Environmental Indicators: Their Development and Application

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ABSTRACT

The need to develop simple and meaningful indicators to measure the temporal and spatial changes in environmental quality can not be overstated. An indicator may be viewed as a univariate approximation to measurements made on standard set of variables that adequately reflect the quality of a well defined environment during a specified time period. Examples of indicators are: a) fecal coliform and/or ecoli are frequently used as indicators of microbiological water quality for human use; and b) particle size PM10 and PM2.5 are used as indicators of air quality. An indictor must be reliable and have clear interpretation in representing environmental conditions. Statistical methods will play an essential role in integrating inputs from relevant scientific and societal spheres in the development of indictors. In this paper, we will discuss the statistical aspects involved using several Canadian case studies on water and air quality.

Keywords: Water Quality objectives, Trend, Bootstrapping, Ranks, Normal Scores

1. Introduction

Indices have a long history particularly in economics, health and social sciences. They are used to measure spatial and temporal changes so that intended information is conveyed to the stakeholders in concise few figures. In most situations, the index is a univariate summary of a complex high dimensional data set which is to be collected over a standard time period and within a specified region. The index can be used to compare

the status among various ecosystems and monitor the evolution of time trend within a specified ecosystem. An ecosystem is a multi-component unit which is hard to define (Fairweather, 1999). It is necessary to identify the component of concern when developing an index. There are three identified stages associated with any index: development; field monitoring and actions. These stages will be discussed in this paper and illustrated by examples. The main discussion will be centered on the Canadian Council of Ministers of the Environment (CCME, 2001) Water Quality Index. This is because it highlights the difficulties involved in developing environmental indices and in making the necessary field measurements which are needed to compute the index score. The emphases will be placed on the contribution of statistical sciences to the process.
Section2 outlines some important characteristics that need to be satisfied in an index, Section 3 describes the CWQI, Section 4 outlines few shortcomings of the index and Section 5 proposes a confidence limits for CWQI.

2. Development of an Index

The development of a meaningful index requires the clear determination of its objectives, the variables to be measured, the manner by which these variables are to be included in the index, the intended range of its use, the cost of its implementation and the speed by which actions can be triggered. Clearly an index designed to protect human health from exposure to waterborne illness will be stricter than the ones designed for agricultural or industrial uses. Even for domestic use the index will differ depending on whether the water will be used for drinking or recreational activities. The selection of the variables to be measured depends on the effect to be avoided. Jolliffe (2002) gives several statistical procedures that will aid in variable selection which could be combined with available prior knowledge about background information. For example, the effect of exposure to pathogenic organisms and or persistent toxic substances (PTS) can be acute or chronic and it is therefore important to know which variables are associated with which effects when selecting a suitable parcel of variables to be include in the formation of the index. Since it is impossible to measure the millions of harmful organisms and or harmful chemicals, the approach commonly used is to measure only a set of representative substances and integrate these measurements into a single number or an index. For example, E. Coli and Enterococci are used as a univariate or bivariate indicators (indices) of the quality of drinking and or recreational waters for domestic use. The protection limits change depending on the intended use. Table 1 gives the limits used by USA EPA for recreational waters. Note that marine water use only Enterococci as water quality index while for fresh water the concentrations of two organisms are used.

The selection of the variables to be measured must satisfy the following requirements:

1. Relevance: the variables indicate the presence of the target pollutants.
2. Responsive: as levels of the variables change so is the quality of receiving water changes. This means that a monotonic relationship exists between the measured variables and the quality of water.
3. Rapid outcome: the results can be easily made available quickly so actions can be made to minimize or avoid the harmful impact of exposure to contaminated water.
4. Cost: to maximize the information gained from the measurements for a fixed budget.

Table 1 The 1986 EPA criteria for recreational waters

Water type	Indicator	Geometric mean	Single sample maximum
Marine	*Enterococci*	35	104
Fresh	*Enterococci*	33	61
	E. coli	126	235

It is clear that two objective rules (known as Maximum Contaminant Levels MCLs) associated with the US regulations: the average rule (geometric mean) and the single sample rule. This highlight the importance of the setting of the action limits associated with water use. In the case of microbial quality of water, El-Shaarawi and Marsalek (1999) discussed various sources of uncertainties associated with the application of guidelines and the setting of criteria in water quality monitoring. Carbonez et al. (1999) assessed the performance of the two rules of MCLs stated in Table 1 above and concluded that it is sufficient to use only the first rule that requires the placing of an upper limit on the mean coliform count.

