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A REVIEW OF THE EXISTING WATER QUALITY INDICES (WQIS)

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ABSTRACT

A comprehensive evaluation and monitoring of South Africa's water resources is vital towards implementing appropriate management and long-term sustainability of the scares water resources. Such practices, are done using significant amount of data, and such information needs to be analysed and applied using methods, tools and or models that are capable of deducing water quality information into usable datasets and structured formats. Proper design and formation of water quality indices is then a pivotal step in assessing our water resources and in cognisance of such, this study endeavours to develop a water quality-monitoring tool that is applicable to distinct catchments in South Africa. This tool should analyse and integrate the significance of physical, chemical and biological constituents of surface water and be able to present them in a simple, but yet technically justifiable method. In order to properly compile and develop a better model, one has to evaluate, review and consider the flaws and limitations of the current and previously developed models of similar nature. Henceforth, this review paper focuses on reviewing the literature relating to the development of the water quality indices (WQIs).

KEY WORDS : River catchments, Water quality, Water quality index (WQI), Water quality parameters, Rand Corporation's Delphi method, Rating curves

INTRODUCTION

A river is a complex large natural flowing watercourse normally fed by converging tributaries, usually containing freshwaters flowing towards another waterbody. In order to establish the suitability and sustainability of any river, both the quantity and quality of the river water has to be considered. The two, can assist in describing the inherent potential of a river, establish whether its condition is stable, ascertain its capacity for self-repair when unsettled and the extent of management support required (Karr *et al.,* 1986; Norris and Thoms, 1999).

River water quantity is considered to be the volumetric measure of water resources available for abstraction without depleting the environmental reserve. Thus, the surplus water available after taking into account the amount of water sufficient enough to cater for the aqua-life and river health as a whole. Whereas river water quality describes the biological, chemical and physical characteristics of river water (Davies-Colley, 2013, Banda, 2015). River water quality is naturally variable, but normally comprises of significant contaminants in the form of dissolved ions, particles and living organisms. Features and details of the pollutants vary depending on the degree of development along the river, size of the river, human activities as well as physical and hydrological catchment characteristics (Chapman, 1996; Alberta, 2011).

Since the efforts by Horton (1965) of developing a water quality analysis tool, our proficiencies to measure and analyse water quality data has evolved over the past decades, expanding our knowledge base and understanding of water quality (Bhargava, 1985; House, 1989, 1986, 1990; Smith, 1987, 1990; Dojlido *et al.,* 1994; Nagels *et al.,* 2001; CCME, 2002; Boyacioglu, 2007; Thi Minh Hanh *et al.*, 2011; Banda, 2015; AL-Sabah, 2016; Gitau *et al.,* 2016; Ewaid and

Abed, 2017a; Shah and Joshi, 2017; Trikoilidou *et al.,* 2017). Regardless of such growth, it is still difficult to provide a simple definition of water quality. It is very complicated to comprehend the combined effect of several complex factors used to describe water quality and the challenges of identifying the most significant variables used to evaluate the status of water resources in the quantitative terms (Chapman, 1996).

Considering the review work by Lumb *et al.* (2011a), Poonam *et al.* (2015) and Sutadian *et al.* (2016), it is noted that several water quality analysis tools have been developed, with the effort to measure and quantify the extent at which water resource quality can vary. Such useful mathematical tools deduce complex water quality data sets and provide a single classifying value that grade water quality based on the degree of pollution. The single grading value is commonly known as water quality index (see Khan *et al.,* 2004; Alberta, 2011; Lumb *et al.,* 2011b; Abdel-Satar *et al.,* 2017; Ewaid and Abed, 2017b). In the same context, the aim of current study is to develop a common water quality index (WQI) model that is applicable to various river catchments in South Africa. The specific objectives of this study are framed towards achieving a practical and sustainable water quality-monitoring system that will provide a holistic approach in solving water quality problems in South Africa. The tool will provide a basic platform to measure whether specific water resources needs to be restored and to what degree. Thus, assisting in the prioritisation of water quality activities.

Historical background and definition of WQIs

The idea of describing water quality based on the degree of cleanliness or contamination level started as early as 1848 in Germany (Lumb *et al.,* 2011a). Subsequently, during the 19th century, Kolkwitz and Marsson (1909) developed the "saprobic system" as a biological concept of determining water quality. The system provides a saprobic index value based on the organic degradable composition of the water resources (Sládeèek, 1973; Cairns, 1974; Lindegaard, 1995; Hawkes, 1998; Rolauffs *et al.,* 2004). The saprobic indexing system relied on the distribution pattern and the relative abundance of various biological aquatic species and such a non-chemical analysis, cannot address the modern challenges relating to water quality. However, the presence of certain species in water, provides assurance that certain minimal water quality conditions have been meet. Which is why the saprobic system has been acceptable to the public and remains as a traditional method of assessing the suitability of water for several applications (Cairns, 1974; Rolauffs *et al.,* 2004).

More than a century after the birth of the saprobic index, Horton (1965) established the first parameter based numerical indexing system. This approach utilises a mathematical model to rate and aggregate the combined implication of selected biological, chemical and physical water parameters and present them in a simple, but scientifically justifiable method (Kannel *et al.,* 2007; Lumb *et al.,* 2011a; Effendi, 2016; Sutadian *et al.,* 2016). After Horton (1965) suggested the first water quality index (WQI), subsequently many other indices were developed with the aim of improving the original concept (Ewaid and Abed, 2017b). Parameters of consideration, mathematical formation, indexing scale (also known as the categorisation schema) and application boundaries are the major aspects being targeted with each improvement. And, the objectives of this study are aiming to address the same, thereby developing a universal water quality index applicable to various river catchments in South Africa.

Water quality is defined by pollutants, which can be grouped as physical, chemical and biological properties of the water. These variables can collectively be integrated into a systematically structured indexing scale, commonly known as water quality index (WQI). It is capable of converting a large quantity of water pollution data into a single dimensionless index value, which represents the level of contamination of the water resources (Boyacioglu, 2007; Darapu *et al.,* 2011; Kalyani *et al.,* 2016; Ewaid *et al.,* 2018). Considering such ability to integrate a pool of water quality variables into a simple easily understood number, WQI is therefore, regarded as a very effective and significant communication tool for water managers and policy makers (Zandbergen and Hall, 1998, Khan *et al.,* 2005; Kankal *et al.,* 2012). Water quality indices are used to simplify and streamline what would otherwise be impractical assignments, thus justifying the efforts of developing such indices.

Existing water quality indices (WQIs)

Since 1965, when the first numerical water quality index (WQI) was established, there have been several more water quality indices developed (Bharti and Katyal, 2011). However, most of such

WQIs are founded on similar structures and principles; the only realisable distinctions are the application boundaries and parameters involved. In general, "conventional" water quality indices are based on comparing observed parameter values with the existing local normative standards (Debels *et al.*, 2005; Sun *et al.*, 2016).

There are in fact, two commonly used methods to develop water quality indices, with subsequent modifications. First, the weighted sum method, whereby sub-indices are generated and further combined into an overall WQI value. Sub-indices are value functions used to convert the different units of water quality variables to a mutual scale (Boyacioglu, 2007; Banda, 2015). Second, the amplitude technique (objective-based), where overall water quality index value is founded through quantifying the extent at which water quality variables deviate from the objectives (CCME, 2001; Khan *et al.*, 2005; Radwn, 2005; Mostafaei, 2014). Both methods can further be deduced into various mathematical models, though with the same scope and outcomes.

Although forty water quality indices (WQIs) were reviewed, only fifteen WQIs are discussed in the following sub-sections. Covering all the existing WQIs in this review is out of reach, hence commonly used and perceived as important WQIs are discussed in detail. Nonetheless, the rest of the reviewed WQIs are presented in summary under Table 4.

Horton model of water quality index (United States of America)

Horton (1965) established a simple mathematical technique of calculating water quality index, based on eight water quality variables as indicated in Table 4, Part 1(c). Rating scales between zero and hundred were assigned for each variable and a weighting factor ranging from one to four was assigned to each parameter depending on its relative impact on the final index value. Weight factor of four was assigned to parameters of high significance, whereas those of minimum impact were assigned a weight factor of one. The overall water quality index values ranged from zero to hundred, with lower values representing poor water quality and vice versa (Debels *et al.*, 2005; Lumb *et al.*, 2011a, Lumb *et al.*, 2011b). Equation (1) represents the mathematical formula suggested by Horton (1965):

$$\mathrm{WQI} = \left[\frac{w_1 s_1 + w_2 s_2 + w_3 s_3 + \ldots + w_n s_n}{w_1 + w_2 + w_3 + \ldots + w_n}\right] m_1 m_2 \quad \text{.. (1)}$$

where: WQI is the aggregated index value; n is the number of water quality variables used to evaluate the WQI value; s_n is the n^{th} sub-index value, which represents the rating number assigned to each variable ranging from zero to hundred; w_n is the n^{th} weight factor ranging from one to four; m_1 is the temperature correction factor; and m_2 is the pollution correction factor.

In this case, the total number of water quality variables (n) is eight and the temperature correction factor (m_1) is regarded as 0.5 when the temperature is less than 34 °C, otherwise 1. Whereas, the pollution correction factor (m_1) is either 0.5 or 1 depending on the degree of pollution which created colour or odour nuisance and this included the formation of sludge, deposits, presence of oil, debris, foam, etc. (Lumb *et al.*, 2011a).

