

## A Systematic Review and Meta-Analysis of Water Quality Indices

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**Abstract:** Water quality indices (WQI) are useful tools for indicating the suitability of water for an expected use. However, they can suffer from some problems. The objective of this paper was to analyze the development of WQI to determine which parameters are used in water quality assessment and to discuss the characteristics of WQI. To screen articles on WQI, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method is applied to include or exclude articles. Four necessary steps are needed to design WQI: parameter selection, standardization, weighting and aggregation. A set of six methods of aggregations of sub-indices are identified: the arithmetic mean, the geometric mean, the root square, the logarithmic function, the fuzzy inference and the minimum operator. The problems encountered for the overall index are different according to the form of aggregation. They are eclipsing, ambiguity, rigidity or flexibility, adaptability and compensation. The chemical parameters (70%) are the most used in the development of WQI with the physical parameters used at 24% and the biological parameters at 6%. Dissolved oxygen (DO, 87%), total coliforms (87%), biological oxygen demand (BOD, 73%), pH (73%), temperature (67%), turbidity (60%), ammonia (53%), ammonium (47%) and total dissolved solids (47%) are the most commonly used parameters for water quality assessment.

Key words: Water quality indices, water quality parameters, water quality assessment, review, meta-analysis.

## 1. Introduction

Recently, water resource managers have been alarmed about the quantity of water available [1]. Several studies have been conducted on water quality due to urbanization and population growth affecting water resource quality [2]. The concept of water quality dates back to 1848 in Germany to determine the purity or the pollution degree of water resources [3], especially to determine the fitness of water bodies using an indicator such as the presence or absence of certain number of organisms [4]. According to Lumb *et al.* [3], since the birth of the concept, it would take more than a century to develop a composite index to evaluate water quality.

The water quality indices (WQI) is an aggregation of several values of physicochemical and biological parameters to a unique value that indicates the overall quality of water sources (groundwater and surface water) vis-à-vis to an intended use or objective [4-8]. Used by water quality monitoring programs, WQI are tools for examining trends, highlighting environmental conditions and helping government decision makers assess the effectiveness of regulatory programs [4, 6]. Moreover, Abassi and Abassi [4] report that various European countries have developed

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and classified water resources according to two types: (1) those concerned by presence of pollution and (2) those concerned by communities of macroscopic and microscopic organisms. The WQI is the most comprehensive way to synthesize and summarize complex data of water parameters to a composite index that is easy to understand and interpret [7].

The increasing level of pollution due to industrialization, population growth and agricultural activities with their consequences on water resources necessitate the development of WQI that quantify and assess the quality of a given water body [9]. The first modern WQI was developed by Horton [10] to assess the pollution in the USA by selecting 10 water quality parameters to form an index with values between 0 (poor quality) and 100 (water of perfect quality). Since then, many other researchers developed WQI to meet a specific objective. Among others, one of the best-known WQI is the one developed by Brown et al. [5] on behalf of the National Sanitation Foundation (NSF) in USA to evaluate the general quality of surface water. Walski and Parker [11] based on the NSF-WQI developed a WQI to evaluate recreational water (such as used for swimming and fishing). Smith [12] developed a WQI to determine "how suitable is particular water for a certain uses?" Stoner [13] developed a WQI used in public water supply and irrigation. The Canadian Council of Ministers of the Environment (CCME) [8] developed the CCME-WQI to evaluate general water quality. Said et al. [14] proposed a water quality index consisting of only five water quality parameters. Swamee and Tyagi [1] also assumed that the previously developed indices may present some problems and have proposed an index that they consider free of these problems.

There are four steps to develop a WQI [5, 7, 11, 14-16]. These are 1) parameter selection, 2) normalization of the observed values of parameters into sub-indices, 3) weighting of parameters due to the difference of their relative importance in terms of water quality and 4) aggregation of sub-indices to the

overall index. The application of a WQI model is easy but the development necessitates all these steps and must avoid some mathematical errors related to the normalization and the aggregation of sub-indices.

Many others researchers have focused on literature reviews of WQI to understand the design of a WQI. Lumb et al. [3] studied the evolution and the design of the WQI based on physical, chemical and biological measurements of water quality and highlighted the advantages and disadvantages of the aggregation formula. Tikey et al. [2] discussed the basic procedure of WQI development and categorized them in terms of intended uses. Gitau et al. [8] discussed WOI in terms of their use as tools for decision-making and management. The objective of this paper was to analyze the development of WQI, especially to determine which parameters are used to develop and to evaluate the water quality, determine which parameters are most used in water quality assessment and discuss the characteristics of WQI to direct further research.

