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AGGREGATION TECHNIQUES APPLIED IN WATER QUALITY INDICES (WQIS)

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ABSTRACT

Since water quality is a prime natural resource, it is then important to conduct regular water quality assessment that describes the degree of pollution and substantiate the healthiness of water resources. And water quality index is an essential tool that can provide an initial quick guide necessary to evaluate water quality status of a given water body. Water quality indices are beneficial for integrating significant physical, chemical and biological constituents of water and provide a simple, but yet scientifically justifiable water quality rating score. Such a valuable and unique rating comprehend the influence of various water quality variables and easily communicate water quality data to non-technical individuals and more importantly the policy-makers. In order to obtain a WQI, sub-indices of water quality variables are employed to indicate water quality on a scale most probably from zero (worst quality) to unity (best quality). Furthermore, the sub-indices are aggregated to yield an overall WQI value normally between zero (poor quality) and hundred (excellent quality). In this review paper, various aggregation techniques have been evaluated, outlining their advantages and disadvantages. Conclusions have been drawn about the similarities and dissimilarities existing among different aggregation methods leading to the suggestion of possible methods applicable in the development of a universal water quality index for South African river catchments.

KEY WORDS : Additive method, Multiplicative method, Minimum operator method, Mixed aggregation technique, Water quality, Water quality index (WQI), Water quality parameters

INTRODUCTION

Water quality is a multi-parameter attribute, it is a function of the cumulative effects of vast amount of water quality variables; and water quality indices provides a sensible solution in resolving lengthy, multi-parameter water analysis and reports as a single digit score (Sarkar and Abbasi, 2006).

Water quality index is a simple, but yet intelligible rating score that provides the composite influence of various water quality variables in a given water body (Luzati and Jaupaj, 2016; Wanda *et al*., 2016; Guettaf *et al*., 2017). The index number is normally measured against a relative scale to explain the quality of water based on categories ranging from zero to hundred, which is further classified from very poor to excellent (Paun *et al*., 2016). Commonly, the development of water quality indices (WQIs) involves (i) selection of the significant water quality parameters; (ii) formation of sub-indices; (iii) establishing relative parameters weights; and (iv) aggregation of the sub-indices (Srebotnjak *et al*., 2012; Al-Mutairi *et al*., 2014; Paun *et al*., 2016; Sutadian *et al*., 2016; Shah and Joshi, 2017, Banda and Kumarasamy, 2020).

This being that, this review paper, attempts to discuss various aggregation techniques applicable to water quality indices (WQIs) and present a comparative analysis of the most important aggregation methods developed since the inception of WQIs. Such contribution is significant towards the current research studies aimed at developing a universal water quality index that is applicable to most, if not all the river catchments in South Africa.

Basic Procedure of Developing a Water Quality Index

A considerable number of indices have been developed since the primary index by Horton (1965), but regardless of such efforts, there is still no globally acceptable manner in which water quality indices are developed (Sutadian *et al.*, 2016). However, there is a certain realisable trend, which is distinguished by the following common steps (Abbasi and Abbasi, 2012; Fu and Wang, 2012; Walsh and Wheeler, 2012; Tyagi *et al.*, 2013; Poonam *et al.*, 2015; Paun *et al.*, 2016, Banda and Kumarasamy, 2020):

(i) **Selection of parameters:** identifying and choosing the most critical variables suitable enough to provide a functional sense to the water quality index. Proficiency is required, in order to provide just enough parameters, not too few or too many. This process can be done by either expert opinion (whether individually or as a group) or through statistical techniques;

(ii) **Formation of sub-index values:** considering that various water quality parameters have different scientific units, it becomes necessary to transform them into a single common scale and this task is achieved by generating sub-indices;

(iii) **Establishing weights:** weightage is assigned to each variable based on the level of importance of each parameter; established through evaluating the potential impact of each parameter when their concentration levels are outside the permissible limits. Though Delphi is a tedious process, the method will minimise subjectivity in establishing weights and enhance credibility of the index; and

(iv) **Aggregation of sub-indices:** this if the final step towards obtaining a final cumulative index value. In cognizance of the assigned weights, mathematical models are used to combine all the sub-indices into one index number. They are various aggregation methods available, but there are three fundamental models commonly used. These are additive, multiplicative and logical functions.

