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An Innovative Index for Evaluating Water Quality in Streams

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ABSTRACT / A water quality index expressed as a single number is developed to describe overall water quality conditions using multiple water quality variables. The index consists of water quality variables: dissolved oxygen, specific conductivity, turbidity, total phosphorus, and fecal coliform. The objectives of this study were to describe the preexisting indices and to define a new water quality index that has advantages over these indices. The new index was applied to the Big Lost River Watershed in Idaho, and the results gave a quantitative picture for the water quality situation. If the new water quality index for the impaired water is less than a certain number, remediation—likely in the form of total maximum daily loads or changing the management practices—may be needed. The index can be used to assess water quality for general beneficial uses. Nevertheless, the index cannot be used in making regulatory decisions, indicate water quality for specific beneficial uses, or indicate contamination from trace metals, organic contaminants, and toxic substances.

Meeting water quality expectations for streams and rivers is required to protect drinking water resources, encourage recreational activities, and provide a good environment for fish and wildlife. The Clean Water Act of 1972 provided the initial legislative means for restoring the quality of the nation's waters. Section 303(d) of the federal Clean Water Act and the 1992 Total Maximum Daily Load (TMDL) regulations established the water quality standards and the maximum amount of a pollutant that a water body can receive and still meet water quality standards (Copeland 2002).

Several regulatory agencies issued very useful water quality criteria for protection of beneficial uses. These criteria can be studied to develop a general water quality index (WQI) that can be used to indicate the overall water quality conditions. It assigns a number to a body of water to indicate its quality. It consists of water quality variables, such as dissolved oxygen (DO), conductivity, turbidity, total phosphorus, and fecal coliform, each of which has specific impacts to beneficial uses.

KEY WORDS: Big Lost River; Idaho; 303(d) list; Total maximum daily load; National Sanitation Foundation; Water quality index

There are several water quality indices that have been developed to evaluate water quality in states and in Canada (SAFE 1995, Mitchell and Stapp 1996, WEP 1996, Zandbergen and Hall 1998, Cude 2001). All of these indices have eight or more water quality variables. However, most watersheds do not have long-term and continuous data for these variables. Therefore, there is a need to develop a new WQI that uses fewer variables and that can be used to compare sites that have water quality expectations. This study aimed at general review of the preexisting indices and development of a new index to provide a simpler method for describing water quality.

Significance of the Environmental Variables

There are basic environmental variables that can be used to construct the new WQI. These variables include DO, fecal coliform, turbidity, total phosphorus, and specific conductance.

Oxygen is the single most important gas for most aquatic organisms and for self-purification processes. DO is a measure of the amount of oxygen freely available in water. It is commonly expressed as a concentration in terms of milligrams per liter, or as a percent saturation, which is temperature dependent. The colder the water, the more oxygen it can hold.

Fecal coliform are bacteria whose presence indicates that the water may have been contaminated with hu-

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*Author to whom correspondence should be addressed, *email:* asaid@cc.usu.edu man or animal fecal material. If fecal coliform counts are high in a site, it is very likely that pathogenic organisms are also present, and this site is not recommended for swimming and other contact recreation.

Phosphorus is important to all living organisms. However, excessive phosphorus causes algae blooms, which are harmful to most aquatic organisms. They may cause a decrease in the DO levels of the water, and in some cases temperature rise. This can result in a fish kill and the death of many organisms.

Turbidity indicates the amount of particles suspended in water. High concentrations of particles can damage the habitats for fish and other aquatic organisms.

The specific conductance represents the salinity of water. It is a measure of the ability of water to conduct an electrical current. It is highly dependent on the amount of dissolved solids in the water. An empirical relationship between total dissolved solids and conductivity can be derived for a stream (APHA 1998, BASIN 2001).

There are other water quality variables that affect the suitability of water for use such as pH, temperature, and nitrogen. However, the effects of these variables are reflected to a certain degree by the basic variables. For example, the temperature effect can be captured if the dissolved oxygen is measured as percent saturation. However, temperature is an important variable because there are critical temperatures for many aquatic species. Conductance is a function of water temperature and the total number of dissolved ions in water. When conductance is reported as specific conductance, it has been corrected to constant temperature of 25°C. The pH of the U.S. natural water is usually between 6.5 and 8.5. The capacity of the pH natural buffer helps to resist significant changes in pH (APHA 1998, BASIN 2002).

