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Assessment of many WQI models and development of new WQI model

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ABSTRACT

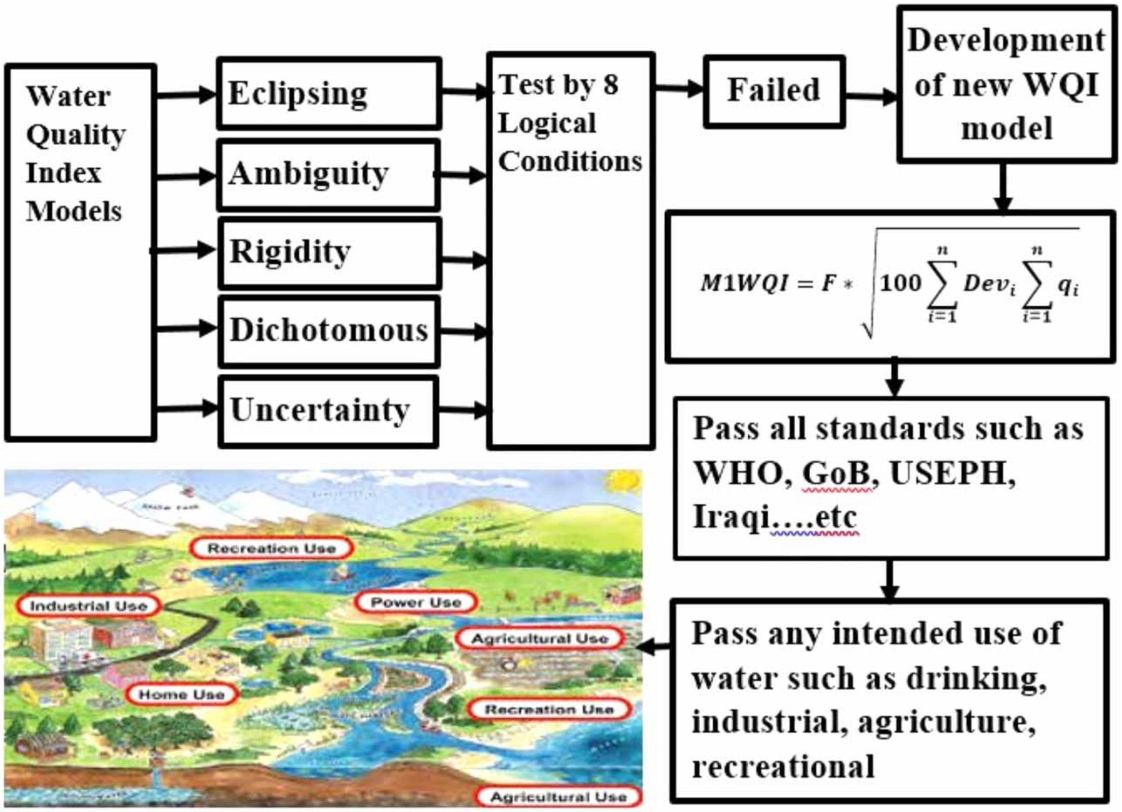
The water quality index (WQI) is widely used to assess water quality. In all WQI models, selected parameter data are transformed into many steps to a single number. Since the first model was developed in 1965, a lot of WQI models have been developed. However, all models suffer from many problems such as they are introduced based on site-specific standards for a particular region and give eclipsing, dichotomous, ambiguity, rigidity, and uncertainty problems. In the present work, an effort is made to test many of the applicable WQI models using many logical conditions. The results showed that no one of the tested models satisfies these conditions. The aim of the present work is to develop a WQI model that can be used universally (regardless of the standard used) and covers different uses of water (drinking, recreational, irrigation, or industrial). Moreover, it can overcome the previously mentioned problem. The suggested new WQI model developed in this work succeeded in achieving these two goals.

Key words: eclipsing, uncertainty, water quality, water quality index, water quality index models

HIGHLIGHT

- A new water quality index model is developed that overcomes all the problems of the previous model.

GRAPHICAL ABSTRACT



INTRODUCTION

Water pollution has become a common problem in all countries due to many reasons, such as increased population, industrial activities, and global warming. Maintenance of water resources thus becomes crucial. Thus all countries set standards for different water uses. These standards include a wide range of parameters that lead to dealing with a great number of data points. Interpretation of water quality depending on these data becomes more difficult. Thus, it is required to identify water quality by a single number to facilitate the monitoring of water quality. The water quality index (WQI) is a single dimensionless number expressing the water quality in a simple form by aggregating the measurements of selected parameters.

