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DEVELOPING A STANDARDIZED WATER QUALITY INDEX FOR EVALUATING SURFACE WATER QUALITY[1]

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ABSTRACT: There is a significant need for a science-based approach to interpret water-monitoring data and to facilitate the rapid transfer of information to water resource managers and the general public. The water quality Index (WQI) is defined as a single numeric score that describes the surface water quality condition at a particular time and location. The objective of this paper is to describe the WQI concept and the approach for developing an ecoregion-specific standardized WQI that meets the needs described above. The premise of the proposed WQI is based on categorizing scientifically documented aquatic life responses to changes in instream water chemistry. The method uses an aggregated procedure that matches the entire range of standardized probable biological responses to standardized narrative water quality evaluation categories and standardized rank score categories. The calculation of WQI and decision-making process are performed within an Excel spreadsheet software program. The article includes examples of the proposed WQI applications that could enhance effective water resource management and facilitate timely communication of water quality conditions to water resource managers and the general public.

(KEY TERMS: water quality index; water quality assessment; aquatic life; biological response; ecoregion.)

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INTRODUCTION

The U.S. Congress, under the legal authority of section 305(b) of the Federal Clean Water Act (33 U.S.C. 1251 et seq.), requires state water resource agencies to assess and report on states' water quality. States allocate significant effort and expense to implement water monitoring (sampling) programs and to generate 305(b) reports. However, the usefulness of 305(b) reports is limited for several reasons. For example: (1) it detects water quality criteria (WQC) violations but does not describe water quality conditions, i.e., "how good or how bad"; (2) it does not perform a simultaneous, multi-parameter, composite evaluation and does not provide a single composite station evaluation that can assess temporal and spatial variations in water quality; (3) it does not priority rank all sampling stations according to the level of stream degradation; (4) the process is lengthy, complex, and labor intensive; (5) the reports do not provide a logical, concise, and composite summary of meaningful information that can be used by the water resource professionals for water quality

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management purposes; and (6) the 305(b) process and reports are not easily understood by the general public. Citizens not only want to just see the water quality data or a summary of the data, but more importantly, "they want to know what the data means" (Ward, 2002).

The water quality index (WQI) is a single numeric score that describes the water quality condition at a particular time and location. There has been interest in developing a WQI since 1970s when the National Sanitation Foundation (NSF) developed a WQI that shows the tendency for occurrence of eutrophication in streams and lakes (National Sanitation Foundation (NSF) (1970). The nine parameter [temperature, dissolved oxygen (DO), 5-day biochemical oxygen demand (BOD), pH, nitrate-nitrogen, total phosphorus (TP), total solids, fecal coliform, and turbidity] index was based on professional judgment of scientists who ranked the water quality from 0 (worst) to 100 (best). Several states have also developed a WQI for various purposes. The Oregon WQI originally developed in 1979 and modified later was designed to aid in the assessment of water quality for general recreational uses, including fishing and swimming (Dunnette, 1979, 1980; Cude, 2001, 2002). The Oregon WQI integrates 10 parameters (temperature, DO concentration, percent DO saturation, BOD, pH, ammonia, nitrate-nitrogen, TP, total solids, and fecal coliform) into a single numeric score that range from 10 (worst case) to 100 (ideal). The State of Washington has developed an index based on eight parameters [temperature, pH, fecal coliforms, DO, turbidity, total nitrogen (TN), TP, and total suspended solids]. The index expresses water quality relative to levels required to maintain designated uses based on criteria specified in Washington's water quality standards (Hallock, 2002). In the Washington index, multiple constituents are combined and results are aggregated over time to produce a single score. The State of Maryland has developed a WQI for Maryland's coastal bays (Carruthers and Wazniak, 2004). It synthesizes the status of four water quality indicators (chlorophyll *a*, TN, TP, and DO) into a single indicator of water quality. In the Maryland Index, 3-year median values of four variables are compared with criteria based on ecosystem function such as maintaining fisheries (DO threshold) and maintaining submerged aquatic vegetation (chlorophyll *a*, TN, and TP thresholds). Canada and some European countries have also introduced some type of WQI (e.g., CCME, 2004).

Smith *et al.* (2002) provided a critique of the Oregon WQI, which is also applicable to many other water quality indices. Most of the developed indices use arbitrary (subjective) unit-less scales from 1 to 100 or 1 to 10 that produces composite index scores without uniformity of scale. The rating curves (graphs) that show the relationship between constituent concentrations and parameter evaluations are often based on statistical data distributions and/or best professional judgment, which is also subjective. Most importantly, developed indices are not always based on biological responses to stream water chemistry.

There is a need for an approach to accurately evaluate water quality data in a way that is both a scientifically valid process and a product that is useful to water resource managers and easily understood by the public. The ideal procedure should evaluate the direct effect of different water quality parameters on aquatic life, clearly describe "how good or how bad" stream conditions are, and generate an accurate and holistic evaluation of temporal and spatial stream water quality conditions.

To meet the needs noted above, the major objective of this paper is to describe the concept and process for developing a standardized WQI that uses the biological response approach as the common scale for evaluating stream water quality. It is a method that can accurately evaluate and summarize water quality data in a way that is scientifically valid and easily understood by professionals and the public. The article also illustrates possible applications of the proposed WQI to water quality management issues.

