The Sediment Quality Index (SQI):

SQI Development

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SUMMARY

A sediment quality index provides a convenient means of summarizing complex sediment quality data and facilitating its communication to a general audience. The Sediment Quality Index is based on the Canadian Water Quality Index (CWQI) developed by the CCME and has been modified by Environment Canada (Ontario Region) , the National Water Research Institute and the CCME to make it applicable to sediment samples. The Water Quality Index incorporates three elements: *scope* - the number of variables not meeting water quality guidelines; *frequency* - the number of times these guidelines are not met; and *amplitude* - the amount by which the guidelines are not met. In contrast, the Sediment Quality Index can be calculated by one of two methods. The first method averages the calculation over area; this mode is the same as the WQI. The second method calculates the SQI site-by-site; only the scope and amplitude factors are engaged. For both methods, the index produces a number between 0 (worst sediment quality) and 100 (best sediment quality). At the time of SQI development, the descriptive ranking categories used in the WQI (e.g., excellent to poor) had yet been tested against the numerical results of the SQI.

The sediment chemistry variables, sediment quality guidelines, and spatial area used in the index are not specified and indeed, will vary from region to region, depending on local conditions and issues. It is recommended at this time that at a minimum, four variables sampled in at least four locations be used in the calculation of index values computed over an area. Additional guidance may be provided at a later date, pending a sensitivity analysis of the formulae. It is also expected that the variables and guidelines chosen will provide relevant information about a particular site. The two methods allow the index to be used both for tracking changes at one site, and for comparisons among sites. If used for the later purpose, care should be taken to ensure that there is a valid basis for comparison. The Proceedings of the National Water Quality Index Workshop (CCME 2004) state that WQI would return the most accurate results when calculated using a suite of locally relevant variables and guidelines. Results of indices calculated in this way would be comparable at the local, regional and national levels as long as a consistent approach is followed and the appropriate details are reported.

Although calculation of index values can be done by hand, this is not practical for even a moderate number of sites, guidelines, or samples. An Excel macro that automates the process is available upon request from the CCME (www.ccme.ca).

INTRODUCTION

An integral part of any environmental monitoring program is the reporting of results to both managers and the general public. This poses a particular problem in the case of sediment quality monitoring because of the complexity associated with analyzing a large number of measured variables. The traditional practice has been to produce reports describing trends and compliance with Canadian Environmental Quality Guidelines (CCME 1999) or other guidelines (e.g., Provincial guidelines or site-specific guidelines) on a variable by variable basis. The advantage of this approach is that it provides a wealth of data and information; however, in many cases, managers and the general public have neither the inclination nor the training to study these reports in detail. Rather, they require statements concerning the general health or status of the system of concern.

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

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

The index was initially developed for use as a water quality index (WQI) but has been modified by Environment Canada (Ontario Region), the National Water Research Institute and the CCME to be used as a sediment quality index (SQI). For more information on the development of the CCME WQI please refer to the CCME Water Quality Index 1.0 Technical Report (CCME, 2001).

The index is based on a combination of three factors:

1. the number of variables whose guidelines are not met (**Scope**)
2. the frequency with which the guidelines are not met, (**Frequency**) and
3. the amount by which the guidelines are not met (**Amplitude**).

These are combined to produce a single value (between 0 and 100) that describes sediment quality.

The SQI captures all key components of sediment quality, is easily calculated, and is sufficiently flexible that it can be applied in a variety of situations. The index can be very useful in tracking sediment quality changes at a given site over time and can also be used to compare sites. However, if the sediment chemistry variables and sediment quality guidelines that feed into the index vary across sites, comparison among sites can be complicated. For example, in calculating the index for a number of sediment samples taken from multiple sites, one might employ site-specific guidelines (e.g., for metals and/or nutrients). The Proceedings of the National Water Quality Index Workshop (CCME 2004) state that the WQI returns the most accurate result when calculated using a suite of locally relevant variables and guidelines. Results of indices calculated in this way are comparable at the local, regional, and national levels as long as a consistent approach is followed and the appropriate details are reported. We are applying this recommendation to the SQI.