Since the novel work of Horton (1965), a lot of models have been developed. Brown *et al.* (1970) tried to improve the Horton model and established a more comprehensive model. Since that, more than 40 WQI models have been developed. Since the introduction of the first WQI model by Horton (1965), thousands of papers have been published concerning the assessment of water quality throughout the world employing a lot of WQI models. The most applicable models are the weighted arithmetic index model (WAWQI), CCMEWQI, and NSFWQI. A simple weighted arithmetic index model (WAWQI) has been employed by a lot of researchers (Cristina *et.al.* 2014; Al-Ani 2019; García-Ávila *et al.* 2022). NSFWQI has its applications in many areas (Wills & Irvine 1996; Hamdan *et al.* 2018; Bambang *et al.* 2022; Asma *et al.* 2023), and CCMEWQI had been used also in a lot of papers (Al-Janabi *et.al.* 2012; Ismail & Robescu 2017; Calmuc *et al.* 2020; Smajl *et al.* 2022). Other models are less widespread and have fewer applications. Abrahão *et al.* (2007) examined two indices developed by Bascarón namely Bascarón adapted water quality index (WQIBA) and the objective water quality index (WQIOBJ) to assess the water quality of a stream that receives industrial effluents from five sites in the Mussuré Stream in Joo Pessoa, in the northeast of Brazil. Kumar & Dua (2009) used the Brown water quality index (BWQI) to determine the river Ravi, an Indus River System tributary water quality. Pei-Yue *et al.* (2010) evaluated Peng Yang groundwater based on an improved WQI. This model uses a simple additive aggregation function but gives a weight for each parameter depending on an entropy weight to find WQI. Majeed (2018) compares the results of the CCMEWQI, Mierels WQI, and weighted arithmetic index for irrigation and drinking purposes. On the Bani-Hassan River, six places were picked. The WAWQI model rates the water's suitability for drinking purposes as unsuitable, but the Canadian WQI model rates it as fair. For irrigation, Meireles WQI model results showed that the water quality is rated as moderate restriction, whereas the Canadian model yields good. Călmuc *et al.* (2018) used three models to calculate WQI for the Danube River: OWQI (Oregon water quality index), WAWQI (weighted arithmetic water quality index), and CCMEWQI. Ewaid *et al.* (2020) developed the Iraqi water quality index (Iraq WQI) and used it to test the Tigris river water quality in Baghdad. Ebenezer & Yahans (2022) employed the water pollution index (WPI) developed by Hossain & Patra (2020) to assess groundwater in Ghana and compared the results with the results of the WQI model. Meseret (2022) assessed the water quality for drinking purposes using Brown *et al.* (1972) WQIs for water samples taken from 16 sources (including springs, hand-dug wells, and tap water) in Ethiopia. Hop *et al.* (2023) developed a new WQI and compared it with WQI obtained from NSFWQI, and the WQI of the Vietnam Environmental Agency (VN-WQI). Wang *et al.* (2023) developed a new WQI named as WQI-Bayesian model averaging (WQI-BMA) model based on the Bayesian model averaging (BMA) method to merge different WQI models. Water samples were collected from Shenzhen, China, and Guangdong Province. Thirty monitoring wells and 16 water quality parameters were utilized to calculate WQI employing four models namely SRDD, National Sanitation Foundation (NSF), West Java model (WJ), and water quadratic model (WQM). The results showed that WQI-BMA gives a WQI range of 35.01–98.45 (fair to good) for most of the studied samples. Liang *et al.* (2023) compared four WQI models namely CCMEWQI, NSFWQI, IWQI, and WQI Malaysia to submit suggestions to improve the accuracy and sensitivity of these models. Zhou *et al.* (2023) used 14 parameters to assess the water quality of a major city in China through four monitoring stations on the M River. These parameters were measured monthly for 10 years (2011–2020) and used to calculate WQI according to Pesce & Wunderlin (2000) model.

The steps followed in developing most of the WQI indices are the selection of parameters, generation of sub-indices, generation of parameter weights, and aggregation process (Abbasi & Abbasi 2012).

Md. Galal *et al.* (2021) reported that out of more than 35 WQI models, only 21 were employed globally (CCME and NSF models have been used in 50% out of 110 reviewed studies). They stated that there are seven basic WQI models from which most other WQI models have been developed. They presented an excellent review and discussion concerning the source of the problems incorporated in the development of WQI models.

Arief *et al.* (2016) stated that, since the 1960s, WQIs have been used as a tool to evaluate the status of water quality. WQI models can monitor the changes in water quality at any particular location and time in a simple and easily understandable manner. Although many WQIs have been developed, there is no universally accepted method for implementing the steps used for developing a WQI. Thus, there is a continuing interest in developing accurate WQIs that suit a local or regional area. They also stated that there is no worldwide accepted method for constructing a WQI and there is no method by which 100% objectivity or accuracy can be achieved in the development of a WQI. Each step in the development of WQI may be a source of problems thus, rigidity, eclipsing, and ambiguity will always be a challenge in the development of a WQI. Moreover, they stated that uncertainty and sensitivity analysis was rarely undertaken to minimize the uncertainty associated with the development of a WQI.

Moez *et al.* (2019) made an extensive review of WQI models and stated that a universal WQI cannot be defined. Van Helmond & Breukel (1997) tested 30 WQI models and found that when using different WQIs to check a given database, disagreements appeared in three situations which are: (1) for the same WQI used but the limits of classes differ, (2) different classifications appeared based on same variables for different WQIs, and (3) different WQIs are used based on different types or numbers of variables.

Al Yousif & Ali (2023) reported a review of the most applicable drinking and irrigation WQIs. They submitted the history, development, application, and, most importantly, advantages. The studied indices are NSFWQI, CCMEWQI, OWQI, and weighted arithmetic WAWQI concerning drinking purposes, while for irrigation purposes models are: irrigation water quality index (WQIFIR), sodium absorption ratio (SAR), Kelly's index (KI), sodium percentage (Na%) or (SSP), and permeability index (PI).

Dorothy *et al.* (2023) reviewed 42 articles from five databases during 2012–2022, covering 12 African countries, and stated that the Weighted Arithmetic Water Quality Index (WAWQI) and the Canadian Council of Ministers of Environment (CCME) were the most applied models which suffer from many problems such as they bias toward physical and chemical parameters over biological metrics, ambiguity, eclipsing, and rigidity.

Lazarus *et al.* (2023) stated that all WQIs suffered from many problems concerning accuracy, robustness, reliability, and wide acceptability. These models involved several subjective methods such as the Delphi technique and expert opinions in the development stages, especially parameter selection which are the source of uncertainty and low model acceptability.

