Water Resour Manage (2016) 30:2591–2610
DOI 10.1007/s11269-016-1311-0

Water Quality Indices as Tools for Decision Making and Management

Margaret W. Gitau[1] **· Jingqiu Chen**[2] **· Zhao Ma**[3]

Received: 22 January 2016 / Accepted: 28 March 2016 /

Abstract Water Quality Indices (WQIs) are composite indicators of water quality that pool together otherwise complex water quality data into an aggregate value that can be quickly and easily communicated to its intended audience. These indices have been used to provide comparisons of water quality status for different locations and at different times, which is helpful in prioritizing management efforts and funds. These WQIs can also be used as tools to predict potentially harmful conditions. They are also potentially valuable in assessing and communicating overall impacts of existing, planned, or proposed water quality interventions and management decisions. This manuscript presents a primarily literature-based look at WQI potentials with regard to their use as tools for decision making and management. Illustrations using monitoring data are also presented to provide additional information and comparisons to literature-based determinations. Of the existing WQIs, objective index formulations offer more flexible options for application allowing incorporation of varying determinant sets to capture location-specific conditions and changing water quality concerns. Incorporation of expert opinion at some level is important for the acceptability of WQIs as tools in water resources management. The use of the indices on a continuous basis provides long-term data which is helpful for decision making and management.

Keywords Water quality · Water quality indices · Decision making and management · Water resources

---

✉ Margaret W. Gitau
mgitau@purdue.edu

[1] Department of Agricultural and Biological Engineering and Center for the Environment, Purdue University, 225 S. University St, West Lafayette, IN 47907, USA

[2] Department of Agricultural and Biological Engineering, Purdue University, 225 S. University St, West Lafayette, IN 47907, USA

[3] Forestry and Natural Resources and Center for the Environment, Purdue University, 195 Marsteller Street, West Lafayette, IN 47909, USA

1 Introduction

Water Quality Indices (WQIs) are composite indicators of water quality that pool together information on different water quality parameters into one overall indicator value that can be quickly and easily communicated to its intended audience (Brown et al. 1970; CCME 2001; Poonam et al. 2013; USEPA 2010), usually policy makers and the general public (Abbasi and Abbasi 2012; Brown et al. 1972; Cude 2001; Gupta et al. 2003). These WQIs provide an advantage by decreasing the number of associated parameters that need to be interpreted in order to make a determination of water quality status (Gupta et al. 2003; Lumb et al. 2011b; Poonam et al. 2013), thus providing a simple yet inclusive means of interpreting the variety of water quality parameter values available (Abbasi and Abbasi 2012; Asadollahfardi 2015). These indices can and have also been used to provide comparisons of the status of different water bodies across space and time (e.g. CCME 2001; Chen et al. 2015; Merrick and Hubler 2013; ODEQ 2015; Sedeño-Díaz and López-López 2007), which is helpful in prioritizing management efforts and funds. These WQIs can also be used as tools to predict potentially harmful conditions (Ferreira et al. 2011). This single indicator value is potentially valuable in assessing and communicating overall impacts of existing, planned, or proposed water quality interventions and management decisions (Brown et al. 1970; Cude 2001; USEPA 2010; Walsh and Wheeler 2013).

A number of WQIs exist primarily because the indices were developed by different entities each seeking to improve on existing indices (e.g. Brown et al. 1970; CCME 2001; Cude 2001; Dunnette 1979; House and Ellis 1987; Smith 1990) and also considering different uses (e.g. Cude 2001; Smith 1990) and different ecological conditions (e.g. USEPA 2010). Table 1 shows commonly used indices along with their value ranges and interpretations. For example, the commonly used National Sanitation Foundation (NSF) Water Quality Index Additive Model (AWQI)- which in itself has variants- derives from the original Horton Model (Brown et al. 1970; Horton 1965; Lumb et al. 2011a). Other WQIs have taken on markedly different approaches, for example based on the harmonic mean (Cude 2001; Dojlido et al. 1994; Dunnette 1979) and the consideration of most impaired variable as the key water quality determinant (minimum operator, Smith (1990)). Factors that have driven the evolution of WQIs include the need for less arbitrary selection of parameters (Brown et al. 1970; Lumb et al. 2011a, b), the need to minimize ambiguity between the overall index and its sub-indices (Swamee and Tyagi 2000), and concerns about index insensitivity to poor quality parameters (Lumb et al. 2011a; Smith 1990; Swamee and Tyagi 2000).

Because of the inherent aggregating nature of the Indices, each index comprises a number of subindices—generally five to nine—that are designed to be reflective of key water quality determinants. Table 2 shows subindex parameters included in the common WQIs. Subindex values are computed in various ways, depending on the index, with the goal being to express parameter values in common water quality units typically based on a scale of zero (worst) to 100 (best). These subindices are then aggregated into one value using functions such as those presented in Table 1 and in the appendix. Subindex parameters and associated value determination procedures generally vary depending on the index and the intended application. For example, subindex parameters and associated values for the NSF indices (AWQI and MWQI) were derived using the Delphi Method (Dalkey et al. 1969; Hsu and Sandford 2007; Sackman 1974), an iterative, four-step process to obtain expert opinion (among other things) in which feedback on ratings is provided to the respondents (experts involved) at each step with a view to building consensus. The Delphi method is also used to select key determinants for the OWQI. However, the determination of subindex values differs; the OWQI uses regression-based algorithms (Cude 2001) while the NSF indices use subindex curves developed using the Delphi method (Brown et al. 1972, 1970).

Table 1 Summary of commonly used water Quality Indices (WQIs) along with value ranges and interpretations

	NSFWQI additive model (AWQI)	NSFWQI multiplicative model (MWQI)	Oregon WQI (OWQI)	Unweighted multiplicative WQI (UMWQI)	Minimum operator (MOWQI)
Equation[a]	$AWQI = \sum_{i=1}^{n} W_i Q_i$	$MWQI = \prod_{i=1}^{n} {Q_i}^{W_i}$	$OWQI = \left[\frac{n}{\sum_{i=1}^{n} {}^{1}/_{Q_i^2}}\right]^{0.5}$	$UMWQI = \left(\prod_{1=1}^{n} Q_i\right)^{{}^{1}/_{n}}$	$MOWQI = \min(Q_1, Q_2, Q_3, \ldots, Q_n)$
Purpose	Assessment, Communication		Assessment, Trends, Planning, Performance Evaluation, Communication,	Comparison with NSFWQIs	Provide index that captures lowest quality parameter
Basis	(Horton 1965) model, which was the first attempt at numerical indices to describe water quality.	Developed to resolve issue of AWQI insensitivity to low subindex values.	Need to account for most sensitive parameter (addressing weakness in AWQI and MWQI).	Need to minimize ambiguity between the overall index and subindex values	"Weakest Link" – WQ is defined by most impaired parameter/indicator
Ranges/Interpretation/ Assigned Ratings	90–100: Excellent (5) 70–89: good (4) 50–69: Medium (3) 25–49: Bad (2) 0–24: Very bad (1)	90–100: Excellent (5) 70–89: good (4) 50–69: Medium (3) 25–49: Bad (2) 0–24: Very bad (1)	91–100: Excellent (5) 85–90: good (4) 80–84: Fair (3) 60–79: Poor (2) 10–59: Very Poor (1)	90–100: Excellent (5) 70–89: good (4) 50–69: Medium (3) 25–49: Bad (2) 0–24: Very bad (1)	100–80: Eminently suitable for all uses (5) 60–79: Suitable for all uses (4) 40–59: Main and/or some uses may be compromised (3) 20–39: Unsuitable for main and/or several uses (2) 0–19: Totally unsuitable for main and/or many uses (1).
References	Brown et al. (1970); Lumb et al. (2011a); Lumb et al. (2011b); Poonam et al. (2013)	McClelland (1974); Lumb et al. (2011a); Lumb et al. (2011b)	Dunnette (1979); Cude (2001); Lumb et al. (2011b); Poonam et al. (2013)	Landwehr and Deininger (1976); Gupta et al. (2003); Lumb et al. (2011b)	Smith (1990); Swamee and Tyagi (2000); Poonam et al. (2013)

[a] n = number of parameters; W_i = relative weight of the ith parameter; Q_i = quality rating (subindex value) of the ith parameter

In general, parameters are developed to capture key water quality determinants while also minimizing redundancies, parameter duplication, and correlations (Brown et al. 1972; Cude 2001). For example, in the original Horton model parameters selected were those that were considered key determinants in most places and for which reliable data were available. The parameters were also limited in number so as not to render the index unmanageable (Horton 1965). In this original model, parameter selection was done primarily by the author (Brown et al. 1970; Horton 1965). In subsequent indices (Brown et al. 1970; Cude 2001; Smith 1990) parameters of significance were established based on expert opinion using the original form or variations of the aforementioned Delphi method. A rejection rationale was employed in Cude (2001) so as to eliminate redundancies while capturing various impairment categories (Oxygen depletion, eutrophication, physical characteristics, dissolved substances, and health hazards). Smith (1990) employed two additional questionnaires and also provided the experts involved with supplemental materials to assist with their decision making.

