Adapted Water Quality Indices: Limitations and Potential for Water Quality Monitoring in Africa

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Abstract: A Water Quality Index (WQI) is a tool that describes the overall water quality by combining complex and technical water quality information into a single meaningful unitless numerical value. WQIs predict water quality since they reflect the impact of multiple Water Quality Parameters (WQPs) and allow for spatial-temporal comparison of water quality status. Most African countries employ adapted WQIs by modifying the original index (or indices) and propose their concepts for evaluating the quality of surface and groundwater, which is normally accompanied by irregularities. The current review examined the process(es) involved in WQI modifications for monitoring water quality in Africa, explored associated limitations, and suggested areas for improvement. A review of 42 research articles from five databases in the last ten years (2012–2022) was conducted. The findings indicated Weighted Arithmetic (WAWQI) and the Canadian Council of Ministers of Environment (CCMEWQI) as the most adapted WQIs. However, several limitations were encountered in WQI developmental steps, mainly in parameter selection and classification schemes used for the final index value. Incorporation of biological parameters, use of less subjective statistical methods in parameter selection, and logical linguistic descriptions in classification schemes were some recommendations for remedying the limitations to register the full potential of adapted WQIs for water quality monitoring in Africa.

Keywords: water quality index; water quality parameters; physicochemical parameters; multivariate statistics; benthic macroinvertebrates; microbiological parameters

1. Introduction

The destruction of natural resources, especially the contamination of aquatic habitats, has been hastened by continued worldwide population increase and socio-economic development. The quality of surface water has been and continues to be impaired by the increased discharge of physical, chemical, and biological contaminants in water sources, which also stresses aquatic life [1]. These contaminants either come from non-point sources (such as surface runoff, airborne contaminants, and sewage outflows), point sources (such as industries and direct effluent disposal), and/or hydro-morphological sources (such as those related to natural processes and human activities including water abstraction). Therefore, it is essential to develop a management strategy to reduce any potential threats to aquatic life and public health in light of the sources of contaminants in aquatic ecosystems. The amount and nature of contaminants present in water should be considered when

deciding whether it is suitable for any usage (drinking, irrigation, recreation, habitat for aquatic life, industrial operations, etc.). Normally, these contaminants are expressed using contamination parameters [2] defined in water quality indices WQIs.

A WQI is a tool that describes the overall water quality by combining or summarizing complex and technical water quality information into a single unitless numerical value [3–5]. Therefore, WQIs are used to predict water quality status since they reflect the overall impact of multiple WQPs and allow for comparing water quality status across time and space [6]. Specifically, WQIs are used to: (i) communicate information about water quality to the general public, policymakers, and non-water experts in a straightforward manner [7] and (ii) improve the understanding of general water quality issues by stakeholders in the decision-making process.

1.1. Development of a WQI

The development of most WQIs involves the following four fundamental steps: (i) Parameter selection; (ii) Estimation of sub-index values for parameter comparison on a common scale; (iii) Weighting of parameters based on their relative significance to the overall water quality; and (iv) Formulation and computation of the overall index [8]. Selecting the right water quality parameters under specific environmental conditions is the most challenging of the four steps [9]. A comprehensive analysis of WQI development steps is provided in the later sections of this review. To reduce biases and select the right number and types of parameters, two approaches have been proposed that eventually yield different classes of indices. These are (1) approaches that rely on expert opinion (Rand Corporation's Delphi Technique) and (2) statistical-based approaches [10]. Using the premise that "Two heads are better than one", the Delphi approach elicits and refines a group's judgment. It was first developed by "The Rand Corporation" in the USA. It included three basic features: anonymous responses, repetitive and controlled feedback, and a group response (an appropriate aggregate of individual opinions on the final round).

Although the features mentioned above are designed to reduce the biasedness of dominant individuals, irrelevant communication, and groups' pressure towards conformity, the final WQI value is subjective primarily because it is solely based on the advice of consulted experts [3]. Some indices have been developed through such expert opinion, for example, the NSFWQI [11], a public index used to monitor general water quality, Oregon and British Columbia WQI [12], and the WQI by Hallock and Ehinger [13] a planning index used as a decision-making tool for designing water quality management projects. On the other hand, statistical-based approaches aim to lessen subjectivity and increase the accuracy of the final index. Principal Component Analysis (PCA), Discriminant Analysis (DA), Cluster Analysis (CA), and Factor Analysis (FA) are some of the multivariate techniques employed [14]. Table 1 provides a summarised history of WQI development along with the progress of each step in a chronological manner.

Table 1. Chronological evolution of WQI development with their respective developmental steps.

WQI Model	Parameters	Standardisation	Weighting	Aggregation Function	Reference
Horton index	DO, pH, SC, Alk, temp, CCE, FC, Cl$^-$, PP, OP	Parameters value used as sub-index value	Fixed and unequal system	Weighted Arithmetic Average $QI = \frac{\sum_{i=1}^{n} Wil_i}{\sum_{i=1}^{n} Wi} M_1 M_2$	[15]
NSFWQI (1)	DO, BOD, pH, temp, FC, Turb, nitrates, phosphates, TDS	Rating curves; Experts' opinion	Expert questionnaire	Weighted Arithmetic Average $WQI = \sum_{i=1}^{n} WiQi$	[11]

Table 1. *Cont.*

WQI Model	Parameters	Standardisation	Weighting	Aggregation Function	Reference
Prati's implicit index	BOD, pH, COD, DO, conc. of permanganate, ammonium, nitrates, Cl⁻, Fe, Mn, CCE, SS Alkyl Benzene sulphonates	Linear and parabolic function	No	Additive $I = {}^1/_{13} \sum_{1=i}^{13} li$	[16]
Dinius index (1)	Temp, DO, pH, EC, colour, BOD, Alk, FC, Cl⁻, hardness, *E. coli*	Linear and nonlinear function	Delphi technique	Weighted $DWQI = \frac{1}{21} \prod_{i-1}^{11} li^{wi}$	[17]
NSFWQI (2)	DO, BOD, PH, temp, FC, Turb, nitrates, phosphates, TDS	Rating curves; Experts' opinion	Expert questionnaire	Weighted Geometric Average $WQI\,(M) = \prod_{i=1}^{n} Qi^{wi}$	[18]
Stoner's index	Irrigation: EC, SAR, SC, Mn, B, As, Cd, Be, Al, Co, Cr, V, Ni, Cu, Zn, F Public water: Cl, MBAs, phenols, nitrates, ammonia, colour, pH, Cu, FC, F, Fe, Zi, sulphates	Limits classes: nonlinear functions	Researcher's experience	Additive $I = \sum_{i=1}^{m} li + \sum_{j=1}^{n} Wjlj$	[19]
Dinius Index (2)	Temp, DO, pH, EC, colour, BOD, Alk, FC, Cl⁻, hardness, *E. coli*, nitrates	The linear and non-linear function	Delphi technique	Geometrical average $IWQ = \prod_{i=1}^{n} li^{wi}$	[20]
Bhargava index	According to the use	Formulas	Weighted Product	Additive $WQI = [\prod_{i=1}^{n} fi(pi)] \times 100^{\frac{1}{n}}$	[21]
Smith index	BOD, temp, Turb, SS, DO, ammonia, FC	Rating curves; Experts' opinion	Delphi technique	Minimum operator $I\ min = \sum min$ $(Isub1, Isub2, \ldots\ldots Isubn)$	[22]
CCME WQI	Minimum of 4, not specified	Standard values	No	Arithmetic average $100 - \frac{\sqrt{F1^2+F2^2+F3^2}}{1.732}$	[23]
New WQI	DO, TP, FC, Turb, SC	No need	Ranking	Logarithmic aggregation $SAID\ WQI = \log$ $\left(\frac{(DO)^{1.5}}{(3.8)^{TP}(Turb)^{0.15}(15^{\frac{Fcol}{10000}}+0.4(SC)^{0.5}} \right)$	[24]
Ewaid index	COD, TDS, DO, total hardness, Cl⁻, TC	Rating curves; Experts' opinion	Expert opinion	Formula $[(-0.019\ TDS + 84.587) \times 0.2] +$ $[(-0.006\ TC + 86.231) \times 0.2] +$ $[10\ DO \times 0.2] + [((-0.119\ TH) +$ $113.68) \times 0.15] + [(-5.886\ COD$ $+99.846) \times 0.1] + [(-0.12\ Cl+$ $106.58) \times 0.15]$	[25]

Notes: The table provides an overview of various WQIs used overtime to monitor water quality. Each WQI has been explained in terms of parameters used, the methods of sub-index development and weighting and finally, the computation of the final index. All the WQIs in the table are original indices developed outside the shores of Africa between 1965 and 2020. Sourced from: [1,3,4,7,22,26,27]. SC—Specific Conductivity, DO—Dissolved Oxygen, Alk—Alkalinity, CCE—Carbon Chloroform Extract, FC—Faecal Coliforms, Cl⁻—Chloride, PP—Percentage of Population, OP—Obvious Pollution, Turb—Turbidity, BOD—Biochemical Oxygen Demand, TDS—Total Dissolved Solids, Mn—Manganese, Fe—Iron, SS—Suspended Solids, EC—Electrical Conductivity, SAR—Sodium Adsorption Ratio, B—Boron, Be—Beryllium, V—Vanadium, F—Fluorine, TP—Total Phosphorus, COD—Chemical Oxygen Demand, TC—Total Coliforms, As—Arsenic, Cd—Lead, Al—Aluminium, Co—Cobalt, Cr—Chromium, Ni—Nickel, Cu—Copper, Zn—Zinc, MBAs—Methylene Blue Active Substances.

1.2. Application of WQIs: The African Perspective

The concept of indexing water using a numerical value based on biological, physical, and chemical parameters dates back to the mid-20th century when the first WQI was developed in the United States [15] and applied in the UK and Europe in the 1970s and later in Africa and Asia [28]. Since then, there has been significant improvement and modification to existing indices as well as the development of new models. Some of the available WQIs include the Scatter score index [29], Index of River Water Quality [30], Overall Index of Pollution [31], Chemical WQI [32], Universal WQI [9], CCMEWQI [23], NSFWQI [33] Oregon WQI [20], and Weighted Arithmetic WQI [34]. These and many other WQIs have been developed with global and regional applicability. However, the most commonly used and applied indices are the NSFWQI, CCMEWQI, and WAWQI, according to reviews of WQIs by Aljanabi and Jawad [1] Poonam et al. [7] and Tyagi et al. [8].

The methodology for developing the NSFWQI was purely based on expert opinion in parameter selection and sub-indices assignment. Out of 35 possible parameters from which 142 experts were expected to select, only nine were selected for index construction [11]. This indexing is easily communicable to non-water experts, while the single index value obtained is considered objective and reproducible [35]. However, the index only represents general water quality and has a high data loss rate. Furthermore, since it is implemented with only nine input parameters, any additional parameters require extra effort and careful consideration [36]. Due to this, the index has found limited applicability, especially in Africa, with only Nigeria adapting and applying it to assess drinking water quality as applied by Kalagbor et al. [37].