Sandra *et al.* (2023) made extensive review of the available WQI and stated that the National Sanitation Foundation Water Quality Index (NSFWQI), Canadian Council of Ministers of Environment Water Quality Index (CCMEWQI), OWQI, and WAWQI were used to reflect the rank of water quality in lakes, streams, rivers, and reservoirs. They studied the advantages and disadvantages of these indices and stated that no index can be used universally, each WQI model has its advantages and disadvantages. Thus, in developing advanced WQI, statistical, GIS, and fuzzy logic techniques have to be used.

There is no WQI model free of the well-known problems associated with any of the WQI models (eclipsing, dichotomous, ambiguity, rigidity, and uncertainty problems). This fact necessitates the development of a new model that can overcome all these problems. The innovations of the present work are the methodology applied to test WQI models depending on the logical conditions and the seven assumptions made before the formulation of the sub-index equation and weighting of the parameters.

It is worth mentioning that all of the above WQI models were developed for drinking purposes only. The above discussion indicated that all models suffer from one or more of the well-known problems associated with WQI models. These problems are eclipsing, ambiguity, rigidity, uncertainty, and sensitivity. Each problem arose from one or more steps of the four steps employed to develop the final WQI model, which are parameter selection, generation of sub-indices, weighing parameter, and aggregation. Many methodologies were employed previously to overcome each problem separately as will be discussed in the following sections. However, it seems that no one can overcome all problems. Bhargava (1985) set five logical conditions that must be fulfilled by any WQI model to overcome these problems but he did not test any model by these logical conditions.

The novel idea of the present work is to apply Bhargava's five logical conditions with another three conditions set by us to test 16 WQI models (some of them are the most widely applicable). To develop a universal model that can be applied for any purpose (drinking, industrial, agriculture, and recreational) and all standards such as WHO, GoB, USEPH, etc., a novel idea is to set seven assumptions that must be satisfied when establishing a sub-index formula that allows the parameter weight to depend on how far it is from the standard value, i.e. when the parameter value is equal to the standard value, the weight will be zero and it increases as the deviation increased. This formulation will overcome all problems except the uncertainty problem which is overcome by a factor **F** that is introduced in the developed model for the first time. Since WQI calculated using the developed model reflects how the water is far from the standard values of the parameters employed, this approach allows the developed model to be used for all purposes of water use regardless of the standard followed, just set the required use standard according to any standard then calculate the WQI. The present approach is made for the first time.

In the following sections, the four steps followed in developing any WQI model with the problems arising in each step with the methodologies used to overcome these problems are presented. Then, testing 16 WQI models is explained followed by the development of new models. Finally, discussion and conclusions are presented.

The present work aims to test many WQI models (some of them are the most widely applicable) through the use of many proposed logical criteria that have to be satisfied by any model. Moreover, to develop a new model that satisfies these criteria and can be used universally for any purpose of water use.

SELECTION OF PARAMETERS

The number of parameters used in WQI models differs greatly ranging from 4 (Ross 1977) to 26 (Dojlido *et al.* 1994). Three systems are followed to accomplish this step and they are as follows.

Fixed systems

These are used by Brown *et al.* (1972), SRDD (1976), Dunnette (1979), House (1986), Cude (2001), Department of the Environment (DoE) Malaysia (2002), Liou *et al.* (2004) and Almeida *et al.* (2012). In this system, only the selected number of parameters can be used in the final index calculation. This system enables the user to compare the water quality of different sites and locations. However, this system has a rigidity problem which is manifested when the necessity arises for additional variables to be included in an index to address specific water quality concerns (Swamee & Tyagi 2007).

Open system

A minimum number of basic parameters are selected (CCME 2001) based on their impacts on the environment (Oudin *et al.* 1999). However, some WQIs do not provide any guidelines for the selection of parameters (Harkins 1974). The user, in such a case, can select as many parameters from the list of potential parameters. This system will avoid rigidity (Swamee & Tyagi 2007).

Mixed system

Basic and additional parameters are selected in this system. Additional parameters are used only if one of the additional parameters has a greater sub-index value than the aggregated index value based on the basic parameters. Thus, WQI should be recalculated by adding those additional parameters (Dojlido *et al.* 1994).

The goal of parameter selection is to select parameters having the largest influence on water quality. However, Abbasi & Abbasi (2012) mentioned that there is no method to remove completely the subjectivity problems. The initial set of parameters should be based on a literature review (Pesce & Wunderlin 2000; Said *et al.* 2004; Kannel *et al.* 2007), data availability (Cude 2001), parameters of similar properties must be excluded (Dunnette 1979), selecting parameters reflecting the overall water quality status (Dunnette 1979; Hanh *et al.* 2011), and the required use of the water body (Prati *et al.* 1971; Stoner 1978; Smith 1990; Hurley *et al.* 2012).

To eliminate subjectivity and uncertainty problems, the initial set has to be refined by employing: expert judgment and statistical methods.

Expert judgement

This method can be used by individual interviews, interactive groups, and the Delphi method (Meyer & Booker 1990). Juwana *et al.* (2012) stated that the Delphi method is the most widely used.

Statistical methods

It includes Pearson's coefficient of correlation and principal component/factor analysis (PCA/PFA). Pearson's coefficient of correlation is used to reduce the number of parameters by eliminating some parameters that are highly correlated with others. However, principal component/principal factor analysis (PCA/PFA) is employed to group the parameters of similar characteristics (Liou *et al.* 2004; Hanh *et al.* 2011) and to reduce the number of parameters.