Beneficial Uses and Protection Criteria of Streams

Each watershed is protected for specific beneficial uses, such as drinking water, agriculture, cold water, warm water, salmonid spawning, and primary contact. Water quality criteria determined by the U.S. Environmental Protection Agency (EPA) designates maximum levels for some water quality characteristics that should not be exceeded. The U.S. EPA ambient water quality criteria for water quality have been used to construct the WQI. However, because these criteria have a certain level for each beneficial use, for WQI to be used for general beneficial uses, it should have some range from ideal to most deteriorated water. As the water becomes ideal, it can be used for various beneficial uses.

Previous Indices

There are several water quality indices that have been developed to help water quality divisions in some U.S. states, Canada, and Malaysia. However, most of these indices are based on the WQI developed by the U.S. National Sanitation Foundation (NSF).

The NSF developed an index, called the NSF Water Quality Index (NSFWQI), to provide a standardized method for comparing the relative quality of various bodies of water. More than 140 water quality scientists were surveyed about 35 water quality tests and were asked to consider, which tests should be included in an index (Mitchell and Stapp 1996). Nine water quality variables are used for the index: DO, fecal coliform, pH, biochemical oxygen demand (BOD), temperature change, total phosphate, nitrate, turbidity, and total solids.

The British Columbia Ministry of Environment, Lands and Parks in Canada developed the British Columbia Water Quality Index, BCWQI (Zandbergen and Hall 1998). The BCWQI was found to be extremely sensitive to sampling design and highly dependent on the specific application of water quality objectives. The BCWQI in its form has serious limitations for comparing water bodies and for establishing management priorities.

The Oregon Department of Environmental Quality (ODEQ) developed the original Oregon Water Quality Index (OWQI) in 1980. The OWQI is calculated in two steps. The raw analytical results for each variable, having different units of measurement, are transformed into unitless subindex values. These values range from 10 (worst case) to 100 (ideal). These subindices are then combined to give a single WQI value ranging from 10 to 100. The OWQI is integrating measurements of eight water quality variables (temperature, DO, BOD, pH, ammonium + nitrate nitrogen, total phosphates, total solids, and fecal coliform) (Cude 2001).

The Florida Stream Water Quality Index (FWQI) was developed in 1995 under the Strategic Assessment of Florida's Environment (SAFE). It is an arithmetic average of water clarity (turbidity and total suspended solids), dissolved oxygen; oxygen-demanding substances (Biological Oxygen Demand [BOD], Chemical Oxygen Demand [COD], Total Organic Carbon [TOC]), nutrients (phosphorus and nitrogen), bacteria (total and fecal coliform), and biological diversity (natural or artificial substrate macroinvertebrate diversity and Beck's Biotic Index). The values for this index were determined as follows: 0 to less than 45 represents good quality, 45 to less than 60 represents fair quality, and 60 to 90 represents poor quality (SAFE 1995).