## 2. Materials and Methods

#### 2.1 Data Sources and Research Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [17] is applied to screen documents on WQI. Moher et al. [17] developed the method to examine a sample of articles by issuing predefined criteria for inclusion and exclusion of the documents to be analyzed to meet a specific objective. In this study, all articles were collected between February 2017 and June 2018 in electronic databases: ScienceDirect four (https://www.sciencedirect.com/), Taylor and Francis (https://www.tandfonline.com/), Online Springer (https://link.springer.com/) and Google Scholar (https://scholar.google.com/). The search keywords were "water quality index", "water quality index development" and "water quality index design". The snowball sampling is used in the case where the keywords research did not satisfy the hypothesis.

#### 2.2 Inclusion and Exclusion Criteria

The present study analyzes the design of WQI and explores the problems related to the variables aggregation and combination of groups of water quality parameters. Therefore, the study included only articles that proposed a development of a WQI. In each study included, the author(s) selected water normalized and parameters, aggregated the sub-indices to a final overall index. All articles that used an original WOI of another author to evaluate the water quality were excluded. For the relevance of the results of this study and in order to be able to give references of the WQI, only articles published in peer-reviewed journals and conference papers were included.

#### 2.3 Screening Articles Treatment and Data Analyses

The excel spreadsheet is used to provide graphs and tables. SPSS statistical tools were used to cluster and to determine the groups of water parameters that were combined by researchers [3, 8] to develop the WQI and draw the tree diagram to show the average linkage between groups of water parameters.

## 3. Results and Discussion

Fig. 1 shows the flowchart [17] of article selection. The total number of articles from the four databases was 194. After removing the duplicate articles and applying the inclusion and exclusion criteria, only 17 out of 194 met the defined criteria. One article was not included in the quantitative study because the WQI proposed did not impose water quality parameters.

#### 3.1 Descriptive Analysis of Screening Articles

In each article selected, the author(s) proposed a water quality assessment index. Although WQI are developed to evaluate water quality, they do not have the same objectives and are not developed in the same way. Table 1 shows the development steps and the scale of application of the WQI. It should, nevertheless, be noted that WQI are developed to

analyze the surface water quality (river and lake) and 75% (Table 1) of the authors followed the same steps to develop the proposed WQI. These steps are: (1) selection of water quality parameters, (2) standardization, (3) weighting and (4) aggregation to overall index. The description of the different WQI is done according to the four basic steps of WQI development.

#### 3.2 Parameter Selection

In the selected WQI, there are different ways to identify the appropriate parameters. These are to ask a panel of water management experts to identify the most important parameters [12, 15] or the Delphi method [5, 9, 18], the literature [14, 15, 19, 20], the water regulators organizations [13, 21, 22], the component principal analysis (CPA) [20, 23] and the personal experience of the authors [11, 24]. The majority of authors (70%) used subjective methods for parameter selection (Table 1). For the objective choice of parameters, statistical methods such as principal component analysis of factors are the best methods for choosing water quality parameters, since they make it possible to avoid redundancies and to choose independent parameters that do not correlate with each other.

#### 3.3 Standardization

Since water quality parameters are not measured with the same unit, they must be made to the same scale. The standardization of parameters is the transformation of variables that are different units and dimensions into a common scale [4, 7, 8]. In addition, the variables did not have the same effect on water quality. Some of the variables were determined to be proportional to water quality, while others are inversely related to water quality. It is therefore obligatory to standardize these values so that the final water index can represent all the parameters chosen with the relative contribution of the strength of each parameter.



Fig. 1 Flow diagram of research protocol and selection of articles [17].

Table 1	Water quality indices (WQI	<ol> <li>development steps and so</li> </ol>	cale of application.