GENERATION OF SUB-INDICES

This step is used to transform the water quality parameters into a common scale because the values of the parameters have different values and ranges (Abbasi & Abbasi 2012). In some WQIs, the actual values of the parameters are used in the final index aggregation (CCME 2001; Said *et al.* 2004). The individual sub-indices can be further aggregated to form a bigger group of sub-indices, which are then aggregated to a final index value (often called composite or aggregated sub-indices) (Bhargava 1985; Oudin *et al.* 1999).

Generally, there are four ways to get sub-indices which are sub-index functions, rating curves, water quality standards, and statistical methods. All parameter values are defined with dimensionless values with 0–100 or 0–1. Sub-index functions or rating curves of different parameters are established using: expert judgment (Brown *et al.* 1970); the Scottish Research Development Department (SRDD) index (SRDD 1976; Dunnette 1979); House's Index (House 1986), and Almeida's Index (Almeida *et al.* 2012). Water quality standards are also used to establish sub-index (Prati *et al.* 1971; Bascarón 1979; Štambuk-Giljanović 2003; Liou *et al.* 2004). Statistical methods are also used (Dunnette 1979).

ESTABLISHING WEIGHT

Establishing weights for all parameters can be performed in two ways. Examples of models employing equal weights are (Nemerow & Sumitomo 1970; Harkins 1974; Dojlido *et al.* 1994; Oudin *et al.* 1999; CCME 2001; Cude 2001; Hallock 2002; Hanh *et al.* 2011). Equal weight is preferred because there were doubts concerning subjectivity over experts' opinions (Harkins 1974). Sensitivity in the final index toward the most heavily weighted parameter can result from unequal weights. It is preferred to get sensitivity to changes in each variable rather than sensitivity to the most heavily weighted variable (Cude 2001). To avoid subjectivity in unequal weights, it is advised to employ the Delphi method and the analytical hierarchy process (AHP) (Arief *et al.* 2016).

INDEX AGGREGATION

The most applicable aggregation methods are the additive (arithmetic) and multiplicative (geometric) methods. The first method is a widely used method for many WQIs (Brown *et al.* 1970; Prati *et al.* 1971; SRDD 1976; Ross 1977; Bascarón 1979; Dunnette 1979; Sargaonkar & Deshpande 2003). However, a modified additive method in which the aggregated function is squared and then divided by 100, is also used by many researchers (SRDD 1976; Bordalo *et al.* 2006; Carvalho *et al.* 2011).

The additive method is a simple aggregation method but creates an eclipsing problem because the final index value does not represent the actual state of overall water quality. In such a case, sub-indices may be dominated by the higher values of other sub-indices or vice versa (Swamee & Tyagi 2007; Liou *et al.* 2004; Juwana *et al.* 2012). Smith (1990) mentioned that this method would never give a zero value of the final index albeit one of the sub-indices is 0.

The multiplicative method which is proposed by Brown *et al.* (1973) was applied in many WQIs (Walski & Parker 1974; SRDD 1976; Bhargava 1985; Dinius 1987; Almeida *et al.* 2012). This method also suffers from the eclipsing problem (Smith 1990; Swamee & Tyagi 2007; Juwana *et al.* 2012). Another ambiguity arises when the parameter weight is very low (close to 0), it will give a sub-index value close to 1. This case is called the dichotomous sub-index problem (Ott 1978; Liou *et al.* 2004). To overcome eclipsing and ambiguity problems, Smith (1990) suggested a minimum operator aggregate sub-indices. Swamee & Tyagi (2007) stated that this method fails to provide a composite picture of overall water quality.

Dojlido *et al.* (1994) proposed a harmonic mean of squares method to aggregate sub-indices to overcome eclipsing problems. Cude (2001) stated that in this method, parameters of low quality will have a larger effect on the WQIBA and stated that different parameters will pose different significance to the overall water quality at different times and locations. Another problem is mentioned by Swamee & Tyagi (2007) who explained that this method has an ambiguity problem.

Another trial was proposed by Liou *et al.* (2004) to overcome eclipsing and ambiguity problems. They used a mixed aggregation method. In this method, parameters are first divided into three groups, and the geometric mean method is employed to aggregate the three sub-indices.

CCME WQI (CCME 2001) developed a new method to overcome these problems. In this method, three factors are calculated. These three factors are scope (F1), frequency (F2), and amplitude (F3). However, this method still suffers from a problem. The scope F1 does not work appropriately when too few parameters are used or when too much covariance exists among them (Tyagi *et al.* 2013).

According to the above presentation, no WQI model can be used universally for all intended water use. This is because of the methodology followed by these models to get the final WQI model, especially in the sub-index equation and final aggregation step. Moreover, some of them are rigid. Therefore, the development of such a model is crucial. The present work aims to develop a universal WQI that can be used with any standard such as WHO, GoB, or USEPH for any intended water use such as drinking, recreational, irrigation, or industrial.

DEVELOPMENT OF NEW WQI MODEL (M1WQI)

The present work approach to solving the problems of all WQI models is unprecedented since it differs from the approaches of the preceding models. The novel idea is to set conditions that enable solving all problems. After setting these conditions, the sub-index equation is formulated such that it gives zero for any parameter when its actual value is equal to the standard value. It is worth mentioning that the sub-index value for each parameter does not depend on the numerical value, it depends on the ratio between the actual and standard value. This will eliminate any problems that arise from the very low standard value for certain parameters (0.001 mg/L for certain metals) and the very high values such as 1,500 for EC. Then, to give a weight for each parameter, the parameter is weighting itself (Equation (3)) so that its weight is increased with the increase of its deviation from the standard value. Another difference is through the introduction of a factor **F** for the first time to overcome the uncertainty problems as will be explained later.