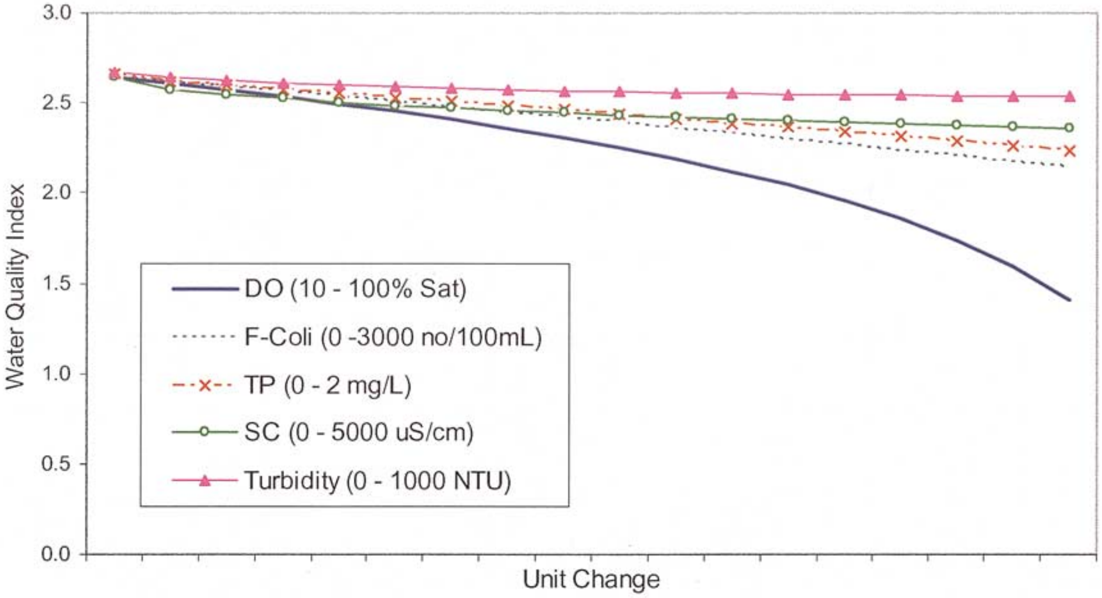


Figure 1. Water Quality Index (WQI) for the unit change of water quality variables. The slope of the lines defines the behavior of the variables. The dissolved oxygen (DO) has the maximum slope and the most rapid effect on WQI followed by fecal coliform (F-coli), total phosphorus (TP), specific conductance (SC), and turbidity.

In 1996, the Lower Great Miami Watershed Enhancement Program (WEP) in Dayton, Ohio developed a water quality index and a river index. This river index is calculated in two steps: the WEPWQI, which consists of chemical, physical, and biologic variables, and then the River Index, which consists of the water quality variables plus measurements of water flow and clarity (turbidity). Both indices are expressed as a "rating" scaled from excellent, good, fair, to poor (WEP 1996).

Methods

Data Descriptions

During a series of visits to departments of environmental quality, we compiled a set of physical, chemical, and biological properties from Utah, Idaho, Oregon, and Virginia (UDEQ, IDEQ, ODEQ, and VDEQ). These data were collected from 1997 to 2000 and were selected from unpublished field/laboratory reports that include physical, field measurements, nutrients, and biological data for a total of 24 sites using relatively consistent sampling and analytical methods. Data reports have supporting information that identifies and describes the water quality constituents and the methods, remarks, laboratories, and the laboratory measurement accuracy. A spreadsheet of these data was constructed and sensitivity analyses were performed by testing different alternative equations for the water quality index.

The New Index

The WQI equation was developed in two steps. The first was ranking water quality variables according to their significance. The variables included in the new WQI are DO, total phosphates, fecal coliform, turbidity, and specific conductivity. Second, several forms were tested to give DO the highest weight followed by fecal coliform and total phosphorus. The percent saturation reflects the temperature effect. Turbidity and specific conductance were given the least influence. A final form was selected that keeps the index in a simple equation and a reasonable numerical range. The logarithm was used to give small numbers that are easily used by the management decision-makers, the stakeholders, and general public as well. A sensitivity analysis was performed to test the performance and to verify that appropriate influences were given for the water quality variables as shown in Figure 1.

In the final form, the powers of the variables were chosen for the WQI based on the effect of each variable on water conditions. For example, higher values of fecal coliform and total phosphorus will be very harmful for health and aquatic life. The forms of the fecal coliform and total phosphorus in the index formula were chosen to give strong responses to these effects.

On the other hand, turbidity and specific conductance have linear effects, which are less sensitive for changing the values of the variables, in the index formula. This is because, for example, turbidity would not be very dangerous unless it is associated with a higher level of disease-causing microorganisms that will make fecal coliform higher as well in the formula.

To calculate this index, there is no need to standardize the variables. The calculations are further simplified through the elimination of sub-indices (percent of ideal situation of each variable). The proposed index is:

$$WQI = log\left[\frac{(DO)^{1.5}}{(3.8)^{TP}(Turb)^{0.15}(15)^{FCol/10000} + 0.14(SC)^{0.5}}\right] \tag{1}$$

where

DO is the dissolved oxygen (% oxygen saturation)Turb is the Turbidity (Nephelometric turbidity units [NTU])TP is the total phosphates (mg/L)FCol is the fecal coliform bacteria (counts/100 mL)SC is the specific conductivity in (MS/cm at 25°C)

The index was designed to range from 0 to 3. The maximum or ideal value of this index is 3. In very good waters that have 100% dissolved oxygen, no TP, no fecal coliform, turbidity less than 1 NTU, and specific conductance less than 5 MS/cm, the value of this index will be 3. From 3 to 2, the water is acceptable, and less than 2 is marginal and remediation, likely in the form of TMDLs, is needed. If one or two variables have deteriorated, the value of this index will be less than 2. If most of the variables have deteriorated, the index is less than 1, which means that water quality is poor.