APPROACH

The basic premise of the proposed standardized WQI is that although measured concentrations (data) of different water quality constituents (parameters) are not directly comparable with each other, the scientifically recorded biological responses to the measured constituent concentrations (data) are directly comparable with each other. The proposed WQI provides a scientifically credible means to determine the cause/effect relationships between water quality parameter concentrations and biological response. It also assigns numerical and narrative values to those relationships and thus indicates the water quality and health condition of streams. The proposed WQI uses an aggregated approach that performs diagnostic and integrated assessment and ranking of water quality condition based on biological response. Complete discussion of the concept of biological response to water quality changes and potential applications of the concept to water quality management can be found in published literature (e.g., Simon, 2003). The concept and rationale for the proposed WQI are described below.

Method

The procedure discussed in this article is ecoregion specific and can be applied to any sampling station only if scientifically documented relationships between probable biological response (PBR) of aquatic organisms and water quality parameter concentrations for that ecoregion are available. Ecoregions are a classification scheme (areas) based on similarities of natural geographic features (e.g., geology, soils, climate, hydrology, vegetation, and wildlife) and land use patterns. The USEPA has divided the continental US into 52 level II ecoregions. Level III ecoregions are smaller ecological areas nested within level II regions that allow specifically oriented management strategies to be formulated for decision-making purposes. For example, the Commonwealth of Virginia is situated within three USEPA level III ecoregions (Southeastern Temperate Forested Plains and Hills, Central and Eastern Forested Uplands, and Eastern Coastal Plain). Each ecoregion is then divided into several sub-ecoregions. The southwestern Virginia ecoregion (Central and Eastern Forested Uplands), where the proposed WQI is tested is divided into three sub-ecoregions (Blue Ridge, Ridge and Valley, and Central Appalachians). Each sub-ecoregion is characterized by unique water chemistry and therefore colonized by different assemblages of aquatic organisms within its boundary. To develop WQI, it is necessary to select an ecoregion-specific organism that is common throughout that area and to collect scientifically credible data on biological responses of those organisms to specific-chemical parameter concentrations. It should be noted that the selection of the appropriate ecoregion-specific biological indicator organism is not driven by officially adopted state or federal WQC but rather by the widespread presence and thorough distribution of the aquatic species within the ecoregion.

In southwestern Virginia ecoregion, the authors selected relatively sensitive game fish species such as smallmouth bass for the Ridge and Valley and Central Appalachians sub-ecoregions and native brook trout for the Blue Ridge sub-ecoregion. Several years of ambient water quality data, fish kill data, fish hatchery data, and fish productivity in exceptionally good waters were available for these sub-ecoregions.

It is recognized that a given chemical concentration for a specific-chemical parameter can have differing biological effects on the same indicator organism depending on its life stage, presence (rearing *vs.* migrating *vs.* spawning) and seasonality. For this reason, it is desirable that databases include observations of biological response to parameter concentrations during different development stages of the indicator organism.

Once the ecoregion-specific indicator organism has been selected, it is necessary to select water quality parameters to be evaluated. The choice of physical and chemical parameters to incorporate into the standardized WQI is not arbitrary. Parameter selection should be based on numerous factors including, but not limited to, sensitivity of aquatic organism to the parameter, existence or absence of WQC for the parameter, and cost of data collection and analysis. It is important to recognize that water quality is a function of biological responses of aquatic organisms to specific concentrations of chemical and physical constituents. Each constituent parameter exerts its own effect on aquatic organisms and must be measured and evaluated on its own. The overall water quality is the aggregated evaluation of the combined effect that all of the constituents together exert on the system.

For the southwestern Virginia example illustrated in this article, the authors have chosen five field parameters: water temperature, DO concentration, percent DO saturation, pH, and conductivity to demonstrate the development and use of the standardized WQI. These parameters were selected because: (1) they are always measured at every monitoring location, (2) there are more data for these parameters than for any other parameters, and (3) for these parameters, there exist more data on simultaneously recorded observations of biological responses than any other.

Dissolved oxygen is one of the critical parameters for aquatic life support and a most often measured parameter. The authors selected DO concentration and percent DO saturation to be incorporated into WQI as two-independent parameters. DO concentration represents the amount of oxygen that is available to aquatic organisms for metabolism/respiration and assimilation of food. Percent DO saturation compares the measured concentration of DO to the amount of DO that unpolluted water is capable of holding at specific temperatures and elevations. Percent DO saturation values below 70% indicating significant oxygen demand and degraded conditions. When percent DO saturation values exceed 120%, supersaturation exists. Supersaturation of DO can result from natural causes such as turbulence within the stream and cold temperatures. Values greater than 120%, especially with high summer temperatures, however, indicate prolific photosynthesis (generation of oxygen) by excessive alga and is indicative of nutrient enrichment and degraded water quality. Therefore, measurements of excessively high percent DO saturation are not necessarily indicators of exceptionally good water quality.

After the indicator organism and constituent parameters have been selected, the next step is to compile a database of documented ranges of parameter concentrations and matching indicator organism biological responses. Biological responses of aquatic organisms to water quality parameters can range from death to prolific life, growth, and reproduction. Sufficient data for the biological response to each parameter are needed to achieve statistical confidence. For instance, it is desirable to compile enough pH data to be able to state that death occurs in native brook trout in the Blue Ridge ecoregion at a pH of 4.5 standard units (s.u.) with a 95% statistical confidence.