The CCMEWQI was incepted in 2001 for use within the Canadian jurisdiction. It comprises three factors: Factor 1 (F_1) deals with a scope that assesses the extent of water quality guidelines for non-compliance over the stipulated period. Factor 2 (F_2) deals with frequency, i.e., how often the observed value was off the acceptable limits. Factor 3 (F_3) deals with the amplitude of deviation or the amount by which the objectives are not met.

This index is flexible in the selection of input parameters and involves simple calculation processes. The calculation formulae involved in the final index computation for CCMEWQI are comprehensively discussed in later sections of this review. Due to its flexibility in adapting to various WQPs and legal requirements by water agencies in different countries with little modifications [38], the index has found both global and regional applicability. For example, in North Africa, the index has been applied in Egypt to monitor surface water for irrigation purposes [39] and evaluate water to protect aquatic systems [39,40]. In Ghana and West Africa, the CCME index was used to assess the surface water quality of Aby Lagoon for the protection of aquatic life [41], while river water for domestic use was also assessed [42].

Furthermore, in East Africa, the CCME index has been applied to test the suitability of groundwater for drinking around Lake Victoria goldfields of northwestern Tanzania [43]. However, despite the versatile applicability, this index applies similar importance to all parameters, is highly subjective, and does not provide guidelines about the objectives specific to each location and particular water use [44]. In addition, the index calculation does not involve sub-index generation for the parameters, establishment of weights, and classical index aggregation [23].

The WAWQI is overly calculated by linearly aggregating the sub-index values with the unit weight. However, with its methodology being modified over time, the WAWQI is among the top three indices universally used since adjustments can be made depending on the parameters in place and system status. Furthermore, the WAWQI is the only index among all specific use indices requiring the least parameters [8]. It is also suitable for assessing ground and surface water for human consumption [45]. As a result, the index has been extensively applied in Africa.

In North Africa, several authors have employed WAWQI in the evaluation of groundwater for drinking purposes, for example, in Libya [46] and Egypt [47,48] as well as in Tunisia for irrigation and protection of aquatic life [49]. Also, this index has been embraced

in East Africa to examine surface and groundwater for various uses. In Kenya, lake and river water were assessed for their ability to cause human health risks [50,51] while the potability of river water was investigated for use [52,53]. Likewise, WAWQI has been applied by Teshome [54] and Berhe [55] to examine the appropriateness of surface water for human use in Ethiopia. Many studies have been performed in West Africa using WAWQI, especially in Nigeria. Both surface and groundwater have been appraised for drinking and other domestic purposes [56–60].

It has also been used in Ghana to assess river and dam water portability for drinking [61,62] and groundwater suitability for drinking and other domestic uses [63]. Aside from Nigeria and Ghana, a study involving WAWQI was documented in Chad, where the suitability of groundwater as drinking water was established [64]. However, despite the wide application, this index cannot meet many uses of the water quality data. At the same time, some water quality parameters may not be included in the overall index [56].

In South Africa, new methodologies have been proposed to establish the applicability of surface water for various purposes besides adapting the existing WQI models. Among the new models are the Equitable raw water pricing model [12], UWQI for South African river catchments [65], and Surrogate WQI for South African watersheds [66]. In addition, similar to other African regional blocs, the fitness of both surface and groundwater has been assessed for drinking and domestic purposes using both WAWQI [67–71] and CCME WQI [72], respectively.

From the above discourse, it is apparent that there exists a tendency to use WQIs adapted from developing countries in Europe and the Americas. The WQI adaptation process is by modifying the original WQIs and proposing their use in evaluating the surface and groundwater quality. Notably, WQIs are developed for a given location and are source-specific. However, despite that fact, it is generally acceptable to adapt and modify WQIs in compliance with varied regulatory criteria for water agencies in different nations [73].

However, before modifying an index for use, it is important to comprehend its development and relationship to local contexts. This evaluation pertains to the initial factors that supported its construction, as represented by WQPs [74], and their applications [22]. If this is not considered, the index picks up irregularities, including ambiguity, rigidity, and eclipsing. Because sub-index values for all WQPs are obtained differently, ambiguous indices suggest worse water quality than expected. Rigid indices, on the other hand, are not adaptable enough to include extra or substitute WQPs. Rigidity happens when impairment develops in a parameter excluded from the WQI or when an index is used in a setting with different usage objectives for which it was designed [75]. Lastly, eclipsing issues frequently arise when a low sub-index value is concealed by a high overall WQI value [27]. From the African perspective, WQIs have been adapted to address various societal purposes guided by the different water uses. The current review, therefore, examined how WQIs have been modified and adapted for monitoring water quality in Africa. Additionally, it explored limitations in the modified WQIs and suggested areas for improvement for their application and full potential to be realized.

2. Materials and Methods

Data Sources, Inclusion and Exclusion Criteria, Analyses

Articles were collected and analysed between March 2021 and June 2022 from five electronic databases: ScienceDirect, Springer, Google Scholar, ResearchGate, and semantic scholar. The search keywords included: "water quality index", "Africa", "surface water", and "groundwater" for the past ten years. Only studies that evaluated water quality using the original WQI of another author or authors incorporating physical, chemical, and microbiological parameters were included. The different modification approaches included replacing the type and/or quantity of WQPs, modification of either of the developmental steps and changing the application or usage of the WQI. Articles that developed a new WQI approach were excluded because the objective of the review was to explore adapted WQI and not original models. MS Excel 2019 was used for graphic presentations,

Sigma Plot v.14 for descriptive statistics, and Xlstat 2019 v.2.2 for multivariate analysis to identify the most popular WQP combinations and average linkage between the WQPs as used by authors.

3. Results and Discussion

Figure 1 displays the flowchart of how articles were located, evaluated, and selected. The five databases produced a total of 165 articles. Forty-two articles were included in this study to eliminate duplications.
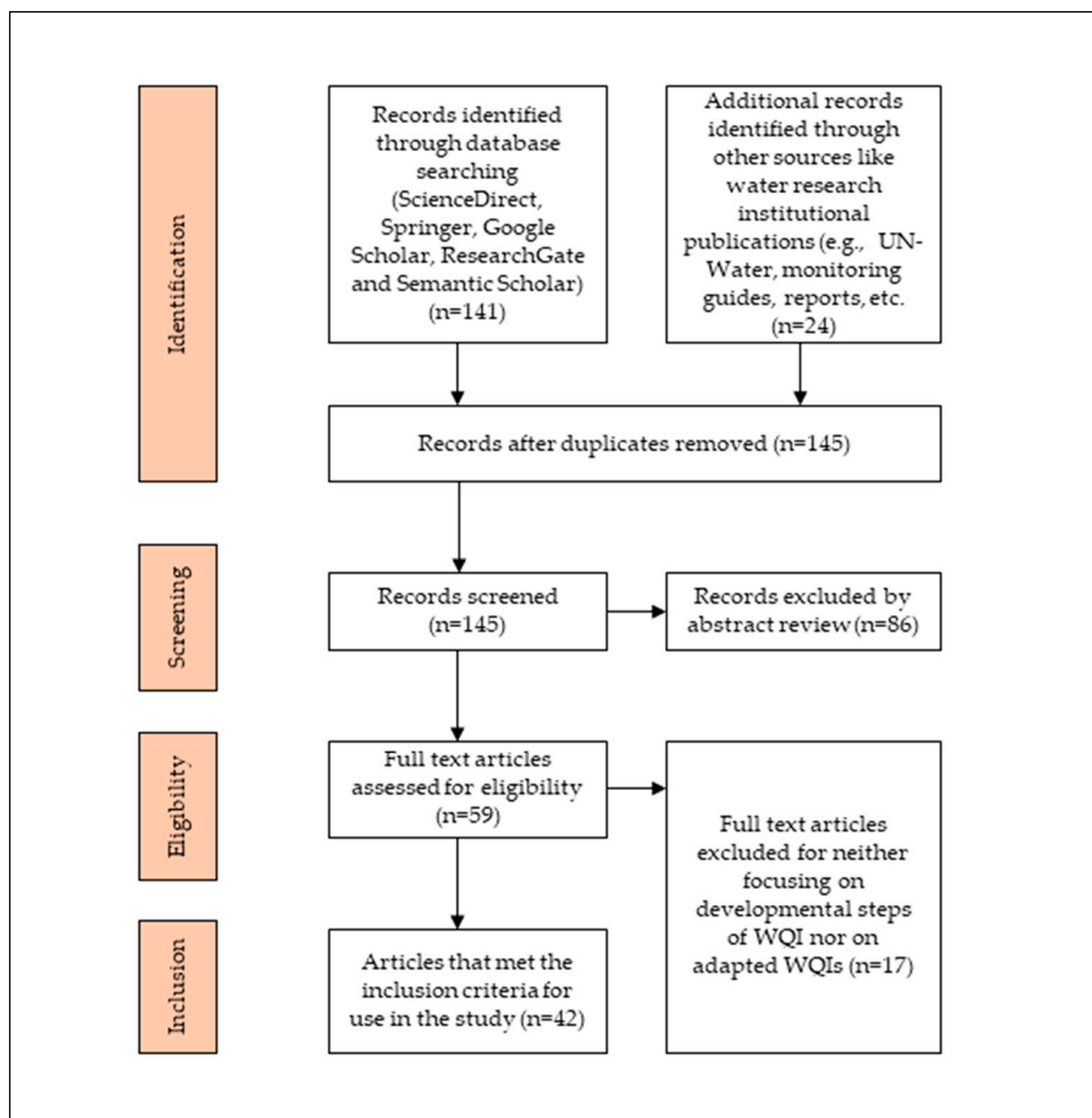

Figure 1. Flow diagram of the research protocol and selection of articles, adapted from [76].