Bhargava (1983) pointed out that, the arithmetic weighted mean used by Horton (1965) lacked sensitivity to the effect of lowering the values of some of the water quality parameters and this problem is commonly known as eclipsing. Furthermore, according to Lumb *et al.* (2011b), one of the significant problems in Horton's concept was the arbitrariness in the selection of parameters forming the water quality index, which led to the improvements suggested by Brown *et al.* (1970), as well as Deininger and Maciunas (1971).

National Sanitation Foundation WQI (United States of America)

In an effort to improve Horton's water quality model, Brown *et al.* (1970) established a more comprehensive and widely used water quality index. The National Sanitation Foundation (NSF) of United States of America (USA) supported the development and application of the model, hence the water quality index is commonly referred to NFS WQI. Although the NFS WQI is similar to Horton's Index, Brown *et al.* (1970) employed more rigorous attention and high precision in parameter selection, development of the rating curves and assigning of parameter weights. The National Sanitation Foundation water quality model comprise of eleven water quality variables which are listed in Table 4, Part 2(c) (Low *et al.*, 2016).

A team consisting of 142 water experts assisted in establishing the list of significant parameters, developing a common ranking scale and assigning weights to the selected water quality variables. Brown *et al.* (1970) floated questionnaires based on a technique commonly known as the Rand Corporation's Delphi method, and with it, expert opinion rating curves were developed to attribute the degree of water quality variation caused by different level of concentration of each chosen parameter (Wills and Irvine, 1996; Bharti and Katyal, 2011; Banda, 2015; Poonam *et al.*, 2015). Utilising the established quality rating curves and associated parameter weights, the original NSF WQI is in the form of additive model as represented in Equation (2) (Abbasi and Abbasi, 2012):

$$\mathrm{WQI} = \sum_{i=1}^{n} w_i T_i(\rho_i) = \sum_{i=1}^{n} w_i q_i \qquad .. (2)$$

where: WQI is the aggregated index value; n is the number of sub-indices; ρ_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 ($T_i \rho_{i=} q_i$); and w_i is the i^{th} weight value such that $w_1 + w_2 + w_3 + \ldots + w_n = 1$ for Equation (2).

The most obvious limitation of this technique is that, it was developed for particular water quality variables, thèrefore it does not recognise and describe specific water functions. Any alteration on the parameter listings, thus inclusion or exclusion of any water quality variable necessitates restarting the whole tedious process again. Furthermore, the weighted arithmetic or additive formulation, although simple to comprehend, it lacked sensitivity in terms of the effect a single bad parameter value on the overall WQI (Banda, 2015; Low *et al.*, 2016).

Modified NSF WQI (United States of America)

Considering the flaws of the original National Sanitation Foundation (NSF) water quality index developed by Brown *et al.* (1970), subsequently Brown *et al.* (1973) proposed the weighted geometric mean (multiplicative) function as a modification of the original NSF WQI. The multiplicative model was successfully adopted and considered more appropriate than the original additive model. However, both models have continued to be in use, regardless of the variation in accuracy. The modified water quality index is expressed as follows (Bharti and Katyal, 2011, Lumb *et al.*, 2011a, Abbasi and Abbasi, 2012, Poonam *et al.*, 2015):

$$\mathrm{WQI} = \prod_{i=1}^{n} \mathrm{S}_i^{wi} \qquad .. (3)$$

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 (3).

Poonam *et al.* (2015), suggested that unweighted harmonic square mean formula can be employed to improve the weighted geometric mean formula. This allows the most impaired parameter to impart the greatest influence on the WQI, hence offering the significance of different variables on overall water quality at different times and locations. The modified NSF WQI used the same water quality variables as the original NSF WQI and they are presented in Table 4, Part 2(c).

Scottish Research Development Department WQI (Scotland)

Similar to the National Sanitation Foundation (NSF) water quality index developed by Brown et al. (1970), the Engineering Division of Scottish Research Development Department (SRDD) developed a water quality index based on the Delphi method (SRDD, 1976). The index is commonly known as the Scottish water quality index (Scottish WQI) and operates with ten water quality indicators established using the Delphi technique. Sub-indices and individual parameter weights were developed through a convergence of water quality experts (Sutadian *et al.*, 2016).

The ten water quality indicators are indicated in Table 4, Part 7(c). The final modified weighted arithmetic function (modified additive), which is the result of squaring the sum of the products of parameter values (q_i), and of the individual variable weightings (w_i), divided by hundred as demonstrated with the following Equation (4) (Bordalo *et al.*, 2001; Bordalo *et al.*, 2006; Dadolahi Sohrab *et al.*, 2012):

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

where: WQI is the aggregated index value; n is the number of sub-indices; q_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 (4).

Regardless of the Scottish WQI being developed for monitoring the water quality in Scotland watersheds, several researchers have modified this particular index and applied it in various countries, which includes Spain, Portugal, and Iran (see Bordalo *et al.*, 2001; Bordalo *et al.*, 2006; Carvalho *et al.*, 2011; Dadolahi Sohrab *et al.*, 2012). Such widespread explains its appropriateness as a water quality monitoring tool.

Oregon water quality index (United States of America)

The Oregon water quality index (OWQI) was suggested by Dunnette (1979) and the index required enormous resources to calculate and produce the final index value which resulted in the index being discontinued in 1983 (Sutadian *et al.*, 2016). Subsequently, Cude (2001) modified the original OWQI by adding two more variables (temperature and phosphorus), refining the sub-indices and improving the aggregation technique.

The original OWQI was modelled after the National Sanitation Foundation (NSF) water quality index, which applied the Delphi method for selecting the most significant parameters. Both Oregon water quality indices (as suggested by Dunnette, 1979, and Cude, 2001), utilised the logarithmic transforms to covert water quality indicators into sub-indices. The advantage of this method is that, a change in magnitude at lower levels of impairment has a greater impact than an equal change in magnitude at higher levels of impairment (Cude, 2001; Poonam *et al.*, 2015). The original OWQI used the weighted arithmetic mean (additive) method and the modified index used the unweighted harmonic square mean function as shown by Equation (5) and Equation (6) respectively (Cude, 2001, Sarkar and Abbasi, 2006, Poonam *et al.*, 2015):

$$\mathrm{WQI} = \sum_{i=1}^{n} \mathrm{SI}_i w_i \quad .. (5)$$

$$\mathrm{WQI} = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{\mathrm{SI}_i^2}}} \quad .. (6)$$

where: WQI is the aggregated index value; n is the number of sub-indices; SI_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).

Cude (2001) claimed that unequal weights are only applicable to water quality indices that are developed for specific application, rather than general uses, where other parameters might contribute more to the index value than the others. Consequently, Cude (2001) employed equal weighted function for the modified OWQI (Sutadian *et al.*, 2016).

Martínez de Bascarón water quality index (Spain)

Martínez de Bascarón (1979) suggested a twenty-six-parameter based water quality index specifically for Spain, and the index has been modified and applied in various studies for countries such as, Argentina, Chile, Brazil, India, Spain and Turkey (refer to; Pesce and Wunderlin, 2000; Debels *et al.*, 2005; Abrahão *et al.*, 2007; Kannel *et al.*, 2007, Sánchez *et al.*, 2007; Koçer and Sevgili, 2014). Although Martínez de Bascarón (1979) recommended twenty-six variables, the index can easily allow the inclusion and exclusion of water quality indicators, hence it is regarded as a flexible water quality index (Abrahão *et al.*, 2007; Sutadian *et al.*, 2016).

Originally, Martínez de Bascarón (1979), suggested the subjective water quality index (WQI_{sub}); whereby, the water quality index value is multiplied with a subjective constant representing the visual impression of the river contamination. WQI_{sub} is represented as Equation (7) (Pesce and Wunderlin, 2000; Abrahão *et al.*, 2007; Kannel *et al.*, 2007; Sánchez *et al.*, 2007; Poonam *et al.*, 2015):

$$\mathrm{WQI}_{\mathrm{sub}} = k\frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i} \quad .. (7)$$

Such an equation overestimates the contamination level due to the application of the subjective constant, which is not necessary correlated to the measured parameter values (Pesce and Wunderlin, 2000). Therefore, a modification has been reported in literature as the objective water quality index (WQI_{obj}). In this case, the constant (k) is considered as one (k=1), thereby allowing the water quality index to represent only the variations caused by measured parameter values, without the influence of human judgement in the form of "visual impressions." The WQI_{obj} is expressed as Equation (8) (Debels *et al.*, 2005, Abrahão *et al.*, 2007, Kannel *et al.*, 2007, Lumb *et al.*, 2011a, Koçer and Sevgili, 2014):

$$\mathrm{WQI}_{\mathrm{obj}} = \frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i} \quad .. (8)$$

A selected few variables, mostly regarded as the crucially important water quality parameters, maybe used to calculate the minimum water quality index (WQImin). The WQImin method could be useful for periodic routine monitoring exercises that requires less precision. The WQImin can be worked out using Equation (9) (Kannel *et al.*, 2007, Koçer and Sevgili, 2014):

$$\mathrm{WQI}_{\min} = \frac{\sum_{i=1}^{n} C_i P_i}{n} \quad .. (9)$$

where: $\mathrm{WQI}_{\mathrm{sub}}$ is the subjective water quality index value; $\mathrm{WQI}_{\mathrm{obj}}$ is the objective water quality index value; $\mathrm{WQI}_{\min}$ 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.