Limitations

The new WQI equation takes into account water quality data, such as DO and turbidity, and compares these data to ideal water quality levels. Although it has the advantage of reducing water quality variables to a minimum subset, it cannot always show the impact of random short-term changes, such as a spill, except if it occurs repeatedly or for a long time. The best results with this index can be obtained in natural conditions and natural measurement sites (not downstream of river outfall). The index can be used to assess water quality for general uses. However, it cannot be used in making regulatory decisions or to indicate water quality for specific uses. The localized changes in water quality may not be immediately reflected. Another change not necessarily reflected in the index is the stream habitat. In addition, the index cannot be used to indicate contamination from trace metals, organic contaminants, or other toxic substances. The factors of water levels or stream velocities may be incorporated into a physical/chemical/biological index in the future.

Results

WQI and Water Quality Criteria

For drinking water, the criteria stipulate an average of less than 1 coliform per 100 mL. The turbidity is health related because it is generally related to the microbial count, and the drinking water standard for turbidity is 0.5 NTU and for specific conductance is 5 MS/cm or less. A combination of these values gives the upper limit for the WQI. For recreational uses, the U.S. EPA standard for *Escherichia coli* is based on a geometric mean of only 126 organisms/100 mL for several samples collected during dry weather conditions or 235 organisms/100 mL for any single water sample. If either criterion is exceeded, the site is not recommended for swimming. Another combination gives the middle level 2 of the index. Therefore, water that has index value between 3 and 2 can be used as a drinking water source and for contact recreation. Although there is no specific standard for total phosphorus in freshwater to prevent eutrophication, it should not exceed 0.025 mg/L in lakes, 0.05 mg/L where streams enter lakes, and 0.1 mg/L in streams that do not flow into lakes. For DO, the U.S. EPA established 75% saturation based on a daily average, and an instantaneous minimum DO concentration of at least 5 mg/L. The DO criterion was that fish growth rates are reduced when the DO is less than 5 mg/L.

Comparisons with Other Water Quality Indices

Table 1 shows a sample calculation using NSFWQI (Mitchell and Stapp 1996) and the new WQI. The NSFWQI value is 77.9, which lies on the good water classification region, so the water is considered good. To get the NSFWQI, the Q-value should be determined for each variable. Also, a weighting factor is assigned to each variable. The NSFWQI includes nine water quality variables (DO, fecal coliform, pH, BOD, temperature, TP, nitrate, turbidity, and TS). The new WQI gives a value of 2.22, which indicates that the water is good in just one simple step. To show how complex the other index is, Table 2 shows sample calculation using the WEPWQI method (WEP 1996). The index value is 54, which lies in the good region according to the ranking criteria of this index. This index includes 15 water quality variables to get the river index. The new WQI

Table 1. An example of the National Sanitation Foundation Water Quality Index (NSFWQI) calculation and the new WQI[a]

Variable	Result	Unit	Q-value	Weight factor	Subtotal
DO	82	% Saturation	90	0.17	15.3
Fecal coliform	12	#/100 mL	72	0.16	11.52
pH	7.67		92	0.11	10.12
BOD	2	mg/L	80	0.11	8.8
Change in temp.	5	°C	72	0.10	7.2
Total phosphate (PO4)	0.5	mg/L	60	0.10	6
Nitrates	5	mg/L NO3	67	0.10	6.7
Turbidity	5	NTU	85	0.08	6.8
TS	150	mg/L	78	0.07	5.46
NSFWQI					77.9
WQI	2.22				

[a] There is no site or date identified. It is given as an example to show the calculations (see the reference below).

NSFWQI: 90–100: Excellent, 70–90: Good, 50–70: Medium, 25–50: Bad, 0–25: Very Bad.

WQI: 3–2: Good, 2–1: Need total maximum daily loads (TMDL), 1–0: Need TMDL and best management practices.