To develop a new model, the following assumptions are made which must be satisfied by any model to ensure that this model is free of any problems:

(1) If only one parameter exceeds the standard limit (except DO when it is lower than the standard limit), it must be reflected in the WQI value, i.e. if all parameters are at their standard values except $pH = 10$ for example, it must be classified as unfit for drinking.
(2) Any parameter that deviates from standard value, must add to WQI values toward worse conditions.

(3) Any parameter(s) that stay at their standard values must not affect the WQI value (add zero).
(4) pH values lower or higher than the standard limit must add to worse conditions.
(5) Any parameter whose value is below standard must not improve the WQI value, it should be excluded from the calculations.
(6) Since unequal weight results in eclipsing problems, therefore parameter weight must be represented by its deviation from the standard.
(7) Sub-index for each parameter must reflect how far is that parameter from the standard value, when it is at the standard value, the sub-index must be zero.

It is obvious that all WQIBA models suffer from subjectivity, rigidity, ambiguity, eclipsing, and uncertainty problems. These problems arose from the four steps of developing any WQI model. In order to overcome these problems in the suggested model (M1WQI), it is allowed to select any number of parameters. Moreover, it is also able to include or exclude any parameter. In the present model weight given to any parameter reflects how far is that parameter from the standard value. In formulating the sub-index values (Equation (3)), the proposed equation gives zero for any parameter sub-index when its value is equal to the standard. Equation (2) is applied for DO and pH values lower than the standard values. The problems encountered in the aggregation step are eliminated through Equation (4) which allows the final WQI value to reflect cumulatively how far the water is beyond the standard. This means that any parameter that exceeds the standard limit will add to worse quality.

$$\mathrm{Dev}_i = \frac{Va_i}{Vs_i} - 1 \tag{1}$$

$$\mathrm{Dev}_i = 1 - \frac{Va_i}{Vs_i} \tag{2}$$

$$q_i = \frac{e^{\mathrm{Dev}_i} - 1}{\sum_{1}^{n} (e^{\mathrm{Dev}_i} - 1)} \tag{3}$$

$$\mathrm{M1WQI} = \sqrt{100 \sum_{i=1}^{n} \mathrm{Dev}_i \sum_{i=1}^{n} q_i} \tag{4}$$

where Dev_i is the deviation from the standard value. Va_i is the actual value of a parameter; Vs_i is the standard value of a parameter. q_i is the sub-index value of the ith parameter; i is the parameter number.

To prepare the grading table, values of any of the 26 parameters that will give the key values 2, 4, 6, 8, and 10 are calculated and given in Table 1. Depending on the results of Table 1, the grades very good, good, and so on are given as shown in Table 2.

The number of parameters used in the WQI model ranged from 4 (Ross 1977) to 26 (Dojlido *et al.* 1994) and it is reported that the problem of uncertainty arose from the parameter selection step. To overcome this problem, a factor ***F*** (Equation (5) and Figure 1) is suggested for the first time in the present work. To prepare this equation, two steps are followed; in the first step, WQI is calculated using 26 parameters with a deviation percent of 10, 30, and 50%. Then in the second step, the same is made employing 5, 10, 15, and 20 parameters successively. The ratio between the results of the second step to that of the first step is graphed in Figure 1 against the number of parameters. ***F*** factor can be found in Figure 1 or using the following equation.

$$\boldsymbol{F} = 5.1757\, \boldsymbol{n}^{-0.505} \tag{5}$$

where n is the number of parameters used in the calculation of WQI.

To check the applicability of ***F***, calculations of WQI are made using only 5, 10, 15, 20, and 26 parameters successively. The obtained results are multiplied by the ***F*** factor obtained from Equation (5) or Figure 1. These data are graphed versus actual data in Figure 2 which indicates that there is excellent agreement.

Table 1 | Data for the developed model (M1WQI)

Key table value	pH	TDS	EC	DO	BOD	COD	SS	TUR	Cl	K	Ca	Mg	NH4
	A parameter value that gives the key table value												
2	7.2, 7.8	1,560	2,080	4.8	5.2	10.4	124.8	5.2	364	10.4	208	156	0.416
4	6.3, 8.7	1,740	2,320	4.2	5.8	11.6	139.2	5.8	406	11.6	232	174	0.464
6	4.8, 10.2	2,040	2,720	3.2	6.8	13.6	163.2	6.8	476	13.6	272	204	0.544
8	2.7, 12.3	2,460	3,280	1.8	8.2	16.4	196.8	8.2	574	16.4	328	246	0.656
9	1.4, 13.6	2,715	3,620	0.95	9.05	18.1	217.2	9.05	633.5	18.1	362	271.5	0.724
10		3,000	4,000	0.001	10	20	240	10	700	20	400	300	0.8
	HCO_3	NO_3	SO_4	PO_4	Cu	Zn	Fe	TEMP	ALK	HARD	PHENOL	Cd	Pb
2	124.8	52	416	0.42	1.56	15.6	1.04	26	208	520	0.0021	0.0031	0.052
4	139.2	58	464	0.47	1.75	17.5	1.16	29	232	580	0.0023	0.0035	0.058
6	163.2	68	544	0.55	2.05	20.5	1.36	34	272	680	0.0027	0.0041	0.068
8	196.8	82	656	0.66	2.46	24.6	1.65	41	328	820	0.0033	0.0049	0.082
9	217.2	90.5	724	0.73	2.72	272	1.81	45.5	362	905	0.0036	0.0054	0.091
10	240	100	800	0.8	3	30	2	50	400	1,000	0.004	0.006	0.1