The intent of this manual is to provide water/sediment quality experts with sufficient background information to allow them to apply the index to their own databases.

For an example of the application of the SQI, please refer to the document "Application of a Sediment Quality Index to the Lower Laurentian Great Lakes". (Marvin et al., 2004).

GENERAL DESCRIPTION OF THE INDEX

The SQI may be calculated by one of two methods. The first method calculates the SQI over area and is calculated the same as the WQI, relying on measures of the scope, frequency and amplitude of excursions from guidelines (see next section). The second method calculated the SQI site-by-site and employs only the scope and amplitude factors.

For both factors, the index value can range from 0-100 where a value of 100 is the best possible index score and a value of 0 is the worst possible score.

Relative differences in SQI values among sites, or over time suggest differences in overall sediment quality; however, the interpretation of the absolute SQI values (e.g. is a score of 80 "good" while a score of 30 "poor") should be verified in conjugation with other information sources and/or expert opinion. At the time of developing this model, generic ranking categories such as those used in the CCME WQI had not been adequately tested to include herein. Practitioners are cautioned against interpreting the results based on arbitrary rankings.

DATA FOR INDEX CALCULATION

The SQI provides a mathematical framework for assessing sediment quality conditions relative to sediment quality guidelines. It is flexible with respect to the type and number of sediment quality variables to be tested, and the area of application tested. These decisions are left to the user. Therefore, before the index is calculated, the sediment body, spatial area, variables, and appropriate guidelines need to be defined.

The sediment bodies to which the index will apply can be defined by one station (*e.g.*, a monitoring site in a particular lake) or by a number of different stations (*e.g.*, sites throughout a lake). Individual stations work well, but only if there are enough data available for them. The more stations that are combined, the more general the conclusions will be.

At a minimum, SQI area calculations should use at least four variables, sampled at a minimum of four sites to compute an index. The maximum number of variables or samples is not specified at this time. Site-specific sediment quality guidelines are preferred when available; however, in their absence Canadian Sediment Quality Guidelines (CCME, 2002) are recommended. The selection of appropriate sediment quality variables for a particular region is necessary for the index to yield meaningful results. Clearly, choosing a small number of variables for which the guidelines are not met will provide a different picture than if a large number of variables are considered, only some of which do not meet guidelines. It is up to the professional judgment of the user to determine which and how many variables should be included in the SQI to most adequately summarize sediment quality in a particular region. Factors to consider could include geology, availability of monitoring data and appropriate guidelines, known local stressors on the system, land use, etc. At the WQI workshop, participants recommended that a decision tree or flowchart be developed to help in the variable selection process (CCME 2004). Once developed for the WQI, it is expected that this tool could be easily modified for the SQI.

CALCULATION OF THE INDEX

After the sediment body, spatial area, and the variables and guidelines have been defined, each of the three factors that make up the index must be calculated. For method 1 in which the SQI is calculated over area, there are three factors, scope (F_1), frequency (F_2), and amplitude (F_3). The calculation of F_1 and F_2 is relatively straightforward; F_3 requires multiple steps. For method 2 in which the SQI is calculated site-by-site, only the scope (F_1) and amplitude (F_3) factors are included.

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

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

F_2 **(Frequency)** represents the percentage of individual <u>tests</u> that do not meet their <u>respective guidelines</u> ("failed tests"):

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

F_2 **(Frequency)** is not required if the SQI is being calculated for a particular site.

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

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

$$excursion_i = \left(\frac{FailedTest\,Value_i}{Guidelines_j} \right) - 1 \qquad (3a)$$

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

$$excursion_i = \left(\frac{Guidelines_j}{FailedTest\,Value_i} \right) - 1 \qquad (3b)$$

ii) The collective amount by which individual tests are out of compliance is calculated by summing the excursions of individual tests from their guidelines and dividing by the total number of tests (both those meeting guidelines and those not meeting guidelines). This variable, referred to as the normalized sum of excursions, or *nse*, is calculated as:

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

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

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

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

The Sediment Quality Index (SQI):