The reviewed articles were a collection from 12 African countries (Figure 2), with Nigeria recording the highest number of modified WQIs—Tanzania, Mozambique, Libya, Chad, Tunisia, and Namibia, with the least.
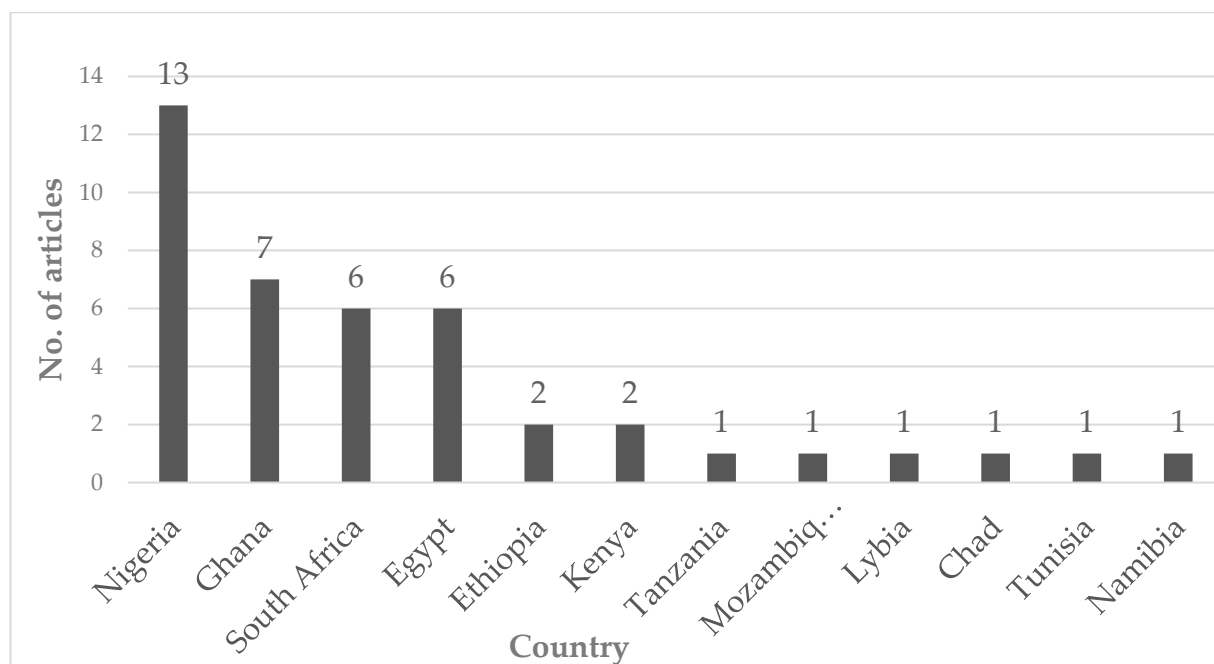
Figure 2. The number of articles with adapted WQI for each country over the last ten years.

The CCMEWQI was adapted by eight articles, including [39–43,71,77], whereas the WAWQI was adapted by 34 articles, including [49,50,62,67,78–82]. The three developmental steps used by the articles that adapted CCMEWQI were the Scope (F_1), Frequency (F_2), and Amplitude (F_3) calculations. On the other hand, those that adapted the WAWQI followed the four main aforementioned developmental steps. From parameter selection, the generation of parameter sub-indices (step 2) and assignment of parameter weights (step 3) was done interchangeably depending on the author's preference before the final computation of the WQI using an aggregation function (Figure 3).
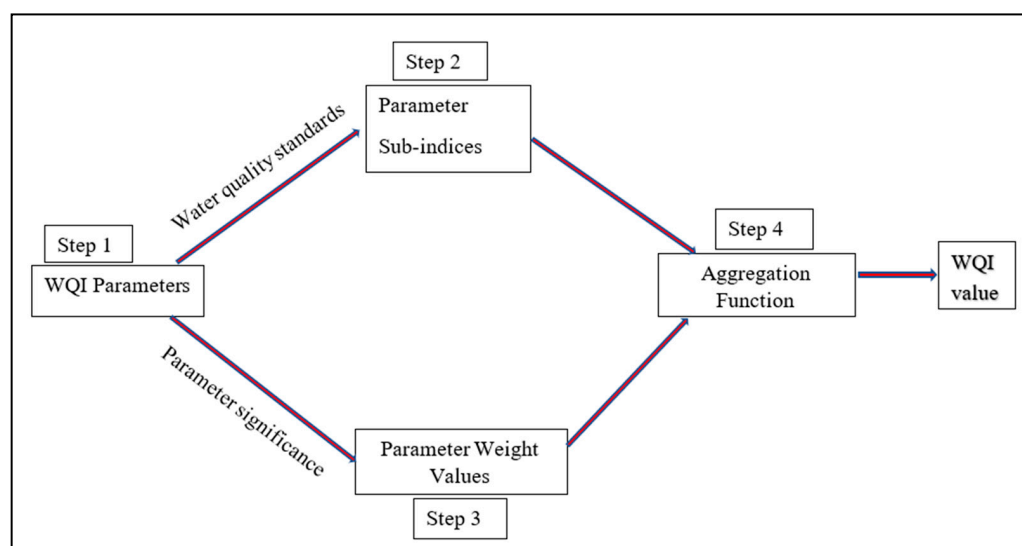

Figure 3. An illustration of the development steps of WAWQI in adapted indices.

Based on the overall index value, the water quality was rated using a categorisation scheme [83]. About 66.7, 28.6, and 4.7% of the articles focused on surface water [39–42,59,68–71], groundwater [48,49,63,81,82,84], and a combination of both surface and groundwater [58,80,85–87] respectively. The types and extent of the various societal needs addressed by the articles are shown in Figure 4. More than half of the reviewed articles addressed water for drinking purposes.
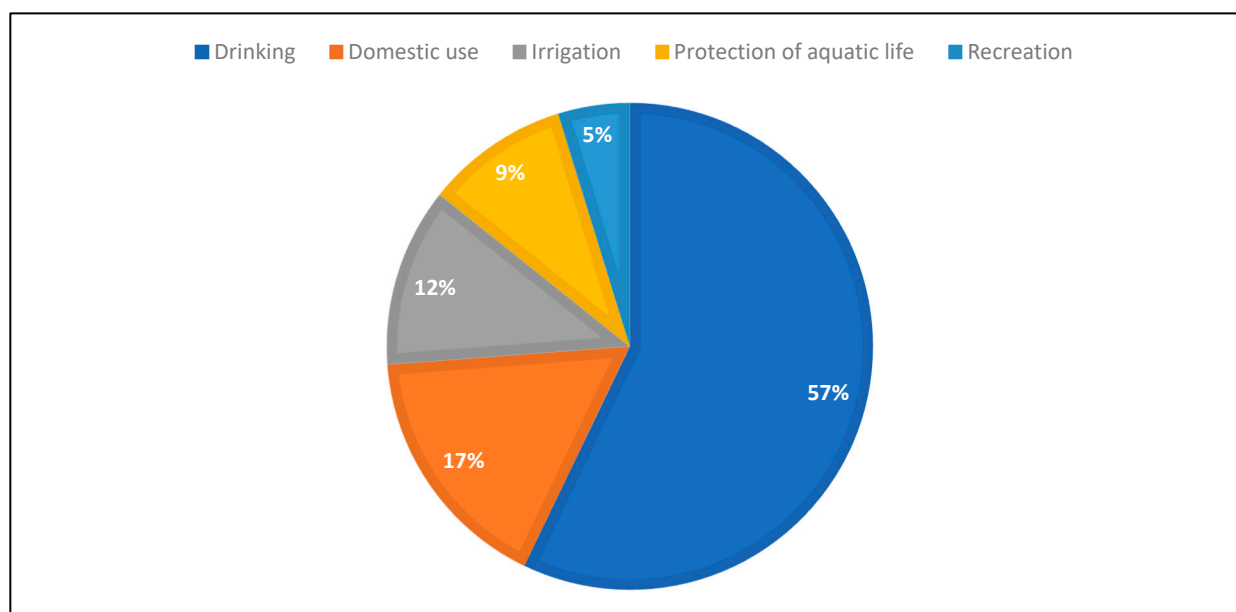
Figure 4. Percentage distribution of societal needs addressed by authors in the adapted indices.

3.1. Parameter Selection Criteria in the Adapted WQIs

From the articles reviewed, 65 WQPs were identified. On average, the articles focused on 14 WQPs with a minimum of 4 and a maximum of 24, which examined the quality of swimming pool water for bathing [87] and the applicability of lake water for irrigation [39] respectively. It has been affirmed that various physical, chemical, and biological factors influence the level of contamination in a specific aquatic system [7]. These categories were employed by authors in the current investigation and are detailed in Table 2.

Table 2. The WQP categories utilised by authors in the 42 articles reviewed.

Chemical Parameters (52)	Physical Parameters (9)	Microbiological Parameters (4)
Dissolved Oxygen (DO), pH, Total Phosphorus (TP), chloride (Cl^-), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), manganese (Mn), Soluble Reactive Phosphorus (SRP), cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), zinc (Zn), sulphates (SO_4^{2-}), arsenic (As), fluoride (F^-), mercury (Hg), selenium (Se), cobalt (Co), vanadium (V), magnesium (Mg), sodium adsorption ratio (SAR),Residual Sodium Carbonate (RSC), Magnesium Adsorption Ratio (MAR), nickel (Ni), calcium (Ca^{2+}), nitrites (NO_2^-), Total Nitrogen (TN), sodium (Na^+), total acidity, total alkalinity, calcium hardness (Ca H), magnesium hardness (Mg H), silica (Si), salinity, boron (Bo), electrode potential (Eh), bicarbonate (HCO_3^-), chlorophyll-a (Chl-a), iron oxide (Fe), Osmotic Potential (OP), barium (Ba), aluminium (Al), potassium (K^+), molybdenum (Mo), strontium (Sr), Uranium (U), titanium (Ti), carbonates (CO_3^{2-}), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), Isotopes 2-H and 18-O.	Hardness, temperature, colour, total solids (TS), turbidity, suspended solids (SS), total dissolved solids (TDS), and electrical conductivity (EC).	Fecal coliform (FC), *Escherichia coli* (*E. coli*), Total Fungi (TF), Total Coliforms (TC).

Notes: The table illustrates the WQI categories employed in the reviewed articles. Chemical WQPs (81.5%) were the most often employed characteristics, followed by physical WQPs (12.3%) and microbiological WQPs (6.2%).

With the input of a panel of 142 experts, the original WAWQI used the Delphi technique to determine the parameters used for index development [11]. In the reviewed articles, parameter selection was at the authors' discretion based on their relevance to water quality. With 57% of articles focusing on water for drinking purposes, the parameters selected included in situ physicochemical parameters, nutrients, heavy metals, faecal indicator bacteria, and organic matter. For other domestic uses, stable isotopes 2-H and 18-O parameters selected for drinking water were also added while exempting colour, alkalinity, total acid, and faecal indicator bacteria. For irrigation purposes, similar parameters to those of drinking water were used with the addition of SAR, RSC, MAR, and TF, excluding the stable isotopes. Physical parameters, nutrients, and heavy metals were considered in water to protect aquatic life and recreation. However, for recreation purposes, heavy metals were excluded as *E. coli* was included (Table 3).

Table 3. Parameters selected for various societal needs in the adapted indices.

