals and physicals, the "synthetic" CCME WQI was calculated in accordance with protocol 2 (which does not include temperature, true color, turbidity, aluminum, copper and iron) and the water quality emerged **excellent** (in the 1960s and 1970s) to **good** (in the 1980s and 1990s). This implies that the physical variables have nearly the uniform effect in lowering the water quality through the study period, while the metals have the added effect in the 1990s. The major reason for this can be attributed to the natural washout of commonly occurring trace metals such as aluminum, copper and iron, whose levels may have been further enhanced by the impacts of point-source orphaned mines.

In terms of the major ions (e.g. chloride, sulfate, fluoride, calcium, sodium, magnesium, potassium), nutrients (e.g. ammonia, nitrate and nitrite), TDS and TSS, the CCME WQIs are *good* to excellent (index values range from 85 to 100), using protocols 6 and 7. The significant point to be noted in the analysis is that the values of the CCME WQI are nearly the same for both of the sites for the concurrent time periods. This similarity in values of the CCME WQI and category is expected because the region where these sites are located is free from non-point source effects of human encroachment. The site-specific objective functions ranked overall water quality in the **fair** (e.g. for mean + 2sd, all data; Background Calculation Procedure of CCME (2003), Protocol 9) to **marginal** (e.g. for the 90th range percentile, Protocol 11) category.

5.2. MACKENZIE RIVER AT NORMAN WELLS (SITE #3)

The site is located near the central region of the Mackenzie River with abundant oil and gas fields, some that have been in production for decades. The water quality is mostly rated as **marginal** (CCME WQI values range from 43 to 59) for overall, drinking and aquatic uses, when evaluated against CCME standards. Table II shows the details of calculations regarding the WQIs for the Norman Wells site for all the

TABLE II
CWQI calculations for various protocols, Mackenzie River at Norman Wells

Decade	CWQI type or protocol number	Sample size, no. of var.	Total no. of tests	% of failed tests	CWQI value	CWQI category
1960s	Overall	72,9	518	13.9	63.6	Marginal
1970s	CWQGs/CDQWGs	60,11	376	19.7	63.5	Marginal
1980s	Protocol No.1	66,18	985	8.6	63.1	Marginal
1990s		90,28	2110	11.0	45.7	Marginal
1960s	Overall minus 3 phys.	72, 6	314	0.0	100.0	Excellent
1970s	minus 3 metals (temp.,	60,8	215	1.4	85.5	Excellent
1980s	turb., true color, total	66,14	745	0.9	87.6	Good
1990s	Al, total Cu, total Fe). Protocol No.2	70,22	1637	2.6	84.1	Good
1960s	Drinking water	72,7	445	16.2	60.2	Marginal
1970s	CDWQGs	60,7	333	21.6	50.4	Marginal
1980s	Protocol No.3	66,10	621	11.3	58.7	Marginal
1990s		90,12	64	10.9	42.9	Poor
1960s	Freshwater aquatic life	72,7	396	18.2	56.9	Marginal
1970s	CWQGs	60,7	287	25.1	46.0	Marginal
1980s	Protocol No.4	66,10	556	12.2	59.0	Marginal
1990s		90,12	989	13.81	43.5	Poor
1960s	Physicals CWQGs	72,5	283	25.4	46.3	Marginal
1970s	Protocol No. 5	60,5	223	32.7	34.1	Poor
1980s		66,6	361	18.8	48.0	Marginal
1990s		90,6	501	15.6	49.6	Marginal
1960s	Nutrients CWQGs	72,4	114	10.5	69.3	Fair
1970s	Protocol No.6	60,3	89	21.3	44.3	Poor
1980s		66,3	183	15.3	59.7	Marginal
1990s		90,4	315	9.8	76.0	Fair
1960s	Major ions CWQGs	72,3	192	0.0	100.0	Excellent
1970s	Protocol No. 7	60,3	143	0.0	100.0	Excellent
1980s		66,3	191	0.0	100.0	Excellent
1990s		90,5	359	0.0	100.0	Excellent
1960s	Trace metals CWQGs	No data	No data		None	none
1970s	Protocol No. 8	60,3	10	0.0	100.0	Excellent
1980s		66,10	481	3.5	76.6	Fair
1990s		90,17	1294	11.8	41.9	Poor
1960s	Overall CWQGs	72,9	518	2.5	61.5	Marginal
1970s	Objective = mean + 2sd.	60,11	376	4.5	57.7	Marginal
1980s	Protocol No.9	66,18	985	6.1	80.4	Good
1990s		90,28	2110	4.8	81.2	Good
1960s	Overall CWQGs	72,9	518	11.8	71.8	Fair
1970s	Objective = mean + 2sd.	60,11	376	14.6	60.3	Marginal
1980s	for freshet data	66,18	985	4.9	79.4	Fair
1990s	Protocol No. 10	90,28	2110	2.2	87.4	Good
1960s	Overall CWQGs	72,9	518	12.4	41.8	Poor
1970s	Objective = 90*	60,11	376	13.8	51.4	Marginal
1980s	Percentile of the data	66,18	985	12.6	44.8 = 45	Marginal
1990s	Protocol No. 11	90,28	2110	2.2	41.8	Poor