Of lately, several attempts have been made to explore the structure and relationship of water quality variables using statistical approaches like cluster analysis, discriminant analysis, factor analysis and principal component analysis (see Mahapatra *et al.*, 2012; Zhao *et al.*, 2012; Wan *et al.*, 2013). Even the application of artificial intelligence methods, which includes fuzzy logic and artificial neural networks has been tested, with the aim of reducing prejudice and improve on the reliability of the water quality index models (Lermontov *et al.*, 2009; Singh *et al.*, 2009; Gazzaz *et al.*, 2012; Scannapieco *et al.*, 2012; Cordoba *et al.*, 2014; Poonam *et al.*, 2015).

Further details regarding the aggregation methods used in the development of water quality indices (WQIs), are discussed at length in the subsequent sections of this review paper.

Aggregation of sub-indices

Aggregation of sub-indices is performed by mathematical functions. These equations integrate sub-index values of selected critical parameters in relation to the assigned weights; and obtain the overall water quality status, which is normally presented as a unit-less number. Their application is governed by the degree of accuracy required and whether the parameter weights are either equally or unequally defined. Aggregation process may occur in sequential phases depending on whether an index has aggregated sub-indices or not. Though there are various aggregation techniques available, the common aggregation methods are the additive (arithmetic) and multiplicative (geometric) methods (Sutadian *et al.*, 2016).

The following sub-sections of the study attempts to discuss only the commonly used aggregation methods and state their mathematical structures. Nevertheless, the rest of the reviewed water quality indices, including their aggregation techniques and mathematical structures are documented towards the end of this review paper as Appendix A: Details of reviewed water quality indices (WQIs).

Additive method

Additive method has been broadly used for aggregation of sub-indices of various water quality indices (see Brown *et al.*, 1970; Prati *et al.*, 1971, Walski and Parker, 1974; SRDD, 1976; Ross, 1977; Stoner, 1978, Martínez de Bascarón, 1979; Dunnette, 1979; House, 1989; Sargaonkar and Deshpande, 2003; Štambuk-Giljanovic, 2003; Liou *et al*., 2004; Boyacioglu, 2007; Shuhaimi-Othman *et al*., 2007; Thi Minh Hanh *et al.,* 2011; Banda, 2015; García-Ávila *et al.,* 2018). A simple technique, wherein, the overall index number calculated by adding the weighted sub-indices. The following Equation (1) and Equation (2) are applicable to parameters with equal weights and unequal weights respectively:

$$\mathrm{WQI} = \sum_{i=1}^{n} s_i \quad .. (1)$$

$$\mathrm{WQI} = \sum_{i=1}^{n} s_i w_i \quad .. (2)$$

where: WQI is the aggregated index value; n is the number of sub-indices; s_i is the i^{th} sub-index value; and w_i is the i^{th} weight value.

Note that, on Equation (2) for unequally weighted sub-indices; the weight (w_i) indicate the relative importance of each sub-index (s_i).

Modified additive method

Research work such as, House (1989); Tyson and House (1989); SRDD (1976); Bordalo *et al.* (2001), Bordalo *et al.* (2006) and Carvalho *et al*. (2011) have applied the modified additive methods; such that, the mathematical model becomes a squared function and divided by 100. The modified additive functions are represented as Equation (3) and Equation (4) for equally weighted parameters and unequally weighted parameters respectively:

$$\mathrm{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} s_i\right)^2 \quad .. (3)$$

$$\mathrm{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} s_i w_i\right)^2 \quad .. (4)$$

where: WQI is the aggregated index value; n is the number of sub-indices; s_i is the i^{th} sub-index value; and w_i is the i^{th} weight value.