TDS, total dissolved solids; EC, electrical conductivity; DO, dissolved oxygen; BOD, biological oxygen demand; COD, chemical oxygen demand; SS, suspended solids; TUR, turbidity

Table 2 | Grades of water quality for M1WQI

Quality	WQI
Very good	$0 < WQI \leq 2$
Good	$2 < WQI \leq 4$
Poor	$4 < WQI \leq 6$
Very poor	$6 < WQI \leq 8$
Unfit	$WQI > 8$

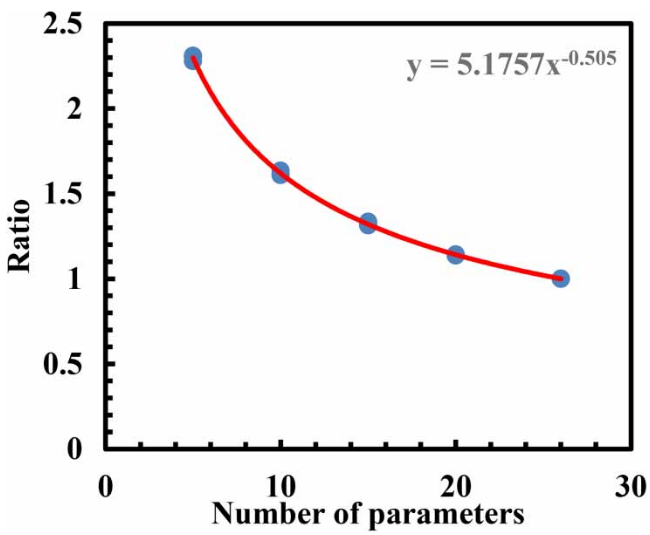


Figure 1 | Relation between the ratio and parameters number.

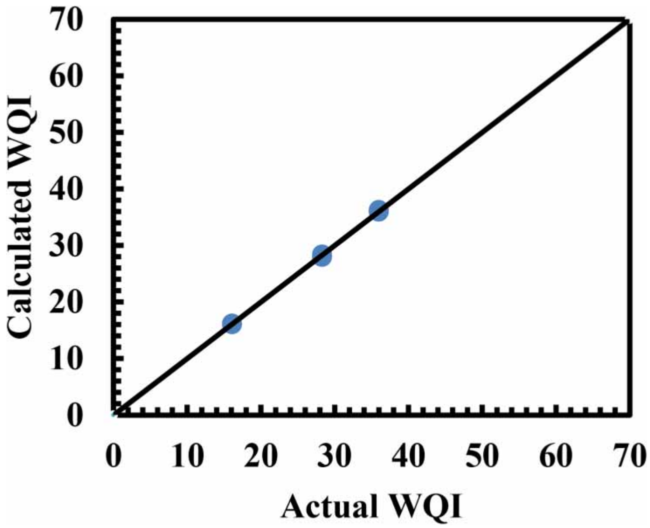


Figure 2 | Calculated versus actual WQI for our model.

Since in the present developed model, the weight and sub-index values depend on how far is the parameter beyond a certain standard, this model can be applied universally and for any intended purpose of water use regardless of the standard used.

TEST OF MANY WQI MODELS

Bhargava (1985) stated that in order to overcome the problems associated with any WQI model, five conditions must be satisfied. However, depending on the above discussion and Bhargava (1985) conditions, eight conditions are set in the present work which must be satisfied by any WQI to overcome all problems and to be used universally for all intended water use. These conditions are:

(1) The WQI value should converge to 0 or 100 when all parameter values fit with any of the standard values.
(2) WQI value should be sensitive to the change of parameter value, i.e. give appreciable change in WQI values with the variation of parameter/parameters values.
(3) WQI should be increased or decreased continuously (depending on the model type whether it is of increasing or descending type) with the increase of parameter/parameters value.
(4) The WQI model should be flexible, i.e. can include or exclude one parameter or more.
(5) When one or more parameters are below the standard value (dissolved oxygen higher than the standard value), it must not improve the WQI or worsen it). Note that pH must worsen WQI whether it is lower or higher than the standard value.
(6) WQI should depend only on the parameters that exceed the standard value, i.e. if other parameter values are equal to their standard values, WQI should be not affected.
(7) WQI should give always positive values and exclude any negative values.
(8) For the same deviation of parameter(s) values from the standard values, WQI should give the same value regardless of a standard type such as WHO, Indian, Iraqi, and so on.

The tested models are Bascaron, Brown, BCWQI, CCME, Dinius, DoE, Hossain, Horton, Iraqi, NSF, NWQI, Oregon, Ramakrishna, Ravindhranath, SRDD, and TMWQI models. Iraqi standard is used in the calculations of WQI. Samples of the results are presented in Figures 3–15.

It is worth mentioning that all WQI models, as their authors stated, converge to 0 or 100 when all parameters are set equal to a given standard such as WHO, Indian, and so on. However, when the Iraqi standard is used, only BCWQI, CCME, Hossain, Ravindhranath, TMWQI, and our developed model (MIWQI) satisfy condition No.1. Figures 3–5 represent a sample of a comparison between the results of the newly developed model with a selected two models (Bascaron and CCME models)

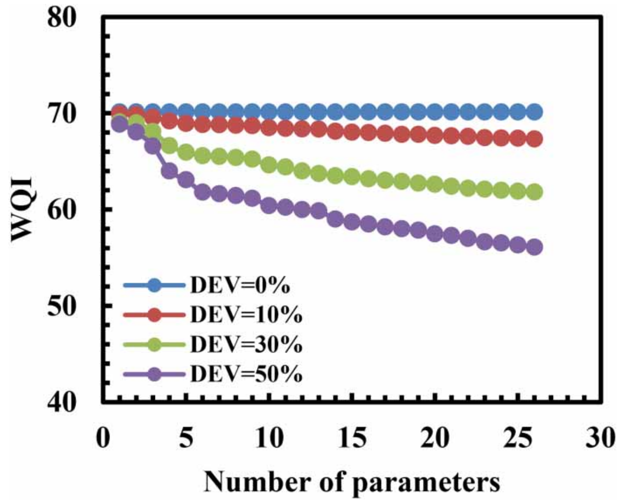


Figure 3 | Effect of parameter number on WQI for different deviation%, Bascarón.