Water quality indices have found uses in various parts of the world with applications documented in both developed and developing countries. Most of the original indices were developed with aquatic fresh water systems in mind (Lumb et al. 2011a). The indices have, however, been found suitable for use with water supply applications including ponds (Sanchez et al. 2007), drinking water sources in general (Hurley et al. 2012), and a farm water supply lagoon (Ferreira et al. 2011). Water Quality indices have also been used successfully with coastal applications, primarily streams and rivers in the coastal zone and near shore areas (Giordani et al. 2009; Gupta et al. 2003; Mrazik 2007; USEPA 2010) as well as in estuarine areas (Ferreira et al. 2011; Ujjania and Dubey 2015). This manuscript presents a primarily literature-based look at WQI potentials with regard to their use as tools for decision making

Table 2 Parameters included in commonly used Water Quality Indices

	Water Quality Index[a]			
Components	AWQI	MWQI/ UMWQI	OWQI	MOWQI
DO, % Sat	√ (%)	√ (%)	√ (mg L^{-1})	√ (mg L^{-1})
Temperature, °C	√	√	√	√ (Temp + Temp Elevation)
BOD_5, mg L^{-1}	√	√	√	√
N, mg L^{-1}	√ (NO_3^-)	√ (NO_3^-)	√($NO_3^- + NH_3$)	–
P, mg L^{-1}	√ (PO_4^{3-})	√ (PO_4^{3-})	√ (TP)	–
TS, mg L^{-1}	√	√	√	√ (TSS, mg L^{-1})
Turbidity, NTU	√	√	–	√
Fecal Coliform, #/100 ml	√	√	√	√
pH	√	√	√	√
Comments	Subindex parameters and curves developed using Delphi method.	Parameters and curves adopted from AWQI.	Series of equations developed for subindex calculations.	Subindex parameters and curves- modification of Delphi method.

[a] AWQI- NSFWQI additive model; MWQI- NSFWQI multiplicative model; OWQI- Oregon Water Quality Index; MOWQI- Minimum Operator Water Quality Index; Temp- Temperature

and management. Illustrations from monitoring data are also presented to provide additional information and comparisons to literature-based determinations.

2 Applications

2.1 Usage

Of the aforementioned common indices, the NSF WQIs are the most commonly used, particularly the AWQI (Fig. 1, Table 3). A variety of other WQIs exist apart from these most commonly used indices. Collectively, these potentially make up more usage than any of the other indices do when considered individually. However, many of them were developed with a view to improving on common indices (e.g. Said et al. 2004) and few are extensively used beyond their development and/or developers. Some exceptions include the Canadian Council of Ministers of the environment Water Quality Index (CCME-WQI) which was developed and is in regular use in Canada (CCME 2001; De Rosemond et al. 2009; Khan et al. 2004), and the indices by Pesce and Wunderlin (2000) and House and Ellis (1987) both of which have been used in various applications (Abrahao et al. 2007; Bordalo and Savva-Bordalo 2007; House and Ellis 1987; Kannel et al. 2007; Sanchez et al. 2007). Formulation of these indices are presented in the appendix.

The most common use for the indices is in water quality assessments including status assessment, spatial comparisons, and trends assessment (Table 3). The indices have also been used to evaluate potential regulatory program benefits (USEPA 2010; Walsh and Wheeler 2013), and to provide guidance for a management project (Wills and Irvine 1996) among other uses. There have also been efforts to compare indices with each other (Akkoyunlu and Akiner 2012; Alexakis et al. 2016; Gupta et al. 2003; Landwehr and Deininger 1976; Walsh and Wheeler 2013) and/or with expert opinion (McClelland 1974) so as to determine, verify, or demonstrate their applicability, usefulness, and effectiveness.

The AWQI and MWQI are easy to use, which is probably why they are the most commonly used. The challenge in using these two (and other weighted) WQIs lies in assigning weights. While existing weights can and have been used, they may not necessarily be applicable in all locations. Hence the need may arise to develop site-specific weights. As with all the other indices, modification for site conditions may be necessary; subindex parameters can be changed or reduced depending on data availability and/or contaminants of concern (e.g. Akkoyunlu and

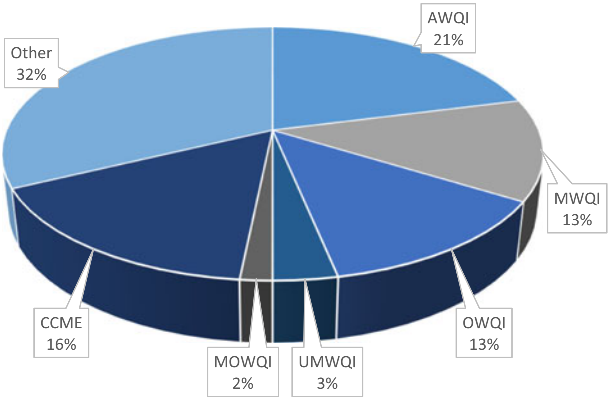


Fig. 1 Frequency of usage for the various Water Quality Indices expressed as a percentage of the total number of entries as obtained from the literature reviewed (Table 3). Values were determined by counting the number of entries for each index and computing associated percentages. Further details including references are provided in Table 3

Table 3 Summary of Applications

Item	Comments	References[a]
Index	AWQI (most common single index)	1, 2, 3, 11, 13, 14, 15, 18, 19, 20, 21, 23, 43
	MWQI (variant of AWQI)	1, 2, 10, 11, 12, 17, 18, 22
	OWQI (mostly Oregon DEQ applications)	3, 4, 5, 6, 7, 8, 9, 11
	UMWQI, MOWQI- not common	1, 2, 11,
	CCME-WQI (Canadian index)	3, 30, 31, 32, 33, 35, 36, 37, 43, 49
	Others	1, 2, 24, 25, 26, 27, 28, 29, 34, 38, 39, 40, 41, 42, 44, 45, 46, 47, 48, 50
Countries	Argentina, Brazil, Canada, China, Croatia, France, Ghana, Greece, Guinea-Bissau, India, Indonesia, Iran, Israel, Italy, Japan, Malaysia, Mexico, Nigeria, Portugal, Spain, Turkey, UK, US, Vietnam	All
Purpose of application	Assessment- status, spatial comparisons, trends (most common)	3,4,5,6,7,8,9, 12, 13, 14, 15, 16, 18, 19, 20, 21, 22, 23, 25, 29, 32, 34, 36, 38, 39, 40, 41, 42, 43, 44, 45, 47, 48, 49
	Evaluation of potential program benefits	10, 17
	Guidance, classification	28, 37, 40, 46, 50
	Index comparison	1, 2, 3, 43
	Verification/demonstration of usefulness/, effectiveness	24, 26, 27, 31, 33, 44
	Communication	21, 35
Water body	Streams/rivers (most common)	2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 15, 16, 17, 18, 20, 21, 22, 24, 25, 27, 28, 34, 38, 41, 42, 47, 48, 49
	Coastal- streams/rivers, lakes in the coastal zone/near shore areas; estuarine areas	1, 4, 5, 6, 7, 8, 9, 23, 39, 50
	Other- springs/wells/ponds/lagoon/lakes; drinking water source (general); other	19, 21, 27, 29, 32, 33, 35, 36, 37, 38, 40, 42, 43, 44; 45, 46, 48, 49, 50