protocols under consideration. The quality was found to be **excellent** to **good** in the absence of physical variables and metals (protocol 2, Table II). The physical variable values frequently exceeded CCME CWQGs during all decades, rendering the water **marginal** in quality (CCME WQI values range from 34 to 64) for protocol 5. Trace metal CCME WQI values (protocol 8) are in the **excellent** to **good** category before the '90s and **marginal** category during the 1990s and afterwards. For the major ions (protocol 6) and nutrients (protocol 7), the water quality is rated as **fair** to **excellent** category (CCME WQI values range from 60 to 100). The nutrients CCME WQI (protocol 7) have decreased on the Mackenzie River between Fort Providence and Norman Wells, due to higher ammonia, dissolved and suspended solids, nitrates, and nitrites values at the downstream site. Petroleum industry activities may have increased the population of communities and soil erosion, at least locally. The concentration of the suspended solids is very high in the Mackenzie River, especially during the spring freshet period. The indices clearly point out that the main culprits lowering CCME WQI values are metals (aluminum, iron, and copper) and physical variables such as turbidity and true color as is evidenced by the simulation protocol (Table III).

The objective functions based on the site-specific values (statistical parameters) all portray an improving water quality index over time, but CCME WQIs based on three sets of objective values do not compare well (Table III), with fair to **excellent** CCME WQI categories obtained using protocols 9 and 10 (i.e. two standards above the mean objectives) and only **good** to **marginal** CCME WQI categories obtained using protocol 11 (i.e. 90th range percentile).

5.3. MACKENZIE RIVER ABOVE ARCTIC RED RIVER (TSIIGHETCHIC – SITE # 4):

This site is located on the Mackenzie River above the Hamlet of Tsiighetchic, formerly known as Arctic Red River and it flows into the Mackenzie Delta beyond this point. The data bank spans from June 1960 to January 2002, with the decadal sample size fairly large, except for the year 2000 to present (only 14 samples). The results of water quality analysis at the Mackenzie River's most downstream site, based on CCME CWQGs, ranked the water as **marginal** to **poor** (WQI values range from 38 to 58) for overall, drinking and aquatic uses. In contrast, the simulated CCME WQI (protocol 2) and major ions (protocol 6) and nutrients (protocol 7) values categorize water quality as **excellent** to **good.** The roles of physical water quality variables (e.g. true color and turbidity) and total trace metals are quite significant in lowering CCME WQI values. The results are in conformity with field observations and local knowledge and suggest the waters of the Mackenzie River and nearby tributaries (e.g. Arctic Red River) are very turbid, colored (thus the name "Arctic Red River"), and rich in suspended sediments.