Reference	Selection technique	Standardization	Weighting	Aggregation	Scale
Said <i>et al</i> . [14]	Literature	No need	Ranking	Logarithmic transformation	Streams
Dinius [9]	Delphi technique	Linear and nonlinear function	Delphi technique	Multiplicative aggregation function	Not determined
Cude [18]	Delphi technique	Non-linear regression function	Delphi technique	Root square	Basin
Prati <i>et al</i> . [19]	Literature	Mathematical expressions: linear and parabolic function	No	Arithmetic mean	Regional or national surface water
House [15]	Expert opinion + literature	Rating curves (based on limits values)	Questionnaire survey from experts	Modified arithmetic formula	River
Brown et al. [5]	Delphi technique	Rating curves: expert opinions	Questionnaire survey from experts	Geometric mean	River
Liou <i>et al</i> . [20]	Literature and principal analysis component	Ranking by compared observed value to limits values	РСА	Geometric mean	River

Reference	Selection technique	Standardization	Weighting	Aggregation	Scale
Walski and Parker [11]	Choice related to their study objective: aquatic life, human health, water appearance	Linear and segmented functions: exponential, parabolic	Ranking	Geometric mean (multiplicative function)	River, lake
Smith [12]	Expert opinion	Rating curves: experts opinion	No	Minimum operator Otto [26]	River
Lermontov <i>et al.</i> [21]	CETESB office (Brazil)	Fuzzy inference	Fuzzy inference	Fuzzy inference	River
Sargoankar and Deshpande [24]	Based on researchers experience	Rating curves: mathematical function (linear and nonlinear)	No	Arithmetic mean	River
Swamee and Tyagi [7]	NSF international parameters Brown <i>et al.</i> [5]	Mathematical function	No	Mathematical function: addition and logistic functions	River
Stoner [13]	National Academy of Sciences and National Academy of Engineering	Limits classes: nonlinear functions	Researchers experience	Additional and weighted multiplicative function	River, lake
Pesce [22]	Global Environmental Monitoring System/United Nations Environmental Program	Ranking based on standards values	Researchers experience	Arithmetic mean	River
Mohan [16]	Arbitrary selection	Ratio between the difference of monitored and ideal values to the standard and ideal values	Value inversely proportional to the recommended standard	Arithmetic average mean	Bore
Hanh et al. [23]	Principal analysis component	Piecewise-linear-memb ership-functions	No	Linear product power and linear sum power	River, lake
CCME [6]	No	Standards values	No	Root square	River or bore

CETESB: Companhia Ambiental do Estado de São Paulo (São Paulo State Environmental Protection Agency); NSF: National Sanitation Foundation.

The standardization of water quality parameters is based on a good understanding of their significance [18]. Abbasi and Abbasi [4] report four major types of functions to standardize water quality parameters: linear functions, segmented linear functions, nonlinear functions and segmented nonlinear functions. For example, to normalize the value of dissolved oxygen (DO) as a percentage of saturation, Dinius [9] used the following linear function:  $I_{Do} = 0.82DO + 10.56$ , where  $I_{Do}$  is the sub index of DO with a value between {0, 100}. Walski and Parker [11] used a nonlinear function to normalize nitrate concentration:  $I_N = e^{-0.16x}$ , where  $I_N$  is the sub-index of nitrate with a value between {0, 1}. Beyond these functions, other types of standardization methods is identified

(Table 1 continued)

such as expert opinion, fuzzy membership functions, and the comparison of observed values to standard values. Fig. 2 shows the percentage of usage of these methods. Moreover, other indices like the one developed by Said *et al.* [14] do not need normalization because of the variable aggregation model.

Standardization by expert opinion consists of asking a panel of experts to draw a curve of the various parameters to indicate graphically the sub-index value or the intended rate of each parameter [12]. On the curve, there are observed value in the respective unit of this parameter on the *x*-axis and in the intended rate of this parameter on the *y*-axis. One of the aggregation methods encountered is to compare



Fig. 2 Percentage of each method used to combine water quality parameters.

the observed values to the standard values. For example, Liou *et al.* [20] used the following formula to normalize some parameters:  $r_i = \frac{C_i}{S_i}$ , with  $r_i$ , the sub-index of the *i*<sup>th</sup> parameter,  $c_i$  the observed concentration of the *i*<sup>th</sup> parameter and  $s_i$ , the maximum permissible concentration. However, the majority (41%) of the selected WQI (Fig. 2) use the four types of functions of the linear and non-linear functions for the standardization of water quality parameters. Fig. 2 shows methods used to combine water quality parameters.