The parameters applicable for $\mathrm{WQI}_{\min}$ varies with the author, purpose of the evaluation, constantly available parameter readings, and desired level of accuracy. Nevertheless, the twenty-six variables as suggested by Martínez de Bascarón (1979), together with their weighting factors are .

Over the past years, several European studies has adopted and applied the Martínez de Bascarón (1979) water quality index (Lumb *et al.,* 2011a), such widely spread use exhibits the flexibility of the index and its ability to be used with minimum water quality indicators (Abrahão *et al.,* 2007). The challenge with the subjective water quality index ($\mathrm{WQI}_{\mathrm{sub}}$), is that; the subjective constant (k) that represents the "visual impression" of the river contamination might be evaluated by an individual without environmental or water quality background (Pesce and Wunderlin, 2000), which may lead to presentation of distorted index values.

Bhargava's water quality index (India)

One of the first Asian based water quality index (Abbasi and Abbasi, 2012), derived exclusively for the classification of water quality for drinking purposes (Lumb *et al.,* 2011a). Unlike most indices, where sub-indices and weighting factors are considered separately; Bhargava (1985, 1983) developed sensitivity functions which included both the effects of concentrations of different parameters and their weightage in relation to their level of importance in the overall index calculation process (AlAni *et al.,* 1987; Avvannavar and Shrihari, 2008; Lumb *et al.,* 2011a; Abbasi and Abbasi, 2012). Therefore, based on an approach were the significance of each water quality parameter is included within the sensitivity function, Bhargava (1985, 1983), suggested a simplified and rational model for calculating water quality index value as expressed by Equation (10):

$$\mathrm{WQI} = \left[\prod_{i=1}^{n} f_i(P_i)\right]^{\frac{1}{n}} \quad .. (10)$$

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.

Bhargava (1985) identified four parameter groupings which included (1) coliform organisms, (2) toxicants, heavy metals, etc., (3) indicators that causes physical effects, that is, odour, turbidity, colour, etc., and (4) inorganic and organic nontoxic substances such as chloride, sulphate, total dissolved solids, etc. The parameters of each group are indicated in Table 4, Part 13(c). The index sensitivity functions assumed values of 1.0, 0.8, 0.5, 0.2 and 0.1; which related to water quality index values of 100, 80, 50, 20 and 1 (almost zero), thus aligning to water class one to five respectively (Bhargava, 1983).

Bhargava (1985), argued that Brown *et al.* (1970) arithmetic mean (additive) index was not significantly sensitive to changes in the values of the water quality parameters, hence, he suggested a model in the multiplicative form. The multiplicative models are designed to eliminate the eclipsing problem since they respond well when sub-indices value almost reaches or equals to zero; the index will respond accordingly and register a lower index value (Bhargava, 1983, Abbasi and Abbasi, 2012).

House's water quality index (United Kingdom)

In the United Kingdom (UK), House (1986, 1989, 1990) established four water quality indices. First, the general water quality index (WQI) for evaluating river health for periodic monitoring programs. Second, the potable water supply index (PWSI) for assessing the quality and suitability of potable water supply. Third, the aquatic toxicity index (ATI) developed to monitor the toxicity in aquatic environment, and lastly; the fourth WQI, which was suggested for evaluating water quality for the wildlife population and the index is commonly known as the potable sapidity index (PSI). These four indices can be used separately or in combination depending on the required outcome and level of accuracy desired (Sutadian *et al.,* 2016). Nevertheless, this study focuses on the initially developed general water quality index; which is then referred to as House's water quality index (House's WQI).

The House's WQI was conceptually developed in the same manner as the National Sanitation Foundation water quality index (NSF WQI) of United States of America (Lumb *et al.,* 2011a), where the nine water quality parameters and their weights are established using the Delphi method. Table 4, Part 14(c) represents the nine water quality parameters as suggested by House (1986, 1989, 1990), and the aggregation formula is expressed as Equation (11):

$$\text{WQI} = \frac{1}{100}\left(\sum_{i=1}^{n} q_i\, w_i\right)^2 \qquad .. (11)$$

where: WQI is the aggregated index value; n is the number of sub-indices; q_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 (11).

Index values produced by various aggregation methods were tested and authenticated for the purpose of selecting the most feasible aggregation technique, and accordingly, the modified arithmetic formula suggested by SRDD (1976) in the development of the Scottish WQI was found more suitable and adopted as the WQI for river management by House (1989).

The WQI developed by House (1986, 1989) can be applied in an objective manner and therefore produces results which are reproducible and repeatable manner, both temporally and spatially (House, 1989). Thereby allowing a structured comparison of various data sets, providing a precise picture of water quality variability and facilitating the development of best management practices (House, 1990).

Smith's water quality index for river systems (New Zealand)

Water quality index (WQI) developed by Smith (1987, 1990) is a hybrid of two common practices in the development of water quality indices; that is, the application of both water quality standards and the Rand Corporation's Delphi method. The Delphi procedure was used to establish significant parameters, develop sub-indices and assigning of relative parameter weightages. Eventually, Smith (1987, 1990) applied the minimum operator technique to calculate the final index scores and the model is expressed in Equation (12) (Smith, 1987; 1990, CCME, 2001; Bharti and Katyal, 2011; Poonam *et al.*, 2015):

$$\text{I}_{min} = \sum \min\left(\text{I}_{sub1}, \text{I}_{sub2}, \ldots, \text{I}_{subn}\right) \qquad .. (12)$$

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).

Smith's WQI was developed for four water uses, which are general, bathing, water supply and fish spawning (salmonids). The index comprises of a maximum of eight water quality variables, grouped differently for each particular application, with distinctive weighting factors relevant to specific water use. However, the relative weights have no effect since Smith (1987) eventually omitted the application of the multiplicative indexing model. The eight water quality variables are included in Table 4, 16(c).

The simplicity and flexibility of the minimum operator index makes it easier to implement, without ambiguity or eclipsing problems. However, the accuracy of Smith's water quality index (WQI) is questionable, since the model can only retain the minimum sub-index value, without considering the effects of the rest of the sub-indices. This implies that, the composite picture of water quality is compromised, since any change, other than the minimum sub-index value is not reflected in the overall WQI. such an insensitive operator is unsuitable for aggregation. That is, it can neither be used for monitoring of a source, nor for comparison of two sources (Swamee and Tyagi, 2000; Abbasi and Abbasi, 2012). Which is why, the application of the minimum operator technique has been limited to a few water quality indices (see Oudin *et al.*, 1999; Hèbert, 2005).

British Columbia WQI (Canada)

In 1995, the Canadian government, under the guidance of the Ministry of Environment, Lands and Parks established water quality index (WQI) for the British Columbia Province (Zandbergen and Hall, 1998, Bharti and Katyal, 2011). The BCWQI is an objective-based index similar to Canadian Council of Ministers of the Environment (CCME) WQI, though one of the factors is not considered in any of the other indices, which factor is the percentage of water quality guidelines exceeded (F_1). The following mathematical expression is used for British Columbia WQI (Zandbergen and Hall, 1998, CCME, 2001, Bharti and Katyal, 2011):

$$\text{WQI} = \left(\frac{\sqrt{F_1^2 + F_2^2 + \left({F_3}/{3}\right)^2}}{1.453}\right) \qquad .. (13)$$

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.

Two factors are comparable to other water quality indices (WQIs). The index factor two (F_2) is similar to Alberta index, whereas, factor three (F_3) corresponds to Centre St Laurent index. Whilst factor one (F_1) does not appear in any of the other WQIs. It was found that BCWQI is exceptionally sensitive to sampling design and highly dependent on specific application of water quality objectives. Furthermore, the British Columbia index in its original form, has serious limitations for comparing water bodies and for establishing management priorities (Zandbergen and Hall, 1998; Said *et al.*, 2004). However, comparable to the Council of Ministers of the Environment water quality index (CCME WQI), the British Columbia WQI is flexible and adaptive to various applications (CCME, 2001).