Reference: http://bcn.boulder.co.us/basin/watershed/wqi nsf.html

NTU, Nephelometric Turbidity Units; TDS: Total Dissolved Solids .

Table 2. An example of the Watershed Enhancement Program Water Quality Index (WEPWQI) (Measurements from the Miamisburg, Ohio monitoring station on November 10, 1999)

Variable	Averaged value	Rating	WQ weighting factor	WQ weighted subtotals	WQ weighting maximums
Total ammonia	3.24	1	2	2	8
Atrazine	0.02	4	—	—	—
Chlorpyrifos	0.01	4	—	—	—
Pesticides	(4 + 4)/2 = 4	2	8	8	
Dissolved oxygen	10.02	4	3	12	12
Escherichia coli	80.00	4	—	—	—
Fecal coliform	105.00	4	—	—	—
Pathogens	(4 + 4)/2 = 4	2	8	8	
Fish toxicity	69.00	2	3	6	12
Nitrate	6.97	1	2	2	8
PAH	0.25	4	2	8	8
pH	8.33	3	1	3	4
Specific conductivity	0.66	2	1	2	4
(Water) temperature	16.82	3	1	3	4
WEPWQI subtotals				54	72
WQI	2.11				

>60: Excellent, 60–46: Good, 45–31: Fair, <31: Poor.

WQI: 3–2: Good, 2–1: Need total maximum daily loads (TMDL), 1–0: Need TMDL and best management practices.

Reference: http://www.mvrpc.org/wq/wep.htm

PAH: Polycyclic Aromatic Hydrocarbon .

gives a value of 2.11, which indicates that the water is good. Although WEPWQI has more water quality variables, it would pick up poor conditions such as cases where pesticide and Polycyclic Aromatic Hydrocarbon (PAH) contamination exist.

Table 3 shows an example of the new WQI for a number of water quality conditions and for the same data presented in the above two examples. A remarkable point from Tables 1 and 2 is the disparity in rating water for the two indices. Although a water with 77.9 of NSFWQI (Table 1) is a good water, another water with 72 WEPWQI is an excellent water (Table 2). This raises the need for the new general index with a unique simple range from 1 to 3. Table 3 shows that most stream waters have values of this index between 2 and 3 except for total phosphorus, which is more than 0.5 mg/L, turbidity more than 50 NTU, fecal coliform more than 200 organisms/100 mL, or specific conductance more than 750 MS/cm. In this table, the lower limit for good waters can be a water that has 50%

Table 3. The new water quality index (WQI) for different hypothetical cases that shows the index ranges

DO (% saturation)	Turbidity (NTU)	Fcol (col/100 mL)	Fcol (col/100 mL/10000)	TP (mg/L)	SC (MS/cm)	WQI
90	1	100	0.01	0.02	1	2.85
70	10	200	0.02	0.7	20	2.12
60	50	500	0.05	1	90	1.71
90	80	1000	0.1	1.4	270	1.66
50	50	200	0.02	0.05	100	2.01
90	100	3000	0.3	0.5	270	1.89
100	200	5000	0.5	0.5	100	1.74
100	270	4000	0.4	0.2	300	1.94
82	5	12	0.0012	0.5	3	2.43
100	0.5	0	0	0	0.5	3.00
60	200	200	0.02	0.1	300	1.96
82[a]	5	12	0.0012	0.5	75	2.30
100[b]	20.35	105	0.0105	0.7	660	2.11

2–3 Acceptable, 1–2 needs total maximum daily loads (TMDL), <1 needs best management practices and TMDL.

[a] Sample calculation of Table 1.

[b] Sample calculation of Table 2.

DO, dissolved oxygen; Fcol, fecal coliform bacteria; TP, total phosphates; SC, specific conductivity.

saturation of DO, 200 organisms/100 mL for a single water sample, 0.05 mg/L TP, turbidity of 50 NTU, and SC of 100 MS/cm as shown in row 5. The last two rows include the WQI for the same samples in Tables 1 and 2.

Figure 2 shows comparison between the new WQI and NSFWQI. This comparison demonstrates some remarkable points. On September 6, 1997, the NSFWQI gives a value of 84%, which is considered very good water from the NSF index rank, whereas the proposed index gives a value of 1.83, which means, according to the proposed index rank, a water that needs remedial action, such as a TMDL. The reason for this is the elevated phosphorus level of 1.5 mg/L. A water with phosphorus concentration of 1.5 mg/L cannot be considered a very good water. In general, the proposed index is more sensitive to the elevated values of phosphorus and turbidity or decreased values of DO for the rest of the table.