#### 3.4 Weighting

Water quality parameters do not have the same relative importance to water quality. While some quality variables affect human health and aquatic life at low concentrations, other quality variables make aquatic life possible through their abundance, such as DO. But the weighting also takes into account the purpose of the study, that is to say, it takes account if the assessment of water quality is made to determine the suitability of water for recreation use or for human consumption or to make environmental management decisions or for any useful purpose. It is clear that not all WQI need weighting (Table 1), such as Hanh *et al.* [23], CCME [6], Swamee and Tyagi [7], Sargoankar

and Deshpande [24] and Smith [12], although that would not necessarily mean that there was no weighting, but only assumes that the authors considered that all parameters have equal weights. There are several methods to weight the different parameters of water before aggregating them: the Delphi method [9, 18] or the opinion of the experts [5, 15], the ranking [11, 14], the principal component analysis [20], the researchers' experience [13, 22], values inversely proportional to the recommended values [16], fuzzy inference [21]. The ranking method consists of classifying the water quality parameters according to their significance. One of the objective weighting methods is to use the inverse of the standard values [16],  $w_i = \frac{1}{S_i}$ , with  $w_i$ , the weight of the  $i^{th}$  parameter and  $s_i$  the recommended standard value of the  $i^{th}$  parameter.

## 3.5 Aggregation

Normalized and weighted sub-indices are combined to form an overall water quality index. A set of six methods (Tables 1 and 2) of aggregations of sub-indices in a composite index were identified. These are the arithmetic mean [15, 16, 19, 22, 24], the geometric mean [5, 9, 11, 20], the root square [6, 18], the logarithmic function [7, 14], the fuzzy membership

Name	Use	Aggregation form	Interpretation	Reference
NSF-WQI	General surface water quality evaluation	$\sum_{i=1}^{n} q_i^{w_i}$ $q_i: i^{\text{th}} \text{ sub-index of } i^{\text{th}} \text{ parameter; } w_i: i^{\text{th}} \text{ weight of } i^{\text{th}}$ parameter	0: very bad 100: excellent	Brown <i>et al</i> . [5]
Dinius-WQI	Evaluation of the level of pollution in fresh water	$\prod_{i=1}^{n} I_{i}^{w_{i}}$ $I_{i}: i^{\text{th}}$ sub-index of $i^{\text{th}}$ parameter; $w_{i}: i^{\text{th}}$ weight of $i^{\text{th}}$ parameter	0: not acceptable 100: acceptable	Dinius [9]
Said-WQI	Assess water quality for general beneficial uses, but not for regulatory decision making	$\log \left[ \frac{DO^{1.5}}{(3.8)^{TP} (Turb)^{0.15} (15)^{\frac{FCol}{10000}} + 1.4(SC)^{0.5}} \right]$ DO: dissolved oxygen; TP: total phosphorus; Turb: turbidity; FCol: fecal coliform; SC: specific conductivity	0: poor 3: acceptable	Said <i>et al.</i> [14]
Oregon-WQI	Assess ambient water quality for general recreational use, including fishing and swimming	$\sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{SI_i^2}}}$ <i>n</i> : number of parameter; <i>SI<sub>i</sub></i> : <i>i</i> <sup>th</sup> sub-index of <i>i</i> <sup>th</sup> parameter	10: very poor 100: excellent	Cude [18]
Walski and Parker-WQI	Evaluate the aptitude of water for recreational water (such as swimming and fishing)	$\left(\prod_{i=1}^{n} I_{i}^{w_{i}}\right)^{\frac{1}{n}}$ <i>n</i> : number of parameter; <i>I<sub>i</sub></i> : <i>i</i> <sup>th</sup> sub-index of <i>i</i> <sup>th</sup> parameter; <i>w<sub>i</sub></i> : <i>i</i> <sup>th</sup> weight of <i>i</i> <sup>th</sup> parameter	0: intolerable 1: perfect	Walski and Parker [11]
Sargoankar and Deshpande-PI	Assess surface water quality status with reference to specific individual parameter	$\frac{\sum_{i=1}^{n} P_i}{n}$ <i>n</i> : number of parameter; $P_i$ : pollution index for $i^{\text{th}}$ parameter	0: excellent 16: heavily polluted	Sargoankar and Deshpande [25]
Swamee and Tyagi-WQI	To avoid aggregation problems of water quality indices and assess overall water quality	$\left(1 - N + \sum_{i=1}^{n} s_i^{-\frac{1}{\log_2(N-1)}}\right)^{-\left(\frac{1}{\log_2(N-1)}\right)}$ <i>N</i> : number of parameter; <i>S<sub>i</sub></i> : <i>i</i> <sup>th</sup> sub-index of <i>i</i> <sup>th</sup> parameter	0: lowest 1: highest	Swamee and Tyagi [7]
CCME-QWI	Evaluate general water quality	$100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$ F <sub>1</sub> : scope = (number of failed parameter/total number of parameters) × 100; F <sub>2</sub> : frequency = (number of failed tests/total number of tests) × 100; F <sub>3</sub> : amplitude = amount by which the objectives are not met	0: bad 100: excellent	CCME [6]
Prati-QWI	Use to assess the water pollution, the purely qualitative features of water	$\frac{1}{13} \sum_{i=1}^{13} I_i$ $I_i: i^{\text{th}}$ sub-index of $i^{\text{th}}$ parameter	1: excellent 8: heavily polluted	Prati <i>et al</i> . [19]
House-WQI	Determine potential use and evaluate change in river water quality	$\frac{1}{100} \left(\sum_{i=1}^{n} q_i w_i\right)^2$ $q_i: i^{\text{th}}$ sub-index of $i^{\text{th}}$ parameter; $w_i: i^{\text{th}}$ weight of $i^{\text{th}}$ parameter	10: badly polluted 100: potable water	House [15]