Use	Parameters
Drinking	Temp, DO, BOD, TDS, TSS, EC, pH, hardness, colour, Alk, total acid, turb, F, Cl^- Mn, HCO_3^-, CO_3^{2-}, SO_4, NO_2-N, NO_3-N, PO4-P, NH_4-N, Cu^{2+}, Fe^{2+}, Fe^{3+}, Cr, K^+, Na^+, Zn^{2+}, Ca^{2+}, Mg^{2+}, Pb, As, Ar, Si, Al, Ba, B, U, Se, Mo, Bo, Cd, Hg, Ni, Co, V, *E. coli*, FC, TC
Domestic use	Temp, pH, turb, EC, TDS, TS, hardness, DO, BOD, COD, NO_3-N, NH_4-N, PO4-P, Cl^-, SO_4, Mg^{2+}, B, Fe, F, As, Cd, Si, Cr, Sr, Ti, Pb, Ni, Hg, Se, Al, Mn, CO_3^{2-}, K^+, Na^+, Zn^{2+}, Cu^{2+} Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4, FC, Eh, salt, SiO_2, Isotopes $\delta^2 H$ and $\delta^{18}O$
Agriculture and irrigation	Temp, EC, TDS, TS, pH, BOD, DO, Alk, turb, colour, K^+, Na^+, Zn^{2+}, Ca^{2+}, Mg^{2+}, SO_4, Cl^-, SO_4, HCO_3^-, CO_3^{2-}, NO_3-N, PO4-P, NH_4-N, SAR, RSC, HCO_3^-, MAR, hardness, B, Al, As, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, V, TC, FC, *E. coli*, Fungi
Protection of aquatic life	Temp, EC, pH, DO, turb, BOD, COD, TSS, TDS, Cl^-, Chl-a, F, NH_4-N, PO_4-N, NO_3-N, NO_2-N, SO_4, OP, Mn, Cu^{2+}, Zn^{2+}, Pb, Cd, Cr, Ni, Fe, TC
Recreation	Temp, pH, turb, EC, Cl^-, TSS, SRP, TP, NH4-N, NO_3-N, *E. coli*

It is noteworthy that given the resource constraints with infrastructure, human capital, and financial resources in most regions of Africa, chemical parameters, especially heavy metals, were prioritised, followed by physical parameters and nutrients for societal needs. The original general use of WAWQI established nine fixed WQPs: DO, FC, pH, BOD, temperature, TP, TN, turbidity, and TS [11]. However, out of the 65 WQPs utilised in the current review, pH (88.1%), Cl^- (81%), EC (73.8%), NO_3-N (6%), TDS (66.7%), Ca^{2-} (66.7%), Mg^{2+} (64.3%), SO_4^{2-} (57.1%), Na^+ (47.6%), and HCO^{3-} (42.9%) were the ten most often used WQPs in water quality analysis. Only pH from the original nine recommended parameters appeared in the ten most popular WQPs in the adapted indices. This may be related to location-specific dimensions [10], allocation, and usage [3]. Additionally, the difference in parameters selected between the original WAWQI and adapted ones can only be interpreted, considering that the original index was designed for the USA.

Furthermore, the original WAWQI was developed with a fixed set of WQPs. There is, therefore, a high likelihood that the final index scores in the reviewed articles faced the effects associated with parameter modification caused by index rigidity [75]. However, the initial CCMEWQI was designed with a minimum of four WQPs and no upper limit [1]. The current study discovered that the eight articles that adapted CCMEWQI to construct their WQIs employed between 7 [1] and 24 [39] parameters. Since CCMEWQI offers the

ability to incorporate more parameters based on existing environmental quality guidelines and local circumstances, the choice of the quantity of WQPs selected in the adapted WQIs was justifiable. Yet, to calculate index values, four of the selected WQP must have been sampled at least four times throughout the necessary sampling period [88].

Six of the eight articles in the current analysis showed that sampling was done at least four times—however, refs. [42,43] did not specify the sampling frequency. Also, when only one application needs to be evaluated using CCMEWQI, it is advisable to employ a core set of parameters, such as nutrients, heavy metals, physical parameters, etc. This inclusion is vital because too few parameters or too much covariance between them could enhance or decrease the significance of any one parameter, giving factor F_1 (scope) too much weight for determining the final index score [44]. Furthermore, the chosen core set of parameters must also address the significant environmental stress faced by the system to retain the relevance and correctness of the final index [23]. According to the results of the current investigation, only [41] maintained a single core set of parameters (nutrients). Figures 5 and 6 show the WQP utilisation in percentages employed by the author(s) to develop customised WQIs.
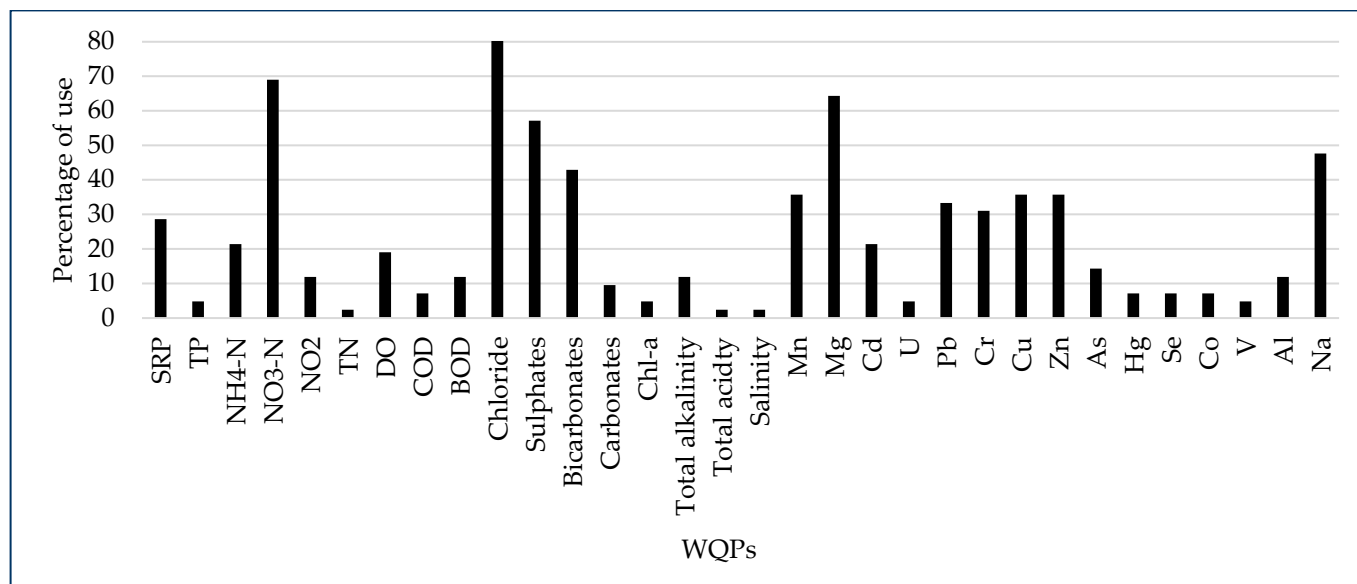

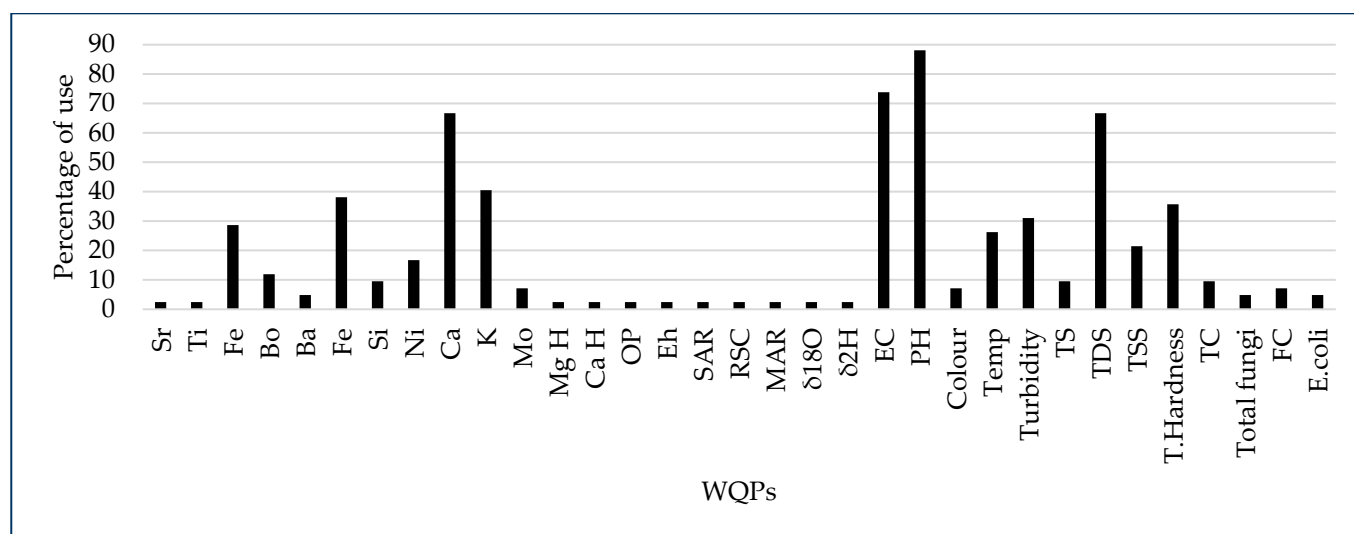**Figure 5.** Percentage of WQPs used among the 42 articles under evaluation.

Figure 6. More WQPs used among the 42 articles as a continuation of Figure 5.

Multiple WQPs were clustered to determine the frequently employed pairing by the articles examined (Figure 7). The cluster analysis connected WQPs based on the distance between parameters, and the more dissimilar the parameters were, the larger the distance was between them. All WQPs were grouped into four sub-clusters and two major clusters (Clusters 1 and 2) and (Sub-clusters 1.1, 1.2, 2.1 & 2.2). Cluster 2 was more heterogeneous with more homogeneous characteristics, while Cluster 1 was more homogeneous with a flatter dendrogram. Both clusters had two sub-clusters, with each sub-cluster bearing various combinations.
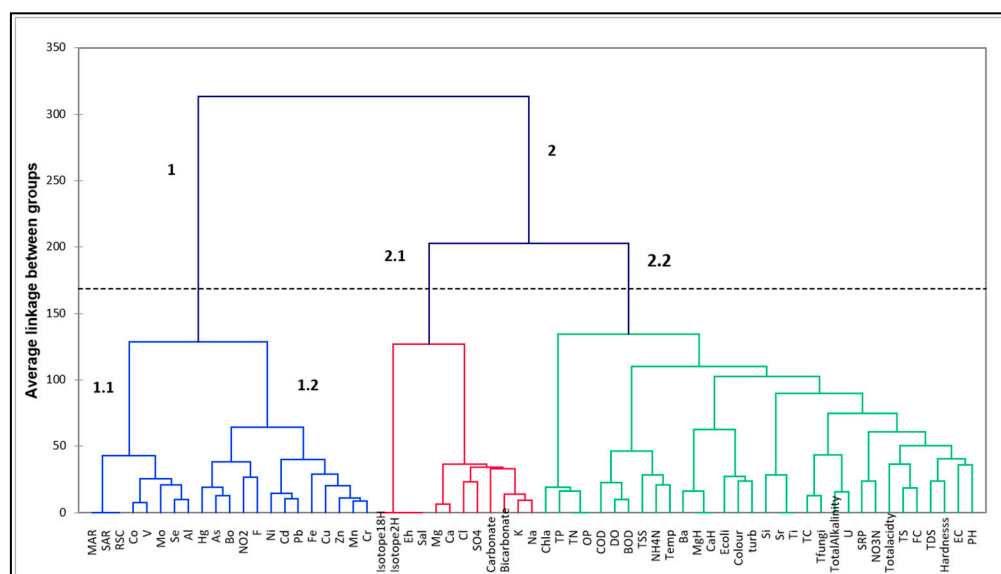

Figure 7. A parameter combination dendrogram from cluster analysis in modified WQIs. Notes—The numbers provide a visual display of how the branching occurs into various clusters and sub-clusters represented by different colors. Every color possesses similar features where blue, red and green represent combinations 1, 2 and 3 respectively. The dotted line provides an idea of the distance between clusters, or the cut off between the main clusters and sub-clusters.