Similar to Equation (2) for unequally weighted sub-indices; the weight (w_i) in Equation (4) indicate the relative importance of each sub-index (s_i).

Another version of the modified additive aggregation function was developed by Martínez de Bascarón (1979). In this particular version, the final index value is achieved by dividing the total sum of the aggregated sub-indices by the total sum of the parameter weights. With continued growth in the application of water quality indices, the Martínez de Bascarón (1979) version has been adopted and modified further in various water quality indices (see Pesce and Wunderlin, 2000; Debels *et al*., 2005; Abrahão *et al*., 2007; Sánchez *et al*., 2007; Koçer and Sevgili, 2014).

According to Smith (1990), additive model would never register zero as a final water quality index value, even if one of the sub-index value is zero. Furthermore, following the review by Lumb *et al*. (2011a), it was found that additive method lacked sensitivity regarding the impact of low value parameter. The mathematical formula actually "hides" the effects of variables with unacceptable levels and this problem is commonly known as eclipsing. In this aspect, the lowly weighted sub-indices might be dominated by highly weighted sub-indices or vice versa; and this ultimately compromise the overall water quality rating (Swamee and Tyagi, 2000, 2007; Bharti and Katyal, 2011; Juwana *et al*., 2012; Juwana, 2012).

Multiplicative method

In an attempt to rectify the eclipsing problem, Brown *et al.* (1973) proposed a multiplicative function as an amendment of the National Sanitation Foundation WQI. Subsequent studies tend to show that experts agreed more to the multiplicative formula than they did with the additive method, which explains the wide spread application of the multiplicative function. However, the additive function has equally being used (Lumb *et al.,* 2011a; Abbasi and Abbasi, 2012). Practical example of multiplicative aggregation indices includes Walski and Parker (1974); Bhargava (1985); Dinius (1987); Štambuk-Giljanovie (1999); Štambuk-Giljanovie (2003) and Almeida *et al*. (2012); Ponsadailakshmi *et al.* (2018); Sutadian *et al.* (2018). The multiplicative functions for equally weighted and unequally weighted parameters are shown as Equation 5 and 6 respectively:

$$\mathrm{WQI} = \prod_{i=1}^{n} \mathrm{S}_i^{\left(\frac{1}{n}\right)} \quad .. (5)$$

$$\mathrm{WQI} = \prod_{i=1}^{n} \mathrm{S}_i^{wi} \quad .. (6)$$

where: WQI is the aggregated index value; n is the number of sub-indices;s_i is the i^{th}sub-index value; and w_i is the i^{th} weight value and $w_1 + w_2 + w_3 + \ldots + w_n = 1$ for Equation (5).

For unequally weighted sub-indices; the weight (w_i) in Equation (5) indicate the relative importance of each sub-index (s_i). When the parameter weights (w_i) are equal, then the function takes the form represented in Equation (6), which is commonly known as the geometric mean of sub-indices (Abbasi and Abbasi, 2012).

As with all the multiplicative aggregation functions, a water quality index value of zero is attained if any one of the sub-indices value is zero. Under such circumstances, the eclipsing problem will not exist, because if any one sub-index demonstrates poor water quality, the overall water quality index will respond accordingly and presents poor water quality (Abbasi and Abbasi, 2012).

Minimum operator method

The minimum operator method was suggested by Ott (1978) and significantly applied by Smith (1987, 1990). Equation (7) represents the general form of the minimum operator function:

$$\mathrm{I}_{min} = \sum \min\left(\mathrm{I}_{sub1}, \mathrm{I}_{sub2}, \ldots, \mathrm{I}_{subn}\right) \quad .. (7)$$

where: I_{min} is the lowest sub-index value; I_{sub1} is the sub-index value of the first parameter (1, 2, …, n); and I_{subn} is the sub-index value of the last parameter (1, 2, …, n).