It should be remembered that the Mackenzie River is the most sediment-laden major river in Canada and the Circum-Polar World. This presents scientists applying the CCME WQI with special challenges. Suspended sediment believed to be derived

TABLE III
WQIs based on CCME and site specific objective functions for overall use in the Mackenzie River basin

Decade	Sampling site name	WQIs and category based on CCME	WQI values and category based on Site specific standards: Mean+ 2sd for all data**	Mean+2sd for the freshet data	90th per centile	Number of Variables, Samples, and total Test	Simulated WQIs based on CCME, Protocol 2
1960s	Fort	70.2 F	78.3 F	65.9 F	54.0 M	8, 72, 168	100.0 E
1970s	Providence	75.3 F	76.9 F	67.8 F	57.8 M	10, 60, 427	100.0 E
1980s		69.6 F	65.9 F	49.1 M	48.1 M	17, 66, 683	86.6 G
1990s		55.6 M	63.6 F	49.1 M	50.4 M	27, 90, 1464	89.0 G
1990s	Strong	56.3 M	60.8 F	60.5 F	46.3 M	28, 77, 1823	90.2 G
2000s	Point	56.4 M	73.1 F	68.9 F	54.2 M	28, 17, 451	94.6 E
1960s	Norman	63.6 F	61.5 F	71.8 F	41.8 P	9, 72, 518	100.0 E
1970s	Wells	63.5 F	57.7 M	60.3 F	51.4 M	11, 60, 376	85.5 G
1980s		63.1 F	80.4 G	79.4 F	45.0 M	18, 66, 985	87.6 G
1990s		45.7 M	81.2 G	87.4 G	41.8 P	28, 90, 2110	84.1 G
2000s		53.2 M	95.0 E	93.5 G	82.6 G	28, 5, 139	95.0 E
1960s	Arctic Red	49.4 M	67.6 F	67.1 F	47.0 M	9, 47, 336	100.0 E
1970s	River	54.1 M	65.2 F	65.1 F	46.3 M	10, 73, 448	91.7 G
1980s		63.0 F	55.8 M	52.3 M	41.9 P	17, 89, 1361	86.7 G
1990s		44.3 P	52.5 M	63.5 F	44.0 P	28, 98, 2199	84.0 G
2000s		39.2 P	65.4 F	47.0 M	54.1 M	28, 14, 365	82.2 G
1960s	Great Bear	90.5 G	100.0 E	85.2 G	79.5 G	8, 8, 21	100.0 E
1970s	River	76.5 F	57.7 M	57.7 M	56.8 M	10, 25, 156	91.7 G
1980s		89.1 G	52.4 M	66.0 F	48.8 M	16, 57, 738	100.0 E
1990s		72.2 F	48.4 M	52.5 M	47.9 M	27, 63, 1357	89.0 G
2000s		93.7 G	95.5 E	93.1 G	89.5 G	27, 8, 216	96.9 E

Note. E:Excellent, G:Good, F:Fair, M:Marginal and P:Poor.
*The trace metals: silver, zinc, selenium, cadmium, lead and manganese had very high concentrations. Therefore cleaning for iron and copper (no data for aluminum) improved WQI very little.
**Background Calculation Procedure (CCME, 2003). No cyanide data for this station. Sample size indicates the total number of samples for analysis of water. No. of var. means the number of water quality variables (parameters) tested.

from erosion of soil (overburden) and bedrock, in headwater streams of the Canadian Cordillera, Western Canadian Mainland Sedimentary Basin, and (to a lesser extent) Canadian Shield. Landslides, mass movement, debris flows, and earthquakes trigger some of this erosion.

The site-specific objective protocols paint nearly the same picture while ranking the water as better quality, largely **marginal to fair** (Table III). This is because the cutoff values provided by these yardsticks were much higher, which are reflected in the improved category of water. In reality, site-specific objective functions appear to be doing a good job in the natural environments, where human interventions through agriculture, deforestation, mining, urban development etc. are minimal. In disturbed environments, they may give an appealing but erroneous picture.