In order to standardize the WQI, the biological responses are categorized (or subdivided) into seven standardized PBRs as illustrated on the left side of Table 1. It is assumed that chronic exposure of an aquatic organism to specific concentrations of a parameter will always cause the organism to respond within the selected PBR categories. The seven PBR categories are then matched to seven standardized narrative water evaluation categories (right side of Table 1) from lethal to exceptional. Each narrative category is assigned a numerical rank score from 1 (lethal) to 7 (exceptional). Table 1 illustrates that rank scores of 1-2 indicate critical stream condition, rank score 3-4 stressed stream condition, and rank scores 5-7 healthy stream condition. It should be noted that to develop a standardized WQI, the seven standardized PBRs categories always remain the same (never change) regardless of geographic position of the water body and regardless of the type of water body being evaluated.

In the next step, a parameter response graph (PRG) is plotted. The graph is arranged such that the parameter concentration is along the abscissa and the PBRs are along the ordinate as shown in the top portion of Table 2. On the right side of the PRG are the seven levels of numeric rank scores and seven levels of narrative water quality evaluations that match the seven PBR categories on the left side of the graph. A PRG includes at least three reference points. One of the three reference points occurs at the threshold point where higher (or lower) param-

TABLE 1. The Relationship Among Probable Biological Responses, Water Quality Evaluations, Rank Scores, and Parameter Concentrations.

			Chronic Exposure of Any WQ Parameter Concentration	**← "Any" WQ Data That Invokes (X) PBR Will Automatically Be Assigned (Y) WQ Evaluation**		
				WQ "Interpretation"		
PBR				**WQ**		**Overall Stream**
Life	**Growth**	**Reproduction**	**↓**	**Evaluation**	**Rank Score**	**Condition**
Exceptional	Exceptional	Exceptional	$\mathbf{X_7} \leftarrow \rightarrow \mathbf{Y_7}$	Exceptional	7	
Improved	Improved	Improved	$\mathbf{X_6} \leftarrow \rightarrow \mathbf{Y_6}$	Excellent	6	Healthy
Normal	Average	Average	$\mathbf{X_5} \leftarrow \rightarrow \mathbf{Y_5}$	Good	5	
Fair	Stunted	Reduced	$\mathbf{X_4} \leftarrow \rightarrow \mathbf{Y_4}$	Fair	4	Stressed
Stressed	Minimal	None	$\mathbf{X_3} \leftarrow \rightarrow \mathbf{Y_3}$	Poor	3	
Injured	None	None	$\mathbf{X_2} \leftarrow \rightarrow \mathbf{Y_2}$	Critical	2	Critical
None (Death)	None	None	$\mathbf{X_1} \leftarrow \rightarrow \mathbf{Y_1}$	Lethal	1	

Note: PBR = Probable Biological Response, WQ = Water Quality.

TABLE 2. Constructing Parameter Response Graph for Dissolved Oxygen.

	Parameter Response Graph (DO)														**Interpretation**	
PBR	**Graph of PBR *vs.* Parameter Concentration DO (mg/l)**														**WQ Evaluation**	**WQ Rank Score**
Exceptional											**X**	X	X	X	Exceptional	7
Improved										X	|				Excellent	6
Normal									**X**		|				Good	5
Fair								X		|	|				Fair	4
Stressed							X			|	|				Poor	3
Injured						X	|			|	|				Critical	2
Death	X	X	X	X	**X**		V			V	V				Lethal	1
	0	1	2	3	4	5	6	7	8	9	10	11	12	13		
	DO Concentration (mg/l)															

Note: PBR = Probable Biological Response, WQ = Water Quality, DO = Dissolved Oxygen.

TABLE 3. Parameter Response Graph for pH.

PBR*	Parameter Response Graph (pH) – Graph of PBR *vs.* Parameter Concentration pH (units)														Interpretation – WQ Evaluation	WQ Rank Score
Exceptional							**X**	**X**							Exceptional	7
Improved															Excellent	6
Normal						**X**			**X**						Good	5
Fair						|			|						Fair	4
Stressed						|			|						Poor	3
Injured						|			|						Critical	2
Death	x	x	x	**X**	x	V	x		V	x	**X**	x	X	x	Lethal	1
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
	Parameter Concentration, pH (units)															

Note: PBR = Probable Biological Response, WQ = Water Quality.

eter concentrations begin to demonstrate adverse effects on the aquatic life, growth, and/or where reproduction and lower (or higher) concentrations have no adverse effect. This threshold concentration is plotted as a normal biological response on the PRG. The threshold concentration for a given parameter just above (or below) where adverse effects begin is where WQC should be set for that parameter.

The second reference point is plotted at that concentration at which death occurs. The third reference point is plotted at the concentration at which growth and reproduction is maximized. Once the three reference points are plotted, a straight line is drawn to connect the three points to complete the PRG. The objective is to plot the three reference point parameter concentrations for each PRG against PBR with 95% confidence. PRGs must be developed for every parameter for which scientifically credible biological response data are available. In this article, for the sake of brevity, PRGs for only DO and pH are demonstrated. The bold X's in Tables 2 and 3 show the reference points for DO and pH, respectively. Example in Table 1 illustrates the response of wild brook trout, an indicator organism in the Blue Ridge Mountain ecoregion of Virginia, to changes in stream water quality. It is essential that each PRG include the entire range of parameter concentrations that span the entire range of PBRs.

Next, parameter evaluation tables (PETs) are constructed. PETs are developed (using PRGs) for every parameter that is to be evaluated in the standardized WQI. Within the PETs, all parameter concentration data are normalized to the same identical (standardized) biological response categories and same identical (standardized) parameter evaluation/rank score categories. Table 4 shows a composite PET for water quality parameters typically measured *in situ* when ambient water samples are collected. In this example, the PETs for DO and pH are developed using their respective PRGs and extrapolating the range of parameter concentrations that invoke corresponding PBR in the lower portions of Table 2 and 3. For instance, a stressed biological response (wild brook trout as indicator) occurs when the DO concentration is between 5.5 and 6.5 mg/l. In this case, water quality, as measured by DO, is evaluated as poor. On the other hand, for the same indicator, an exceptional biological response occurs when the pH is between 7.0 and 7.99 and the water quality, as measured by pH, is evaluated as exceptional. As PETs are derived directly from PRGs, they have the same statistical confidence as the PRG from which they are derived.