[a] 1. Gupta et al. (2003); 2. Landwehr and Deininger (1976); 3. Akkoyunlu and Akiner (2012); 4. Mrazik (2007); 5. Mrazik (2008); 6. Hubler and Merrick (2012); 7. Merrick and Hubler (2013); 8. ODEQ (2015); 9. Mrazik (2004); 10. USEPA (2010); 11. Walsh and Wheeler (2013); 12. Egborge and Benka-Coker (1986); 13. Dien et al. (2014); 14. Samantray et al. (2009); 15. Wills and Irvine (1996); 16. Lapong et al. (2012); 17. USEPA (2002); 18. McClelland (1974); 19. Chaturvedi and Bassin (2010); 20. Bonanno and Giudice (2010); 21. Stambuk-Giljanovic (1999); 22. Sedeño-Díaz and López-López (2007); 23. Giordani et al. (2009); 24. Pesce and Wunderlin (2000); 25. Abrahao et al. (2007); 26. Kannel et al. (2007); 27 Sanchez et al. (2007); 28. House and Ellis (1987); 29. Bordalo and Savva-Bordalo (2007); 30. Ferreira et al. (2011); 31. Terrado et al. (2010); 32. Vijayakumar et al. (2015); 33. Hurley et al. (2012); 34. Said et al. (2004); 35. Khan et al. (2004); 36. De Rosemond et al. (2009); 37. Boyacioglu (2010); 38. Boyacioglu and Gundogdu (2013); 39.Ujjania and Dubey (2015); 40. Parparov et al. (2014); 41. Fulazzaky (2009); 42. Chen et al. (2015); 43. Alexakis et al. (2016); Hou et al. (2016); 45. Singh et al. (2016); 46. Yidana and Yidana (2010); 47. Zhao et al. (2013); 48. Nikoo and Mahjouri (2013); 49. Norman et al. (2012); 50. Whittaker et al. (2015)

Akiner 2012; Chaturvedi and Bassin 2010; Giordani et al. 2009; Stambuk-Giljanovic 1999; USEPA 2002, 2010; Walsh and Wheeler 2013). The same is true for subindex determination, which can be modified to better reflect site conditions (e.g. USEPA 2010). For weighted indices the challenge again comes in reassigning the weights. Where index comparisons have been conducted, multiplicative indices have been found to work best (Gupta et al. 2003; Landwehr and Deininger 1976; McClelland 1974; Walsh and Wheeler 2013).

In general, WQIs have been found useful, practical, and cost-effective for various uses including water quality assessments and classification, as well as evaluation of regulatory program benefits. Despite the original intent that the indices be used as communication tools, there has been relatively little work done in evaluating their usefulness in that regard. Khan et al. (2004), for example, tested the suitability of the CCME-WQI for assessing drinking water quality and made modifications to the categorization based expert opinion. The authors proposed a secondary testing phase which would involve obtaining public feedback on its suitability as a communication tool. The tool in its original formulation was already accepted for communicating ambient water quality. More work is needed in this area especially with regard to the more common indices.

2.2 Related Concerns and Potential Solutions

As with many computational methods, there are some general concerns associated with the WQIs. Common concerns are discussed in this subsection along with potential solutions.

2.2.1 Eclipsing, Ambiguity and Rigidity

Eclipsing refers to the masking of low value subindices in an overall high WQI value (Abbasi and Abbasi 2012; Lumb et al. 2011a; Swamee and Tyagi 2000) and is especially a problem with the additive model (Lumb et al. 2011a). Attempts to get around this problem include the use of alternative indices using either weighted or unweighted multiplicative models (e.g. McClelland 1974), new index formulations (Cude 2001; Dojlido et al. 1994; Swamee and Tyagi 2007), and/or new approaches to subindex value determination (e.g. Swamee and Tyagi 2007). Another possibility would be to report the lowest scoring determinant alongside the WQI which would provide a flag in the event that a critical determinant was masked in the overall WQI. The minimum operator approach (Smith 1990) provides another alternative that focuses solely on the most impaired water quality parameter. However, this method is insensitive to changes in the other parameters (Abbasi and Abbasi 2012; Walsh and Wheeler 2013) which limits its applicability. Table 4 provides an example of resulting index values and associated interpretations in a case where a low value subindex exists based on the commonly used WQIs. For this table, raw data values were obtained from the Florida Department of Environmental Protection's Impaired Water Rule (IWR) database. In this case, the low value subindex is associated with temperature. While indeed this low value is masked in the AWQI rating, the MOWQI penalizes the water quality rather severely on account of this one parameter. The multiplicative indices seem to have a more uniform rating capturing the parameters across the board.

Ambiguity refers to a situation where the overall index suggests worse water quality than would be expected based on subindex values of all determinants (Lumb et al. 2011a; Swamee and Tyagi 2000). This is a problem that would be primarily encountered with weighted indices, depending on how weights are assigned, although would also be seen with the MOWQI which categorizes water quality based on the most impaired parameter.

Rigidity refers to index inflexibility to accommodate additional or alternate water quality determinants (Swamee and Tyagi 2007). This is especially critical where an impairment occurs in a determinant(s) not included in the index or if an index is applied in an area with concerns different from those for which it was developed (Swamee and Tyagi 2007). The index and subindex value determinations developed by Swamee and Tyagi (2007) provide a means to

Table 4 Example of the impact of the different WQIs on water quality rating in the presence of a low subindex value determinant

	DO % Sat	Temp °C	BOD_5 mg L^{-1}	NO_3^- mg L^{-1}	PO_4^{3-} mg L^{-1}	TS mg L^{-1}	Turb NTU	pH	FC #/100 ml	WQI	Rating	Rating
Raw value	61.5	29.7	1.7	0.08	0.1	319	2.03	7.4	37.2			
AWQI	64	10	84	98	99	67	95	90	68	74	4	Good
MWQI	64	10	84	98	99	67	95	90	68	65	3	Fair
OWQI[a]	30	10	71	96	64	10		100	98	27	1	Very poor
UMWQI	64	10	84	98	99	67	95	90	68	65	3	Fair
MOWQI[b]	60	20	88				40	100	90	20	1	Very poor

[a] Uses TP, a combination of DO saturation and concentration, and $NO_3^- + NH_3$. Q_i shown is for TP; [b] Uses DO concentration. Also uses TSS (mg/l) and Temperature elevation (°C). Q_i values are 90 and 78 respectively. Raw data station: Caloosahatchee River Watershed @S-79, SW Florida, May 2003. Raw data (individual parameter values) source: FDEP IWR Database Run 47

avoid ambiguity and rigidity problems. Indices such as the CCME-WQI which are nonspecific with regard to determinant selection allow sufficient flexibility to accommodate more and/or different determinants. Khan et al. (2004) also instituted a system to flag exceedances associated with any contaminants of health concern (based on the most recent sample) and to prevent water quality rating for that instant. Subindex parameters can also be varied to reflect location-specific concerns. For weighted indices, this would mean establishing new subindex weights.

2.2.2 *Expert Bias*

As previously described, most of the indices rely on expert opinion to establish the determinant set to be used with the index. Virtually all weighted indices also rely on expert opinion to determine the weight assigned to each determinant. Where subindex curves are used to determine parameter values, these are also developed based on expert opinion. This is potentially a concern as it introduces elements of individual bias into the indices. In some cases, the likelihood of perpetuating the bias is higher for example where only a few panel members are engaged. The influence of individual biases is lowered with the engagement of larger panels (Abbasi and Abbasi 2012) and when expert opinion is incorporated into the development of WQIs in a rigorous manner. For example, to develop the NSFWQIs, a panel of experts was assembled, comprising 142 experts including 101 regulatory officials, 26 academicians, 6 consulting engineers, 5 local public utilities managers, and 4 others including engineers and representatives from professional organizations (Brown et al. 1970). The Delphi method was used to obtain feedback from the panel. The Delphi method is a well-established and commonly used method of obtaining feedback and developing scientifically useable/ defensible information (Hsu and Sandford 2007). It has the advantage of maintaining anonymity of participants (participants do not assemble at a common location) and shrouding individual responses thereby overriding response biases that could arise from factors such as sociocultural norms or effects of influential and/or outspoken individuals (Cyphert and Gant 1971; Hsu and Sandford 2007). However, even in this case, some have questioned the basis associated with this approach- which is to converge opinions through an iterative procedure in which prior results are provided to survey respondents at each iteration– as this could potentially pressure participants into altering their judgement to fit with the most common responses (Cyphert and Gant 1971; Hsu and Sandford 2007; Witkin and Altschuld 1995).