Method 1 – SQI for area

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

Equation (6) is used for calculating the area SQI for a number of sites. The divisor 1.732 normalises the resultant values to a range between 0 and 100, where 0 represents the "worst" sediment quality and 100 represents the "best" sediment quality. The normalization (1.732) is calculated by following method:

$$\sqrt{\frac{100^2 + 100^2 + 100^2}{100}} = 1.732$$

Method 2 – SQI for a particular site

$$SQI = 100 - \left(\frac{\sqrt{F_1^2 + F_3^2}}{1.414} \right) \quad (7)$$

Equation (7) is used for calculating the SQI for one particular site. The divisor 1.414 normalises the resultant values to a range between 0 and 100, where 0 represents the "worst" sediment quality and 100 represents the "best" sediment quality. The normalization (1.414) is calculated by following method:

$$\sqrt{\frac{100^2 + 100^2}{100}} = 1.414$$

EXAMPLE CALCULATION

Calculation of the index by hand for a large amount of data is not recommended. An Excel macro has been developed for that purpose. To better understand how the index works, however, it is is useful to work through the following example which uses a simplified data set from the Lake Erie and the Canadian interim sediment quality guidelines.

Nine variables will be considered in the index calculation (arsenic, cadmium, chromium, copper, zinc, mercury, ppDDT, ppDDE and ppDDD).

Lake Erie

STATION	As µg/kg	Cd µg/kg	Cr µg/kg	Cu µg/kg	Zn µg/kg	Hg µg/kg	ppDDT µg/kg	ppDDE µg/kg	ppDDD µg/kg
1	0.0	900	21700	16200	121200	62	1.63	4.21	0.59
2	5700	1000	35900	40400	168900	126			
3	0.0	0.0	26000	24700	109500	72	2.26	4.15	0.88
4	700	1200	43100	37700	198400	136	3.02	4.74	6.37
5	9700	800	38000	46400	164500	114	**4.95**	5.63	2.48
6	2400	0.0	32000	32600	130900	72	1.24	2.64	0.30
7	14400	0.0	34000	33300	137300	86	1.63	2.88	0.78
8	0.0	800	22400	26200	76100	16	0.56	0.00	0.22
9	0.0	1100	25900	32600	112200	84	6.23	2.07	4.02
10							2.10	0.91	0.64
11	15200	1000	29600	35600	155700	130			
12	1700	0.0	14000	17000	48900	16	1.12	0.00	0.26
PELs:	*17000*	*3500*	*90000*	*197000*	*315000*	*486*	*4.77*	*6.75*	*8.51*

[1] Bolded values do not meet the guideline.

The number of variables that exceed their respective guideline is 1 (ppDDT). The total number of variables is 10. Therefore:

$$F_1 = \left(\frac{1}{10}\right)\times 100 = \mathbf{10}$$

The number of tests that exceed their respective guideline is 1, and the total number of tests is 106. In this case:

$$F_2 = \left(\frac{1}{106}\right)\times 100 = \mathbf{0.9}$$

The excursions, their normalized sum, and F_3 are calculated as follows:

$$excursion = \left(\frac{4.95}{4.77}\right) - 1 = 0.04$$

$$nse = \frac{(0.04)}{103} = 0.0039$$

$$F_3 = \left(\frac{0.0039}{0.01(0.0039) + 0.01}\right) = \mathbf{0.39}$$

With the three factors now obtained, the index value can be calculated:

$$SQIa = 100 - \left(\frac{\sqrt{10^{2} + 0.9^{2} + 0.39^{2}}}{1.732} \right) = \mathbf{94}$$

The SQI for the specific site 5 is calculated using the F_1 & F_3 terms only. In this case:

$$SQIs(5) = 100 - \left(\frac{\sqrt{10^{2} + 0.39^{2}}}{1.414} \right) = \mathbf{93}$$

Sediment quality at Station 5 is comparable to the Lake Erie as a whole.

For presentation purposes, it is important that a narrative statement explaining the result accompany the calculated SQI value. In this example, the statement might read, "The SQI score of 93 out of 100 indicates that sediment quality in Lake Erie can be considered suitable for the protection of aquatic life. Measured ppDDT exceeded the guideline on one occasion; however, these excursions were fairly small.

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