Case Study

The Big Lost River Watershed, Idaho, is considered a relatively clean watershed. Table 4 shows some stream water quality variables and the calculated values using the proposed index for the Big Lost River Watershed.

The calculations in Table 4 show that the values of the index are generally more than 2 except for near Arco, which means that the water is otherwise acceptable. These streams are not mentioned in the U.S. EPA 303(d) list for impaired water bodies in the Big Lost River Watershed. However, they may not show up on the 303(d) list because "Listing Policies" differ from water quality criteria–based decision-making. These data along with data from Ott (1988) and field measurements and samples collected by Idaho Department of Environmental Quality (IDEQ) in July 2000 for the tributaries of the Big Lost River were used to depict Figure 3 which shows the index for different subbasins in the Big Lost River Watershed.

Discussion

Equation 1 was designed to classify the water into three ranges: from 3 and up to 2, the water is good and it can be used for drinking water in the upper limit and for recreational purposes for the lower limit. Less than 2, the water cannot be used for used for certain beneficial uses such as drinking water and swimming. This is likely attributed to high fecal coliform, which will need to be reduced by appropriate wastewater treatment or other management strategies (i.e., TMDLs). From 1 to 0 are waters that need TMDLs and/or Best Management Practices (BMPs) to improve the water quality situation for most or all the variables in the formula. The index can be used to evaluate the input water to a water treatment plant because it includes the most important variables for drinking water treatment operations. In addition, it can be related to the cost of the treatment because it includes the variables that affect the treatment costs. Furthermore, the WQI is very useful in generating trends, demonstrating the importance of maintaining good water quality, and disseminating technical water quality information to the general public.

Water quality assessment can be performed using a WQI (classification) or statistical approach. However,

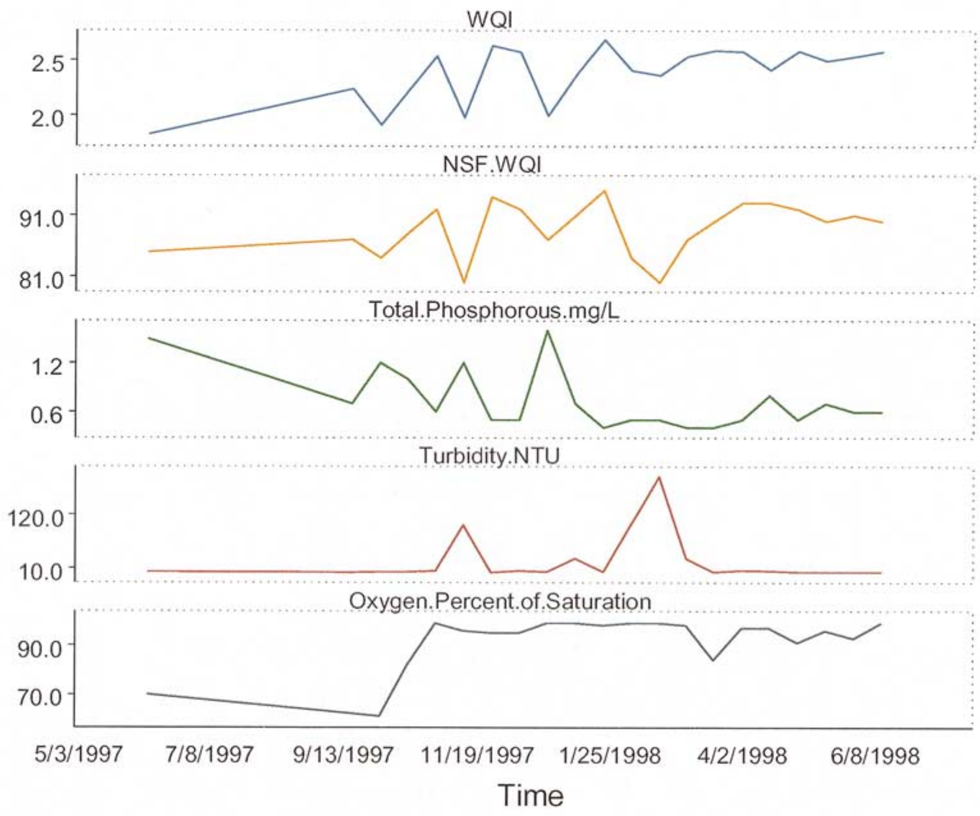


Figure 2. Comparison between National Sanitation Foundation Water Quality Index (NSF WQI) and the new water quality index. Data from Boulder Creek Watershed, Colorado, http://bcn.boulder.co.us/basin/data/COBWQ/, over the period March 1997 to June 1998.