The following were some of the authors' more inventive combo uses:

- Combination one; Zn^{2+}, Mn, Cu^{2+}, Fe, Pb, Cd, Ni, Bo, As, Hg, Al, Se, Mo, and Co with Cr, V, MAR, SAR, and RSC as outliers.
- Combination two; Mg, Ca, Cl^-, SO_4, HCO_3, K^+, and Na^+ with Eh, Sal, and the stable isotopes as outliers.
- Combination three; COD, DO, BOD, TSS, NH_4-N, Temp, *E. coli*, colour, turbidity, TC, Total fungi, Total Alkalinity, SRP, NO_3-N, Total acidity, TS, FC, TDS, Hardness, EC, and pH with outliers like OP, MgH, CaH, Sr, Ti, and U.

Combination one consisted of a cluster of heavy metals associated with groundwater contamination, among other factors. Most of the authors who employed this combination investigated groundwater suitability for drinking, domestic use, or its suitability for irrigation. For example, refs. [49,50]. On the other hand, combination three comprised physicochemical parameters in conjunction with nutrients and faecal indicator bacteria. These are parameters used to assess the ecosystem health of any water body, and almost all the authors included physicochemical parameters and nutrients for all the societal needs addressed. The faecal indicator bacteria parameter was included by authors who investigated water for drinking and recreation since faecal indicator bacteria indicates recent contamination of the system with faecal matter, hence the presence of faecal bacteria.

3.2. Generation of Parameter Sub-Indices

In this developmental step, parameter concentrations and levels are compared on a similar scale and transformed into unit-less sub-index values from different units like ppm,

saturation, %, mg/L, and counts [44]. To create sub-indices, one can use expert judgment, water quality standards, and statistical techniques.

3.2.1. Use of Expert Judgment

Judgement can come from a single expert or a team of specialists who create the critical points of rating curves and draw graphs to illustrate each parameter's effects on water quality at various concentration levels. The graphs are also transformed into linear or non-linear sub-index functions [11].

3.2.2. Use of Water Quality Standards

The developed rating curves are transformed into sub-index functions using the recommended water quality standards. Because the critical points on the graphs are obtained using the recommended values for each particular parameter, this technique is less arbitrary than expert judgment. Sub-index values can be obtained through categorical scaling, linear interpolation rescaling, and comparison with recommended limits. Each recommended limit is allocated to the appropriate water quality class and a matching sub-index in linear interpolation. The sub-indices vary from 0–100 or 0–1, much like the water quality classes listed in a sequence [73]. For illustration.

(a)   Recommended standards—20, 30, 40, 80, 120
(b)   Sub-index ranges—100, 75, 50, 25, 1
(c)   Pairing—class 1 (20–100), class 2 (30–75), class 3 (40–50), class 4 (25–80), and class 5 (1–120) are used. The paired data are the bases for sub-index development since they are the key points of the rating curves. If the actual measured value falls between two classes, the sub-index value is obtained using mathematical equations. For example, Equation (1) is used when a parameter decreases the level of water quality with an increase in the parameter value.

$$S_i = S_1 - \left[(S_1 - S_2) \left(\frac{x_i - x_1}{x_2 - x_1} \right) \right] \tag{1}$$

where, S_i is the ith sub-index value; S_1 and S_2 are the sub-index values for the upper and lower classes, respectively; x_i is the ith parameter value; and x_1 and x_2 are values of permissible limits for the upper and lower class.

In a case where a parameter increases the level of water quality with an increase in parameter value, Equation (2) is employed.

$$S_i = S_1 - \left[(S_1 - S_2) \left(\frac{x_1 - x_i}{x_1 - x_2} \right) \right] \tag{2}$$

In categorical scaling, the actual parameter values are converted into sub-index values by using constant values of either 0 or 1. The values 0 or 1 are assigned to parameter levels when concentrations exceed and fall below the recommended standard, respectively. These mathematical functions are essential in this technique.

(a) $S_i = 0$ if x_i > recommended standard
(b) $S_i = 1$ if x_i < recommended standard

The measured parameter values and the recommended standards are compared from the sub-indices produced based on the established water quality criteria. The values range between 0 and 1, as shown in Equation (3).

$$S_i = \frac{x_i}{\mathcal{X}\text{max}} \tag{3}$$

where S_i is the ith sub-index value, x_i is the ith actual parameter value (mg/L); and $x$max is the maximum value of the recommended standard (mg/L) [10].

3.2.3. Statistical Methods

Statistical analysis and historical parameter data identify critical points for generating sub-index values. The metrics in question and their consistently measured average values and multiple quantiles are used. The individual sub-index values are multiplied by the parameter weightage values to generate the final index value. This technique has been used by Dunnett and Bhargava indices [10].

3.3. Sub-Index Development in the Adapted Indices

This step was bypassed by the eight WQIs that utilised the CCMEWQI. This procedure follows [23], which developed a multivariate statistical procedure to combine the initial parameter values without sub-indices. In the original WAWQI, respondents were asked to create a rating curve for each of the nine parameters and sub-indices determined by expert judgment [11]. In the current review, all the articles that adapted WAWQI used water quality standards to develop sub-index values by comparing the measured parameters with existing recommended standards, both internationally and locally. The internationally adopted standards were WHO guidelines for drinking water [63]. FAO guidelines for irrigation [39], ANZECC guidelines for the conservation of aquatic areas [77], and WHO standards for swimming pools and similar environments [87] among others. On the other hand, the local standards included but not limited to; SANS241-1:2015 [68], LNCSM [46], and Ghana's WRC guidelines for domestic use and protection of aquatic life [41], among others.

Going by Equation (4) [30] 61.8%, including [51,62,64,67,68,78,81], among others, assigned a quality rating scale (q_1) by dividing the concentration in each water sample with its corresponding standard following the suggested recommendations and multiplying the result by 100.

$$q_i = \left(\frac{Ci}{Si} \right) \times 100 \tag{4}$$

where qi is the quality rating, *Ci* is the concentration of each parameter in each water sample in mg/L, S_i is the maximum permissible guideline limit for each parameter in mg/L.

On the other hand, 32.4% of articles, including [47,48,54,61,79,80,87], considered using a function that multiplied the result by 100 and included the ideal WQP values in addition to the maximum allowable guidelines, as illustrated in Equation (5).

$$Qn = 100 \left[\frac{vn - vo}{sn - vo} \right] \tag{5}$$

where vn is the observed value of the nth parameter, vo is the ideal value of the nth parameter in pure water. vo = 0, except for pH = 7.0 and DO = 14.6 mg/L, sn is the recommended standard value of the nth parameter.

3.4. Assignment of Parameter Weights

In essence, parameters are given weighted values based on their relative importance to the overall quality of the water [73]. While some WQI models give each parameter the same weight and see them as equally important to water quality, most WQIs give each parameter an unequal weight while ensuring the sum of all weights equals 1. This weighting approach is appropriate because the overall impact of WQP shouldn't be greater than 100% [12]. The integrity of the final index score is negatively impacted and is regarded as dysfunctional if improperly conducted, giving a parameter more or less relevance than it deserves. Therefore, care should be taken when assigning unequal parameter weights [83]. This consideration ensures that the final index value reflects the water quality status. There are two approaches to establishing parameter weights: (i) the Delphi Method and (ii) the AHP.

3.4.1. The Delphi Technique

This approach seeks professional judgment from significant players in the water quality field to weigh parameters. They typically base their weightings on environmental relevance, the recommended guideline values, and the application to the particular water body [83]. In certain circumstances, some authors establish parameter weights based on existing values in the literature using a scale of 1–5 [89] or 1–4 to compare the environmental significance of different factors. To achieve relative weightings between 0 and 1 for the least influential and most influential parameters, respectively, all of the ratings are pooled, and their arithmetic mean values are determined by mathematical functions or compared to existing standards [10,90]. This technique was employed in Horton and Brown indices.

3.4.2. AHP

With this multidisciplinary technique, the decision-making process considers both quantitative and qualitative factors [10]. AHP uses pair-wise comparison principles in WQI development, where experts present their preferred option by contrasting many choices from a complex collection of factors [10]. Sutadian et al. [73] have effectively used this technique, which enables the reliability check of the evaluations being made and reduces subjectivity in the decision-making process [83].

3.5. Assignment of Parameter Weights in the Adapted Indices

The parameters in the eight articles that used the CCMEWQI were not assigned weights. This pre-condition is consistent with the original CCMEWQI model, which assumes that all parameters have equal weights and does not call for weight values when predicting the final index score [2]. Brown and his associates applied the Delphi method to the original WAWQI to give parameter weight values. When the respondents' replies were compiled, the unit weight was summed up to 1, and they were asked to compare the weights of several parameters using a scale of 1 (highest) to 5 (lowest) [11].

Articles that adapted the WAWQI used two approaches to assign weights to parameters; (1) assignment of parameter weighs by the Delphi technique and fitting the values into Equation (6) [47,62,64,68,78,81] and (2) assignment of parameter weights by Delphi technique and fitting values into Equation (7) through the application of a value inverse of recommended guideline [46,61,80,84,87,91,92]. However, parameter weights were assigned in accordance with [11] with a scale of 1 (highest) to 5 (lowest), refs. [47,82] employed a scale of 1 (highest) to 4 (lowest).

$$\text{Wi} = wi / \sum_{i=1}^{n} wi \tag{6}$$

where Wi is the unit weight, wi is the weight of each parameter, and n is the number of parameters.

$$\text{Wi} = k / s_n \tag{7}$$

where k is a proportionality constant determined as.

$$k = \frac{1}{\sum_{i=i}^{n} \frac{1}{si}} \tag{8}$$

where s_i is the standard permissible value for the ith parameter.