Canadian Council of Ministers of the Environment WQI (Canada)

The CCME water quality index (CCME WQI) is a modification of the British Columbia water quality index (BCWQI). Similar to the British Columbia index, the CCME WQI comprises of three factors regarded as, (i) scope, (ii) frequency and (iii) amplitude (CCME, 2001; Khan *et al.*, 2005; Radwn, 2005, Alberta, 2008, 2011; Abbasi and Abbasi, 2012). The composition of the CCME index and the three factors are discussed as follows:

Factor 1 - Scope (F_1): This factor quantifies the water quality variables that do not meet water quality objectives. Which is the extent of water quality non-compliance over specific period of concern (percentage of parameters that do not meet objectives). Factor 1 is calculated using the following Equation (14).

$$F_1 = \left(\frac{\text{number of failed variables}}{\text{total number of variables}}\right) \times 100 \quad .. (14)$$

Factor 2 - Frequency (F_2): This factor describes how frequently does measurement not meet water quality objectives. This is the percentage of individual tests that fail to meet objectives ("failed tests"); and test refers to an individual parameter value per observation. Equation (15) is applied to calculate frequency.

$$F_2 = \left(\frac{\text{number of failed test}}{\text{total number of tests}}\right) \times 100 \quad .. (15)$$

Factor 3 - Amplitude (F_3): This factor represents by how much do measurements not meet objectives. Which is the amount by which failed test values do not meet their objectives. Unlike the scope and frequency factors, amplitude factor is calculated in three steps. First step, the calculation of the excursion, which is the number of times by which an individual variable is greater than or less than the water quality objective, and is defined in two ways. Scenario A, represented by Equation (16), that is ideal when the test value must not exceed water quality objective and Equation (17), is applicable to Scenario B, whereby the test value must not fall below water quality objective.

$$\text{excursion}_i = \left(\frac{\text{failed test value}_i}{\text{objective}_j}\right) - 1 \quad .. (16)$$

$$\text{excursion}_i = \left(\frac{\text{objective}_j}{\text{failed test value}_i}\right) - 1 \quad .. (17)$$

The second step involves the calculation of normalised sum of excursions (*nse*). That is, the collective amount by which individual tests are out of compliance is calculated by summing the excursion of individual tests from their objectives and dividing by the total number of tests. Normalised sum of excursions (*nse*) is denoted by the following Equation (18):

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{total number of tests}} \quad .. (18)$$

Upon that, the third step can be performed, which covers the calculation of the amplitude factor. Amplitude is derived by an asymptotic function that scales the normalised sum of excursion (*nse*) from water quality objectives to yield a value ranging from zero to hundred. The following Equation (19) is applicable when calculating the amplitude factor:

$$F_3 = \left(\frac{nse}{0.01nse + 0.01}\right) \quad .. (19)$$

Finally, using the scope factor (F_1), frequency factor (F_2) and amplitude factor (F_3); the overall water quality index is obtained using Equation (20) as follows (Nikoo *et al.*, 2011; Hurley *et al.*, 2012):

$$\text{WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right) \quad .. (20)$$

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 100.

Since each of the three factors values can reach as high as hundred, it means that the vector length $(100^2+100^2+100^2)^{0.5}$ can reach 173.2, hence the factor 1.732 was introduced into the index model to contain the index values not to exceed a maximum of hundred (Lumb *et al.*, 2006).

Considering that the CCME technique does not require statistically defined data to function, it is beneficial in the sense that, it provides leverage to alter the selection of water quality variables. In view of this, the CCME WQI is a flexible tool adaptable to accommodate various water quality parameters, as long as the appropriate pollution limits are properly defined. Which explains the wide spread and application of the Canadian Council of Ministers of the Environment water quality index (refer to, Khan *et al.*, 2003; Davies, 2006; Boyacioglu, 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).

Liou's water quality index (Taiwan)

Liou *et al.* (2004), employed a distinctive river status index (RSI) for monitoring Keya River in Taiwan. The index is a hybrid of additive and multiplicative model, which relay on six water quality variables as listed in Table 4, Part 26(c). Based on principal component analysis (PCA), the water quality variables are categorised into three groups namely organics, particulates and microorganisms. The overall index consists of three phases. Firstly, an additive model employed to aggregate the grouped variables into group sub-indices; secondly, multiplicative function used to aggregate the three group sub-indices, and further multiplied by three prefixed coefficients which addresses the effects of temperature, pondus Hydrogenium (pH) and toxic substances (Liou *et al.*, 2004, Sutadian *et al.*, 2016). The index proposed by Liou *et al.* (2004) is defined as follows:

$$\mathrm{RSI} = C_{temp}\,C_{pH}\,C_{tox}\left[\left(\sum_{i=1}^{3}\mathrm{I}_i w_i\right)\left(\sum_{j=1}^{2}\mathrm{I}_j w_j\right)\left(\sum_{k=1}^{1}\mathrm{I}_k w_k\right)\right]^{\frac{1}{3}} \quad .. \ (21)$$

Equal weights are assigned for the variables associated in the same category, that is, organic variables are assigned weighting factor of 0.33, whereas particulates are assigned 0.50 and microorganisms retain factor of 1.00 since its only one variable associated with this group. Thus, satisfying the following:

$$\sum_{i=1}^{n} w_i = 1;\ \sum_{j=1}^{n} w_j = 1;\ \text{and}\ \sum_{k=1}^{n} w_k = 1 \quad .. \ (22)$$

where: RSI 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; 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.

The concern of eclipsing and ambiguity occurring from aggregation and or large number of water quality variables, was minimised through categorisation of parameters and assigning appropriate mathematical functions. From the proposed hybrid function; if any of the parameters approaches zero value, the overall index responds accordingly lowering the river status index value towards zero (Liou *et al.*, 2004).

Fuzzy-based water quality index (Spain)

Fuzzy-based water quality index (FWQI) is one of the most useful tools developed by Ocampo-Duque *et al.* (2006) for assessing water quality of Ebro river in Spain. FWQI is a rule based fuzzy model that deals with non-linear, but ill-defined, mapping of input variables to appropriate outputs (Nikoo *et al.*, 2011). That is, a linguistic description is assigned to each fuzzy set and then, the sets are named based on a perceived degree of quality ranging from poor to excellent (Lermontov *et al.*, 2009).

Fuzzy logic data sets allow the inclusion of the qualitative aspects of human knowledge and reasoning process, through qualitative conditional expressions with verbal meaning, without employing precise quantitative analysis (Nikoo *et al.*, 2011). The method of modelling using intrinsically vague linguistic knowledge is based on the mathematics of fuzzy sets originally suggested by Zadeh (1965), and further explored by various water scientists including Ocampo-Duque *et al.* (2006); Lermontov *et al.* (2009); Nikoo *et al.* (2011), and Ocampo-Duque *et al.* (2013).

The FWQI for Ebro river in Spain uses a comprehensive set of twenty-seven water quality variables, divided into five parameters groupings as indicated in Table 4, Part 28(c). The index operates with ninety-six linguistic data rules, three for each parameter and three for each partial group score. Ocampo-Duque *et al.* (2006) used trapezoidal membership functions to represent the various fuzzy sets, and the functions are derived from Equation (23), whereas the final index score is achieved by Equation (24):

$$\mu(x; a, b, c, d) = \max\left(\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right) \quad .. (23)$$

$$\mathrm{FWQI} = \frac{\int \mu(z)\cdot z\mathrm{d}z}{\int \mu(z)z\mathrm{d}z} \quad .. (24)$$

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 as summarised in Table 4, Part 28(c).

Though regarded less accurate than the traditional numerical indices, water quality models based on fuzzy rules are perceived as adequate tools to represent uncertainties and inaccuracies in knowledge and data. The advantages brought by the simplicity, flexibility and computational speed of fuzzy-based models, may successively compensate the loss in accuracy (Lermontov *et al.*, 2009). Hence the choice on applicable methodologies depends on whether the index developer is concerned with accuracy, or simplicity and computational capabilities. Of which, the debate is biased towards the purpose of the water quality index.

Universal water quality index – Boyacioglu index (Turkey)

An index that describe the appropriateness of surface water for drinking purposes was developed by Boyacioglu (2007) and the model is commonly known as the universal water quality index (UWQI). The indexing tool utilises twelve water quality variables to describe quality of drinking water and the parameters are listed in Table (25). Temporary weights ranging from one to four on a basic scale of importance were assigned to the water quality parameters. Thereafter, the weights were divided by the sum of all the temporary weights to establish the final weighting factors The UWQI uses the weighted sum method to aggregate the twelve sub-indices and the formula is as follows (Boyacioglu, 2007; Abbasi and Abbasi, 2012; Boyacioglu and Gündogdu, 2013):

$$\mathrm{WQI} = \sum_{i=1}^{n} w_i \, \mathrm{I}_i \quad .. (25)$$

where: WQI is the universal water quality index value; wi is the weighted coefficient for the ith water parameter; Ii sub-index for the i^{th} water parameter; and n total number of the ranked water parameters.

The universal water quality index (UWQI) is based on permissible limits of relevant water quality standards set by the Council of European Communities and the Turkish water pollution control regulations.

Unlike most of the existing indices which are based on particular national water quality standards, UWQI was developed by considering multinational standards, thus ultimately extending its application boundaries. Similar to Boyacioðlu (2007) study, the purpose of this study includes development of a universal water quality index suitable for use across various catchment areas in South Africa, which may be distinct in their characteristics. By so doing, we ascertain the functionality of the WQI, improve simplicity and expand the application boundaries of the model.

Vaal water quality index (South Africa)

Banda (2015) developed an index for evaluating surface waters particularly for the Vaal Basin in South Africa, hence the term Vaal water quality index (Vaal WQI). The index comprises of fifteen critical water quality parameters as indicated in Table 4, Part 33(c). A ranking criterion with five levels was adopted for the Vaal WQI, whereby the maximum score of five being the highest order and minimum score of one expressing the ranking of variables with effects of the slightest significance. The rankings were assigned separately for human and environmental health effects and later combined to form single aggregated ranking value; thus, selecting the highest of both the human and environmental effects. The final weight coefficients were then formulated using Equation (26) and the overall classification of water quality is achieved through the weighted sum method (additive) as represented by Equation (27) (Banda, 2015).

$$w_i = \frac{b_i}{\sum_{i=1}^{n} b_i} \quad .. (26)$$

$$\mathrm{WQI} = \sum_{i=1}^{n} w_i \, \mathrm{I}_i \quad .. (27)$$

where: WQI is the universal water quality index value; b_i is the assigned ranking of the i^{th} water parameter (1 minimum and maximum of 5); is the weighted coefficient for the i^{th} water parameter (decimal value); I_i sub-index for the i^{th} water parameter; and n total number of the ranked water parameters.