3. Canadian Water Quality Index (CWQI)

This index is a work in progress. The CWQI is the result of a joint effort of the federal and provincial Canadian governments. Two types of data are required to calculate CWQI. First, measurements on several water quality variables made over the period and region of interest. Second, numerical values representing water quality objectives associated with each water quality variable. Three measures of violations are computed based on comparing the data to their corresponding objectives and the three measures are then combined to calculate the value of the index. The ideal data can be represented as a matrix X with p columns and n rows (cases) with the entry in i^{th} row and j^{th} column x_{ij} representing the measurement on j^{th} water quality variable (j =1, 2, …, p) for i^{th} case (i =1, 2, …, n). There is one or more water quality limits (objectives) u_j associated with the j^{th} variable (column). Violation of the objective occurs when the variable does not meet its own specified limits. It is more common to have the objective stated as a single limit representing an upper or lower concentration limit for the water quality variable. Example of an upper limit objective is bacterial level (E coli in drinking or recreational waters) and for lower limit is dissolved oxygen concentration in the water. In other cases an allowable range is used as in the case of pH or when dealing with water level in the cases of draughts and floods. The index is defined as

$$WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}$$

Where:

$$F_1 = \frac{Number\ of\ \ failed\ variables}{Total\ number\ of\ variables} \times 100$$

$$F_2 = \frac{Number\ of\ \ failed\ tests}{Total\ number\ of\ tests} \times 100$$

$$F_3 = \frac{nse}{nse + 1} \times 100$$

and

$$nse = \frac{\sum_{i=1}^{n} \frac{Failed\ Test_i}{Objective_i} - n}{\#of\ Tests}.$$

In the above formula, the water quality index is calculated using the following three factors:

1. F1 is the Scope, it is the percentage of variables that do not meet their objectives (limits) at least once during the time period under consideration.
2. F2 is the Frequency, it is the percentage of individual tests that do not meet objectives;
3. F3 is the Amplitude, measures the amount by which failed.

4. Some Shortcomings with WQI Formulations

There are a number of objections to the index formulation:

1. It concentrates on the violations of the criteria and thus ignores the data below the threshold. The ignored data contain information about trends and not including such information in the index makes the index to have low trend detection power. It is possible that the values are in compliance with the objectives but they are progressing toward non-compliance and such an index should reflect this trend tendency.
2. It is not easy to assess the statistical uncertainty in the index since the three factors F_1, F_2 and F_3 are not independent and indeed they are positively dependent.
3. The distribution of non-compliance values among the variables will have a major impact on the value of F_1. This can be seen when the number of non-compliance values are equal to the number of variables p. In this case the possible values of F_1 will range between 100/p and 100 depending on the distribution of the non-compliance values among the variables with the minimum value of F_1 occurring

4. The index does not allow for weights to reflect the importance of the variables. Clearly different pollutants should not be symmetrically treated.
5. The division by the observed value when computing nse when non-compliance occurs in the case of values occur below a lower limit is inappropriate for it makes F_3 unstable.
6. The Index as a statistics does not have a measure of uncertainty.

5. Confidence Interval for CWQI

To develop an uncertainty measure and confidence bounds for the index, it is important to realize that it is impossible to define an analytical expression for the variance of the index and thus the confidence limits for its values. Although there are several possibilities, the easiest approach is to use a computational method. In this case we propose two (re-sampling) bootstraps (Efron, B. and Tibshirani, R.J. (1993)) procedures. The first is variable based procedure works as follows:

1. First Step: For the j^{th} variable (j^{th} column of the data matrix) draw with replacement a bootstrap sample of the same size as the number of observations available for this variable.
2. Second Step: Repeat step 1 for each variable, thus reproduce a bootstrap replica of the original data.
3. Use the bootstrap data generated in step 2 and compute the index.
4. Repeat the above steps B times (B is very large).
5. Select the appropriate two percentiles based on the B samples as the confidence limits for the index. For example to obtain 95% limits, use the 2.5% percentile and 97.5% percentile to correspond to the lower and upper confidence bounds of the confidence limits.