3.6. Final Computation of the WQI

This last step combines sub-indices and weighted factors from all metrics using various aggregation methods to get a unitless value representing the overall water quality status [10]. The most often utilised are the multiplicative (geometric) and additive (arithmetic) functions [44]. Continuous efforts have been made since the initial WQI to address the shortcomings of earlier aggregating functions. For example, moving from the weighted arithmetic average [11,15] to the weighted geometric average [18], weighted

product [90], harmonic mean [74], minimum operator [22], and finally to logarithmic-based functions [93].

The overall WQI is directly impacted by the parameter values in any given aggregation approach. The WQI tends to be zero in geometric average functions if the value of one of the parameters is near zero. Regardless of how the parameters are weighted, indices produced with arithmetic average functions are most frequently affected by extreme values of the parameters (eclipsing) [94]. Weighted arithmetic and weighted geometric averages are thought to be outperformed by the unweighted harmonic square average. This function has been found to reduce the eclipsing effect while accounting for other indicators' impact by being more sensitive to the most degraded indicators [26]. Although the most recent method uses logarithmic functions, most researchers still use arithmetic or geometric aggregations.

3.7. Aggregation Function for the Adapted CCMEWQI

The original aggregation formula [23] was employed by the eight articles that adopted the CCMEWQI to get the overall index value, which is based on three parameters;

Factor 1 (F_1): Scope—assesses the extent of water quality guideline non-compliance during the period of interest.

$$F_1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables} \right) \times 100 \qquad (9)$$

where variables indicate those WQP with objectives that were tested during the period for the index calculation.

Factor 2 (F_2): Frequency represents the mean frequency and number of times the tested or observed value was out of acceptable limits or standards.

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ variables} \right) \times 100 \qquad (10)$$

Factor 3 (F_3): Amplitude—It represents the amount by which the failed test values do not meet their objectives and is calculated in three steps:

(i)   Calculation of Excursion

An excursion is the number of times an individual concentration is greater than (or less than, when the objective is a minimum) the objective.

-     When the test value must not exceed the objective.

$$Excursion_i = \left(\frac{Failed\ Test\ value\ i}{Objective\ j} \right) - 1 \qquad (11)$$

-     When the test value must not fall below the objective.

$$Excursion_i = \left(\frac{Objective\ j}{Failed\ Test\ value\ i} \right) - 1 \qquad (12)$$

(ii)   Calculation of Normalised Sum of Excursions

The normalised sum of excursions, *nse*, is the collective amount by which individual tests are out of compliance. This value is calculated by summing the excursions of individual tests from their objectives and dividing them by the total number of tests (both those meeting objectives and those not meeting objectives).

$$nse = \frac{\sum_{i=0}^{n} excursion\ i}{Number\ of\ tests} \qquad (13)$$

(iii)   Calculation of F_3

F_3 is calculated by an asymptotic function that scales the normalized sum of the excursions from objectives to yield a range from 0 to 100.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01} \right) \tag{14}$$

The WQI is then calculated as follows:

$$WQI = 100 - \left(\frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732} \right) \tag{15}$$

The factor of 1.732 arises because each of the three index factors can range as high as 100. Therefore, the vector length can reach.
$\sqrt{100^2 + 100^2 + 100^2} = \sqrt{30000} = 173.2$ as a maximum. A division using 1.732 reduces the vector length to 100 as a maximum.

3.8. Aggregation Function for the Adapted WAWQI

All 34 articles in this model employed the WA aggregation function to compute the final index value. After weighing the parameters and sub-indices, two approaches were used to calculate WQI.

(i)   67.6% of the 34 articles, including [51,62,67,79,86,92] employed an additive function to combine relative weight from expert opinion and water quality ratings from recommended guidelines in these two equations;

$$Sli = Wi \times qi \tag{16}$$

$$WQI = \sum_{i=1}^{n} Sli \tag{17}$$

where *Sli* is the sub-index value of the *i*th parameter, Wi is the relative weight of the ith parameter, *n* is the number of parameters.

(ii)   The remaining 32.4% [46,48,84,87,91] who incorporated the quality rating and relative weight from suggested standards employed an additive function;

$$WQI = \sum \frac{QnWn}{Wn} \tag{18}$$

where *Qn* is the quality rating, *Wn* is the relative weight, and *Wn* = 1

3.9. Classification of WQIs and Index Scores

The assignment of final WQI values to classes or categories is known as classification or categorisation. It can be done using one of two sets of categorisation scales: (i) an increasing scale, where the index value rises with the level of contamination, and (ii) a decreasing scale, where the index value falls with the level of contamination. In both instances, the final objective is to express the water quality status by determining the degree of contamination [10]. Classifying WQI values should be based on the public's expectations for water quality, professional judgment, and the most up-to-date information [23]. Typically, the index values range between 0 and 100. Further, the values are grouped into classes 1 through 5, depending on whether the author employs an increasing or decreasing scale. Tables 4 and 5 showcases the various WQI developed using increasing and decreasing scales.

Table 4. WQI classification using increasing scale.

Class	a. CCME WQI		b. OWQI	
	Rank	**Index Score**	**Rank**	**Index Score**
Class 1	Excellent	95–100	Excellent	90–100
Class 2	Good	80–94	Good	85–89
Class 3	Fair	60–79	Fair	80–84
Class 4	Marginal	45–59	Poor	60–79
Class 5	Poor	0–44	Very poor	0–59

Note: Source: a. [4,23]; b. [20,95]. CCME WQI (Canada); OWQI: Oregon WQI (Oregon).

Table 5. WQI classification using decreasing scale.

Class	a. TMWQI		b. RWQI	
	Rank	**Index Score**	**Rank**	**Index Score**
Class 1	Excellent	<26	Excellent	<50
Class 2	Good	26–50	Good	50–100
Class 3	Medium	51–75	Poor	100–200
Class 4	Poor	76–100	Very poor	200–300
Class 5	Unsuitable	>100	Unsuitable	>100

Note: Source: a. [6]; b. [96] TMWQI; WQI proposed by Tiwari and Mishra (India), RWQI; Ramakrishaniah WQI (India).

3.9.1. Classification of Water Quality in the Adapted WQIs

As shown in Table 4 part a, the original CCMEWQI used the CCME categorisation scheme described in [4,23]. All eight articles that used the CCME WQI followed the same trend. On the other hand, Brown and his colleagues' original WAWQI plan called for using colour schemes to categorise water quality across the state (Table 6).

Table 6. Classification of WQI value using colour schemes in the original WAWQI model.

Colour	Rank	Index Value
Dark red	Very poor	0–10
Orange	Poor	*
Yellow	Medium/Average	50
Green	Good	**
Dark blue	Excellent	90–100

Notes: Source: [3,4]. * and ** are not given, and this review assumes >10 WQI <50 and >50 WQI <90 for poor and good water quality, respectively.

All the 34 papers that applied the WAWQI used a decreasing scale to classify their subjects, ranging from 0 to 100 [59,61,79,84,87] in some cases, and 0 to 300 in others, [62,67,68,78,80,81] while [79,91] used 4 and 6 classes respectively. Majority of reviewed articles (approx. 94%) ranked the WQI values in 5 classes. Of the 34, 19 had their final index values classified according to (Table 7 part a following [97]), and 6 (Table 7 part b based on [8]).

Table 7. Classification scale for WQI scores in the adapted indices.

Class	a.		b.	
	Rank	Index Score	Rank	Index Score
Class 1	<50	Excellent	0–25	Excellent
Class 2	50–100	Good	26–50	Good
Class 3	100–200	Poor	51–75	Poor
Class 4	200–300	Very poor	76–100	Very poor
Class 5	>300	Unsuitable for human consumption	>100	Unsuitable for human consumption

Note: Source: a. [97] and b. [8]

3.9.2. Limitations Identified in the Classification Scales of Adapted Indices in Reviewed Articles

In the classification by [97] (Table 7 part a, the final index score may fall within two classes. For instance, a score of 100 could either fall within class 2 ("good") or class 3 ("poor"), while 200 could fall within class 3 ("poor") or class 4 ("very poor"). Such a limitation has been reported elsewhere [98]. To solve this shortcoming, ref. [1] modified the CCMEWQI classification scale by minimising the difference between classes to a decimal fraction. In the adapted indices, two articles [47,63] introduced decimal fractions in their classification scheme; <50 ("excellent"), 50–100.1 ("good"), 100–200.1 ("poor"), 200–300.1 ("very poor"), and >300 ("unsuitable for human consumption"). Nevertheless, such a classification scheme still faces the challenge of some scores falling within two classes, like 100 in class 2 ("good") and class 3 ("poor"), as well as a score of 200 falling between class 3 ("good") and class 4 ("very poor"). Also, an overlap exists in classes as seen from poor choice of lower and upper limit of values assigned to classes whereby class 2 ("50–100.1") suggests good water quality compared to class 3 ("100–200.1") of poor quality. Since 100 is a figure less than 100.1, its quality is expected to be better than that of 100.1 but that is not the case here. The same applies to classes 3 and 4; 100–200.1 ("poor"), 200–300.1 ("very poor").

The classification by Tyagi and his colleagues makes it impossible for some final index scores to be accommodated. For example, there is no provision for index scores between 25–26, 50–51 and 75–76 unless the index score is rounded off to the nearest whole number. Other works with similar limitations in class-assigning index values have been reported [10,98]. Finally, there is a possibility of a lack of representation for index score values falling below 50 in the scheme used by [61], which runs from 50 to >300, i.e., 50 ("excellent") 50–100 ("good") 101–200 ("poor") 201–300 ("very poor") >300 ("unsuitable for human consumption"). It can be noted that unless performed carefully, classification schemes will certainly fail to accommodate all the achievable index scores. Despite the dynamic nature of aquatic ecosystems due to the continuous influence of allochthonous and autochthonous factors, a final index value must be attained and categorised. It is, therefore, imperative to introduce logical linguistic descriptions like less than, equal to and greater than to ensure inclusivity of all index scores, as demonstrated in Table 8.

Table 8. Classification of WQI scores using logical linguistic descriptions.

Class	a.		b.	
	Rank	Index Score	Rank	Index Score
Class 1	$91 \leq Index \leq 100$	Good	>2.8	Excellent
Class 2	$61 \leq Index < 91$	Acceptable	2.3–2.8	Good
Class 3	$31 \leq Index < 61$	Regular	<2.3	Poor
Class 4	$16 \leq Index < 31$	Bad		
Class 5	$0 \leq Index < 16$	Very bad		

Note: Source: a. [99] adapted from the Bascaron method (1979); b. [100].

3.10. Potential Solutions to Uncertainties Associated with Adapted Iindices

The concerns center on how differences in a WQI's developmental stages might impact the ultimate index score. These may arise at any WQI developmental steps, including parameter selection, sub-indexing and weighting [73], and the final aggregation function [22].