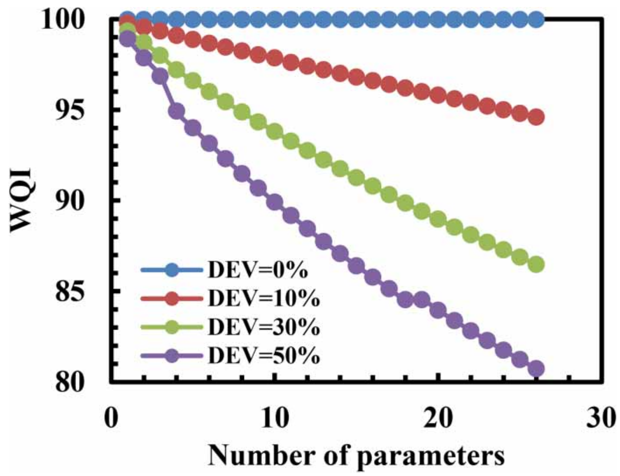


Figure 4 | Effect of parameter numbers on WQI for different deviation%, CCME.

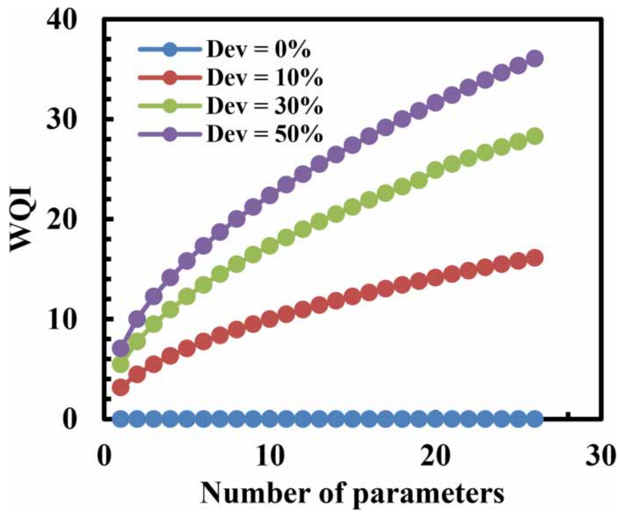


Figure 5 | Effect of parameter numbers on WQI for different deviation%, M1WQI.

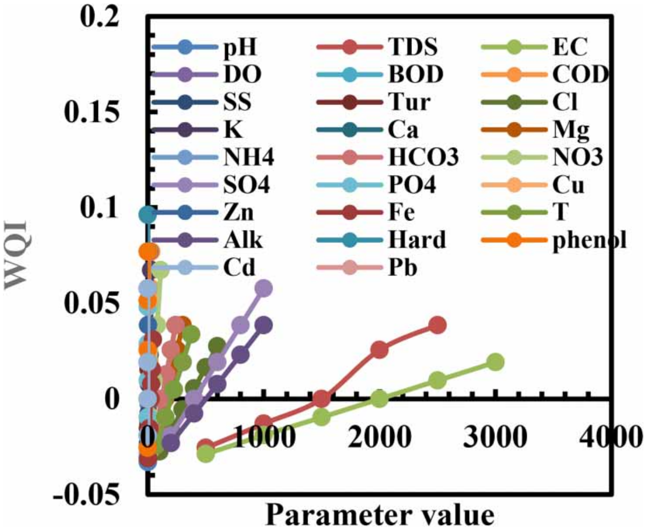


Figure 6 | Effect of parameter values on WQI, Hossain.

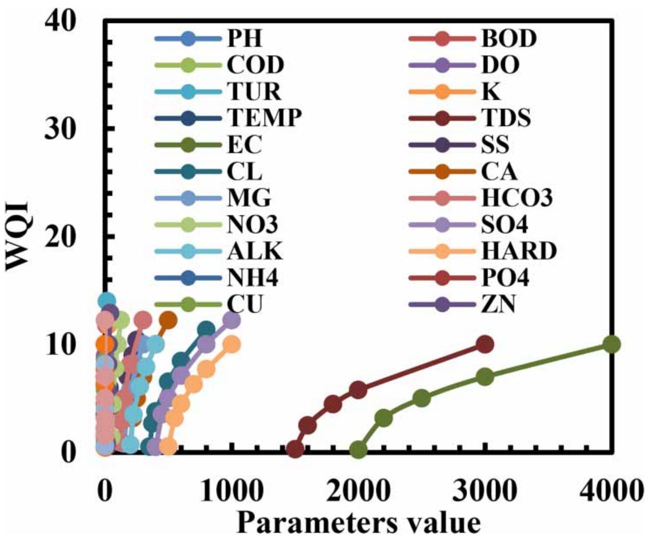


Figure 7 | Effect of parameter values on WQI, M1WQI.

concerning the effect of the number of parameters on WQI. These figures indicated that CCME satisfies condition No. 1 while the Bascaron model does not satisfy it.