It should be noted that: a) the computation required to obtain the bootstrap distribution could be substantially reduced by restricting the resampling only to the variables that violate their control objectives; and b) the procedure ignores or assumes lack of correlations among the variables.

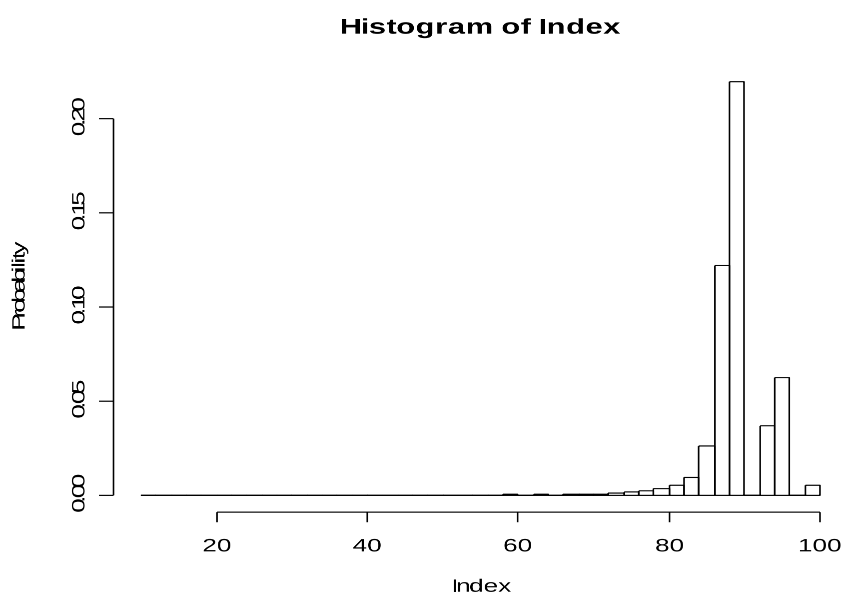
The second method is case bootstrapping and it operates on the rows of the data matrix instead of its columns as the procedure used in the first method. This procedure maintains the correlation among the water quality variables: The procedure works as follows:

1. Step 1: sample the rows; that is obtain a sample of size n from the numbers 1,…., n with replacement. These samples can be denoted as $i_1, \cdots, i_n$
2. For the cases $i_1, \cdots, i_n$ compute the index.
3. Repeat the above steps B times (B is very large).

6. Select the appropriate two percentiles based on the B samples as the confidence limits for the index. For example to obtain 95% limits, use the 2.5% percentile and 97.5% percentile to correspond to the lower and upper confidence bounds of the confidence limits.

6. Examples for the Confidence Interval (based on method 1)

Fig.1 The distribution of the bootstrapping index



Example 1:

The proposed procedure for computing the confidence interval for the Index is demonstrated using the data in Table 1. This data set was used in CCME user manual to demonstrate its calculation. The data set consists of 10 variables (dissolved oxygen, pH, total phosphorous, total nitrogen, fecal coliform bacteria, arsenic, lead, mercury, 2,4-D, and lindane) and was collected in 1997 from North Saskatchewan River at Devon.

Table 1. North Saskatchewan River at Devon 1997 Water Quality Data

Date	DO	pH	Tp	TN	FC	As	Pb	Hg	2,4-D	Lindane
	Mg/L		mg/L	mg/L	#/dL	mg/L	mg/L	g/L	g/L	g/L
7-Jan	11.4	8.0	.006	.160	4	.0002	.0004	L.05	l.005	L.005
4-Feb	11.0	7.9	.005	.170	L4	L.0002	.0094	L.05		
4-Mar	11.5	7.9	.006	.132	4	L.0002	L.0003	L.05		
8-Apr	12.5	7.9	.058.	.428	L4	L.0002	.0008	L.05	.004	L.005
6-May	10.4	8.1	.042	.250	L4	.0002	.0008	L.05		
3-Jun	8.9	8.2	.108	.707	26	.0006	.0013	L.05		
8-Jul	8.5	8.3	.017	.153	9	.0002	.0004			
5-Aug	7.5	8.2	.008	.153	8	L.0002	L.0003	L.05	L.005	L.005
2-Sep	9.2	8.2	.006	.130	12	.0003	.0018	L.05		
7-Oct	11.0	8.1	.008	.093	12	L.0002	.0011	L.05	L.004	L.005
4-Nov	12.1	8.0	.006	.296	8	L.0002	.0051	L.05		
1-Dec	13.3	8.0	.004	.054	4	L.0002	L.0003	L.05		
Objective	5.0	6.5-9.0	0.05	1	400	.05	.004	0.1	4	.01