Although the minimum operator method is free from the eclipsing and ambiguity problems, the operator function fails to provide a composite representation of the overall water quality. Since any change, other than the lowest quality variable is not reflected by Equation (7); consequently, it becomes inappropriate to aggregate sub-indices using such an insensitive model (Swamee and Tyagi, 2000, Abbasi and Abbasi, 2012). That is, the operator cannot be effectively employed to monitor water quality; hence the application of this method has been limited to few indices such as Oudin *et al.* (1999) and Hèbert (2005). This promoted the birth of yet another aggregation method namely the harmonic mean of squares method.

Harmonic mean of squares method

In an effort to resolve the eclipsing problem by improving both the arithmetic mean formula and the geometric mean method, Dojlido *et al.* (1994) proposed the harmonic mean of squares method in the following form:

$$\mathrm{WQI} = \left(\frac{n}{\sum_{i=1}^{n}\left(\frac{1}{s_i^2}\right)}\right)^{0.5} \quad .. (8)$$

where: WQI is the aggregated index value; n is the number of sub-indices; and s_i is the i^{th} sub-index value.

If $s_i \neq 0$ for each i^{th} sub-index, then Equation (8) applies, but if $s_i = 0$ for any i^{th} sub-index, then the water quality index value will be zero (WQI = 0).

According to Cude (2001), the harmonic mean squares method allows the low-quality variables to influent the overall water quality index and further acknowledged that the method significantly tolerates water quality variability in relation to the change in parameter values. Regardless of such attributes, Swamee and Tyagi (2000) stated that the harmonic method has ambiguity problems. Such a problem occurs where the sub-indices are acceptable, but yet the overall index is not. In this case, the water might be of acceptable quality, but the aggregation index declares it unacceptable (Sutadian *et al.*, 2016).

With the continuous efforts of improving the aggregation techniques, Liou *et al.* (2004) proposed the combination of the additive and multiplicative methods.

Mixed aggregation method (combination of additive and multiplicative methods)

In order to minimise the eclipsing and ambiguity problems, Liou *et al*. (2004) proposed a different approach, whereby water quality variables are grouped into three categories depending on their correlation characteristics. The clustered parameters are aggregated into group sub-indices using the additive method, and further of which, the group sub-indices are aggregated using the multiplicative method in the form of geometric mean model. In addition, the aggregated index is multiplied by three prefixed scaling coefficients, addressing the effects of temperature, pondus Hydrogenium (pH) and toxic substances. The following is the general form of the combined aggregation method (Sutadian *et al.*, 2016):

$$\mathrm{WQI} = C_{temp}\, C_{pH}\, C_{tox} \left[\left(\sum_{i=1}^{3} \mathrm{I}_i w_i\right)\left(\sum_{j=1}^{2} \mathrm{I}_j w_j\right)\left(\sum_{k=1}^{1} \mathrm{I}_k w_k\right)\right]^{\frac{1}{3}} \quad .. (9)$$

where: WQI is the aggregated index value; n is the number of sub-indices; w_i is the i^{th} weight value for organic parameters; w_j is the j^{th} weight value for particulate parameters; w_k is the k^{th} weight value for faecal coliform; I_i is the i^{th} sub-index value for organic parameters; I_j is the j^{th} sub-index value for particulate parameters; I_k is the sub-index value for faecal coliform; c_{temp}, c_{pH} and c_{tox} are temperature, pondus Hydrogenium (pH) and toxic substance coefficients respectively.

Though with some modifications, Thi Minh Hanh *et al.* (2011) also applied a similar hybrid aggregation method to aggregate the sub-indices of the Basic Water Quality Index (WQI_B) and further multiplied the hybrid aggregation method with a geometric mean function to form a model namely the Overall Water Quality Index (WQI_O).

Another significant technique was introduced in the development of the Canadian Council of Ministers of the Environment (CCME) WQI. A unique, but simple method of calculating the final water quality index using the compliance objectives as established in the national water quality standards.