5.4. Great Bear River at the Outlet of Great Bear Lake (Site #5)

The sampling site is located near the outlet of Great Bear Lake at its only outlet, which allows the settlement of sediments from upstream sources. Therefore, this site provides a good basis to discern the role of the lake in the settling of trace metals, sediments and other contaminants, if any. The settling of metals has been very effective as evidenced by the dramatic rise in CCME WQIs in the range from 70 (**Fair**) to 97 (**Excellent**) (protocol 8, trace metals; protocol 1, overall use; protocol 2, simulation) from the 1990s decade and onward, when sampling of metals was done intensively. It appears most of the metals adhere to sediments, which settle in the lake enabling the water quality in terms of trace metals, turbidity and true color to improve. The site specific yardsticks in this case also appear to respond in a mixed manner as for other sites in depicting the CCME WQIs. In particular, site-specific standards put the water in a **marginal** category in the 1990s as against good by the CCME yardsticks (Table III).

6. Discussion

6.1. A Comparison on the Use of CCME Based and Site Specific Objectives

In order to examine the relative worth of site specific objectives, in relation to CCME based yardsticks, a simple cross correlation analysis was run between CCME WQIs using Protocol 1 as x and those using protocol 9 (mean + 2 sd) as y. These cross correlations were also worked out between CCME WQIs for protocols 1 (CCME) and 10 (mean + 2sd of the freshet period), and protocol 1 and 11 (90th ranked percentile). The correlation coefficient turned out to be 0.27 (statistically insignificant), 0.43 (significant) and 0.49 (significant) respectively, implying that the best choices of CCME WQI are CCME based (overall uses) yardsticks (protocol 1) and 90th ranked percentile of the historical data base for all the variables in question (protocol 11). Unfortunately, protocols 1 and 11 both emphasize the frequent number of exceedances/failed tests due to high suspended sediment load effects, and are likely falsely alarmist and inaccurate. The mean +2 sd yardstick (Protocols 9, 10) based on the entire data set and the freshet period yields higher CCME WQI values and categories that pass the “common sense test” which respects the facts that the Mackenzie River is one of the most pristine rivers in the world and that the sediments also carry nutrients and food sources (i.e. a more biological and less purely chemical focused, CCME WQI would have more optimistic results). However, rigorous work is required to make a definite recommendation based on the inter-comparison of a large number or water quality indices from several gauging sites across Canada. In particular, there is a need to identify the probability distribution functions for the variables in question in order to estimate the above statistics, which is beyond the scope of this paper.

The choice of decadal time intervals may cause lower CCME WQI values and categories to result. A few sensitivity analyses tests were carried out for shorter (one to three year) time periods and CCME WQI values increased. This matches experiences and findings of 60 other CCME WQI practitioners from across Canada, as per discussions at the CCME WQI Workshop (Mercier and Leger, 2003) in Halifax in November 2003, where three year rolling averages were a popular standard protocol.

6.2. Water quality and human health in the Mackenzie basin

Low values of CCME WQIs have been attributed to a high level of trace metals for all five sampling sites. This implies that there is a common factor or reason (e.g. larger number of parameters monitored caused Factor 1 (Scope) to dominate), which emerged since the 1990s. Quebec WQI practitioners considered Factor 1 (Scope) problem so significant that they excluded it from their index calculation.

The potential use of CCME WQIs to examine impacts of abandoned mines may have some promise, though more rigorous sampling programs and additional CCME WQI statistical examination of results would be required. The point of interest from the results refer to CCME WQIs for the raw water as the drinking water source, which appears to be less satisfactory on the main Mackenzie River (CCME WQIs largely falling in the **fair to marginal** range). This clearly indicates that the water must be treated to remove the physical impurities and major metals. When the simulation exercise was carried out (protocol 2), the indices jumped sharply making water highly suitable for drinking purposes (CCME WQIs falling in the **good to excellent** range). The need of water treatment for drinking purposes is aptly demonstrated and in small communities, where people draw water from rivers, advisories to boil and filter the water must be in place. In terms of aquatic life, the raw waters appear to be less favorable, although they are rich enough in the nutrient levels. The main culprits for this state are high turbidity, high true color and high concentrations of metals (i.e. total Al, Cu, Fe). The soil erosion is abundant because of the lack of ground cover, and the features associated with the permafrost conditions.