The MOWQI development used the Delphi approach although it involved a smaller panel than the original NSFWQI application, and did not require panel members to respond if they felt they had insufficient knowledge to provide an opinion on a particular aspect (Smith 1990). Panel members were also provided with supplemental materials at some point in the process. A similar method was used for the OWQI with the exception that a rejection rationale was employed to reduce redundancies and account for impairment categories in determinant selection, resulting in six determinants for the index (Dunnette 1979). Khan et al. (2004) solicited expert opinion in evaluating the CCMEWQI and found ratings to be generally in line with expert determinations, although they did find the need to re-categorize index ratings based on expert opinion (Khan et al. 2004). The authors suggest the incorporation of expert opinion in categorization of index ratings as important for index development and application, particularly with regard to providing meaningful interpretations of the results.

2.2.3 Link to Water Quality Standards

The CCME-WQI takes into account water quality objectives which can be directly linked to water quality guidelines, criteria, and/or standards. Most other indices do not incorporate this information, which limits their application in that regard. The MOWQI incorporates proposed numeric standards where data are available, with a score of 60 (corresponding to waters just meeting the "suitable for all uses" designation) being assigned to the numeric standard (Smith 1990). A similar approach was taken by USEPA (2010) to score waters based on proposed nutrient criteria with a score of 70 being linked with the proposed water quality criterion for each determinant. Higher scores were assigned to cleaner waters with a score of 100 reflecting pristine conditions. The link to standards is important as it is theoretically possible for a water body to be rated favorably when standards are not being met for at least some of the key determinants.

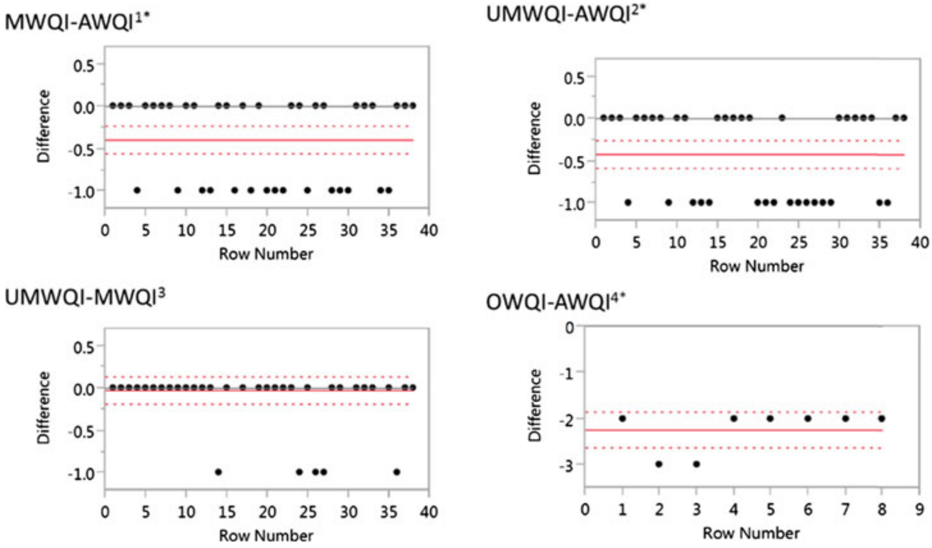
3 Welcome Warning or False Alarm? Choosing the Right Index

Looking back at Table 4, it is evident that the key parameters of concern for that data set are DO, temperature, and total solids (in this case total dissolved solids which are much higher that suspended solids). If the index values were being used in decision making, very low ratings (such as with the MOWQI) could potentially lead to unwarranted investment in remediation programs, while complacency could result from ratings that are very lenient (such as with the AWQI). Thus, in making the decision on which WQI to use, it is important to understand the basis behind the development of the index and to link this basis with location-specific concerns. It is also important to understand how the indices compare to each other with regard to their water quality ratings.

For example, the OWQI was developed for Oregon conditions and to capture concerns in that area such as the need to support cold water fisheries (Cude 2001), thus it would be particularly sensitive to the higher temperatures inherent in the data. It was also developed to be particularly sensitive to high concentrations of dissolved solids and to use DO concentration (rather than saturation as with other indices) so as to provide a better representation of DO requirements for associated aquatic habitats (Cude 2001). It is thus that a rating of "very poor" is obtained from the index as, indeed, the conditions represented by the data would not be suitable for Oregon's aquatic ecosystem needs. On the other hand, the MOWQI was designed to rate water quality with regard to suitability for different water uses- notably water supply, fish spawning, bathing, and general use (Smith 1990) which would explain the heavy emphasis on the most impaired parameter. This is not always practical especially where waters are classified and managed for a designated use. The AWQI was designed to provide a simple means of rating and communicating water quality. It has an inherent weakness in that it cloaks the impact of low value subindices, hence its generous rating despite the existence of impaired determinants.

Figures 2 and 3 and Table 5 show a comparison of ratings obtained using the different WQIs. For Fig. 2, the WQI data were obtained from existing literature (Akkoyunlu and Akiner 2012; Gupta et al. 2003; Landwehr and Deininger 1976). For Fig. 3, WQIs were computed based on data obtained from the Florida Department of Environmental Protection's Impaired Water Rule (IWR) database and covering the period January 2001-June 2012. Table 5 presents a summary of ratings obtain from the IWR data. As shown in Table 1, WQI ranges and interpretations vary across indices; for example, a WQI of 60 gives a rating of "medium" for the AWQI, while the same value if obtained for the OWQI would give a rating of "poor". However, each of indices has five water quality ratings (Table 1) which can be generalized as ranging from 1 (very poor) to 5 (excellent) given that corresponding classes have similar interpretations. For example, a rating of 4 would be associated with a water quality designation of "good" for the NSFWQIs, OWQI, and UMWQI, and "suitable for all uses" for the MOWQI and similarly for other generalized ratings.

In all cases (Figs. 2 and 3; Table 5) the WQI data were reclassified using the numbers 1–5 as described. For the literature-based data, resulting ratings were analyzed to determine standardized mean differences among the different WQIs. This was with the exception of the OWQI-AWQI comparisons as only one set of data was available for the comparison- in which case a mean difference was computed. Mean differences were also computed for the ratings based on

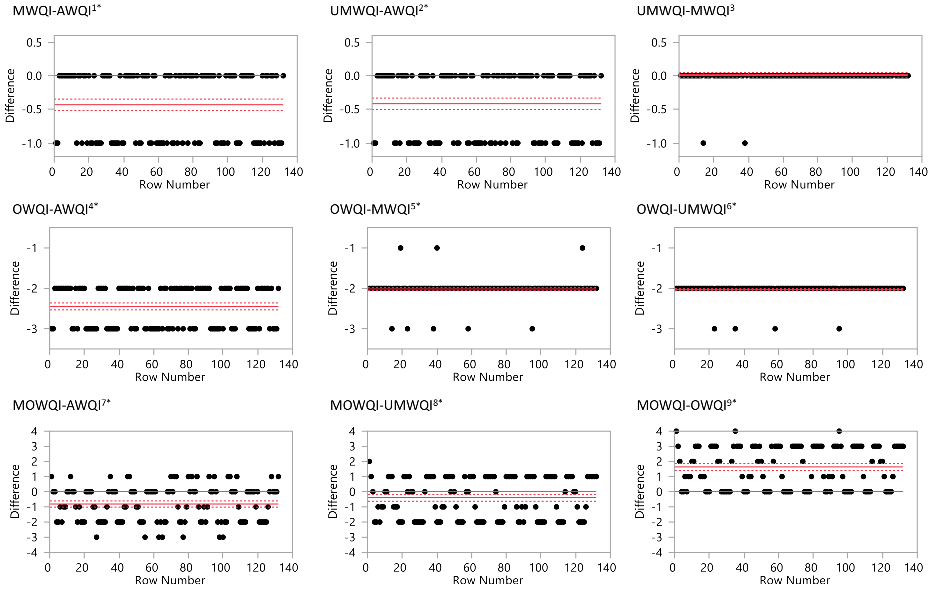

MWQI-AWQI^{1*}

UMWQI-AWQI^{2*}

UMWQI-MWQI^{3}

OWQI-AWQI^{4*}

Fig. 2 Comparison of differences in water quality ratings from different water quality indices based on published data. Dots represent the differences in ratings between the WQIs. Solid lines represent the mean differences. Dotted lines represent the upper and lower 95 % confidence bounds for the mean. Standardized mean difference ($n=38$): 1) -0.5; 2) -0.5; 3) 0.01; 4) Mean Difference ($n=8$) $=-2.25$; *Significant; Base WQI data sources: Akkoyunlu and Akiner (2012); Gupta et al. (2003); Landwehr and Deininger (1976)