CCME method

Conceptually, the Canadian Council of Ministers of the Environment (CCME) method consist of three factors namely, scope (F_1), frequency (F_2) and amplitude (F_3). The first factor, scope (F_1) institutes the number of parameters that are not complying with the water quality standards. Whereas, the second factor, frequency (F_2) defines the number of occasions with which the objectives are not met. Finally, the third factor, amplitude (F_3) describes the magnitude of deviation; that is, the amount by which the objectives are not met (CCME, 2001a,b; Lumb *et al.*, 2011a; Sutadian *et al.*, 2016). The CCME aggregation function is denoted by the following formula:

$$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \quad .. (10)$$

where: WQI is the final index value; $F_1$is the scope ("failed variables"); $F_2$is the frequency ("failed tests"); $F_3$is the amplitude (magnitude of failed tests"); and 1.732 is a factor to normalise the WQI to a maximum value of 100.

Even though Tyagi *et al*. (2013) have mentioned that, the first factor (F_1) does not work properly when too few variables are considered or when too much covariance exist among them, the CCME method have gathered wide spread and applied in various water quality indices (that is, Khan *et al.*, 2003; Davies, 2006; Boyacioðlu, 2007; Tobin *et al*., 2007; de Rosemond *et al.*, 2009; Terrado *et al.*, 2010; Lumb *et al.*, 2011b; Nikoo *et al*., 2011; Sharma and Kansal, 2011; Espejo *et al*., 2012; Hurley *et al.*, 2012; Damo and Icka, 2013; Mostafaei, 2014).

DISCUSSION

Although several aggregation techniques have been established, with various modifications being suggested, additive (arithmetic mean) and multiplicative (geometric mean) functions remain as the commonly applicable methods. Selection of the most appropriate aggregation technique is an ongoing challenge, considering that each method has its own advantages and disadvantages. It is therefore, upon the water quality index (WQI) developer to apply their expertise and knowledge, in order to select the most suitable method, preferably with minimal disadvantages. The selection process is usually guided by the degree of accuracy required, available data and whether the water quality variables have equal or unequal weights.

The most significant aggregation techniques used in various water quality indices (WQIs) are summarised and recorded towards the end of this review paper as Appendix A, Table 1. The WQIs included herein Table 1, are regarded as the most important WQIs considering their wide application rate.

CONCLUSION

Water quality indices (WQIs) are developed to (i) deliver a single number that can be used to directly compare various water bodies; (ii) allow the analysis of spatial and temporal water quality trends and establish priorities for the sustainability of water resources; (iii) describe and distinguish water resources that are "good" and "bad" for various applications; and (iv) provides a solitary rating that the public and water quality professional can simply understand and apply to describe water quality status.

Validation of the most appropriate aggregation technique is a demanding task which requires due diligence, technical background and experience in the development of water quality indices (WQIs). If not properly considered, aggregation process might suffer the possibility of misrepresenting the overall water quality scenarios. Although various aggregation methods have their own limitations, but their benefits are significant when considering the impact of consolidating the effects of individual parameter measurements into a single reproducible indexing score. Aggregation techniques are not aimed at describing the effect of individual parameters, rather they are mechanisms that integrate a sum of complex water quality data and generate a score that describes water quality status.

Though some information is lost during the aggregation process, however, the data loss is compensated by the gain in describing water quality in simple terms that can be understood by the public and policy-makers.

It is suggested that the current research study entitled the "Development of a universal water quality index and water quality variability model for South African river catchments," apply due diligence and compare water quality results produced by the following three aggregation techniques, (a) weighted additive method, Equation (2); (b) modified weighted additive method, Equation (4) and (c) weighted multiplicative method, Equation (6).