TABLE 4. "Composite" Parameter Evaluation Table for All Field Parameters.

Parameter Evaluation – Evaluation	Rank Score*	Instream Concentrations (Field Parameters) – Temp (°C)	DO (mg/l)	pH (Units)		Conductivity (umho/cm^2)	DO Saturation (%)	
Exceptional	7	<20.00	>9.50	7.00-7.99		<100	95-104.99	
Excellent	6	20.00-24.99	8.50-9.50	6.35-6.99	8.00-8.64	100-174.99	90-94.99	105-109.99
Good	5	25.00-27.49	7.50-8.49	6.00-6.34	8.65-8.99	175-249.99	80-89.99	110-119.99
Fair	4	27.50-29.99	6.50-7.49	5.35-5.99	9.00-9.64	250-499.99	70-79.99	120-129.99
Poor	3	30.00-32.49	5.50-6.49	4.65-5.34	9.65-9.99	500-999.99	60-69.99	130-139.99
Critical	2	32.50-35.00	4.50-5.49	4.50-4.64	10.00-10.50	1,000-3,000	50-59.99	140-150.00
Lethal	1	>35	<4.50	<4.50	>10.50	>3,000	<50	>150

Note: *Rank scores represent standardized evaluations of normalized data based on PBRs.
DO = Dissolved Oxygen.

The accuracy of the PRGs, PETs, parameter rank scores, sample rank scores, parameter index scores, and overall WQI scores and evaluations are only as statistically accurate and reliable as the underlying database that generates them. If there are insufficient records of baseline parameter concentrations and biological response data, preliminary PRGs and PETs can be developed from the existing dataset, statistical data distributions, and best professional judgment. However, this approach must be considered very subjective. One of the primary objectives of the standardized WQI is to remove as much subjectivity and variability from the process as possible. Preliminary PRGs and PETs should be replaced as soon as a complete and statistically valid database becomes available. It is recognized that it may require years of sample (data) collection to assemble a database capable of being statistically valid with 95% confidence.

Upon careful examination of Table 4, it becomes obvious that rank scores and their respective evaluations represent standardized evaluations of normalized data. The water quality evaluation of each data point, as measured by each chemical parameter's rank score, is automatically determined by each respective PET. PETs provide the basis to accurately assess with statistical confidence the water quality influence of every parameter data point has on the overall WQI score and evaluation.

Next, it is necessary to develop and support a computer program that facilitates the following functions: (1) receiving raw parameter data from field or laboratory measurements, (2) comparing each parameter data point with its respective PET, (3) generating the rank score for each parameter's data point that represents its water quality evaluation, (4) combining all of the individual parameter rank scores for all the parameters measured within the stream sample and generating a fully integrated sample rank score that accurately represents the sample as a whole, (5) calculating parameter index scores that clearly evaluate and rank each parameter measured according to its overall impact on the combined water quality at the stream station, (6) aggregating all sample rank scores of all the samples within the evaluation period and calculating a single WQI score and evaluation for that sampling station, and (7) generating a well organized and easy to understand WQI printout form for every stream station being evaluated.

Table 5 is an Excel spreadsheet that accomplishes the listed requirements and calculation steps outlined above. It illustrates a functional example of a real ambient water quality monitoring (AWQM) station "Laurel Fork at Pocahontas" located in Ridge and Valley sub-ecoregion, southwest Virginia. Smallmouth bass is the specific-indicator organism used for developing the WQI for this sub-ecoregion. The database contains six sampling dates during the 1-year evaluation period. In the computer program, look-up tables are used to assign rank scores (specific value) based on parameter concentrations (input data). Look-up formulas compare individual sample rank scores to the rank score evaluation and render appropriate evaluation for each individual sample rank score. Look-up tables also contain a narrative diagnostic term (word) component that accurately describes the meaning of the rank score. The WQI station single score is the composite average of the minimum parameter rank scores (limiting factor and worse case) of each sample. The WQI for Laurel Fork at Pocahontas was calculated to be 3.33 (cell R20) indicating poor water quality condition.

The WQI and sample rank scores are always based on the minimum rank score among the parameter rank scores in that sample. The minimum rank score for a sample represents the parameter that causes the greatest harm (limiting factor) to aquatic life for that sample date. In the above example (Table 5), the sample rank score for December 18 (cell R9) is 1, and the water quality for that date is rated as "lethal" because the DO is only at 49% saturation. The percent DO saturation for this sample date represents the limiting factor (worst condition). If 49% DO saturation causes a fish kill, then it does not matter if the average condition in which the aquatic life is exposed to be rated "Good" (cell Q9).

Discussion

Annual average WQI scores are recommended because the overall health condition of stream needs to be examined on some set frequency. Year-to-year review seems to be practical and appropriate. Water resource managers should carefully examine those streams that show dramatic changes in WQI scores from year-to-year or continuous degradation in overall health over time. Changes in WQI scores from year-to-year reflect changes in the stream overall health condition. They do not reflect the specific changes and trends of each specific-chemical or -physical parameter that makes up the overall WQI score.