For the data set above the computed value of WQI is 88. To obtain a confidence interval associated with this value, we conduct 10000 bootstrap samples from the observed data by sampling the values of each variable separately. The bootstrap median is found to be 88.22 which is slightly above the value of the observed index value. This is a consequence of left skewed bootstrap distribution as indicated in the figure above. Two confidence intervals are given as follows: the 95% CI is (79.584 – 94.1999) and 90% CI is (83.593 – 94.1999).

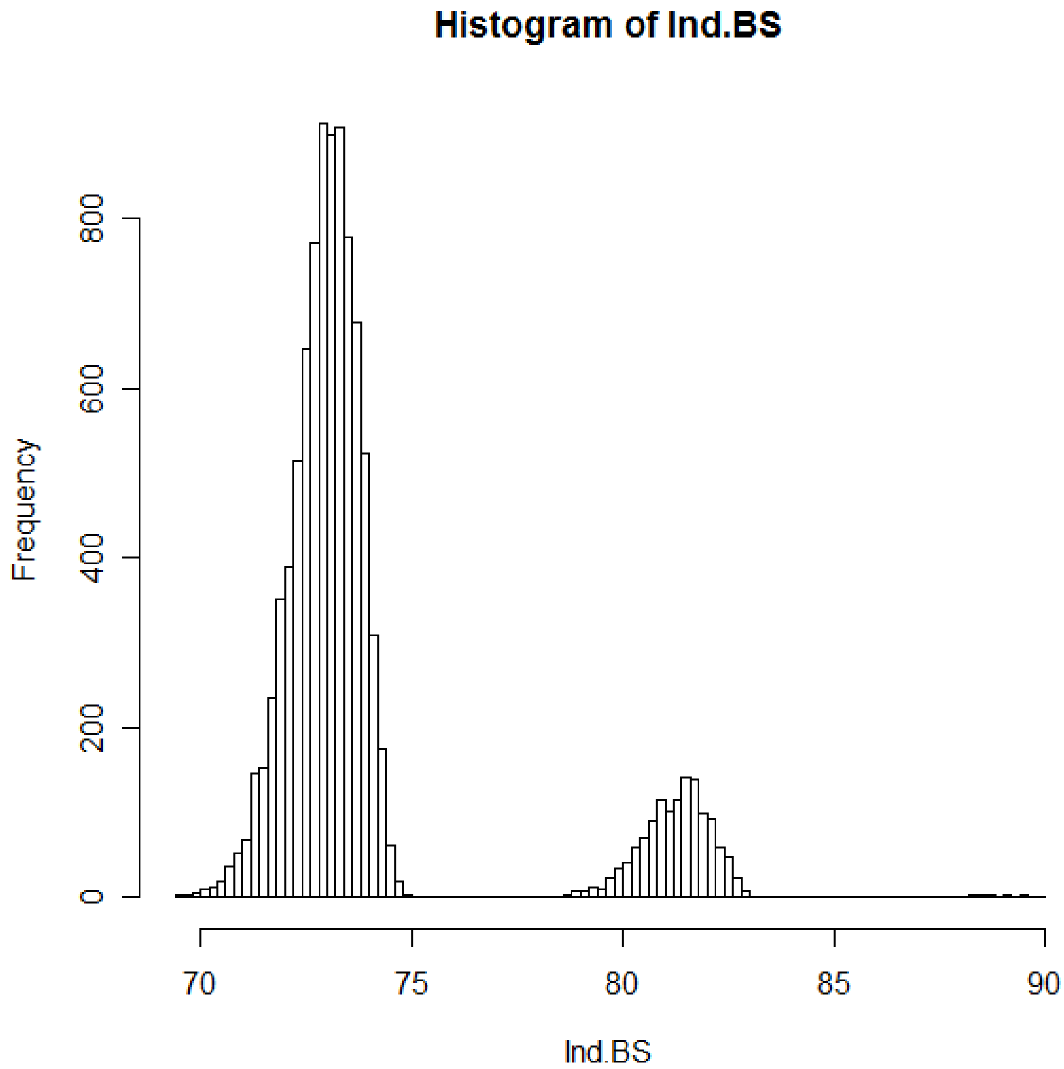
Example 2.