Author Contributions

The authors contributed equally to the publication of the research article.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix A: Details of reviewed water quality indices (WQIs)

The aggregation functions applicable to the fifteen water quality indices (WQIs) reviewed under this current study are summarized herein Appendix A, under Table 1 below. The summary only focuses on the aggregation method used in the calculation of the index value. The fifteen WQIs are widely used and perceived as the most fundamental water quality indices. Each aggregation method has its own problems; therefore, the developer has to decide on the most appropriate and relevant method, preferably with minimum problems that might negatively impact on the final water quality index. Otherwise, selection of the best aggregation method is close to impossible. It has been noted that, there is no clear definite and favourable aggregation technique, various methods have been suggested and modified to meet specific requirements. Henceforth, the ongoing process of further modification of the existing aggregation methods and proposal of alternative methods.The original National Sanitation Foundation water quality index (NSF WQI) and the modified NSF WQI are recorded as one in Table 1. Therefore, the numbering of the WQIs in the following table, is recorded as fourteen instead of fifteen.

Table 1. Aggregation formulation of the reviewed WQIs

WQI name and symbol description	Aggregation formulation	
1: Horton Water Quality Index (Horton's WQI). Horton (1965); Debels *et al.* (2005); Lumb *et al.* (2011a), and Lumb *et al.* (2011b). Additive (arithmetic weighted mean), where: WQI is the index value, n is the number of variables, s_i is the i^{th} sub-index value which represents the rating number assigned to each variable (0-100), w_i is the i^{th} weight factor (1-4), m_1 is the temperature correction factor (0.5 or 1) and m_2 is the pollution correction factor (0.5 or 1).	$\mathrm{WQI} = \left[\frac{w_1 s_1 + w_2 s_2 + w_3 s_3 + \ldots + w_n s_n}{w_1 + w_2 + w_3 + \ldots + w_n}\right] m_1 m_2$	A1.1
2: National Sanitation Foundation Water Quality Index (NSF WQI). Brown *et al.* (1970), Brown *et al.* (1973), Deininger (1980), dos Santos Simões *et al.* (2008), Bonanno and Giudice (2010), and Lumb *et al.* (2011b). Additive (1970) and multiplicative (1973), where: WQI is the aggregated index value, r_i is the measured value of the i^{th} parameter, T_i is the quality rating transformation curve of the i^{th} parameter, q_i is the individual parameter quality rating ($T_i r_i = q_i$), n is the total number of weighted parameters and w_i is the i^{th} weight value such that $w_1 + w_2 + w_3 + \ldots + w_n = 1$ for both Equation A1.2 and Equation A1.3	First version, 1970 $\mathrm{WQI} = \sum_{i=1}^{n} w_i T_i(\rho_i) = \sum_{i=1}^{n} w_i q_i$	A1.2
	Second version, 1973 $\mathrm{WQI} = \prod_{i=1}^{n} S_i^{wi}$	A1.3
	$w_1 + w_2 + w_3 + \ldots + w_n = 1$	A1.4