Table 2
 WQI use, aggregation form and interpretation.

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Name	Use	Aggregation form	Interpretation	Reference
RSI	Overall water quality assessment	$C_t C_{pH} C_{tox} \left[ \left( \sum_{i=1}^3 I_i w_i \right) \times \left( \sum_{j=1}^2 I_j w_j \right) \times \left( \sum_{k=1}^1 I_k \right) \right]^{\frac{1}{3}}$ $C_i$ : temperature sub-indices; $C_{pH}$ : pH sub-indices; $C_{tox}$ : toxic substances sub-indices; $I_i$ : DO, BOD <sub>5</sub> , ammonia nitrogen sub-indices; $I_j$ : turbidity sub-indices; $I_k$ : fecal coliform sub-indices	0: polluted 100: excellent	Liou <i>et al</i> . [20]
Smith-WQI	Determine "how suitable is a particular water for a certain uses?"	$\min\{I_1, I_2, \dots, I_i\}$ $I_i: i^{\text{th}}$ sub-index of $i^{\text{th}}$ parameter	0: unsuitable for several uses 100: suitable for all uses	Smith [12]
FWQI	To evaluate surface water quality and use in decision-making in environmental management	Two fuzzy functions: $\mu A: x \to [0, 1]$ $(1) f(x; a, b, c, d) = \begin{cases} 0, x < a \text{ or } d < x \\ (a - x) \\ (a - b), a \le x \le b \\ 1, b \le xc \\ (d - x) \\ (d - c), c \le x \le d \end{cases}$ $(2) f(x; a, b, c, d) = \begin{cases} 0, x < a \text{ or } d < x \\ (a - x) \\ (a - b), a \le x \le b \\ 1, b \le xc \\ (a - b), a \le x \le b \\ 1, b \le xc \\ (c - x) \\ (c - b), c \le x \le d \end{cases}$ <i>x</i> : the observed value; <i>a</i> , <i>b</i> , <i>c</i> , <i>d</i> : limits of the related membership functions	0: poor 100: excellent	Lermontov <i>et al.</i> [21]
Stoner-WQI	Use in public water supply and irrigation	$\sum_{i=1}^{n} q_i w_i + \sum_{j=1}^{z} q_j$ $q_i: i^{\text{th}} \text{ sub-index of } i^{\text{th}} \text{ parameter affecting aesthetic conditions of water; } w_i: i^{\text{th}} \text{ weight with } i^{\text{th}} \text{ parameter; } q_j: j^{\text{th}} \text{ sub-index of } j^{\text{th}} \text{ toxic parameter; } n: \text{ number of parameters affecting aesthetic conditions; } z: \text{ number of toxic parameters}$	(-): unfit water for uses 0: water properties are at their recommended limits 100: perfect water	Stoner [13]
Pesce-WQI	Assess spatial and seasonal changes of surface water quality	$k \frac{\sum_{i=1}^{n} C_i \times P_i}{\sum_{i=1}^{n} P_i}$ k: a subjective constant, refers to a visual impression of river contamination; $C_i$ : <i>i</i> <sup>th</sup> sub-index of <i>i</i> <sup>th</sup> parameter; $P_i$ : <i>i</i> <sup>th</sup> weight of <i>i</i> <sup>th</sup> parameter	0: low quality 100: high quality	Pesce et al. [22]
HPI	Evaluate the overall water quality with respect to heavy metal pollution in bores	$\frac{\sum_{i=1}^{n} q_i \times w_i}{\sum_{i=1}^{n} w_i}$ $q_i: i^{\text{th}} \text{ sub-index of } i^{\text{th}} \text{ parameter}; w_i: i^{\text{th}} \text{ weight of } i^{\text{th}}$ parameter	HPI value is compared to the permissible value	Mohan <i>et al</i> . [16]
WQIo	Evaluate spatial and temporal changes of surface water quality and contamination	$\overline{\left(\prod_{1}^{n} C_{i}\right)^{\frac{1}{n}} \left[\frac{1}{5}\sum_{1}^{5} q_{i} \times \frac{1}{2}\sum_{j=1}^{2} q_{j}q_{k}\right]^{\frac{1}{3}}}$ <i>C<sub>i</sub></i> : coefficients addressing the sub-indexes of Tw, pH and toxic substances; <i>n</i> : number of coefficients; <i>q<sub>i</sub></i> : organic and nutrients group sub-index; <i>q<sub>j</sub></i> : particulates group sub-index; <i>q<sub>k</sub></i> : bacteria group sub-index	0: poor water quality 100: excellent water quality	Hanh <i>et al.</i> [23]