3.10.1. Parameter Selection Uncertainties

There are no set criteria or procedures for choosing WQPs to be included in the various WQI models. The researcher could be directed toward the best WQPs to choose by aspects like data accessibility, environmental relevance [101], and use or purpose of the water body [102]. It is important to emphasise that data availability is a significant cause for concern when selecting parameters, especially in developing nations [83]. This is mainly because water quality monitoring programs require much labour and have significant analytical costs. This likely explains why most authors in the examined articles only used the fundamental criteria to assess water quality. Additionally, the inability of researchers to access comprehensive data on water quality is hampered by the lack of contemporary analytical laboratory facilities due to insufficient capital, such as financial assistance and competent human resources [101].

Approximately 80% of the articles in the current review focused on drinking water or water for human use. At the same time, the minority concentrated on recreation, irrigation, protecting aquatic life, and health risk issues. As can be deduced, practically all the authors focusing on drinking water largely prioritised heavy metals with other ancillary parameters, though the list was not exhaustive. Heavy metals, especially in gold mining areas, are a source of environmental contamination and threaten human health. For instance, Pb, Hg, Cd, and As are carcinogenic if they exceed the maximum tolerable upper intake levels [103].

Additionally, Cr, Cu, Zn, and Ni threaten all aquatic inhabitants by disrupting food chains via bioaccumulation—some heavy metals, like Ni nanoparticles, damage liver cells [104]. Furthermore, chronic exposure to Pb may result in mental retardation, congenital disabilities, psychosis, autism, allergies, dyslexia, weight loss, hyperactivity, paralysis, muscular weakness, brain damage, and kidney damage. It may even cause death [105].

On the other hand, Fe in water may chemically bond with free hydrogen radicals, hence attacking DNA cells, leading to mutations and malignant transformations that cause many diseases [106]. In addition, long-term ingestion of water with a high concentration of Zn has been found to cause the death of human brain cells, trauma, and prostate cancer [107]. Sometimes, water samples for drinking may comply with the state or international set standards, especially for physical parameters like colour, odour, and turbidity. However, harmful hazardous, and hardly detectable compounds may also be present due to the universal solvent nature of water. This presents a challenge in analysing each of the chemicals present in water [38]. Therefore, even though it is key to prioritising WQPs, it is important to include data on physical, chemical, biological, and hazardous factors to thoroughly analyze and portray the ideal water quality conditions [108]. None of the articles under consideration used radioactive or hazardous components to assess the water quality.

Additionally, four WQPs were used in the modified indices to evaluate the swimming pool water quality in hotels in Nigeria [87] while at the other extreme, 24 WQPs were chosen to evaluate the appropriateness of surface water for agriculture in Egypt [109]. It should be emphasised that since water quality varies on a wide range of natural and anthropogenic factors, too few parameters may not provide a good picture of the final WQI. Likewise, it is doubtful that all the data from the 24 collected parameters would be readily available in addition to being data of high quality. Although the original CCMEWQI and West Java WQI, which used four and 26 WQPs, respectively, may have been provided as inspiration for the author(s). Considerable care must be taken to ensure that the parameters chosen are just enough, neither too few nor too many [10] and based on the study at hand and end-use objectives [90].

Given resource constraints, it was important to prioritise parameters that directly impacted water quality. These included parameters related to eutrophication, dissolved

chemicals, dissolved oxygen levels, physical qualities, and health issues [95]. The relevance of prioritised parameters for whatsoever societal needs cannot be overemphasised. For example, DO concentration is normally used to indicate water quality to the extent that high DO concentrations indicate good water quality. Conversely, low DO concentration could mean reduced organismal growth, disruption of life cycles, migration to avoid poor conditions, and even death of benthic organisms and fish (reviewed in Vaquer-Sunyer and Duarte 2008; cited in [110].

On the other hand, inorganic nutrients (mainly nitrogen and phosphorus) may stimulate the growth of algal blooms causing eutrophication. In addition, nitrites, reduced forms of nitrates, have been proven to cause blue baby syndrome (Methemoglobinemia) in infants after long-term ingestion. Furthermore, physical attributes like suspended solids and turbidity, odour and colour affect water's suitability for domestic uses like washing and drinking. High turbidity may also clog the gills of some benthic macroinvertebrates, causing death.

For microbiological water quality, faecal coliforms (FC) have been conventionally used as indicator organisms for faecal contamination. Some WQI models have been incorporating as part of the WQPs, e.g., ref. [111]. However, WHO commonly accepts *E. coli* as a better indicator of faecal and microbiological water contamination and recommends using it instead of FC. This is the case where water for drinking purposes is being assessed [112]. In the articles reviewed, where more than three-quarters of articles focused on drinking water, microbiological constituents (TC, FC, TF, and *E. coli*) accounted for less than 10%, while *E. coli* alone accounted for only 4.8% of the WQPs used.

Nevertheless, bio-assessments using aquatic organisms such as plankton, macroinvertebrates, and fish have proved to be a fair reflection of the current water quality status and the overall ecosystem health. Unfortunately, this aspect was overlooked in all the reviewed articles. Biological components of water bodies, especially benthic macroinvertebrates, phytoplankton, and microbiota, are therefore highly recommended for integration with physicochemical parameters for adapted WQIs since they can indicate the future direction of the overall aquatic ecosystem health.

3.10.2. Eclipsing, Ambiguity and Rigidity

In additive/arithmetic models, eclipsing—where the total WQI conceals the underlying nature of water quality—is frequent [27]. Eclipsing might result from faulty sub-indexing, weighting, or an inadequate aggregation procedure [22] Ambiguity is a situation where the overall index shows that the water quality is worse than expected based on the sub-index values for all WQPs. Due to how weights are applied and because these indices base their categorisation on the parameter with the greatest impairment, ambiguity is mainly observed in weighted indices [27]. On the other hand, rigidity is the condition in which an index is not adaptable enough to consider new or alternative criteria [75]. It frequently happens when an impairment arises in a parameter or parameters that the index does not consider or when an index is applied to a circumstance where the concerns differ from those for which it was designed [75].

There was a high likelihood of articles that adapted the WAWQI to develop the abovementioned abnormalities. This was owed to the fact that WAWQI is an additive, weighted model and was also employed in a field with distinct concerns from the ones from which it was derived. Additionally, the WA-adapted model was adjusted throughout the process of adapting from an original index with a set number of parameters, changing both the type and the number of parameters. On the other hand, articles that adapted CCMEWQI were less likely to experience the mentioned abnormalities as the original index is not explicit about the parameters to be chosen and gives the flexibility to accommodate more or alternative factors. Moreover, CCMEWQI does not use either parameter weighting or standard arithmetic computation. Therefore, CCMEWQI uses a variety of intricate aggregating procedures, which may cause the final index value to be uncertain [73].

Either weighted or unweighted multiplicative models can be used as a potential remedy for eclipsing, or new methods of calculating sub-index values can be used [75]. If a crucial parameter was concealed in the overall WQI, the lowest scoring parameter buried within the overall high WQI value might also be reported along with the WQI. To lessen eclipsing abnormalities, ref. [22] also suggested using the minimum operator aggregation function. Finally, applying multivariate statistical tools like PCA, CA, and DA in parameter selection could significantly minimise ambiguity and eclipse and establish new sub-index weights. Location-specific issues regarding rigidity can be reflected through the adjustment of sub-index parameters. To increase uniformity among the WQI models, great care must also be taken to employ local water quality parameters that are in sync with international guidelines [27]. The AHP technique is advised for weight assignment because it reduces abnormalities brought about by improper parameter weighting by determining parameter significance [83].

3.11. Applied Analysis and Comparison of Adapted WQIs and New Models

Since the review's sole objective was to analyse the development stages for WQIs that were modified versions of existing WQIs, techniques that created a new model were among those disqualified under the exclusion and inclusion criteria. Accordingly, this section summarises four novel approaches WQIs from an African perspective and compares their similarities and differences to the adapted indices.

3.11.1. Water Quality Index Based on DEA: Application to Algerian Dams [113]

The methodology was applied to a sample of 47 dams situated in hydrographic basin areas in Algeria's Tellian region, specified by ten physicochemical parameters. The input variables, dubbed "optimistic closeness values", were skillfully constructed from the hydrochemical parameter values before applying a DEA model.

Because of its objective data-driven nature, DEA is one strategy that avoids using a priori elicited weights [114]. The power of DEA has been demonstrated for the performance evaluation of DMUs, which employ many inputs to produce numerous outputs, permitting explicit segmentation of these DMUs into efficient and inefficient units [115]. WQIs, benchmark frequencies, and slack values from the DEA model are used to determine the bounds of the quality ranges, rank the dams, and design a priority scale for treating the hydrological parameters. When analysing the performance of a DMU, the DEA model operates on the fundamental concept of using fewer inputs to generate more outputs.

As a result, when viewed implicitly as an element of a production process, every input has to adhere to the maxim that "less is better" [116]. Therefore, the WHO [103] and the ANRH [113] drinking water standards were used in this article to classify each hydrochemical parameter into one of four quality levels: Excellent, Acceptable, Poor, and Unsuitable. On the other hand, the Acceptable, Poor, and Unsuitable ranges required basic, refined, and highly advanced treatments, respectively, to achieve the necessary water quality. At the same time, the Excellent interval expressed the satisfactory quality of the water that could be utilized without any special requirements.

Sturges's rule [117], was used to determine the best number of intervals to classify data samples of size K, and in this case,

$$I = 1 + 3.322\log 10(K) \tag{19}$$

where K = number of dams (47), and the number of adequate classes for the samples of WQIs would be I = 7.

The DEA-WQI model is not only a risk-ranking tool but also has great potential to support vital decisions on the water treatment of vulnerable dams.

3.11.2. UWQI: South African Catchments [65]

The information was gathered from six sampling stations spread across four distinct catchments that fall under the purview of the Pongola-Mtamvuna Water Management

Area, located in the South African province of KwaZulu-Natal. The four watershed regions are the Umgeni, Umdloti, Nungwane, and Umzinto/uMuziwezinto River catchments. The four catchments employed were sufficient to determine the model's functionality. The procedure was a step toward the ultimate objective of testing the model against the majority, if not all, of the catchment areas in South Africa. This model employed the four classical steps involved in developing conventional WQIs.

Parameter Selection

A fixed set of 10 parameters were established using expert opinions.

Weight Coefficients

Ratings of parameter significance were provided based on data gathered from the existing literature and via Delphi questionnaires. The preliminary ratings from the two methodologies were then combined to create parameter significance ratings (bi). Equation (20) was used to calculate the relative weight coefficients (wi), which were directly proportional to the significant ratings and obtained by dividing the parameter significance rating value (bi) by the summation of all ratings (bi).

$$wi = \frac{bi}{\sum_{i=1}^{n}(bi)} \tag{20}$$

where bi is the assigned significance rating of the water parameter; wi is the final weight coefficient for the water parameter; n is the total number of the rated water quality parameters.