MWQI-AWQI[1*] UMWQI-AWQI[2*] UMWQI-MWQI[3]

OWQI-AWQI[4*] OWQI-MWQI[5*] OWQI-UMWQI[6*]

MOWQI-AWQI[7*] MOWQI-UMWQI[8*] MOWQI-OWQI[9*]

Fig. 3 Comparison of differences in water quality ratings from different water quality indices based on monitoring data. Dots represent the differences in ratings between the WQIs. Solid lines represent the mean differences. Dotted lines represent the upper and lower 95 % confidence bounds for the mean. Mean Difference: 1) -0.43; 2) -0.42; 3) 0.02; 4) -2.45; 5) -2.02; 6) -2.03; 7) -0.81; 8) -0.39; 9) 1.64. *Differences are significant. Raw data station: Caloosahatchee River Watershed @S-79, SW Florida. Raw data (individual parameter values) source: FDEP IWR Database Run 47, January 2001-June 2012

monitoring data. Figures 1 and 2 were developed based on matched-pair comparisons of the ratings obtained based on each of the datasets. Based on the analyses associated with Fig. 2, the AWQI offered a more generous water quality rating than any of the other indices (absolute standardized mean difference = 0.5) while the OWQI tended to be more strict than the AWQI (absolute mean difference = 2.25). Ratings from UMWQI and MWQI were about the same. Similar patterns were observed for these indices based on monitoring data (Fig. 3- top, Table 5) with the mean differences observed being close to those obtained using literature-based data. With the MOWQI, however, patterns obtained were erratic (Fig. 3- bottom, Table 5) with no clear indication as to the behavior of the index relative to the other indices.

Table 5 Summary of monthly water quality ratings obtained from the various indices based on monitoring data

Water quality rating	Number of months with corresponding water quality rating				
	AWQI	MWQI	UMWQI	OWQI	MOWQI
5	0	0	0	0	3
4	60	6	5	0	54
3	72	123	127	0	12
2	0	3	0	1	19
1	0	0	0	131	44
Total months	132	132	132	132	132

Raw data station: Caloosahatchee River Watershed @S-79, SW Florida. Raw data (individual parameter values) source: FDEP IWR Database Run 47, January 2001-June 2012

The discussed considerations then point to the need for site- and use-specific evaluations, as well as testing of specific indices prior to index selection and application. In the absence of site-specific indices or if there are no plans to pursue such development, the multiplicative indices seem to provide a more balanced determination as they are neither too strict nor too lenient in their ratings. If need be, determinants can be changed to better reflect water quality concerns in the area. Subindex calculation methods including weights and curves where applicable, and/or equations can also be modified for a particular site, location, or region. For example, USEPA (2010) used the MWQI with a reduced and redefined set of determinants (DO, BOD_5, total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and fecal coliform) in line with expected ecosystem responses and water body type, and also based on data availability. The OWQI approach was used to develop region-specific total TP, TN, TSS, and DO curves for clear and colored lakes, and flowing waters in Florida. Subindex values of TN, TP, and TSS meeting pre-specified water quality criteria were set to 70, while determinant values above the 90th percentile were assigned a value of 100 and those in the 10th percentile and below were assigned a value of 10. Subindex values ranged from 10 (worst) to 100 (pristine) with the exception of fecal coliform which was capped at 98.

4 Exploring Potentials

Because of their aggregated nature, WQIs are potentially valuable tools in water quality decision making and management. Their utilization can be viewed as a process which starts with flagging contaminants of concern (Fig. 4). The information can then be used to predict potentially harmful conditions and to guide the prioritization of management efforts and funds. The same indices can then be used to assess the overall impacts of those management decisions and associated interventions as well as to communicate those impacts. Further, the indices can be used to continuously monitor the health of the associated water resource. The process resets if the same (or other) contaminants are flagged.

4.1 Flag Contaminants and Predict Potentially Harmful Conditions

Generally, water quality parameter values are reported in different units, this being dependent on the parameter in question. Furthermore, different determinants are environmentally significant at different levels, making it difficult to discern potentially harmful effects based solely on raw data. For example, Benzo(a)pyrene (pesticide) may cause harmful effects at levels quantifiable in ng/l (0.0002 mg/l) while for nitrates harmful effects will occur at much higher levels (10 mg/l) (USEPA-CCR 2015). Presentation of water quality data in its raw form could potentially mask the pesticide as a contaminant of concern, particularly with respect to communicating the information and having it be used meaningfully for decision making. In normalizing the values to a 0–100 (or 10–100) scale, WQIs allow contaminant impacts to be assessed comparatively, allowing a definitive flagging of contaminants of concern. Furthermore, in indices which are tied to water quality objectives or standard (e.g. the CCMEWQI), the normalization allows determinants to be viewed comparatively relative to their relationship with prevailing water quality guidelines and/or standards. As water may not show obvious signs of contamination (or obvious pollution as described in Brown, 1965), subindex values will flag a potential contaminant and, more importantly, help in communicating the associated concern by putting the information in terms that are generally understood.

Fig. 4 Exploring potentials for use of Water Quality Indices for decision-making and management

In flagging contaminants of concern, WQIs offer added value in that they can then be used to predict potentially harmful conditions. For example: low DO can result in reduced fish growth and reproduction and impaired immune responses. Conditions can become lethal to some organisms and can also result in changes in predator–prey interactions (Breitburg et al. 2009, 1997); Temperature affects DO saturation, solubility and chemical reaction rates, substance toxicity, metabolism, growth and reproduction, and species diversity (Armour 1993; Coulter et al. 2014). It can also upset the biological clocks of some organisms (Armour 1993) causing for example offspring to emerge early before conditions are suitable for their growth; Solids cause habitat destruction, can inhibit or harm biological life, can be a source of other contaminants, and also lead to the loss of aesthetic value (Bilotta and Brazier 2008; Kemp et al. 2011). Thus, if any of these determinants is flagged, associated harmful conditions can be predicted.

4.2 Guide Prioritization of Management Efforts and Funds

Horton (1965), in conceptualizing the original index, had the intention of enabling comparative assessments of waters in different locations by subjecting them to the same overall measure. Such assessments provide information that is valuable guiding decision making. For example, the Oregon Department of Environmental Quality (ODEQ) uses the OWQI extensively to provide a general assessment of water quality in Oregon streams; results form part of Oregon's water quality assessments and help guide the development of action plans to address water quality issues in the state (e.g. ODEQ 2013). In this regard, the OWQI is calculated on a regular basis for stations across the state. This is done for overlapping 10-year periods (e.g. 1998–2007; 2001–2010; 2003–2012) to provide an assessment of changes occurring in the streams (Hubler and Merrick 2012; Merrick and Hubler 2013; Mrazik 2008; ODEQ 2015). Non-parametric seasonal trends analyses are also conducted on resulting data to determine whether there have been improvements or declines in water quality over time at the various locations. Table 6 shows OWQI values at various stations as extracted from various ODEQ reports and their progression across time. Based on this table, it is possible to see locations at which there has been no change in water quality status over time, and where this is a desirable situation (Kilchi, Youngs) as well as where it is of concern (Klaskanine, Skipanon). It is also possible to identify areas of water quality improvement (Nehalem) and where water quality is declining (Trask).