RSI: river status index; DO: dissolved oxygen; BOD<sub>5</sub>: 5 d biochemical oxygen demand; FWQI: fuzzy water quality index; HPI: heavy metal pollution index; WQI<sub>0</sub>: overall water quality index;  $w_i$ : weight of  $i^{th}$  organic parameter (DO, BOD<sub>5</sub> and ammonia nitrogen);  $w_i$ : weight of  $j^{th}$  particulates parameter (suspended solids and turbidity).

equations [21] and the minimum operator [12]. Some researchers often combine two methods to aggregate the parameters: the geometric and arithmetic mean [13] or the arithmetic and geometric mean under power [23]. Many authors have reported problems, which are developed in the next section, related to the aggregation of sub-indices to an overall index. Table 2 shows the usage of WQI, their aggregation forms and signification.

# 3.6 Advantages and Disadvantages of Water Parameter Aggregation

In the literature, several authors [1, 3, 4, 7, 8, 25, 26] have mentioned problems related to the aggregation of sub-indices into a composite index. The problems encountered with the overall index are different from one aggregation method to another. These are eclipsing, ambiguity, rigidity or flexibility, adaptability and compensation. Eclipsing is when a WQI fails to reflect the poor water quality for one or more parameters; in other words, the final WQI shows good quality when one or more parameters are above the permissible limit [4, 7, 26]. Ambiguity is when the final WQI shows poor water quality, while none of the parameters that compose it has exceeded the permissible limit [4, 7, 26]. Both of these problems are common to WQI with a form of additive aggregation or arithmetic mean [19]. This is the case of the WQI of Prati et al. [19] and Sargoankar and Deshpande [24]. According to Abbasi and Abbasi [4], WQI with a multiplicative and power aggregation model such as Liou et al. [20], Walski and Parker [11], House [15], Brown et al. [5] and Dinius [9] make it possible to avoid both ambiguity and eclipsing problems. Swamee and Tyagi [7] was designed specifically to avoid both problems. Smith's [12] WQI was also developed to avoid the eclipsing problem. An aggregation model with a good compensation is one that is not biased towards the minimum or the maximum of the sub-indices [4]. This is the case for all indexes based on the minimum-maximum operator

aggregation method, such as the Smith [12] method.

Rigidity, also called flexibility, exists when there is a need to add other variables to the basic variables used to construct the index but the aggregation method cannot allow it. The index of CCME [6] is flexible in adding other parameters since the choice of parameters is not imposed to the user. Swamee and Tyagi [1] reported that the majority of WQI have rigidity problems, since it is difficult to add other parameters to the basic parameters used to develop the WQI without affecting the final value of the index. For example, the WQI of Said *et al.* [14] has a rigidity problem since a user cannot add another parameter without completely modifying the aggregation form of the WQI.

Adaptability is when an aggregation model of an index designed for a specific use cannot be adapted to assess the quality of the water for another use or location because of geographic differences or environmental conditions [4]. All the indices selected have no problem with adaptability. The NSF-WQI [9] is the most widely used [3] because of its easy use [8] with 21% of water quality assessment studies using it.

#### 3.7 Interpretation of the Overall Index

The values of the overall index are usually classified in an increasing way to the water quality with values between 0 (for bad quality) and 100 (excellent quality) or between 0 and 1. However, there are exceptions, such as WQI classified between 0 (poor quality) and 3 (acceptable quality) [14], between 0 (excellent) and 16 (highly polluted) [24], and between 0 (excellent) and 8 (highly polluted) [19].