Parameter index scores (cells K20-O20) in Table 5 provide a ranking of water quality, parameter-by-parameter. Parameter index scores not only indicate what parameter(s) is causing the stream degradation, but also provide clues of what/where the pollution sources are. Parameter index scores are determined by simply averaging the lowest half (worst conditions) of the rank scores within each parameter column over the evaluation period. The parameter with the lowest index score is the parameter of greatest concern. Parameters with high index scores (> = 5.0)

TABLE 5. Water Quality Index (WQI) Station Evaluation Spreadsheet (Excel Program)-Station: Laurel Fork at Pocahontas, Ridge and Valley Sub-Ecoregion, Southwest, Virginia.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	**WQI-Station Evaluation Spreadsheet**				**Field Parameters**						**Parameter Rank Scores**					**WQI-Evaluation**			
2	**Station & Sample Information**				**(Input Data)**						**(Look-Up Formulas)**					**"Example" Only**		**Sample WQI**	
3	Date	Time	Station ID	Description	Temp	DO	pH	Cond	Theo-Sat	% DO Sat	Temp	DO	pH	Cond	%DO Sat	Avg	Eval.	Sc	Evaluation
4	Feb 10	10:05	9-LRR002.19	Laurel Fk at Pocahontas, VA	2.0	7.64	7.15	203	12.76	60	7	5	7	5	2	5.20	Good	2	Critical
5	Apr 5	13:00	9-LRR002.19	Laurel Fk at Pocahontas, VA	8.5	9.11	7.11	99	10.82	84	7	6	7	7	5	6.40	Excellent	5	Good
6	Jun 21	13:15	9-LRR002.19	Laurel Fk at Pocahontas, VA	19.4	8.00	7.09	434	8.50	94	7	5	7	4	6	5.80	Excellent	4	Fair
7	Aug 7	12:40	9-LRR002.19	Laurel Fk at Pocahontas, VA	18.7	8.46	7.60	249	8.62	98	7	5	7	5	7	6.20	Excellent	5	Good
8	Oct 12	12:20	9-LRR002.19	Laurel Fk at Pocahontas, VA	3.0	7.63	7.12	456	12.50	61	7	5	7	4	3	5.20	Good	3	Poor
9	Dec 18	11:30	9-LRR002.19	Laurel Fk at Pocahontas, VA	1.0	6.35	6.69	219	12.92	49	7	4	6	5	1	4.60	Good	1	Lethal
18																			
19	Sample Count				Average Parameter Concentration						Parameter Index Scores							Station WQI	
20	6	*n*			8.77	7.87	7.13	277	11.02	74%	7.00	4.67	6.67	4.33	2.00			3.33	Poor
21																			
22				305(b) Assessment							0	0	0	0	1				
23											0	0	0	0	0				
24											0	0	0	1	0				
25											0	0	0	0	0				
26											0	0	0	1	1				
27											0	1	0	0	1				
28				305(b) Assessment (for parameters with WQC)							Temp	DO	pH	Cond	% DO Sat				
29				Number of samples that violate WQS ——————>>							0	1	0	2	3				
30				Number of samples (*n*) ——————————>>>							6	6	6	6	6				
31				Violation rate (%) ————————————>>>>							0	17	0	33	50				
32				305(b) Impairment (Rate >10% violation threshold) >>>>>							No	Yes	No	N/A	N/A				

Note: WQI = Water Quality Index, DO, Dissolved Oxygen.

represent healthy conditions, while those <5.0 represent degraded conditions. The lower the index score, the more stress the parameter exerts on the aquatic life. In Table 5, the parameter of greatest concern is percent DO saturation (cell O20). Accordingly, the source(s) of pollution in Laurel Fork exert a high oxygen demand as indicated by the lower dissolved saturation index score (2.00).

Rank scores and index cores of 5-7 indicate healthy water quality conditions. A rank score of 7 is assigned to conditions that demonstrate exceptional growth and reproduction. It is recognized that the greatest biological productivity may not necessarily represent pristine water quality conditions and the WQI may be biased toward productivity. For example, mild organic enrichment may result in the availability of more food, which in turn may result in a rapid growth rate. Therefore, a rank score of 7 or index score >6.5 is exceptional, but it is not necessarily pristine (naturally unpolluted). Some pristine streams may be biologically unproductive. Organic enrichment from waste loads is also accompanied by higher demands of DO to assimilate or metabolize the waste. Therefore, when DO in the stream begins to fall below ideal concentrations, the DO parameters will detect it and render lower rank scores for the oxygen components, which in turn can lower the overall WQI score. Additional WQI parameters such as BOD, total organic carbon (TOC), phosphorous, and nitrogen that measures organic nutrient loads can be added to the standardized WQI if sufficient biological response data and WQC are available. Despite the above argument, using PBR to five field water quality parameters, the WQI can be used effectively to show if the surface water meets designated uses for ecosystem services.

In Table 5, the total number of samples included in the evaluation period is located in cell A20. This number is useful in understanding the statistical confidence on the evaluation (the larger the number of samples, the more accurate will be the results of statistical analysis). The total number of samples being evaluated is also important in developing the 305(b) assessment, which is discussed later under applications. Statistical analysis of WQI scores would be meaningless as there is constant variability in the parameter rank scores that make up the WQI. However, statistical analysis of a stream station's parameter rank scores is appropriate to detect seasonal trends, etc. if sufficient data are available.