In summary, the water from the rivers under question must be treated for drinking purposes. There is a need to reduce soil erosion by watershed management techniques, which will cut down the turbidity and aluminum in the waters that threaten the aquatic life.

7. Conclusions

This study suggests that the water quality of the Mackenzie-Great Bear sub-basin is impacted by high turbidity, color and total (mostly particulate) trace metals due to high suspended sediment load. This can be attributed to natural and anthropogenic sources of global, upstream or local origin. Local origin for anthropogenic sources is very unlikely (except on the most local scale), given that total annual discharge from all communities and industries within this sub-basin represents only a fraction of a percent of the total annual discharge of the Mackenzie River at the head of the Mackenzie Delta.

Based on CCME WQIs model, the raw water quality in the basin is categorized as marginal to fair along the Mackenzie River for overall, drinking and aquatic water uses. The water quality declines downstream to the Mackenzie Delta for the above uses. Major ions and nutrients CCME WQI values are categorized as **excellent** to **good.** Physical water quality variables (turbidity, true color, suspended solids) and total (mostly particulate) trace metals are lowering CCME WQI values and categories for protocols 5 and 8 significantly.

The CCME WQIs analysis reflected that the water quality of the Mackenzie River basin may have deteriorated over the 1990s due to an increase in the level of the trace metals, if the larger number of 1990s samples are not raising the Scope factor (F1) and lowering the CCME WQI values. The excessive presence of trace metals can be attributed to natural (mostly) and anthropogenic sources. Several mines were abandoned around that period, which might have encouraged uncontrolled runoff from those point-source areas. In this paper, CCME WQI value calculations are based on total concentrations of metals in the water. Had the study used the bio-available dissolved metals instead of total metals (as do the water quality indices employed in Quebec and Alberta), the overall, freshwater aquatic life and trace metal CCME WQI would certainly be higher indicating improved water quality.

Increased erosion and weathering of trace metal-rich and trace organic-rich bedrock (possibly related to increased access roads and survey lines, and/or climate change/climate variability) may be the main natural or part natural/part anthropogenic reason for higher metal concentrations: mining is not expected to be a major cause from relatively small areas.

The categories of water quality evaluated by CCME WQI values based on site-specific objectives and CCME CWQGs showed no conclusive differences. Therefore, no preferential use of either of them can be emphasized. However, site-specific thresholds allow the use of more water quality variables, are more site-specific, better characterize water quality and ecosystem health, and better respect the diverse natural spatial variability across Canada and local biogeochemical backgrounds/biogeochemical processes. CCME CWQG-based CCME WQIs compare values to national standards which may or may not be appropriate for deriving absolute site-specific values for CCME WQIs, but can better illustrate relative values and spatial variability between sites (e.g. four Mackenzie River sites), as long as the same variables are analyzed at all sites. The CCME Water Quality Index technical sub-committee has recently (2003) released a 159 page document which gives guidance on site-specific application of CCME WQIs. It strongly recommends use of site-specific objective based CCME WQIs, giving five procedures. The Background Calculation Procedure recommended by CCME (2003) coincides with protocol 9, shown in the fourth column of Table III, which involves all end uses, two standard deviations above mean objective using all data. The second best choice, protocol 1, shown in the third column of Table III, is the best choice for a CCME CWQG-based CCME WQI, and uses overall end uses and all data.

This study demonstrated that using different CCME WQI protocols and sensitivity analyses to evaluate water quality does identify the specific problematic variables/parameters that may be contributing towards lowering the CCME WQI values and categories. This information can be of great value for water users (public), water suppliers (municipalities and city councils), planners, policy makers, and scientists reporting on the state of the environment. While CCME WQIs are useful in illustrating "What is changing in the environment?", CCME WQIs are unlikely to single-handedly answer the other state-pressure-response State of Environment Reporting questions like "Why is it happening?" or "What does it mean?" without additional scientific, traditional and local knowledge.

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