Figure 5 shows UMWQI time series at locations in the Caloosahatchee Estuary in Southwest Florida, beginning at the upstream end (Tidal 3) and down to the mouth (Tidal 1). Raw data for this figure were obtained from the aforementioned IWR database covering the period January 2001-June 2012, and WQI was calculated based on (USEPA 2010) sub index determinations. While WQI values at all locations fluctuated with time, water quality was mainly between “bad” and “medium” at the upstream end and between “bad” and “good” in mid estuary. Water quality improved downstream at the mouth of the estuary fluctuating between “medium” and “good”. This suggests the need for particular attention at the upstream end. However since the water quality generally does not go above “good” at any of the locations, WQI values suggest the need for water quality interventions at all locations albeit with particular attention to the upstream end.

4.3 Assess Overall Impacts of Water Quality Interventions

A water quality indexing system is valuable in assessing the overall impacts of existing, planned, or potential interventions as WQI values can be calculated to capture “before” and “after” scenarios. Often times, management interventions for water quality protection or remediation are assessed based on their effectiveness in reducing the amount or concentrations of specific contaminants. Such assessments are typically done on a watershed, farm, or field scales. While these kinds of assessments provide valuable information on contaminant reduction capabilities and potentials of the interventions, they do not give an indication of resultant water quality status on the basis of that contaminant and in general. In that regard, WQIs can be used to provide a more in-

Table 6 Oregon Water Quality Index values showing water quality progression at various locations. OWQI values extracted from Oregon Department of Environmental Quality Reports: Mrazik (2008); Hubler and Merrick (2012); Merrick and Hubler (2013); ODEQ (2015)

Station	OWQI values and associated water quality ratings								
	1998–2007	Rating	2001–2010	Rating	2003–2012	Rating	2005–2014	Rating	Overall
Kilchis at Alderbrook			85	Good	87	Good	87	Good	No Change
Klaskanine at Young’s river	65	Poor	63	Poor	65	Poor	63	Poor	No Change
Nehalem at Birenkfeld	83	Fair	85	Good	86	Good	86	Good	Improved
Skipanon at 101	37	Very poor	37	Very poor	37	Very poor	35	Very poor	No Change
Tillamook at Bewley	59	Very poor	56	Very poor	64	Poor	66	Poor	Improving
Trask at 101	86	Good	83	Fair	82	Fair	83	Fair	Declining
Youngs at Loop	89	Good	87	Good	88	Good	87	Good	No change

depth and holistic view of water quality impacts. For example, if a proposed management practice could potentially reduce nitrate concentrations by 20 %, then an initial contaminant level of 20 mg/l would be reduced to 16 mg/l. While this is valuable information, some questions remain unaddressed: What does the reduction mean in the context of water quality as impacted by the said contaminant? By how much does the contaminant need to be reduced in order for the water quality classification to improve? What else needs to be addressed in terms of overall water quality improvements? Using this value (20 mg/l) with the UMWQI (as an example) gives a subindex value of 64 and an associated rating of "medium" for the determinant. Based on associated subindex values, nitrate concentrations would need to be reduced by about 75 % before the determinant can be rated as "good" and by about 90 % before it can be rated as "excellent." The point at which these reductions would result in a change in overall water quality status would need to be determined but may depend on other determinants and whether or not they were impacted.

4.4 Communicate Impacts of Management and Policy Decisions

In their original formulation, WQIs were intended as tools to communicate water quality status to a variety of audiences. This use can be further extended to communicating the impacts of management and policy decisions. For example, USEPA (2010) and Walsh and Wheeler (2012) document a

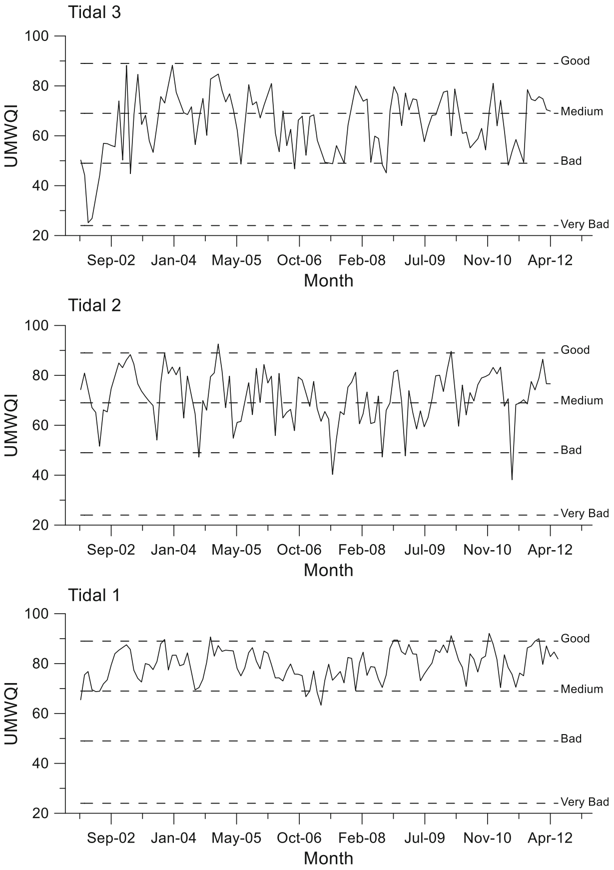


Fig. 5 Historical UMWQI time series at locations in the Caloosahatchee Estuary in Southwest Florida, beginning at the upstream end (Tidal 3) and down to the mouth (Tidal 1). Raw data (individual parameter values) source: FDEP IWR Database Run 47

cost-benefit analysis of the impact of proposed nutrient criteria for flowing waters in Florida; this analysis has WQIs as its basis. As noted earlier, the effectiveness of WQIs as communication tools has not been evaluated widely. This is an area in which more research is warranted.

4.5 Monitor the Health of the Water Resource

Abbasi and Abbasi (2012) suggested the use of WQIs as indicators of the health of the water resource. As water quality encompasses physicochemical and microbiological constituents as well as the ecological integrity of the water body, WQIs can be used alongside biotic indices (e.g. Karr 1993) to give an overall assessment of water body health. Overall interpretations such as "Extremely Healthy", "Healthy", "At Risk", "Poor Health", or "Unhealthy' can be explored to rate the health of a water body. It should be noted, however, that such qualitative ratings are only to provide an aggregate indication of water quality/body status and should derive from and be used alongside (and not in place of) quantitative data. It should be noted too that water resource health goes beyond its physicochemical, microbiological and ecological components to encompass other dimensions notably ones related to society, economics, and policy (Flint 2006; Goldin 2013; Karr 1993). Continuous evaluation and reporting of overall water quality status as is done in Oregon with the OWQI and in Canada with the CCMEWQI would go a long way in ensuring the integrity of the water resource and in addressing any concerns/flags as they arise. The approach of Khan et al. (2004) which runs all contaminants of health concern to flag any exceedances before calculating an overall status offers added benefits as it precludes the rigidity that is common with other indices.

5 Summary and Conclusions

Water Quality Indices offer a means of pooling together otherwise complex water quality data into a composite value that provides an indication of the overall water quality status of a water body. While their usefulness and effectiveness has been tested and verified in a variety of locations and settings, WQIs do not replace analysis of detailed water quality and other environmental data; they are, in fact, dependent on these detailed data to drive the algorithms behind the aggregate values. The number and variety of WQI models that exist is overwhelming with a marked lack of progress towards a single, widely applicable WQI. With their potential as decision making and management tools, this lack of a standardized model is unfortunate. The variety of water quality determinants of concern along with locational differences that impact WQI performance may make it difficult to have a single WQI formulation. The use of more objective and less rigid formulations would help in moving towards a single index. An index that allows flexible designation of determinants based on contaminants of concern and that does not necessitate the determination of weights or site-specific subindex curves may serve such a purpose. With such development, there is the further need to develop performance measures, evaluation procedures, and criteria to allow assessments of index validity. While objective index formulations would offer more flexible options for WQI application, incorporation of expert opinion at some level is important for the acceptability of WQIs as tools for water resources management. WQIs can be used together with other indicators, such as indices of biological integrity, to give a comprehensive view of water resource health. A detailed look at individual subindices or other potentially key determinants helps provide insights on existing and potential threats. The use of the indices on a continuous basis provides long-term data which is helpful for water quality decision making and management.