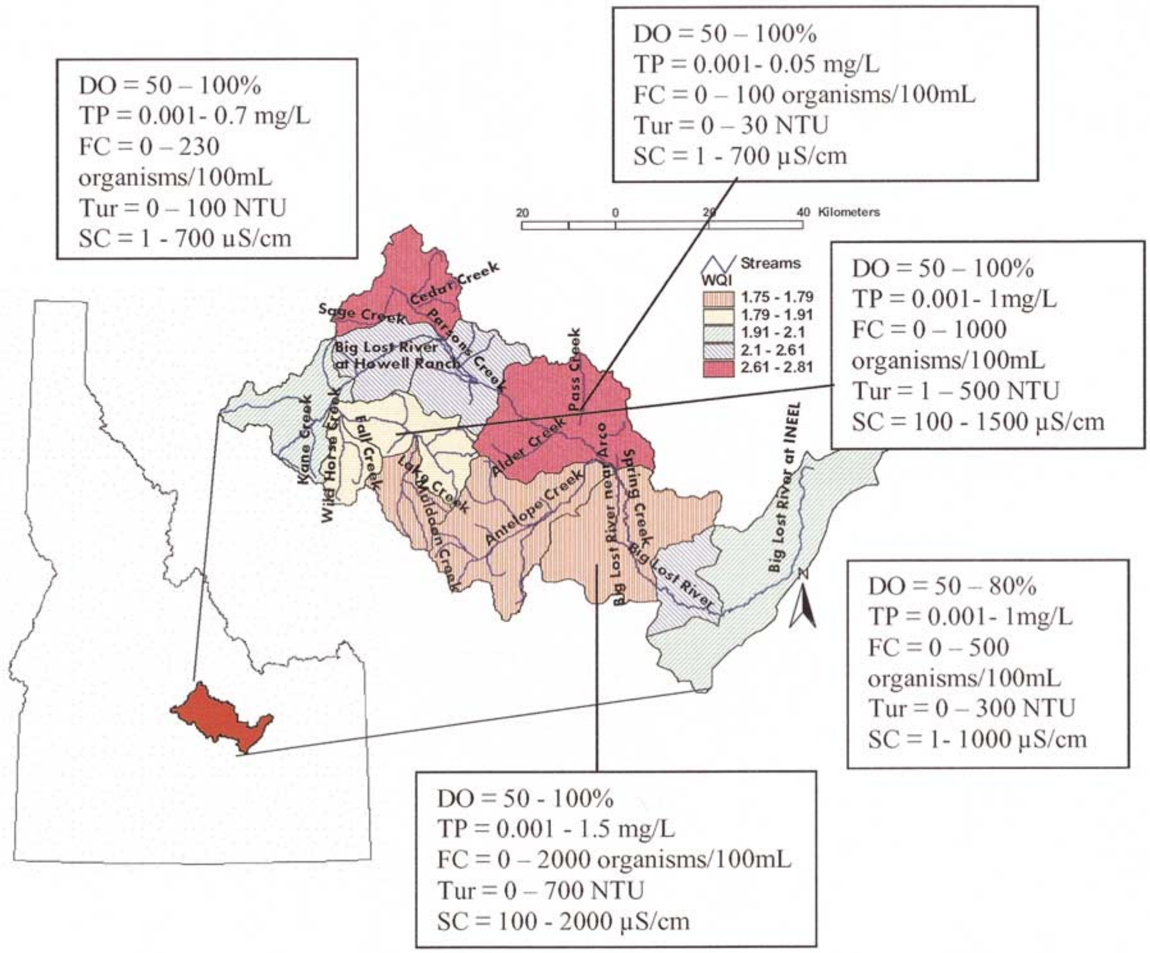
Table 4. Streams in the Big Lost River Watershed and their water quality index (WQI) values measured on November 6, 2000