The coefficients are represented as decimal numbers and the sum of all coefficients is one, thereby guaranteeing that the overall does not exceed hundred percent ($w_1 + w_2 + w_3 + \ldots + w_n = 1$ for Equations (26) and (27). The ranking coefficients are depended on the toxic effects of the pollutant. Death due to short term exposure being the highest in the order of effects is ranked five, whereas death because of long term expose ranked four. Ranking three and two represents debilitating effects due to immediate exposure and long-term exposure respectively. A minimum score of one express the ranking of water quality variable with effects of slightest significance.

The Vaal WQI is specific to the Vaal Basin, hence restrict its application boundaries. And this study attempts to break such barriers, through the development of a universal index that is applicable to most river catchments in South Africa. Thereby promoting a standardised way of monitoring and comparing water quality of various watersheds in South Africa, which eventually assist in the prioritisation of water resources across all the nine provinces of South Africa.

The fifteen water quality indices (WQIs) discussed are summarised in Appendix A. The summary includes application boundaries, water quality parameters, type of sub-indices and aggregation method used in the formulation of the index score. For comparison and benchmarking purposes, it is common practice that water quality index values be presented and described as classes. The categories and details of each class are discussed in the following section.

Water classification and index scores

Water quality index scores can be classified in two different ways. The first approach is whereby the index value increase with the increase of contamination level. This approach is referred to as the increasing scale indices. The second approach is where the index value decreases with the degree of pollution. This approach is referred to as the decreasing scale indices (Abbasi and Abbasi, 2012). Nevertheless, the purpose of scaling is the same, both indices reflects water quality based on pollution levels (Banda, 2015).

The assignment of water quality index values to classes of water quality is termed "categorisation" or "classification" and indicates an imperative but somewhat subjective process. Classification should be based on the best available information, expert judgment, and the general public's expectations of water quality (CCME, 2001). Normally, water quality index values are between zero and hundred (0 to 100) and classified in categories ranging from class 1 to class 5. The meaning of the index values and classes depends on whether the model is an increasing or decreasing scale index and typical examples are included in Table 1 and 2, for increasing scale indices and decreasing scale indices respectively.

A major gap identified in most of the water quality classification scales is that, not all possible index scores are accommodated in various WQ classification systems reviewed under this study. For instances, considering a classification schema by Rao *et al.* (2010), index score values between 25-26; 50-51; and 75-76 cannot be categorised, unless

Table 1. Typical WQI classification for increasing scale index

Class	Increasing scale water quality indices					
	House, Bordalo & Carvalho WQI		CCME WQI		Universal & Vaal WQI	
	Rank	Index Score	Rank	Index Score	Rank	Index Score
Class 1	Very good	91 to 100	Excellent	95 to 100	Excellent	95 to 100
Class 2	Good	71 to 90	Good	80 to 94	Good	75 to 94
Class 3	Reasonable	51 to 70	Fair	65 to 79	Fair	50 to 74
Class 4	Polluted	26 to 50	Marginal	45 to 64	Marginal	25 to 49
Class 5	Badly polluted	10 to 25	Poor	0 to 44	Poor	0 to 24

Source: CCME (2001); Bordalo *et al.* (2006); Boyacioglu (2007); Carvalho *et al.* (2011); Banda (2015); Banda and Kumarasamy (2020). Notes: House WQI: House's water quality index (United Kingdom), Bordalo WQI: Bordalo et al water quality index (Iberian Peninsula: Portuguese-Spanish Border), Carvalho WQI: Carvalho et al water quality index (Portugal), CCME WQI: Canadian Council of Ministers of the Environment WQI (Canada), Universal WQI: Universal water quality index – Boyacioðlu index (Turkey) and Vaal WQI: Vaal water quality index (South Africa).

otherwise the final index score is rounded-off to a whole number. Which is not the case with most of the research work reviewed under this chapter. Some of the water quality indices with similar challenges includes, Kannel *et al.* (2007); Ramakrishnaiah *et al.* (2009); Al Obaidy *et al.* (2010); Yadav *et al.* (2010); Khanna *et al.* (2013); Rao and Nageswararao (2013); Bhadra *et al.* (2014); Sharma *et al.* (2014); Banda (2015); Meher *et al.* (2015); AL-Sabah (2016); Sudha *et al.* (2016), and Wanda *et al.* (2016); Abdel-Satar *et al.* (2017); Ewaid and Abed (2017b).

In some instances, possible index scores fall within two categories; for example, index scores of 25; 50; 70 and 90 in a scale of 'very bad' (0-25), 'bad' (25-50), 'medium' (50-70), 'good' (70-90) and 'excellent' (90-100). Index score 25 falls under the 'very bad' and 'bad' categories, whereas index score 50 falls under the 'bad' as well as the 'medium' categories, and so forth. Practical examples of this scenario are water classification scales developed by Hamid *et al.* (2013); Vatkar *et al.* (2013); Kalyani *et al.* (2016); Luzati and Jaupaj (2016); Guettaf *et al.* (2017), and Shah and Joshi (2017).

Zhao *et al.* (2012); Al-Janabi *et al.* (2015); Abtahi *et al.* (2015); Al Obaidy *et al.* (2015), and García-Ávila *et al.* (2018), attempted to resolve the problem by minimising the difference between classes to a decimal fraction. Though, the problem has been minimised, the fact remains, the categorisation schema does not accommodate all the achievable index scores. It is then crucial that, the use of logical

Table 2. Typical WQI classification for decreasing scale index

Class	Decreasing scale water quality indices					
	BCWQI		Rao, Vatkar & Vasanthavigar WQI		Rao et al WQI	
	Rank	Index Score	Rank	Index Score	Rank	Index score
Class 1	Excellent	0 to 3	Excellent	< 50	Excellent	0 to 25
Class 2	Good	4 to 17	Good	50.1 to 100	Good	26 to 50
Class 3	Fair	18 to 43	Poor	100.1 to 74	Bad	51 to 75
Class 4	Borderline	44 to 59	Very poor	25 to 49	Very bad	76 to 100
Class 5	Poor	60 to 100	Unsuitable	> 300	Unfit	100 and above

Source: Zandbergen and Hall (1998); Rao *et al.* (2010); Vasanthavigar *et al.* (2010); Rao and Nageswararao (2013); Vatkar *et al.* (2016); Banda and Kumarasamy (2020). Notes: BCWQI: British Columbia water quality index (Canada), Rao WQI: Rao and Nageswararao water quality index (India), Vatkar WQI: Vatkar *et al* water quality index (India), Vasanthavigar WQI: Vasanthavigar *et al* water quality index (India) and Rao et al WQI: Rao *et al* water quality index (India).

Table 3. Index score classification for Martínez de Bascarón WQI

Rank	Water quality classification	
	Description of rank and classification	Index score
1	**Class I – Good water quality** Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels	91 ≤ Index ≤ 100
2	**Class II – Acceptable water quality** Water quality is usually protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels	61 ≤ Index < 91
3	**Class III – Regular water quality** Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels	31 ≤ Index < 61
4	**Class IV – Bad water quality** Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels	16 ≤ Index < 31
5	**Class V – Very bad water quality** Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels	0 ≤ Index < 16

Source: Abrahão *et al.* (2007); Banda and Kumarasamy (2020). Notes: Class 1 index values (excellent) can only be obtained if all measurements are within objectives virtually all of the time.

linguistic descriptions like, less than, equal to and greater than, be adopted to allow the inclusion of all possible index values. Abrahão *et al.* (2007); Rabee *et al.* (2011); Rubio-Arias *et al.* (2012), and Sutadian *et al.* (2018), are good examples of water categorisation schema with appropriate mathematical functions that encompasses all the possible index values.

DISCUSSION

Water quality indices (WQIs) have been recognised as significant environmental performance indicators and the concept of expressing water quality using a numerical value has been easily appreciated, leading to the suggestion of various indexing models. Traditionally water quality indices were developed for a particular region and their application limited to such basins at which they were designed for. Of lately, various countries have embarked on the process of developing composite universal indices to evaluate and describe the state of their domestic water. In similar manner, the current studies attempt to develop a universal water quality index for South African river catchments, and this review paper forms part of the research study.

Fifteen specific water quality indices were identified as most significant, based on their wider application and they are discussed in detail in this article. Nevertheless, the rest of the reviewed indices are documented towards the end of this review paper as Appendix A, Table 4.

CONCLUSION

Water quality index (WQI) is a unique technique employed to describe water quality and has proven to be an effective method to evaluate spatial and temporal water changes in South African river catchments, and the world at large. Water quality indices (WQIs) consolidates vast amount of complex water quality data and generates a single value in a simple and reproducible manner. Which explains the successful application of WQIs over the past years, because they help deducing vast amount of scientific data and describe water quality status to the public and policy makes, using a simple dimensionless score. Even non-technical stakeholders will understand the water quality rating scores, especially when disseminated to classes presented as "poor," "fair," "medium," "good," and "excellent."

A considerable number of indices has been developed for various uses, but mainly applicable to a specific region. This is, perhaps, the most demanding scientific need; that is, the development of a unified water quality index, that can be applicable to most, if not all the water sheds of a given country. An index that is not limited to certain application boundaries, and thus the aim of this current study.