Acknowledgments The authors are grateful for the support provided by Purdue University's Center for the Environment.

Appendix

Table 7 Other Key Indices

Index	Formulation	Ranges/ Interpretation	Reference
Canadian council of ministers of the environment water quality index (CCME-WQI)	$CCMEWQI = 100 - \left(\frac{\sqrt{F_1^2+F_2^2+F_3^2}}{1.732}\right)$ The factor 1.732 normalizes values to range between 0 and 100 F_1 is a scope factor which represents the extent to which water quality objectives were not met, thus: $F_1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables}\right)*100$ F_2 is a frequency factor representing the proportion of individual tests in which the water quality objectives were not met, thus: $F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right)*100$ F_3 is an amplitude factor representing the amount by which failed tests deviate from their respective water quality objective, thus: $F_3 = \left(\frac{nse}{0.01*nse+0.01}\right)$ Normalized sum of excursions (nse) is determined as: $nse = \frac{\sum_{i=1}^{n} excursion_i}{Number\ of\ tests}$ Where the test value must not exceed the criteria, the excursion is determined as: $excursion_i = \left(\frac{Failed\ test\ value_i}{Objective_j}\right) - 1$ Where the value must not fall below, it is determined as: $excursion_i = \left(\frac{Objective_j}{Failed\ test\ value_i}\right) - 1$	95–100 Excellent 80–94 Good 65–79 Fair 45–64 Marginal 0–44 Poor	CCME 2001
WQIsub	$WQIsub = k\frac{\sum_i C_i P_i}{\sum_i P_i}$ k = subjective constant based on visual impression of pollution C_i subindex value P_i weights (similar to AWQI excepts weights do not equal one hence the division		Pesce and Wunderlin 2000
Alternative index	$WQI = \frac{1}{100}\left[\sum_{i=1}^{n} Q_i W_i\right]^2$ Q_i = subindex value; W_i = weighting value; n = number of determinants		House and Ellis (1987)

References

Abbasi T, Abbasi SA (2012) Water quality indices. Elsevier

Abrahao R, Carvalho M, da Silva W, Machado T, Gadelha C, Hernandez M (2007) Use of index analysis to evaluate the water quality of a stream receiving industrial effluents. Water SA 33:459–465

Akkoyunlu A, Akiner ME (2012) Pollution evaluation in streams using water quality indices: a case study from Turkey's Sapanca lake Basin. Ecol Indic 18:501–511

Alexakis D, Tsihrintzis VA, Tsakiris G, Gikas G (2016) Suitability of water quality indices for application in lakes in the Mediterranean. Water Resour Manage 30:1621–1633. doi:10.1007/s11269-016-1240-y

Armour CL (1993) Evaluating temperature regimes for protection of smallmouth bass. DTIC Document

Asadollahfardi G (2015) Water quality indices (WQI). In: Asadollahfardi G (ed) Water quality management: assessment and interpretation. Springer, Heidelberg, pp 21–39

Bilotta G, Brazier R (2008) Understanding the influence of suspended solids on water quality and aquatic biota. Water Res 42:2849–2861

Bonanno G, Giudice RL (2010) Application of two quality indices as monitoring and management tools of rivers. Case study: the Imera Meridionale River, Italy. Environ Manage 45:856–867

Bordalo AA, Savva-Bordalo J (2007) The quest for safe drinking water: an example from Guinea-Bissau (West Africa). Water Res 41:2978–2986

Boyacioglu H (2010) Utilization of the water quality index method as a classification tool. Environ Monit Assess 167:115–124

Boyacioglu H, Gundogdu V (2013) Efficiency of water quality index approach as an evaluation tool. Ecol Chem Eng S 20:247–255. doi:10.2478/eces-2013-0017

Breitburg DL, Loher T, Pacey CA, Gerstein A (1997) Varying effects of low dissolved oxygen on trophic interactions in an estuarine food web. Ecol Monogr 67:489–507

Breitburg DL, Hondorp DW, Davias LA, Diaz RJ (2009) Hypoxia, nitrogen, and fisheries: integrating effects across local and global landscapes. Annual Rev Marine Sci 1:329–349

Brown RM, McClelland NI, Deininger RA, Tozer RG (1970) A water quality index- do we dare? Water Sewage Works 11:339–343

Brown RM, McClelland NI, Deininger RA, O'Connor MF (1972) A water quality index—crashing the psychological barrier. In: Thomas WA (ed) Indicators of environmental quality. Plenum Press, New York, pp 173–182

CCME (2001) CCME water quality index 1.0 technical report. Available at: http://www.ccme.ca/files/Resources/calculators/WQI%20Technical%20Report%20%28en%29.pdf. Last accessed 12/22/2015. Canadian Council of Ministers of the Environment, Canada

Chaturvedi M, Bassin J (2010) Assessing the water quality index of water treatment plant and bore wells, in Delhi, India. Environ Monit Assess 163:449–453

Chen Z, Zhu Z, Yin L, Wei S, Deng L (2015) The changing water quality characteristics from urban drinking water sources in Guangdong, China. Water Resour Manage 29:987–1002. doi:10.1007/s11269-014-0855-0

Coulter D, Sepúlveda M, Troy C, Höök T (2014) Thermal habitat quality of aquatic organisms near power plant discharges: potential exacerbating effects of climate warming. Fisheries Manag Ecol 21:196–210

Cude C (2001) Oregon water quality index: a tool for evaluating water quality management effectiveness. J Am Water Resour As 37:125–137. doi:10.1111/j.1752-1688.2001.tb05480.x

Cyphert FR, Gant WL (1971) The Delphi technique: a case study. Phi Delta Kappan 52:272–273

Dalkey NC, Brown BB, Cochran S (1969) The Delphi method: an experimental study of group opinion vol 3. Rand Corporation, Santa Monica

De Rosemond S, Duro DC, Dubé M (2009) Comparative analysis of regional water quality in Canada using the water quality index. Environ Monit Assess 156:223–240

Dien LD, Lan MT, Hung ND (2014) The changes of water quality in space and time in the Mekong River, Bassac River and adjacent waterways. J Life Sci 8:481–488

Dojlido J, Raniszewski J, Woyciechowska J (1994) Water-quality index applied to rivers in the Vistula river basin in Poland. Environ Monit Assess 33:33–42. doi:10.1007/BF00546659

Dunnette D (1979) Geographically variable water-quality index used in Oregon. J Water Pollut Con F 51:53–61

Egborge AB, Benka-Coker J (1986) Water quality index: application in the Warri River, Nigeria. Environ Pollut B 12:27–40

Ferreira N, Bonetti C, Seiffert W (2011) Hydrological and water quality indices as management tools in marine shrimp culture. Aquaculture 318:425–433. doi:10.1016/j.aquaculture.2011.05.045

Flint RW (2006) Water resource sustainable management: thinking like a watershed. Ann Arid Zone 45:399

Fulazzaky M (2009) Water quality evaluation system to assess the Brantas River water. Water Resour Manage 23:3019–3033. doi:10.1007/s11269-009-9421-6

Giordani G, Zaldivar J, Viaroli P (2009) Simple tools for assessing water quality and trophic status in transitional water ecosystems. Ecol Indic 9:982–991. doi:10.1016/j.ecolind.2008.11.007

Goldin J (2013) From vagueness to precision: raising the volume on social issues for the water sector. Water Policy 15:309

Gupta A, Gupta S, Patil R (2003) A comparison of water quality indices for coastal water. J Environ Sci Heal A 38:2711–2725. doi:10.1081/ESE-120024458

Horton RK (1965) An index number system for rating water quality. J Water Pollut Con F 37:300–306

Hou W et al (2016) Assessing water quality of five typical reservoirs in lower reaches of Yellow River, China: using a water quality index method. Ecol Indic 61:309–316. doi:10.1016/j.ecolind.2015.09.030

House M, Ellis J (1987) The development of water-quality indexes for operational management. Water Sci Technol 19:145–154

Hsu C-C, Sandford BA (2007) The Delphi technique: making sense of consensus. Pract Assessment, Res Evaluation 12:1–8