#### 3.8 Water Quality Parameters Used

Water quality parameters should be classified into physical, chemical and biological parameters, and the suitability of water for expected use should depend on the magnitude of these parameters [1]. Of the 17 articles selected, 16 WQI imposed water quality parameters for the use of their respective WQI, only CCME [6] did not impose a set of parameters to the user. The results of this study show that an average of 12 water quality parameters are used to develop a WQI. The minimum number of parameters used was four [16] and the maximum was 26 [21]. Table 3 shows the different parameters used to develop the selected WQI.

Figs. 3 and 4 show the proportion of times that each parameter was used on the number of WQI selected during this study. The chemical parameters (70%) are the most used in the development of WQI while the physical parameters are used at 24% and the least used are the biological parameters (6%).

From 54 parameters identified in this study (Table 3), the number of times each individual parameter was used in the selected WQI is determined to estimate the

proportion of use. It can be seen (Figs. 3 and 4) that DO (87%), total coliforms (87%), biological oxygen demand (BOD) (73%), pH (73%), temperature (67%), turbidity (60%), ammonia (53%), ammonium (47%) and total dissolved solids (47%) are the most commonly used parameters for assessing water quality.

The combination of different parameters is analyzed to determine which parameters are usually combined in the development of WQI. Fig. 5 shows the different groups of parameters used together to develop the WQI. One of the groups that stands out the most are the set: DO, BOD, pH, fecal coliforms, temperature, nitrate, often accompanied by total phosphorus, turbidity, total dissolved solid and ammonium. This group is close to that identified by Lumb *et al.* [3]: DO, BOD, pH, fecal

Table 3 Water quality parameters in categories used in all 16 WQIs selected.

Chemical parameters (40)	Physical parameters (10)	Biologic parameters (3)
DO, total phosphorus (TP), chloride (Cl), ammonia (NH <sub>3</sub> ), ammonium (NH <sub>4</sub> <sup>+</sup> ), COD, BOD, permanganate (KMnO <sub>4</sub> ), iron (Fe), manganese (Mn), phosphates (PO <sub>4</sub> <sup>3-</sup> ), cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), zinc (Zn), dissolved inorganic nitrogen (DIN), sulfate (SO <sub>4</sub> <sup>2-</sup> ), arsenic (As), fluoride (F <sup>-</sup> ), aluminum (Al), cyanide (CN <sup>-</sup> ), mercury (Hg), selenium (Se), boron (B), beryllium (Be), cobalt (Co), vanadium (V), ammonia-nitrogen (NH <sub>3</sub> -N), phenols, magnesium (Mg), oil and greases, surfactants, methylene blue active substances (MAS), sodium adsorption ratio (SAR), acrylonitrile butadiene styrene (ABS), CCE, nickel (Ni), calcium (Ca), nitrite (NO <sub>2</sub> <sup>-</sup> )	Specific conductivity (SC) Alkalinity (Alk) Hardness Temperature (T) Color pH Total solids (TS) Turbidity (Turb) Suspended solids (SS) Upstream water levels	Fecal-coliform Bacteria <i>E. coli</i>

DO: dissolved oxygen; BOD: biochemical oxygen demand; COD: chemical oxygen demand; CCE: carbon chloroform extract.

![](_page_9_Figure_10.jpeg)

Fig. 3 Percentage of individual parameters used in all 16 WQIs selected.

![](_page_10_Figure_1.jpeg)

Fig. 4 Percentage of individual parameters used in all 16 WQIs selected.

coliform or *E. coli* and total dissolved solids. It is also close to that identified by Gitau *et al.* [8]: DO, BOD, pH, fecal coliform, total dissolved solids, temperature, phosphorus, nitrate and turbidity.