Author Contributions

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

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Conflict of Interest

The authors declare no conflict of interest.

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

Fifteen significant water quality indices (WQIs) were discussed in detail in this article, essentially to establish the existing knowledge and provide background information to the current study. Consequently, this works as guidance towards the selection of the most appropriate research methods and ensure that objectives set for the research study are attained. Which becomes a logical basis (rationale) for evaluating more existing WQIs. Hence the purpose of Appendix A, Table 4 in particular, is to provide further information on existing WQIs and enables the researcher to anticipate the most appropriate methods. It also provides a theoretical framework to justify the outcome of the study and substantiate the choices made. There are numerous water quality indices developed since the 19th century, and it is extensive work and beyond reach to attempt discussing all of them under this review; therefore, only forty WQIs are reviewed and presented in Table 4.

Table 4. Specific Details of the reviewed water quality indices (WQIs)

Identity		Specific details of the reviewed water quality indices (WQIs) (a) Name and associated authors, (b) Region of application and purpose, (c) Selected water quality parameters, (d) Sub-indices and weights, and (e) Aggregation method (mathematical composition)
1	(a)	Horton Water Quality Index (Horton's WQI). Horton (1965); Debels *et al.* (2005); Lumb *et al.* (2011a), and Lumb *et al.* (2011b)
	(b)	Developed for United States of America for general assessment of water quality, through the Ohio River Valley Water Sanitation Commission in USA
	(c)	8 parameters: Alkalinity, carbon chloroform extract, chlorides, coliform density, dissolved oxygen, pondus Hydrogenium [pH], sewage treatment and specific conductance. Note that, temperature and pollution are included as factors rather than parameters
	(d)	Horton's rating scales and unequal weights were used with the weights ranging from 1 to 4
	(e)	The WQI utilities an Arithmetic weighted mean function
2	(a)	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)
	(b)	Developed for United States of America and further applied in Brazil, India and Iran. Created for general assessment of water quality
	(c)	11 parameters: dissolved oxygen, faecal coliform, pondus Hydrogenium [pH], five-day biochemical oxygen demand, phosphates, nitrates, temperature, turbidity, total solids, pesticides and toxic elements
	(d)	Associated rating curves and unequal weights were developed through Delphi Method of involving expert's opinions. Sum of weights equals to 1. Pesticides and toxic elements were handled differently without weights
	(e)	Additive aggregation function was used for the first version in 1970, whereas, multiplicative was adopted for the second version in 1973
3	(a)	Water Pollution Index (WPI). Nemerow (1971); Xu *et al.* (2010)
	(b)	Index instituted by United States of America specifically for direct and indirect human contact uses as well as remote contact uses
	(c)	15 parameters: alkalinity, chloride, colour, dissolved oxygen, faecal coliform, hardness, temperature, total dissolved solids, total nitrogen, turbidity, manganese, pH, suspended solids, sulphates and Iron
	(d)	Sub-indices are generated based on the mean and highest ratio between the particular parameter value over the standard allowable limits. The index is developed using equal weightage
	(e)	WPI utilises the root mean square model to aggregate the equally weighted sub-indices and obtain one final index value
4	(a)	Prati Single Index of Pollution (Prati's Pollution Index). Prati *et al.* (1971)
	(b)	Italy index of pollution instituted to describe the extent of surface water pollution
	(c)	13 parameters: alkyl benzene sulfonates, ammonia, carbon chloroform extract, chemical oxygen demand (based on permanganate), chlorine, dissolved oxygen, five-day biochemical oxygen demand, Iron, manganese, nitrates, pH and suspended solids
	(d)	All parameters are considered as indices of pollution with unequal weights adding to a total sum of 1
	(e)	Additive method is used to combine the indices of pollution to provide the pollution index value
5	(a)	Harkin Water Quality Index (Harkin's WQI). Harkins (1974); Landwehr *et al.* (1974)
	(b)	A scientific tool initiated for collective evaluation of water quality within the United State of America
	(c)	No parameter guidelines: any number of parameters may be used to compute the water quality index (WQI) value depending upon the intended ultimate use and or objective of the evaluation
	(d)	In cognisance of the permissible limits (target values), standardisation of the variables is performed to achieve one dimensional scale of the water quality parameters. Unequal weights are assigned with total sum of one whole number
	(e)	A non-parametric classification statistical procedure is used to establish the WQI value, through Multivariate Kendall's Static technique
6	(a)	Walski and Parker Water Quality Index (Walski WQI). Walski and Parker (1974)
	(b)	Index for analysing the suitability of water resources earmarked for recreational uses in the United States of America (USA)
	(c)	10 parameters: coliform count, colour, grease, nutrients, odour, pH, suspended solids, temperature, toxicity and turbidity

Table 4. *Continued ...*

Identity		Specific details of the reviewed water quality indices (WQIs) (a) Name and associated authors, (b) Region of application and purpose, (c) Selected water quality parameters, (d) Sub-indices and weights, and (e) Aggregation method (mathematical composition)
	(d)	All parameters are considered as sub-indices with unequal weights adding to a total sum of 1
	(e)	Additive aggregation equation is utilised to describe the water quality index (WQI)
7	(a)	Scottish Research Development Department Water Quality Index (SRDD Index) SRDD (1976); Bordalo *et al.* (2001); Bordalo *et al.* (2006); Carvalho *et al.* (2011), and Dadolahi Sohrab *et al.* (2012)
	(b)	Water quality index developed by the Scottish Government for general water quality assessment in Scotland. Though SRDD Index was applied in several studies for Spain, Portugal, Thailand and Iran
	(c)	10 parameters: dissolved oxygen, pH, free and saline ammonia, five-day biochemical oxygen demand, total oxidised nitrogen, suspended solids, phosphorus, *E. coli*, conductivity and temperature
	(d)	Conceptually similar to NSF WQI, the parameter rating curves and unequal weights were developed through Rand Corporation's Delphi Technique with the sum of all weights adding to 1
	(e)	Final index value was established based on the additive aggregation function
8	(a)	Ross Water Quality Index (Ross WQI). Ross (1977)
	(b)	Established for the United Kingdom territory for general water quality assessment
	(c)	4 parameters: ammoniac nitrogen, dissolved oxygen, five-day biochemical oxygen demand and suspended solids
	(d)	Sub-indices with rating curves developed through Rand Corporation's Delphi Technique with unequal weights and the sum of all weights adding to 10
	(e)	Additive aggregation method is used by Ross WQI
9	(a)	STORET Water Quality Index (STORET Index). Canter (1977), Ministry of the Environment of Indonesia (2003)
	(b)	Index for general water quality evaluation for the North America
	(c)	No specified list of parameters. Rather variables are categorised into 3 groups (biological, chemical and physical)
	(d)	Unequally weighted 3 group sub-indices derived from an analysis of monitored parameter values against the permissible limits
	(e)	The additive function is used to combine the group sub-indices into a single index value
10	(a)	Stoner Water Quality Index (Stoner' Index). Stoner (1978)
	(b)	WQI specifically modelled for assessing the suitability of irrigation water within the United States of America
	(c)	16 parameters (irrigation): aluminium, arsenic, beryllium, boron, cadmium, chromium, cobalt, copper, faecal coliform, fluoride, manganese, nickel, sodium absorption ratio [SAR], specific conductance, vanadium and zinc 13 parameters (water supply): ammonia-nitrogen, chloride, colour, copper, faecal coliform, fluoride, Iron, methylene active blue substance [MBAS], nitrate-nitrogen, pH, phenols, sulphate and zinc
	(d)	All water quality parameters are taken as a sub-index with unequal weights adding to a total sum of 1
	(e)	Additive aggregation function is used to provide the final index number
11	(a)	Oregon water quality index (OWQI) Dunnette (1979), Cude (2001), and Sarkar and Abbasi (2006)
	(b)	Utilised by Oregon (pacific northwest, west coast) and Idaho (north-western region), United States of America. Both indices were developed for general water quality assessment of Oregon and Idaho States
	(c)	6 parameters (first version): dissolved oxygen, faecal coliform, pH, five-day biochemical oxygen demand, nitrates, ammonia and total solids 8 parameters (second version): temperature and total phosphorus, adding to the parameters of the first version of the water quality index (WQI)
	(d)	Both indices used logarithmic transforms to convert water quality variables into sub-indices values. The first version used unequally weights with total sum of weight adding to 1, while, the second version used equal weights
	(e)	Additive formula and un-weighted harmonic mean of squares of the sub-indices were used to aggregated the final WQI value for both the first version and second version of the index respectively
12	(a)	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)