Stream	DO (% Sat)	Turbidity (NTU)	Fecal coliform (no/100 mL/10^4)	TP (mg/L)	SC MS/cm	WQI
Big Lost River at Howell Ranch	100	10	0.015	0.25	285	2.36
Big Lost River Nr Arco	80	25	0.032	0.05	513	1.76
Antelope Creek	85	12	0.015	0.18	485	2.20
Pass Creek	90	5	0.010	0.09	488	2.27
Lower Cedar Creek	90	7	0.011	0.13	370	2.29
Big Lost River at INEEL	80	12	0.013	0.13	385	2.20

Reference: http://www.tmdl.org/ineel/

DO, dissolved oxygen; NTU, Nephelometric Turbidity Units; TP, total phosphorus; SC, specific conductivity.

the classification has some limitations. WQI formulas are not used as absolute measures of the degree of pollution or the actual water quality in a stream. Using these formulas results in inherent loss of information. In the conventional statistical approaches, comparisons and analysis of data demonstrate complications that arise if the assessment results obtained from one data set are used to compare with the results from a different data set, unless all data sets are evaluated together simultaneously and have the same types of data. Thus, a statistical approach to evaluate the water quality is less applicable than the WQI classification approach, which is considered as more objective and repeatable (Ali 2003). In addition, because of the requirements from



DO = 50 – 100%
TP = 0.001- 0.7 mg/L
FC = 0 – 230 organisms/100mL
Tur = 0 – 100 NTU
SC = 1 - 700 uS/cm

DO = 50 – 100%
TP = 0.001- 0.05 mg/L
FC = 0 – 100 organisms/100mL
Tur = 0 – 30 NTU
SC = 1 - 700 µS/cm

DO = 50 – 100%
TP = 0.001- 1mg/L
FC = 0 – 1000 organisms/100mL
Tur = 1 – 500 NTU
SC = 100 - 1500 µS/cm

DO = 50 – 80%
TP = 0.001- 1mg/L
FC = 0 – 500 organisms/100mL
Tur = 0 – 300 NTU
SC = 1- 1000 µS/cm

DO = 50 - 100%
TP = 0.001 - 1.5 mg/L
FC = 0 – 2000 organisms/100mL
Tur = 0 – 700 NTU
SC = 100 - 2000 µS/cm

Figure 3. Water Quality Index values for the Big Lost River Watershed. Data for U.S. Geological Survey (USGS) water quality: http://waterdata.usgs.gov/nwis/qwdata and USGS unpublished field reports (USGS, Boise, Idaho) average during the period 1980–2000. DO, dissolved oxygen; TP, total phosphorus; FC, fecal coliform bacteria; Tur, turbidity; SC, specific conductance.

some international or regional directives on critical issues related to water pollution, most countries need to report the status of their water quality based on a classification scheme. Although different countries are applying different classification schemes and the assessment approach in the index classification schemes differs greatly, they can be combined together into a single assessment technique that can be represented as a global index.

In addition, the WQI concept is different from the 303(d) listing process, which varies from state to state. The 303(d) list is not completely based on water quality criteria. For example, before a 303(d) list is accepted, DO must violate its criteria within a given time period. Nevertheless, the 303(d) list is designed to determine the individual pollutants that are degrading water bodies. On the other hand, the WQI is based on its limits on water quality criteria.

Summary and Conclusions

In this study, a number of water quality indices were presented and a new WQI was developed. The new WQI has some advantages over the others. It is very simple, fast, does not need to standardize the water quality variables or to calculate subindices, and it decreases the number of water quality variables that are needed to evaluate the water quality situation. This index contains five variables compared to eight variables for other indices. However, the measurements should not be performed downstream of a wastewater treatment plant or in areas where large amounts of animal or untreated human waste is deposited into the stream. This index gives results very similar to those calculated using NSF and WEP methods while using fewer variables. This index has small numerical values: from 0 to 3. Water with index values less than 2 may require remediation, likely in the form of TMDLs for the streams that contribute to the water body from which measurements are taken. If the values of this index are less than 1, in addition to the TMDLs, changing the management practices for the upstream may be required.

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