This paper, for illustration purposes, has only demonstrated the PETs for field parameters. The proposed standardized WQI can be applied to any parameter for which scientifically valid parameter response graphs can be developed. The WQI spreadsheet (Table 5) example demonstrated in this paper could be considered a field parameter sub-index. Other sub-index components could be developed and incorporated into the WQI station evaluation spreadsheet. For example, there could be an organic load sub-index for evaluating constituents like BOD, TOC, total dissolved solids, etc. A nutrient sub-index could include constituents such as total and dissolved phosphorus, the nitrogen parameter series, and chlorophyll-*a*. Additional sub-indices for dissolved metals, sediment metals, organic compounds, and physical habitat and substrate components could be incorporated as well. These sub-indices would be extremely helpful in determining the cause (and possible sources) of water quality degradation. The proposed method allows the addition of new parameters to the WQI station evaluation spreadsheet by simply inserting columns in the data input area of the WQI station evaluation spreadsheet and inserting properly sequenced matching columns and appropriate look-up formulas in the parameter rank score section of the spreadsheet.

It is important to realize that a single WQI score cannot capture the complexity of stream water quality because there are so many different factors in which water quality can vary. WQI scores and evaluations represent the average stream condition over the evaluation (monitoring) period. Although annual average WQI scores (general stream health) may remain identical at a station from year-to-year, the fluctuation of parameter rank scores that make up each year's WQI score are dynamic. It is also important to realize that while an identical annual average WQI score of say 2.37 (the stream's water quality condition is critical) may be reported at two different stations, it does not imply that the two stations are suffering from the same type of pollution. One station may be suffering from oxygen deprivation from organic waste, while the other suffers from acidification from acid mine drainage. It is also important to realize that a stream's degraded condition may be caused by more than one parameter. The parameter index scores identify the relative impact that each parameter has on the overall health of the stream. Parameter index scores make it easy to identify and rank the most troublesome parameters.

Although the overall WQI score indicates the relative health level in a stream and can be used to compare and rank the condition of multiple stream stations, the WQI score should never stand alone for the full interpretation of the nature of the station's water quality. It is imperative for water resource managers to thoroughly scrutinize the parameter rank scores and parameter index scores to determine the nature of each stream's condition and determine the parameters that are causing the greatest stress within the stream. One of the advantages of the standardized WQI is that it not only accurately communicates the relative health (degree of severity) of the stream through its overall WQI score, but just as importantly, it accurately detects and identifies the nature of water quality problems when and where they exist.

APPLICATIONS OF STANDARDIZED WQI

The proposed standardized WQI can be used in several ways. Two examples are illustrated below. In the first example, the WQI is used to perform a 305(b) assessment and show how it could improve the 305(b) reporting process. In the second example, for a biologically impaired stream case study site, WQI is used to measure incremental (yearly) water quality improvements and demonstrate the effectiveness of stream restoration process to agency personnel and interested citizens. A few other possible applications of WQI are briefly described as well.

305(b) Assessment

The proposed WQI method allows continuous updating of the water quality condition at each sampling station within the AWQM network. The WQI station evaluation spreadsheet can perform a 305(b) water quality assessment for parameters that have established WQC. It can also perform a hypothetical 305(b) assessment for constituents that do not have established WQC. Standardized WQI scores together with the official 305(b) reports can be utilized to help water resource managers set priorities for conducting special stream surveys, implementing total maximum daily load (TMDL) contracts, etc.

A 305(b) assessment example using information provided in Table 5 (cell D22 to O32) is illustrated below. The WQI uses the parameter rank score of 5 as the threshold between good/bad water quality. Parameter rank scores that are <5 will violate the WQC and those >5 do not. Excel logic formulas are written (cells K22 to O27) to detect WQC violations and perform the 305(b) assessment. These logic formulas place a 1 in the cells between K22 and O27 of Table 5 when there is a WQC violation and a 0 is placed where there is no WQC violation. As an example, for the total number of samples (6), one WQC violation of DO represents a 16.7% violation rate among the samples collected over the evaluation period (cell L31). And as 16.7% exceeds the 10% violation threshold set by the USEPA guidance, the monitored segment of the stream at Laurel Fork at Pocahontas is declared as impaired for DO (cell L32). It should be noted that neither the USEPA nor the State of Virginia have established WQC for conductivity and percent DO saturation, therefore, there is no official assessment on these parameters and "N/A" is placed in cells N32 and O32 for that reason. However, the spreadsheet evaluates all parameters based on the reasoning that parameter rank scores <5 indicate degraded water quality. Following this logic, the hypothetical violation rates for conductivity and percent DO concentration are 33% and 50% percent, respectively, indicating serious water quality problems in Laurel Fork at Pocahontas.

The WQI can be utilized for performing the official 305(b) water quality assessments, provided that the rank score of 5 has been officially adopted by a state as the threshold concentration between good/bad water quality. In order to maximize the utility of the standardized WQI, the authors suggest that users develop PRGs and PETs that assign a rank score of 5 to the threshold concentrations above (or below) which begins to have adverse biological effects, rather than the artificially designating the rank score of 5 to the officially adopted WQC concentration for a particular parameter. Conceivably state water resource agencies could perform the official 305(b) assessment based on adopted parameter WQC and also perform the standardized WQI evaluation (not using the rank score of 5 for WQC) for determining actual stream conditions at each monitoring station, ranking water quality conditions among stations, etc.