Table 1. *Continued ...*

WQI name and symbol description	Aggregation formulation	
3: Scottish Research Development Department Water Quality Index (Scottish WQI) SRDD (1976), Bordalo et al. (2001), Bordalo et al. (2006), Carvalho et al. (2011), and DadolahiSohrab et al. (2012). Additive, where: WQI is the aggregated index value, n is the number of variables, q_i is the i^{th} sub-index value, and w_i is the i^{th} weight factor such that $w_1 + w_2 + w_3 + \ldots + w_n = 1$ for Equation A1.5.	$$\mathrm{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} q_i w_i\right)^2$$ $$w_1 + w_2 + w_3 + \ldots + w_n = 1$$	A1.5 A1.6
4: Oregon Water Quality Index (OWQI) Dunnette (1979), Cude (2001), and Sarkar and Abbasi (2006) Additive (1979) and unweighted harmonic mean of squares (2001), where: WQI is the aggregated index value, n is the number of variables, SI_i is the i^{th} sub-index value, and w_i is the i^{th} weight factor such that $w_1 + w_2 + w_3 + \ldots + w_n = 1$ for Equation A1.7.	First version, 1979 $$\mathrm{WQI} = \sum_{i=1}^{n} \mathrm{SI}_i w_i$$ $$w_1 + w_2 + w_3 + \ldots + w_n = 1$$ Second version, 2001 $$\mathrm{WQI} = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{\mathrm{SI}_i^2}}}$$	A1.7 A1.8 A1.9
5 : Martínez de Bascarón Water Quality Index (Bascarón Index). Martínez de Bascarón (1979), Pesce and Wunderlin (2000), Debels et al. (2005), Abrahão et al. (2007), Sánchez et al. (2007), Kannel et al. (2007), and Koçer and Sevgili (2014). Modified additive, where: $\mathrm{WQI}_{\mathrm{sub}}$ is the subjective water quality index value, $\mathrm{WQI}_{\mathrm{obj}}$ is the objective water quality index value, $\mathrm{WQI}_{\mathrm{min}}$ is the minimum water quality index value, n is the number of sub-indices, k is the subjective constant representing the visual impression of river contamination, C_i is the value assigned to parameter i^{th} after normalisation, and P_i is the relative weight assigned to the i^{th} parameter and ranges from 1 to 4 as highest.	Model for the subjective index $$\mathrm{WQI}_{\mathrm{sub}} = k\frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i}$$ Model for the objective index $$\mathrm{WQI}_{\mathrm{obj}} = \frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i}$$ Model for the minimum index $$\mathrm{WQI}_{\mathrm{min}} = \frac{\sum_{i=1}^{n} C_i P_i}{n}$$	A1.10 A1.11 A1.12
6: Bhargava's Water Quality Index (Bhargava's Index). Bhargava (1985), AlAni et al. (1987), and Avvannavar and Shrihari (2008). Modified multiplicative, where: WQI is the water quality index value, n is the number of variables considered more relevant, and $f_i(P_i)$ is the sensitivity function of the i^{th} parameter which includes the effects of weighting of the i^{th} parameter.	$$\mathrm{WQI} = \left[\prod_{i=1}^{n} f_i(P_i)\right]^{\frac{1}{n}}$$	A1.13
7: House's Water Quality Index (House's Index). House (1986, 1989, 1990), Tyson and House (1989), and Carvalho et al. (2011). Additive, where: WQI is the aggregated index value, n is the number of variables, q_i is the i^{th} sub-index value, and w_i is the i^{th} weight factor such that $w_1 + w_2 + w_3 + \ldots + w_n = 1$ for Equation A1.14.	$$\mathrm{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} q_i w_i\right)^2$$ $$w_1 + w_2 + w_3 + \ldots + w_n = 1$$	A1.14 A1.15