#### 3.9 Analysis of the WQI Selected

Of the 167 articles analyzed, approximately 10% (17 articles) met the pre-established inclusion and exclusion criteria. Of the 17 articles selected, 16 WQIs imposed water quality parameters for the use of their respective WQI, only CCME [6] did not impose a set of parameters to the user. These 16 articles correspond to water quality indices developed around the world, depending on their environmental problem and the purpose of developing the index. In general, these indices selected for the study follow four main steps: parameter selection, weighting, normalization and aggregation. Nearly 63% of the WQI (Table 1) used all stages in the development of the index, and the other 27% used at least three of these stages. Most of the WQI (70%) used subjective methods to select water quality parameters (Table 1) and 12% used subjective methods to standardize the parameters (Fig. 2). The remaining indices of these selected WQI used parameters predefined by the water quality agencies respectively in their countries (Table 1) to select the parameters and mathematical formulas to standardize

and combine the parameters. Almost 31% of the WQI did not use weighting, so they assumed that the parameters have the same contributions. Near 37.5% of the indices used subjective methods such as expert opinion, Delphi technique, questionnaires, etc. to weight the parameters (Table 1), and the rest of the WQI used statistical methods and comparisons with the recommended limits of the respective parameters.

A total sum of 54 physical, chemical and biological parameters were identified for all 16 WQIs. An average of 12 water quality parameters were used to develop a WQI. The minimum parameters used is four [16] and the maximum is 26 [13]. The chemical parameters (70%) are the most used in the development of WQI, the physical parameters are used at 24% and the least used are the biological parameters (6%). From 54 parameters identified in this study, the number of times each individual parameter was used in the selected WQI is determined. It can be seen (Figs. 4 and 5) that DO (86, 67%), total coliforms (86, 67%), BOD (73, 33%), pH (73, 33%), temperature (66.67%), turbidity (60.00%), ammonia (53.33%), ammonium (46.67%) and total dissolved solids (46.67%) are the most commonly used parameters to assess water quality. One of the groups of parameters that stands out the most are the set: DO, fecal coliforms, BOD, pH, temperature, nitrate, which

![](_page_11_Figure_1.jpeg)

Dendrogram using Average Linkage (Between Groups)

Fig. 5 Average linkage between groups of parameters combined to design the WQI.

can be added total phosphorus, turbidity, total dissolved solid and the ammonium. At least one metallic trace element is used in 44% of the WQI selected in this study. The most commonly used are cadmium (26.67%), arsenic (20.00%), chromium (20.00%), zinc (26.67%), lead (20.00%), iron (26.67%), aluminum (13.33%) and copper (26.67%).

The majority (41%) of the selected WQI use the four categories of functions for the standardization of water quality parameters (Fig. 2). Six methods (Tables 1 and 2) of aggregations of sub-indices in a composite index are identified: the arithmetic mean [6, 9, 10, 15, 16], the geometric mean [1, 2, 5, 11], the root square [4, 8], the logarithmic function [3, 7], the fuzzy membership equations [13] and the minimum operator [12].

For the selected WQI, the values of the final composite index are generally between 0 and 1 or between 0 and 100. Only a few WQI have made the exception, such as Said *et al.* [14], Sargoankar and Deshpande [25], Prati *et al.* [19] and House [15], whose index values are respectively between 0 and 3, 0 and 16, 1 and 8, and 10 and 100. Small values mean that the corresponding water quality is of poor quality and large values mean that the water is of very good or excellent quality (Table 2).

## 4. Conclusions

The values of the WQI are in their majorities proportional to the quality of the water with values between 0 (for poor water quality) and 100 (excellent quality) or 0 to 1. The choice of the parameters, the weighting, the standardization of the parameters into the sub-index and the aggregation of the sub-indices are the most important steps during a WQI development. Nearly 63% of WQI selected used all stages in the development of the index and the other 27% used at least three of these stages. The analysis of these WQI tools has shown that all these WQI have developed to assess surface water quality. The result of this study indicates that the form of aggregation of

some WQI can present problems related to the combination of sub-indices of parameters such as eclipsing, ambiguity, compensation and rigidity or flexibility. It can be noted that all WQI present some advantages and disadvantages. Therefore, there is no best WQI possible as long as each WQI has been developed to meet a specific need. The majority of WQI are subjective, since they involve at least one expert opinion step. This is not bad, since the weights relative to the different parameters make it possible to converge the relative contribution of each parameter to the overall index and to avoid both problems of eclipsing and ambiguity. However, the application of statistical methods to the selection and weighting of parameters can decrease the subjectivity of WQI. The cost of developing a WQI can be very high or at least its application when it requires a large number of parameters to be analyzed in a laboratory. In addition, the majority of these WQI generally use many parameters, an average of 12 parameters. Therefore, future developments of WQI should focus on reducing the number of parameters and accessibility to the public.

In this literature review, only articles published in English were included. The articles were extracted from only four databases. Therefore, this study is not an exhaustive analysis. However, it provides an embryonic idea on WQI development.

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