It is recognized that it will require time and expense to develop and support a computer program to perform the steps outlined in the standardized WQI. It is also recognized that, although automatic, instantaneous, and continuously updated WQI scores and evaluations are possible, publishing, reporting, and communicating the results to federal agencies, public, and other entities are not automatic, instantaneous, and continuous. However, the generation of near-term WQI assessments has tremendous advantages over the official 305(b) reports that utilize data up to 6-years old and are not published but once every 2 years. Unlike the 305(b) report, the standardized WQI provides a simple but accurate way to compare and rank overall stream conditions among all stream stations that are evaluated by the WQI. Additionally, the computer could be programmed to automatically alert water resource managers when critical rank scores, sample rank scores, parameter index scores, overall WQI scores, and evaluations are detected so that special investigation and mitigation activities can be activated.

Effectiveness of Stream Restoration Efforts

The proposed WQI can be used to observe the incremental trend in water quality improvement when a post-remediation monitoring program is implemented. Below is an illustrative example where the WQI was used to determine the effectiveness of stream restoration efforts and incremental improvement in water quality.

Batie Creek is located within the Ridge and Valley sub-ecoregion in Lee County, southwest Virginia. A study conducted in 1997-98 established that the creek is highly polluted with leachate from a 2.6 million cubic-ft sawdust pile that existed in the creek vicinity. Investigators recommended removal of sawdust piles in order to restore the stream water quality (Frago *et al.*, 1998; Younos *et al.*, 2001). Following this recommendation, the sawdust pile was removed over a 4-year period (1998-2001). Simultaneously, quarterly water quality monitoring of the creek was performed during the period of 2001-04 in order to document the effects of pollutant reduction on stream restoration and biological recovery. A water quality database was developed for the 1997 impaired condition and the follow-up restoration process. Measured parameters included DO concentration, percent DO saturation, pH, and conductivity.

Table 6 shows the WQI appraisal for the 1997 data, i.e., severely impaired (lethal) condition of the creek. Table 7 shows annual evaluations of water quality as compared with the 1997 condition using the WQI. Table 7 not only shows overall improvement as indicated by the annual WQI evaluations, but it also shows how each water quality parameter improved during the evaluation period. The validity of the WQI evaluation at the study site was confirmed by comparable improvements in both the physical and biological conditions at the site as shown in Table 8.

With regard to using the standardized WQI for tracking restoration progress in the Batie Creek, one can argue that the correlation of the WQI with the physical, chemical, and biological observations is unquestionable; the recovery of the spring was so dramatic, and so clearly evident by any measurement, that surely anyone could see that the stream was improving, without troubling to calculate an index. One could also question the benefit of calculating the WQI because one can simply compare the beginning and ending points (1997 and 2003) of the Batie Creek recovery as illustrated in Tables 7 and 8. However, to counter that argument, the WQI not only shows the beginning, endpoints, and the dramatic recovery of the stream, but it also documents the incremental water quality improvements in 2001 and 2002. During this time, local citizens and water

TABLE 6. Parameter Evaluations and Annual Appraisal of 1977 Raw Data at Batie Creek, Ridge and Valley Region (Lee County, Virginia).

Monitoring Year →	**1997 Raw Data**								**1997 Appraisal**	
Sample Dates →	**7/15**	***n***	**7/29**	***n***	**8/12**	***n***	**<Avg. *n*>**		**Evaluation**	**Rank Sc**
Dissolved Oxygen (mg/l)	0.06	**1**	1.87	**1**	0.04	**1**	1.00	>	Lethal	**1**
pH	6.21	5	5.90	4	6.04	5	4.67	>	Good	5
Conductivity (umho/cm^2)	415	4	513	3	463	4	3.67	>	Fair	4
% Dissolved oxygen saturation	1%	**1**	19%	**1**	0%	**1**	1.00	>	Lethal	**1**
WQI-Score		1		1		1	1.00	>	Lethal	1
WQI-Evaluation	Lethal		Lethal		Lethal					

Note: WQI = Water Quality Index, *n* = WQI "Rank Scores."

TABLE 7. Annual Appraisals and Incremental Water Quality Improvement at Batie Creek, Ridge and Valley Sub-Ecoregion, Lee County, Virginia (1997, 2001-04).

	Annual Rank Scores (From 1997 to 2004)												
Constituent Parameter	**1997**	***n***	**2001**	***n***	**2002**	***n***	**2003**	***n***	**2004**	***n***	**Parameter Evaluation**	***n*** *	**Stream Condition**
											Exceptional	7	
DO (mg/l)	Lethal	1	Critical	2	Poor	3	Good	5	Good	5	Excellent	6	Healthy
pH	Good	5	Excellent	6	Excellent	6	Exceptional	7	Exceptional	7	Good	5	
Conductivity (umho/cm^2)	Fair	4	Fair	4	Fair	4	Good	5	Good	5	Fair	4	Stressed
% DO Saturation (%)	Lethal	1	Lethal	1	Critical	2	Good	5	Good	5	Poor	3	
Annual WQI Scores		1		1		2		5		5	Critical	2	Critical
Annual WQI Evaluation	Lethal		Lethal		Critical		Good		Good		Lethal	1	

Note: WQI = Water Quality Index, DO = Dissolved Oxygen *n* = WQI "Rank Scores."

TABLE 8. Batie Creek Recovery as Documented by Chemical, Physical, and Biological Evidence and Changes in WQI.