Comparison of the changes at stations 1006000102 for the years 2007 and 2008. Note that the tables below give the 90% and 95% confidence limits based CWQI (Method 1) and for two other proposed procedures (Method 2 and Method 3) for computing the index. The other two procedures are not described in this report.

The output for 2007

Station Number 1006000102

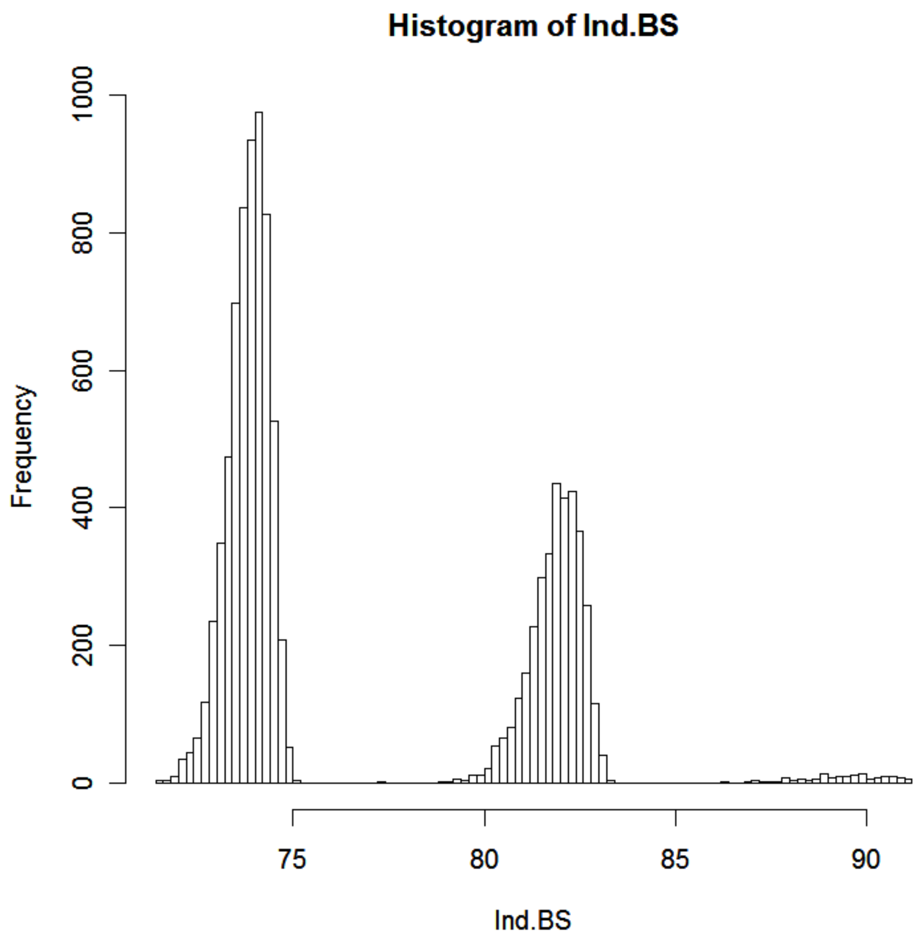
Data		Method 1	Method 2	Method 3
Station Number 1006000102	estimate	73.08	81.32	85.70
	90% CI	(71.59,81.58)	(77.63, 85.69)	(83.17,89.51)
	95%CI	(71.28,82.00)	(76.93,86.53)	(82.73,90.26)



The output for 2008

Station number 1006000102

Data		Method 1	Method 2	Method 3
Station number 1006000102	estimate	73.98	84.11376	87.80508
	90% CI	(72.99, 82.64)	(80.41, 88.19)	(85.25,91.44)
	95%CI	(72.75, 82.87)	(79.67, 88.85)	(84.73,91.67)



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