Hubler S, Merrick L (2012) Oregon water quality index summary report: water years 2001–2010. Oregon Department of Environmental Quality, Hillsboro

Hurley T, Sadiq R, Mazumder A (2012) Adaptation and evaluation of the Canadian council of ministers of the environment water quality index (CCME WQI) for use as an effective tool to characterize drinking source water quality. Water Res 46:3544–3552. doi:10.1016/j.watres.2012.03.061

Kannel P, Lee S, Lee Y, Kanel S, Khan S (2007) Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environ Monit Assess 132:93–110. doi:10.1007/s10661-006-9505-1

Karr JR (1993) Defining and assessing ecological integrity: beyond water quality. Environ Toxicol Chem 12: 1521–1531

Kemp P, Sear D, Collins A, Naden P, Jones I (2011) The impacts of fine sediment on riverine fish. Hydrol Process 25:1800–1821

Khan A, Paterson R, Khan H (2004) Modification and application of the Canadian council of ministers of the environment water quality index (CCME WQI) for the communication of drinking water quality data in Newfoundland and Labrador. Water Qual Res J Can 39:285–293

Landwehr JM, Deininger R (1976) A comparison of several water quality indexes. J Water Pollut Con F 49:954–958

Lapong E, Fujihara M, Izumi T, Hamagami K, Kobayashi N, Kakihara T (2012) Water quality characterization and index optimization: the case of agricultural rivers in Southern Ehime, Japan. J Rainwater Catchment Syst 18:1–8

Lumb A, Sharma T, Bibeault J (2011a) A review of genesis and evolution of water quality index (WQI) and some future directions. Water Qual Expo Health 3:11–24. doi:10.1007/s12403-011-0040-0

Lumb A, Sharma T, Bibeault J, Klawunn P (2011b) A comparative study of USA and Canadian water quality index models. Water Qual Expo Health 3:203–216. doi:10.1007/s12403-011-0056-5

McClelland NI (1974) Water quality index application in the Kansas River Basin. US Environmental Protection Agency, Kansas City

Merrick L, Hubler S (2013) Oregon water quality index summary report: water years 2002–2011 and 2003–2012. Oregon Department of Environmental Quality, Hillsboro

Mrazik S (2004) Water quality report: ambient monitoring stations in the Oregon coast Coho evolutionarily significant unit. Oregon Department of Environmental Quality, Portland

Mrazik S (2007) Oregon water quality index summary report: water years 1997–2006. Oregon Department of Environmental Quality, Portland

Mrazik S (2008) Oregon water quality index summary report: water years 1998–2007. Oregon Department of Environmental Quality, Portland

Nikoo MR, Mahjouri N (2013) Water quality zoning using probabilistic support vector machines and self-organizing maps. Water Resour Manage 27:2577–2594. doi:10.1007/s11269-013-0304-5

Norman ES, Dunn G, Bakker K, Allen DM, de Albuquerque RC (2012) Water security assessment: integrating governance and freshwater indicators. Water Resour Manage 27:535–551. doi:10.1007/s11269-012-0200-4

ODEQ (2013) South coast Basin water quality status and action plan. Oregon Department of Environmental Quality, Portland

ODEQ (2015) Oregon water quality index summary report: water years 2005–2014 (Oct. 1, 2005 through Sept. 30, 2014). Oregon Department of Environmental Quality, Hillsboro

Parparov A, Hambright KD, Berman T (2014) Water quality assessment. In: Zohary T, Sukenik A, Berman T, Nishri A (eds) Lake Kinneret – ecology and management. Springer, Dordrecht

Pesce S, Wunderlin D (2000) Use of water quality indices to verify the impact of Cordoba City (Argentina) on Suquia River. Water Res 34:2915–2926. doi:10.1016/S0043-1354(00)00036-1

Poonam T, Tanushree B, Sukalyan C (2013) Water quality indices—important tools for water quality assessment: a review. Int J Advances Chem 1:15–28

Sackman H (1974) Delphi assessment: expert opinion, forecasting, and group process. DTIC document. Rand Corporation, Santa Monica

Said A, Stevens DK, Sehlke G (2004) An innovative index for evaluating water quality in streams. Environ Manage 34:406–414

Samantray P, Mishra BK, Panda CR, Rout SP (2009) Assessment of water quality index in mahanadi and atharabanki rivers and Taldanda Canal in Paradip Area, India. J Hum Ecol 26:153–161

Sanchez E, Colmenarejo M, Vicente J, Rubio A, Garcia M, Travieso L, Borja R (2007) Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. Ecol Indic 7:315–328. doi:10.1016/j.ecolind.2006.02.005

Sedeño-Díaz JE, López-López E (2007) Water quality in the Río Lerma, Mexico: an overview of the last quarter of the twentieth century. Water Resour Manage 21:1797–1812

Singh SK, Singh P, Gautam SK (2016) Appraisal of urban lake water quality through numerical index, multivariate statistics and earth observation data sets. Int J Environ Sci Technol 13:445–456. doi:10.1007/s13762-015-0850-x

Smith D (1990) A better water-quality indexing system for rivers and streams. Water Res 24:1237–1244. doi:10.1016/0043-1354(90)90047-A

Stambuk-Giljanovic N (1999) Water quality evaluation by index in Dalmatia. Water Res 33:3423–3440. doi:10.1016/S0043-1354(99)00063-9

Swamee P, Tyagi A (2000) Describing water quality with aggregate index. J Environ Eng-ASCE 126:451–455. doi:10.1061/(ASCE)0733-9372(2000)126:5(451)

Swamee PK, Tyagi A (2007) Improved method for aggregation of water quality subindices. J Environ Eng-ASCE 133:220–225

Terrado M, Borrell E, de Campos S, Barcelo D, Tauler R (2010) Surface-water-quality indices for the analysis of data generated by automated sampling networks. Trac-Trend Anal Chem 29:40–52. doi:10.1016/j.trac.2009.10.001

Ujjania N, Dubey M (2015) Water quality index of estuarine environment. Curr Sci 108:1430–1433

USEPA (2002) Estimation of national economic benefits using the national water pollution control assessment model to evaluate regulatory options for concentrated animal feeding operations. U.S. Environmental Protection Agency, Washington

USEPA (2010) Economic analysis of final water quality standards for nutrients for Lakes and flowing waters in Florida. Available at: http://www.epa.gov/sites/production/files/2015-07/documents/florida-economic-anaylis-report.pdf. Last accessed 12/22/2015. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, DC

USEPA-CCR (2015) Consumer confidence reports- appendix A to subpart O - Regulated contaminants. Available at: http://www.epa.gov/ccr/appendix-subpart-o-regulated-contaminants. Last accessd December 2015

Vijayakumar N, Gurugnanam B, Nirmaladevi C, Panchamin K (2015) CCME based water qulaity index assessment of Upper Thirumanimuttar sub basin Cauvery River South India. Int J Scientific Res Dev 3:10–13

Walsh PJ, Wheeler WJ (2012) Water quality index aggregation and cost benefit analysis. U.S. Environmental Protection Agency, National Center for Environmental Economics, Washington

Walsh PJ, Wheeler WJ (2013) Water quality indices and benefit-cost analysis. J Benefit-Cost Analysis 4:81–105

Whittaker G, Barnhart B, Färe R, Grosskopf S (2015) Application of index number theory to the construction of a water quality index: aggregated nutrient loadings related to the areal extent of hypoxia in the northern Gulf of Mexico. Ecol Indic 49:162–168

Wills M, Irvine KN (1996) Application of the national sanitation foundation water quality index in Cazenovia Creek, NY, pilot watershed management project. Middle States Geographer 1996:95–104

Witkin BR, Altschuld JW (1995) Planning and conducting needs assessments: a practical guide. Sage Publications, Thousand Oaks

Yidana SM, Yidana A (2010) Assessing water quality using water quality index and multivariate analysis. Environ Earth Sci 59(7):1461–1473

Zhao P, Tang XY, Tang JL, Wang C (2013) Assessing water quality of three gorges reservoir, China, over a five-year period from 2006 to 2011. Water Resour Manage 27:4545–4558. doi:10.1007/s11269-013-0425-x