Table 4. *Continued ...*

Identity		Specific details of the reviewed water quality indices (WQIs) (a) Name and associated authors, (b) Region of application and purpose, (c) Selected water quality parameters, (d) Sub-indices and weights, and (e) Aggregation method (mathematical composition)
	(b)	Formulated for use in Spain and later modified by various researchers for application in Argentina, Brazil, Korea and India. Original index was for general water quality assessment, but the evolution of the index, was targeting specific uses
	(c)	26 parameters: pH, five-days biochemical oxygen demand, dissolved oxygen, temperature, total coliform, colour, turbidity, permanganate reduction, detergents, hardness, pesticides, oil and grease, sulphates, nitrates, cyanides, sodium, free carbon dioxide, ammonia nitrogen, chloride, conductivity, magnesium, phosphorus, nitrites, calcium and apparent aspect
	(d)	Sub-indices generated from segmented (piecewise) linear transformation. Unequal weights were assigned with a total sum of 54
	(e)	The final index value was obtained through the application of a modified additive function
13	(a)	Bhargava's Water Quality Index (Bhargava's Index). Bhargava (1985), AlAni et al. (1987), and Avvannavar and Shrihari (2008)
	(b)	Established to evaluate water quality of River Yamuna, Delhi, India
	(c)	Identified 4 parameter groups: (i) coliform organisms to represent bacterial variables, (ii) toxicants, heavy metals, etc., (iii) physical parameters and (iv) organic and inorganic nontoxic substances
	(d)	Water quality parameters clustered in the same group were aggregated to obtain 4 different group sub-indices. Unequal weights with a total summing up to 1
	(e)	Bhargava's index used a modified multiplicative model
14	(a)	House's Water Quality Index (House's Index). House (1986, 1989, 1990), Tyson and House (1989), and Carvalho *et al.* (2011)
	(b)	Water quality index for the United Kingdom, which was further modified for application in Spain. Its purposes included general assessment of water quality, appraisal of portable water supply and evaluating suitability of aquaculture
	(c)	9 parameters: dissolved oxygen, ammonia nitrogen, pH, five-day biochemical oxygen demand, chlorides, total coliform, total phosphorus, nitrates and temperature
	(d)	Conceptually similar to NSF WQI, the parameter rating curves and unequal weights were developed through Rand Corporation's Delphi Technique with the sum of all weights adding to 1
	(e)	Final index value was established based on the additive aggregation function
15	(a)	Dinius Water Quality Index (Dinius WQI). Dinius (1987), Sarkar and Abbasi (2006)
	(b)	Dinius WQI established in United Kingdom for general water quality evaluation, which included public water supply, recreation, fisheries, shellfish, agriculture and industrial waters
	(c)	12 parameters: alkalinity, chlorides, coliform count, colour, dissolved oxygen, E-coli count, five-day biochemical oxygen demand, hardness, nitrates, pH, specific conductance and temperature
	(d)	Parameter sub-indices with unequal weightage assigned based on the evaluation of importance by the Delphi panel members
	(e)	Multiplicative aggregation function is utilised to combine all the sub-index functions into one overall index value
16	(a)	Smith Water Quality Index (Smith's WQI). Smith (1987, 1990)
	(b)	River and stream water quality index for New Zealand. Used to assess suitability of water resources for various uses such as bathing, water supply and fish spawning
	(c)	7 parameters (water supply): ammonia, dissolved oxygen, faecal coliform, five-day biochemical oxygen demand (unfiltered), temperature, turbidity and suspended solids 6 parameters (general and bathing): dissolved oxygen, faecal coliform, five-day biochemical oxygen demand (unfiltered), temperature, turbidity and suspended solids 4 parameters (fish spawning): five-day biochemical oxygen demand (unfiltered), temperature, turbidity and suspended solids
	(d)	Sub-indices and rating curves developed through a panel of experts (Delphi's Method) with sum of unequal weights adding to 1
	(e)	The lowest value of all the sub-indices is retained as the final index value, thus the minimum operator technique

Table 4. *Continued ...*

Identity		Specific details of the reviewed water quality indices (WQIs) (a) Name and associated authors, (b) Region of application and purpose, (c) Selected water quality parameters, (d) Sub-indices and weights, and (e) Aggregation method (mathematical composition)
17	(a)	Ved Prakashi Water Quality Index (Ved Prakashi's Index). 1990
	(b)	Index for India attempting to evaluate the general water quality status of Indian water resources
	(c)	4 parameters: biochemical oxygen demand, dissolved oxygen, faecal coliforms and pH
	(d)	Each water quality variable was considered as a sub-index with unequal weights adding to a total sum of 1
	(e)	Parameter sub-indices were combined using the additive aggregation function
18	(a)	Diljido Water Quality Index (Diljido's Index). Dojlido *et al.* (1994)
	(b)	Mathematical tool developed in Serbia for analysing the water quality status of various water sources
	(c)	7 basic parameters: ammonia, chemical oxygen demand (Mg), chlorides, dissolved oxygen, dissolved solids, five-day biochemical oxygen demand, suspended solids, phosphates 19 additional parameters: cadmium, chemical oxygen demand (Cr), chlorides, chromium, copper, free cyanides, hardness, lead, iron, manganese, mercury, nickel, nitrate, organic nitrogen, phenols, total chromium, sulphates and zinc
	(d)	Sub-indices with equal weights
	(e)	Combination of parameter sub-indices was achieved through the application of a mathematical function simply known as the harmonic mean square root formula (harmonic model)
19	(a)	British Columbia water quality index (BCWQI). Zandbergen and Hall (1998), CCME (2001), Bharti and Katyal (2011)
	(b)	Though adaptive to various applications, the BCWQI was designed for general water quality assessment for the British Columbia Province in Canada
	(c)	No prescribed list of parameters, instead, a minimum of 4 parameters are required and there is no defined maximum number of parameters
	(d)	The index does not use neither sub-indices nor weights, rather the deviation of the monitored parameter value form the standards is used to describe water quality
	(e)	No aggregation function, in fact, 3 factors are employed to express the extent of water quality noncompliance and divergence from water quality standards
20	(a)	Status and Sustainability Index (SS Index). Oudin *et al.* (1999); Fulazzaky (2010)
	(b)	Developed for France mainly for general water quality assessment
	(c)	15 parameter clusters: based on their similar nature and their impact on environment. Acidification, colour, metals in bryophytes, microorganisms, mineralisation, mineral micro pollutants, nitrates, non-pesticides, organic micro-pollutants, pesticides, phosphorus matter, phytoplankton, suspended particles and temperature
	(d)	Colour, nitrates and temperature alteration classes are considered directly as sub-indices, whereas, with the other classes, only one variable with the worst monitored value is considered as sub-index of that particular alteration class, obeying the minimum operator method. All parameters have equal weights
	(e)	Minimum operator function is used to aggregate the final index value
21	(a)	Contact Recreation Index (NZ Recreation Index). Nagels *et al.* (2001)
	(b)	Established in New Zealand for assessing recreational water resources
	(c)	8 parameters: Escherichia coli (or faecal coliform), colour, dissolved inorganic nitrogen, dissolved reactive phosphorus, five-day biochemical oxygen demand, pH, turbidity and visual clarity
	(d)	Parameter sub-indices with equal weights
	(e)	The final index value is obtained through the application of the minimum operator function
22	(a)	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), Boyacioglu (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)
	(b)	Originally for Canada and adopted for India, Albania, Chile, Egypt, Iran, Spain, Turkey and Poland. The original WQI was designed for general water quality assessment, whereas the modified indices are for specific uses
	(c)	No prescribed list of parameters, instead, a minimum of 4 parameters are required and there is no defined maximum number of parameters

Table 4. *Continued ...*

Identity		**Specific details of the reviewed water quality indices (WQIs)** (a) Name and associated authors, (b) Region of application and purpose, (c) Selected water quality parameters, (d) Sub-indices and weights, and (e) Aggregation method (mathematical composition)
	(d)	The index does not use neither sub-indices nor weights, rather the deviation of the monitored parameter value form the standards is used to describe water quality
	(e)	No aggregation function, in fact, 3 factors (scope, frequency and amplitude) are employed to express the extent of water quality noncompliance and amplitude from the standards
23	(a)	Hallock Water Quality Index (Hallock's Index). Hallock (2002)
	(b)	Developed for United States of America for routine stream monitoring exercise
	(c)	8 parameters: dissolved oxygen, faecal coliform bacteria, pH, temperature, total nitrogen, total phosphorus, total suspended sediments and turbidity
	(d)	Total suspended sediments and turbidity are combined to become one sub-index using average mean value. Whereas faecal coliform bacteria, pH, and temperature are considered as parameter sub-indices generated from permissible limits. The rest of the parameters are directly considered as sub-indices developed using historical data. All the sub-indices are weighted equally
	(e)	Hallock's Index is based on an additive function
24	(a)	Dalmatian Water Quality Index (Dalmatian Index). Štambuk-Giljanovie (1999, 2003)
	(b)	Used in Serbia as a tool for general water quality evaluation
	(c)	9 parameters: five-day biochemical oxygen demand, dissolved oxygen, corrosion coefficient, mineralisation, protein N, temperature, total coliforms, total nitrate and total phosphorus
	(d)	Parameter sub-indices with unequal weights adding to a total sum of 1
	(e)	Additive or multiplicative functions can be utilised to aggregate the final index rating
25	(a)	Overall Index of Pollution (Indian OIP). Sargaonkar and Deshpande (2003)
	(b)	OIP is designed as an indicator of surface water pollution in India
	(c)	13 parameters: arsenic, biochemical oxygen demand, chloride, colour, dissolved oxygen, fluoride, hardness, nitrate, pH, turbidity, sulphate, total coliform and total dissolved solids
	(d)	Individual water quality parameter sub-indices with equal weights
	(e)	The final OIP value is obtained through the application of additive aggregation function
26	(a)	Liou's Water Quality Index (Liou's WQI). Liou *et al.* (2004)
	(b)	Taiwan WQI developed for general water quality assessment
	(c)	At least 9 parameters: ammonia nitrogen, dissolved oxygen, faecal coliform, five-day biochemical oxygen demand, pH, suspend solids, temperature, toxicity and turbidity
	(d)	All parameters have sub-indices, which are further grouped into 3 cluster sub-indices, which are [a] microorganism sub-index (total coliform), [b] organics sub-index (ammonia nitrogen, chemical oxygen demand, dissolved oxygen and five-day biochemical oxygen demand) and finally [c] particulates sub-index (suspended solids and turbidity)
	(e)	Both additive and multiplicative functions are used. Additive formula combines water quality parameters of the same characteristic into group sub-indices (that is, organic and nutrients as well as particulates). Whereas the multiplicative function aggregates all the 3 group sub-indices
27	(a)	Said Water Quality Index (Said's WQI). Said et al. (2004)
	(b)	WQI produced for general water quality evaluation of surface water resources in the United States of America
	(c)	5 parameters: dissolved oxygen, faecal coliform, total phosphates, turbidity and specific conductivity(d) Utilises equally weighted parameter sub-indices
	(e)	Index value generated through the application of a specific linear function
28	(a)	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)
	(b)	WQI for Spain and introduced in Iran, India, Brazil and Columbia. Fuzzy Index was developed for general water quality evaluation
	(c)	No guidelines provided
	(d)	Using fuzzy logic and unequal weights
	(e)	Using fuzzy logic