Formation of Sub-Indices

The allowable concentration limits were used to establish the fixed key points of the rating curves graphically. Next, the plotted points were converged using straight lines to create a sequence of linear graphs, which were then transformed into linear sub-index functions. The procedure included consultation with the Target Water Quality Ranges (TWQRs), laid out by DWAF [118].

Aggregation Formula

The final UWQI, an improved version of the weighted sum approach, was developed by modifying and aligning the model with local conditions using scenario-based analysis. As a result, the model equation obtains the overall water quality status as a unitless number ranging from 0 to 100, as stated in the equations below, by integrating sub-index values of selected parameters regarding the defined weights.

$$\text{WQI} = \frac{1}{100}\left[\sum_{i=0}^{n} siwi\right]^2 \tag{21}$$
$$\text{(Modified weighted sum model)}$$

$$\frac{2}{3}\left[\sum_{i=0}^{n} siwi\right]^{1.0880563} \tag{22}$$
$$\text{(Final universal water quality index model)}$$

Classification of WQI Scores in UWQI

An increasing scale index serves as the basis for the classification mechanism. The UWQI model produces WQI values ranging from 0 to 100. The WQI scores are thus divided into classes ranging from one to five, with "Class 1" designating water of the highest degree of purity with a maximum possible score of one hundred and, conversely, "Class 5" designating water quality of the lowest degree with index scores close to or equal to zero. The classification involves the use of appropriate mathematical operations with logical linguistic descriptors, such as, but not limited to, "greater than", "less than", and "equal to", to evaluate WQI scores that were assigned to each category to fill in gaps in some of the

existing classification scales. This classification has also been used in literature by Banda & Kumarasamy [10].

Due to the fixed number of parameters, this model can be used in various catchments without affecting its structure or operation. As a result, stakeholders may be able to compare the water quality of various sites and establish a more impartial management prioritisation. Furthermore, expert opinion has the benefit of promoting the model's acceptability because most of the experts involved are also the model's intended end users. As a result, their participation in the development of the UWQI may eventually bring about acceptance through a sense of ownership.

3.11.3. The Surrogate Water Quality Index Based on Multivariate Statistical Analysis: South African Watersheds [66]

The parameters for water quality in this model were determined via a two-phase testing process that encompassed (i) the Delphi method used for the UWQI, where twenty-one parameters were reduced to thirteen variables, and (ii) further reducing the parameters to four proxy variables using statistical analysis, including electrical conductivity, chlorophyll-a, pH, and turbidity. Pattern recognition and elucidating the underlying dataset's structure were both accomplished during this process using PCA [119].

The most significant parameters that can be employed as proxy variables were identified, and it also offered important statistical data on the intercorrelated parameters. Furthermore, HCA was used to demonstrate the intuitive correlations between various water quality data. Finally, the process produced a dendrogram illustrating how the clusters were arranged and how close the various parameters were to one [120]. The resulting regression equation and coefficients represent the surrogate WQI model. The surrogate model outline displays the structure of the surrogate WQI with the four-proxy water quality input variables x_1, x_2, x_3, and x_4; their corresponding coefficients b_1 to b_4, intercept term b_0, error term for the regression model symbolized as ε, and the regression model function:

$$f(x) = b_0 + b_1x_1 + b_2x_2 + \ldots + b_4x_4 + \varepsilon \tag{23}$$

The beneficial aspect of this model is that, regardless of the absence of the entire data set, optimally chosen parameters could still reflect water quality [120]. Likewise, it conforms with the requirements of the study and offers an essential quick guide equal to the outcome of a high-fidelity model.

3.11.4. The Hounsinou Scale: Its Development and Use to Determine the Overall Quality of Groundwater Used for Drinking and Bathing in the Municipality of Abomey-Calavi in Benin [121]

Twenty-three physicochemical parameters and three microbiological parameters were used to evaluate the overall water quality of 68 wells in the municipality of Abomey-Calavi in Benin using the Hounsinou scale. The Hounsinou scale, which is novel and superior to the conventional WQIs, independently indicates water's chemical and microbiological properties. The Hounsinou scale combines the CWQI and MWQI scales to provide a final chemical and microbiological contamination assessment.

Weighted arithmetic sums of the values of the physicochemical and microbiological parameters and the WHO standards are used to calculate the CWQI and the MWQI. CWQI computation involves several steps: parameter selection, determination of the ideal values of the parameters, development of sub-indices, assignment of weights, and aggregation of sub-indices to produce an overall index expressed as.

$$CWQI \sum QnWn / \sum Wn \tag{24}$$

Akoteyon, ref. [56] inspires the classification scheme used in this model whereby CWQI $\leq$ 50 means water is very excellent to >500, water is very unsuitable for drinking. As

for the MWQI, the model is based on the contents per mL of water of TC, FC, and intestinal enterococci (IE). The final index is expressed as.

$$MWQI = 1/3 \ (10/9 \ TC + 20 \ FC + 1000 \ EI) \tag{25}$$

The classification scale in MWQI ranges from 'Absence of any germ for Excellent water' to 'Presence in the water of pathogen germs with or without TC, FC or EI', meaning the consumption of this water exposes users to water-born illness within a short time.

This new scale is superior to the water quality index that has been used to date because it is more accurate, provides the public with more comprehensive information on water quality, and is constantly applicable across the globe. International institutions can use this new scale, which combines the CWQI and MWQI scales to provide a total rating of chemical and microbial contamination, to rate and monitor the quality of water resources in all countries, and to evaluate the efforts made by those countries to safeguard and clean up their water resources. A summary of the comparisons between the new models and adapted WQIs is shown in Table 9.

Table 9. Comparison table among adapted WQIs and the new approach WQI models.

Metrics of Comparison	Adapted WQIs	The DEA Model	UWQI	Surrogate WQI	Hounsinou Scale
1. Parameter selection	Researchers' discretion	Value observation	Expert opinion	Delphi technique multivariate statistics	Researchers' discretion
2. No. of parameters	average: 14	10	13	4	27
3. Type of parameters	Physical, chemical, microbiological	Physical, chemical	Physical, chemical	Physical, chemical	Physical, chemical, microbiological
4. Index development steps	Parameter selection, the establishment of parameter weights, the formation of sub-indices and the final aggregation function	Creation of input variables, classification to obtain optimistic closeness values, Banker Charnes Cooper, (BCC) model with a single output, WQI	Parameter selection, the establishment of weight coefficients, formation of sub-indices and aggregation formula	Delphi method, PCA, Hierarchical Cluster Analysis (HCA), Multivariate Regression Analysis (MRA), Regression model	Parameter selection, the establishment of parameter weights, formation of sub-indices and the final aggregation function
5. Index aggregation function	Weighted Arithmetic function $WQI = \sum \frac{QnWn}{Wn}$	$WQI = E^*_{dd}$	Modified weighted sum to to Final UWQI function $WQI = \frac{1}{100}[\sum_{i=0}^{n} siwi]^2$ to $\frac{2}{3}[\sum_{i=0}^{n} siwi]^{1.0880563}$	Surrogate WQI = f(x) $= b_0 + b_1x_1 + b_2x_2 + \ldots + b_4x_4 + \varepsilon$	$CWQI = \sum \frac{QnWn}{Wn}$ $MWQI = 1/3 \ (10/9$ $TC + 20 \ FC + 1000 \ EI)$
6. Water quality standards	Sub-index development using FAO guidelines for irrigation, South African National Water Standards, etc.	Classification of each hydrochemical parameter into quality categories using WHO guidelines for drinking water, National agency for hydraulic resources, etc.	Sub-index development using South Africas water quality guidelines implemented by water and forestry depatment	-	Sub-index development usingWHO guidelines for drinking water quality
7. Index categorisation scheme	Adapted CCMEWQI-increasing categorisation scale with 5 classes Adapted WAWQI-decreasing scale with 5 classes	Sturges's rule $I = 1 + 3.322\log_{10}(K)$	Increasing categorisation scale with 5 classes, including logical linguistic descriptors	Increasing categorisation scale with 5 classes	CWQI-decreasing categorisation scale with 7 classes MWQI-decreasing categorisation scale with 8 classes

Notes: The table provides a comparison of similarities and differences between the adapted WQIs and the new models from the African perspective.

4. Future Perspectives

Given the historical adaptation and contextualisation of WQIs for African water resource management, the continent is well-aligned to develop its region-specific (North, Western, Central, Eastern, and Southern) integrated water quality monitoring indices. We believe there is a plethora of scientific data on water science research and emerging technologies in the continent from which the requisite WQPs can be obtained, harmonised, and incorporated within the index development frameworks for specific regions. An additional advantage in WQI development is facilitating access to scientific data repositories and standardisation of water quality monitoring and data processing protocols across these regions. Such a transition towards customisation of WQIs will improve Africa-based models' accuracy and predictive power while increasing confidence in interpreting water quality assessment and implementing water resource management interventions.

5. Conclusions

Effective water quality monitoring and management in Africa is hampered by a lack of "indigenous" or region-specific WQIs due to the long-term trend of adapting and adopting WQIs from outside the continent. We reviewed the 10-year trends in adapting WQIs for water quality monitoring in Africa to examine performance and potential for water quality monitoring in the continent.

The most commonly adapted indices for water quality monitoring in Africa were WAWQI and CCMEWQI, which exhibit a general bias towards physical and chemical parameters over biological metrics. In addition, these indices tend to suffer from abnormalities such as ambiguity, eclipsing, and rigidity, which limits their application potential.

There is a need to integrate physicochemical, biological, and hazard indicators in adapting or developing WQI for the African context to address the broad spectrum of WQP requirements. In addition, non-subjective statistical approaches could further provide uniformity in WQI model development. Nevertheless, the potential for developing Africa-derived WQIs that provide region-specific water quality status of the region's aquatic ecosystems is unlimited.

Abbreviations

AHP—Analytical Hierarchy Process, ANRH—Agence Nationale des Resources Hydrauliques, ANZECC—Australian and New Zealand Environment and Conservation Council, BCC—Banker, Charnes, and Cooper, CA—Cluster Analysis, CCME—Canadian Council Ministers of Environment, DA—Discriminant Analysis, DEA—Data Envelopment Analysis, DMU—Decision-Making Units, DWAF—Department of Water Affairs and Forestry, FA—Factor Analysis, FAO—Food and Agriculture Organisation, HCA—Hierarchical Cluster Analysis, MRA—Multivariate Regression Analysis, MWQI—Microbiological Water Quality Index, NSFW—National Sanitation Foundation, PCA—Principal Component Analysis, RWQI—Ramakrishaniah Water Quality Index, SANS—South

African National Standard, TMWQI—Tiwari & Mishra Water Quality Index, TWQR—Target Water Quality Ranges, UWQI—Universal Water Quality Index, WA—Weighted Arithmetic, WHO—World Health Organisation, WQI—Water Quality Index, WQPs—Water Quality Parameters, WRC—Water Resource Commission.

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