1997	2003
A. Chemical Evidence-WQI Evaluation	
1. WQI Rank Score in 1997 = 1.00 = Lethal,	1. WQI Rank Score in 2003 & 2004 = 5.00 = Good,
2. The DO Sag in Batie Creek falls well below water quality criteria.	2. The DO throughout Batie West Spring and Batie Creek is well above criteria.
B. Physical Evidence	
1. 100% of the sawdust pile is on the site,	1. 99% of the sawdust pile has been removed,
2. Pooled leachate is visible at several locations,	2. No pooled leachate remains,
3. Foul odor (rotten eggs) is overpowering,	3. No foul odors present,
4. Black substrate evident,	4. Substrate returned to normal,
5. Stinky gray water discharged from spring,	5. Clear, odorless discharge from spring,
6. Esthetic appearance is unacceptable.	6. Esthetic appearance has been fully restored.
C. Biological Evidence	
1. Heavy growth of Sphaerotilus (sewage fungus) blankets the bottom of Batie West Spring area,	1. No Sphaerotilus present in Batie West Spring,
2. Abundant growths of Tubificid (sludge) worms within the Batie West Spring discharge area,	2. No Tubificid worms remain in Batie W. Spring,
3. Blue-green algae covers the substrate of Batie Creek for more than a mile,	3. All Blue-green algae is gone in Batie Creek, and the substrate has returned to normal,
4. Minnows are all gone,	4. Minnows have returned to Batie Creek,
5. The expiration of the "Lee Co. Cave Isopod" from Thompson Cedar Cave causes this Species to become listed on the USFWS's Endangered Species List,	5. The "Lee Co. Cave Isopod" has recolonized Thompson Cedar Cave (delisting soon),
6. No beavers present in the Batie Creek area.	6. Beavers are present and actively building dams.

Note: WQI = Water Quality Index, DO = dissolved oxygen.

quality enforcement managers were demanding evidence for clear progress in water quality improvement. Even though, chemical, physical, and biological data collected during the recovery period revealed the existence of lethal and critical conditions, the WQI indicated the trend for water quality improvement in such a way that was understandable to all interest groups.

Other Possible Applications

The fact that the standardized WQI can be used to detect recent trends in water quality condition is an important feature of the WQI. In many occasions, state and local governments need to prioritize stream restoration process within watersheds or political boundaries in order to maximize the use of limited financial resources. The WQI can be applied to detect water quality problems and rate stream water quality conditions within sub-watersheds, a particular ecoregion, or political boundaries. The comparison and ranking of WQI scores in the sub-watersheds provides valuable information that water resource managers can use to make informed decisions on how to efficiently and effectively prioritize financial resources for stream restoration projects within a watershed or a region. Water resource managers can capitalize on this information by prioritizing needs and providing greater staff time and resources at those stations and in those watersheds where major water quality problems exist and where the direction of water quality trend is toward degradation. If sufficient and long-term data is available, WQI station scores at individual stations throughout the AWQM network can also be tracked over time and statistically analyzed to detect temporal trends.

CONCLUSIONS

The proposed standardized WQI provides an accurate, integrated, multi-parameter, composite, appraisal of the stream water quality. The WQI presented in this article takes into account the natural variability among ecoregions and the indicator organisms that inhabit them. It also takes into account the unique biological responses of aquatic organisms to the various constituents that affect water chemistry. These unique features of the standardized WQI, allow the direct comparison (and ranking) of stations in different ecoregions.

Unlike many indices developed across the country, the proposed standardized WQI scores and evaluations do not require artificial (subjective) adjustments to account for flow variability and different geological conditions across the geographical area because these are already incorporated into the index. Neither there are subjective penalty factors or coefficients applied to weigh adverse parameter concentrations more heavily. Adjustments (corrections) are not necessary to account for the use of multiple parameters that may exert an undue over-weighting of related parameters (such as DO, percent DO saturation, and BOD). No artificial adjustments are needed for the standardized WQI because, unlike other indices, this index evaluates water quality based on scientifically documented biological responses of aquatic life to constituent concentrations.

This proposed method does not present a universal WQI. Instead, it presents a logical, science-based, systematic, and comprehensive method to create ecoregion-specific indices that can be a very practical and useful planning tool for water resource managers. It allows water resource manager to conduct, review, study, and utilize a science-based, fully integrated, and evaluation of every sample station in the AWQM network provided that accurate and statistically valid ecoregion-specific parameter response graphs, parameter evaluation tables, and parameter look-up tables are developed and incorporated into the WQI station evaluation spreadsheet.

The WQI spreadsheet can simultaneously perform the 305(b) assessment and it is far more comprehensive than the 305(b) assessment. The WQI can evaluate the most recent data and automatically update the evaluation of the stream condition at every AWQM station in the network as the parameter data are entered into the WQI station evaluation spreadsheets. It identifies recent water quality problems and trends much sooner and faster as compared with conventional approaches. The lead time provided by the WQI could afford water resource managers the opportunity to locate and correct water quality problems before needing to designate stream segments as impaired. The ability to prevent some stream segments form being listed in the 303(d) list that require developing TMDL reports can potentially save taxpayers substantial tax dollars.

The standardized WQI can be used to accurately track incremental improvements among the various parameters as well as overall progress of stream restoration projects. One of the distinct advantages of the standardized WQI is that once it is fully developed, it simplifies the complexity of water quality conditions into a very comprehensive holistic presentation. The WQI evaluation is both mathematically analyzable and easily understood through the use of simple and single-word narratives. The meaning/significance of each parameter and the overall evaluation is very comprehensible.

Federal and state water resource agencies, local governments, consulting firms, citizen monitoring groups, academia, and others can benefit by using the standardized WQI. The WQI is a useful tool for water resource agencies to reach out to the general public and public interest groups with an easily understood (yet scientifically valid) method to interpret the meaning (significance/consequence) of water quality data. It will help citizens to understand how specific-parameter concentrations affect aquatic life. A WQI can be utilized to facilitate communications between decision makers and the public.

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