Table 4. *Continued ...*

Identity		Specific details of the reviewed water quality indices (WQIs) (a) Name and associated authors, (b) Region of application and purpose, (c) Selected water quality parameters, (d) Sub-indices and weights, and (e) Aggregation method (mathematical composition)
29	(a)	Universal Water Quality Index - Boyacioglu Index (UWQI). Boyacioglu (2007)
	(b)	WQI developed to evaluate the suitability of drinking water supplied in Turkey
	(c)	12 parameters: arsenic, cadmium, cyanide, dissolved oxygen, five-day biochemical oxygen demand, fluoride, mercury, nitrate-nitrogen, pH, selenium, total coliform and total phosphates
	(d)	Sub-indices are generated in cognisance of the permissible limits governed by Turkey water standards. The WQI utilises unequal weights adding up to a total sum of 1
	(e)	Aggregation of the sub-indices is achieved through the utilisation of an additive formula
30	(a)	Malaysian Water Quality (Malaysian Index). Shuhaimi-Othman *et al.* (2007)
	(b)	Applied in Malaysia for general water quality valuation
	(c)	6 parameters: sulphates, phosphate, pH, chemical oxygen demand, nitrates and ammonia nitrogen
	(d)	Variable directly considered as sub-indices using unequal weights adding up to a total sum of 1
	(e)	Additive aggregation method applied to aggregate the final water quality index value
31	(a)	Hanh Water Quality Index (Hanh's WQI). Thi Minh Hanh *et al.* (2011)
	(b)	WQI formulated to evaluate surface water resources in Vietnam
	(c)	Minimum of 11 parameters: ammonium nitrogen, chemical oxygen demand, dissolved oxygen, five-day biochemical oxygen demand, orthophosphate, total coliform, suspended solids, temperature, turbidity and toxicity
	(d)	All parameters have sub-indices, which are further clustered into 3 group sub-indices, thus [a] bacteria sub-index (total coliform), [b] organic and nutrients sub-index (ammonia nitrogen, chemical oxygen demand, dissolved oxygen, five-day biochemical oxygen demand, and orthophosphate) and lastly [c] particulates sub-index (suspended solids and turbidity
	(e)	Both additive and multiplicative functions are used. Additive formula aggregates water quality variables of the same characteristic into clustered parameter sub-indices (that is, organic and nutrients together with particulates). Whilst the multiplicative model combines all the 3 group sub-indices
32	(a)	Almeida Water Quality Index (Almeida's Index). Almeida *et al.* (2012)
	(b)	Research initiative for Argentina, created mainly for water quality assessment of recreational water resources
	(c)	9 parameters: chemical oxygen demand, detergents, Escherichia coli, enterococci, faecal coliforms, nitrates, phosphate, pH, and total coliforms
	(d)	Parameter sub-indices with unequal weights adding to a total sum of 1
	(e)	Almeida's Index uses multiplicative function to combine the sub-indices into a single index grading
33	(a)	Vaal Water Quality Index (Vaal WQI). Banda (2015)
	(b)	Specifically developed for the Vaal Basin in South African to evaluate the status of surface raw water intended for purification to portable standards
	(c)	15 parameters: ammonia/ammonium, calcium, chlorophyll 665, chloride, electrical conductivity, fluoride, hardness, magnesium, manganese, nitrate/nitrite, orthophosphate, pondus Hydrogenium [pH], sulphate, total alkalinity and turbidity
	(d)	Variable directly considered as sub-indices using unequal weights adding up to a total sum of 1
	(e)	Vaal WQI utilises additive aggregation model to combine the unequally weighted sub-indices
34	(a)	Wanda Water Quality Index (Wanda's Index). Wanda *et al.* (2016)
	(b)	Suggested for evaluating water resources for Mpumalanga and North-West Provinces in South Africa
	(c)	7 parameters: pondus Hydrogenium [pH], electrical conductivity, five-day biochemical oxygen demand, *Escherichia coli* [*E-coli*], temperature, turbidity and nutrients (nitrogen and phosphates)
	(d)	Parameter sub-indices with unequal weights adding to a total sum of 1
	(e)	The final index value is obtained through the application of the modified additive function
35	(a)	Medeiros Water Quality Index (Medeiros WQI). Medeiros *et al.* (2017)
	(b)	Developed for evaluating water quality for Murucupi River Basin, Barcarena City in the Pará State, Brazil
	(c)	11 parameters: temperature, pH, total dissolved solids, total suspended solids, dissolved oxygen, five-day biochemical oxygen demand, thermotolerant, coliforms, total nitrogen, total phosphorus, and turbidity

Table 4. *Continued ...*

Identity		Specific details of the reviewed water quality indices (WQIs) (a) Name and associated authors, (b) Region of application and purpose, (c) Selected water quality parameters, (d) Sub-indices and weights, and (e) Aggregation method (mathematical composition)
	(d)	All parameters are considered as sub-indices with unequal weights adding to a total sum of 1
	(e)	Multiplicative aggregation equation is utilised to describe the water quality index (WQI)
36	(a)	García-Ávila Water Quality Index (García-Ávila Index). García-Ávila *et al.* (2018)
	(b)	Developed to analyse drinking water for Azogues City in Ecuador
	(c)	13 parameters: turbidity, temperature, electrical conductivity, pondus Hydrogenium [pH], total dissolved solids, total hardness, calcium, magnesium, alkalinity, chlorides, nitrates, sulphates and phosphates
	(d)	Variable directly considered as sub-indices using unequal weights adding up to a total sum of 1
	(e)	García-Ávila Index is based on additive aggregation function that combine unequally weighted sub-indices
37	(a)	Drinking Water Quality Index (DWQI). Ponsadailakshmi *et al.* (2018)
	(b)	Index established to assess the drinking water in Nagapattinam, Tamil Nadu in Southern India
	(c)	17 parameters: pondus Hydrogenium [pH], electrical conductivity, sodium, chloride, sulphate, alkalinity, total hardness, calcium, magnesium, iron, fluoride, nitrate, manganese, zinc, chromium, lead and copper
	(d)	Parameter sub-indices with unequal weights adding to a total sum of 1
	(e)	Both arithmetic and geometric methods were applied to aggregate the final water quality index value
38	(a)	Fuzzy-based Water Quality Index (FWQI). Tiri *et al.* (2018)
	(b)	WQI for El Hai Basin in Algeria
	(c)	10 parameters for both FWQI and the traditional WQI: pondus Hydrogenium [pH], total dissolved solids, calcium, magnesium, Sodium, potassium, chloride, sulphate, bicarbonate and nitrate
	(d)	Using fuzzy logic and unequal weights the traditional WQI uses parameter sub-indices and unequal weights
	(e)	Using fuzzy logic and the traditional WQI uses additive method to aggregate sub-indices into WQI
39	(a)	West Java Water Quality Index (WJWQI). Sutadian *et al.* (2018)
	(b)	Tool developed to assess water quality in rivers of the West Java Province in Indonesia
	(c)	17 parameters: temperature, suspended solids, chemical oxygen demand, dissolved oxygen, nitrite, total phosphate, detergent, phenol, chloride, zinc, lead, mercury, and faecal coliform
	(d)	Parameters directly considered as sub-indices with unequal weights adding up to a total sum of 1
	(e)	WJWQI utilises geometric aggregation model to combine the unequally weighted sub-indices
40	(a)	Mhlongo's Water Quality Index (Mhlongo's Index). Mhlongo *et al.* (2018)
	(b)	Index suggested for evaluating mining water along the Upper Olifants River, Witbank Dam, South Africa
	(c)	5 parameters: pondus Hydrogenium [pH], turbidity, total dissolved solids, sulphates and manganese
	(d)	The index does not use neither sub-indices nor weights, rather the deviation of the monitored parameter value form the standards is used to describe water quality
	(e)	No aggregation function, in fact, allowable upper and lower limits are used to express the extent of water quality noncompliance from the national standards

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 4 above is based on the year at which the WQI was developed and or published, rather than preference.

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