Table 1. *Continued ...*

WQI name and symbol description	Aggregation formulation	
8: Smith Water Quality Index (Smith's WQI). Smith (1987, 1990). Minimum operator, where: I_{min} is the lowest sub-index value, I_{sub1} is the sub-index value of the first parameter (1, 2, …, n), and I_{subn} is the sub-index value of the last parameter (1, 2, …, n).	$I_{min} = \sum \min (I_{sub1}, I_{sub2}, \ldots, I_{subn})$	A1.16
9: British Columbia Water Quality Index (BCWQI). Zandbergen and Hall (1998), CCME (2001a), and Bharti and Katyal (2011) Objective-based model, where: WQI is the overall water quality index value, F_1 is the percentage of water quality guidelines exceeded, F_2 is the frequency with which objectives not met as percent of objectives checked, F_3 is the maximum by which any of the guidelines were exceeded, and 1.453 is the factor to normalise the WQI to a maximum value of 100.	$WQI = \left(\frac{\sqrt{F_1^2 + F_2^2 + \left(F_3/3 \right)^2}}{1.453} \right)$	A1.17
10: Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI). CCME (2002), Khan et al. (2003), Khan et al. (2004), Davies (2006), Lumb et al. (2006), Tobin et al. (2007), de Rosemond et al. (2009), Boyacioðlu (2010), Terrado et al. (2010), Nikoo et al. (2011), Sharma and Kansal (2011), Espejo et al. (2012), Hurley et al. (2012), Damo and Icka (2013), and Mostafaei (2014) Objective-based model, where: WQI is the final index value, *nse* is the normalised sum of excursions, n is the total number of the excursions, F_1 is the scope ("failed variables"), F_2 is the frequency ("failed tests"), F_3 is the amplitude (magnitude of failed tests"), and 1.732 is a factor to normalise the WQI to a maximum value of 1.	$F_1 = \left(\frac{\text{number of failed variables}}{\text{total number of variables}} \right) \times 100$	A1.18
	$F_2 = \left(\frac{\text{number of failed test}}{\text{total number of tests}} \right) \times 100$	A1.19
	$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{total number of tests}}$	A1.20
	$F_3 = \left(\frac{nse}{0.01 nse + 0.01} \right)$	A1.21
	$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right)$	A1.22
11: Liou's Water Quality Index (Liou's WQI). Liou et al. (2004). Combination of additive and multiplicative, where: RSI is the aggregated river status index value, is the number of sub-indices, w_i is the i^{th} weight value for organic parameters, w_j is the j^{th} weight value for particulate parameters, w_k is the k^{th} weight value for microorganisms, I_i is the i^{th} sub-index value for organic parameters, I_j is the j^{th} sub-index value for particulate parameters, I_k is the sub-index value for microorganisms, and C_{temp}, C_{pH} and C_{tox} are temperature, pondus Hydrogenium (pH) and toxic substance coefficients respectively.	$RSI = C_{temp}\, C_{pH}\, C_{tox} \left[\left(\sum_{i=1}^{3} I_i w_i \right) \left(\sum_{j=1}^{2} I_j w_j \right) \left(\sum_{k=1}^{1} I_k w_k \right) \right]^{\frac{1}{3}}$	A1.23
	$\sum_{i=1}^{n} w_i = 1; \sum_{j=1}^{n} w_j = 1; \text{and} \sum_{k=1}^{n} w_k = 1$	A1.24

Table 1. *Continued ...*

WQI name and symbol description	Aggregation formulation	
12: Fuzzy-based Water Quality Index (Fuzzy Index). Ocampo-Duque et al. (2006), Lermontov et al. (2009), Nikoo et al. (2011), Mahapatra et al. (2012), and Ocampo-Duque et al. (2013).	$\mu(x; a, b, c, d) = \max\left(\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right)$	A1.25
Fuzzy logic, where: FWQI is the fuzzy-based water quality index value (between 0 and 100), z is the independent variable of the output fuzzy set in each rule, and a, b, c, and d are membership function parameters.	$\mathrm{FWQI} = \frac{\int \mu(z)\cdot z\mathrm{d}z}{\int \mu(z) z\mathrm{d}z}$	A1.26
13: Universal Water Quality Index - Boyacioðlu Index (UWQI). Boyacioðlu (2007).	$\mathrm{WQI} = \sum_{i=1}^{n} w_i \mathrm{I}_i$	A1.27
Additive, where: UWQI is the universal water quality index value, w_i is the weighted coefficient for the i^{th} parameter presented as decimal, I_i is the sub-index for the i^{th} parameter and n is the total number of the ranked water parameters.	$w_1 + w_2 + w_3 + \ldots + w_n = 1$	A1.28
14: Vaal Water Quality Index (Vaal WQI). Banda (2015)	$\mathrm{WQI} = \sum_{i=1}^{n} w_i \mathrm{I}_i$	A1.29
Additive, where: WQI is the index value, w_i is the weighted coefficient for the i^{th} parameter presented as decimal, I_i is the sub-index for the i^{th} parameter and n is the total number of the ranked water parameters.	$w_1 + w_2 + w_3 + \ldots + w_n = 1$	A1.30

Source: As indicated with each WQI (also see Lumb et al., 2011a, Poonam et al., 2015, Sutadian et al., 2016). Notes: The listing of the water quality indices (WQIs) in Table 1 above is based on the year at which the WQI was developed and or published, rather than preference.

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