The results show that all models are sensitive to parameter values; however, the sensitivity differs appreciably within the same model and from one model to another. Figures 6–8 represent a sample of a comparison between the results of the newly developed model with that of Hossain and TMWQI concerning the effect of parameter value on WQI. It is found that only the TMWQI model gives a very low change in WQI values until the parameter number reaches 23. Thus, all models considered fit condition number 2 except the TMWQI model. Figures 3–8 show that the value of WQI increases or decreases with the increase of the number of parameters and the extent to which they move away from the standard value (condition 3 is satisfied).

It is found that only BCWQI, CCME, Hossain, TMWQI, and M1WQI are flexible models (i.e. condition 4 is satisfied).

Table 3 includes two values for each WQI model, the first is calculated when all parameters are at the standard value and the second when only one parameter is less than the standard value. These results clarify that only the M1WQI model satisfies condition 5.

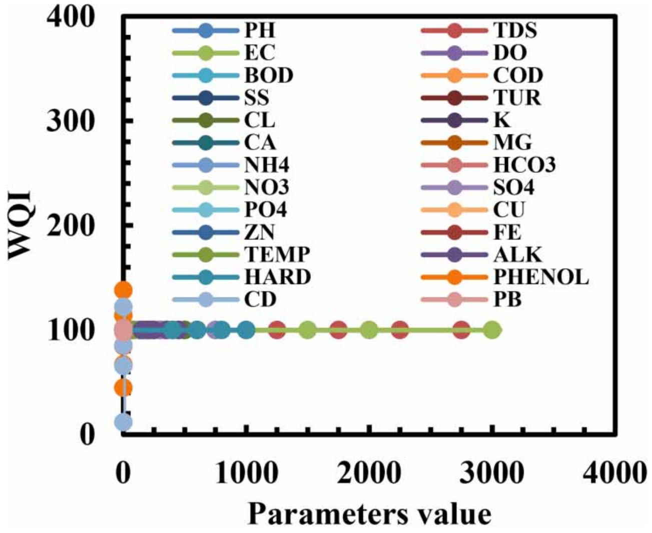


Figure 8 | Effect of parameter values on WQI, TMWQI.

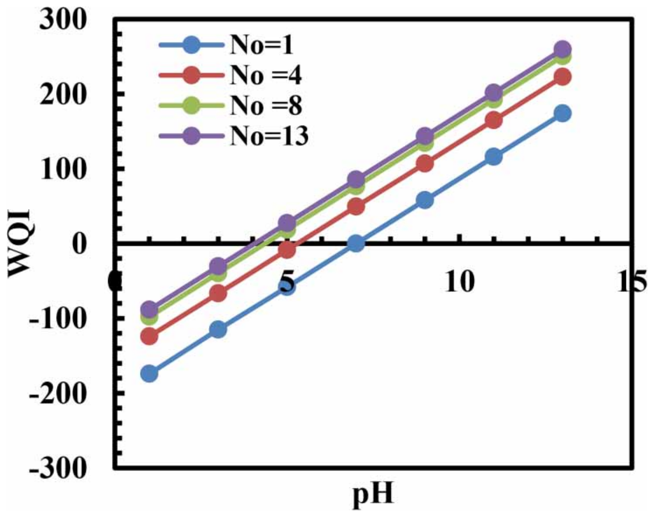


Figure 9 | Effect of pH on WQI for different parameter numbers, Brown.

Figures 9–13 represent a sample of a comparison between the results of the newly developed model with that of Brown, Hossain, NSF, and Ramakrishnia models concerning the effect of pH on WQI. These figures show the performance of WQI when changing the number of parameters from 1 to 26, all at their standard values except for one parameter where its values are changed within a specific range. These figures show that WQI is highly dependent on the number of parameters unless their values are at standard conditions (all models except M1WQI disobey condition No. 6). It is also found that Brown, Hoaasin, Ramakrishna, and Ravindhranath models have a direct proportionality between WQI and pH values (the first three models give some negative values of WQI, disobeying conditions 7).

Figure 14 shows a comparison of the newly developed model with the 16 models tested in the present work. These figures show the WQI values for all models calculated at the standard values using Iraqi, GoB, WHO, and USEPH standards. These Figures indicated that WQI values for Bascaron, Brown Dinius, DoE, Horton, Iraqi, NWQI, NSF, and Oregon models varied as the standard is varied (condition 8 is not satisfied). Figure 15 represents the performance of M1WQI with various

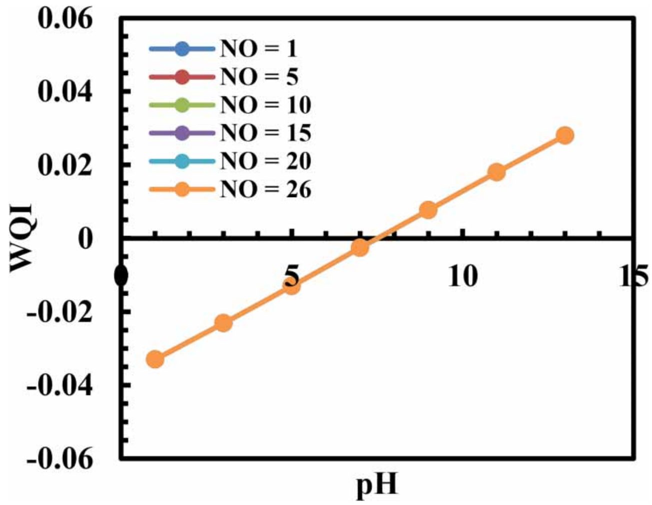


Figure 10 | Effect of pH on WQI for different parameter numbers, Hossain.

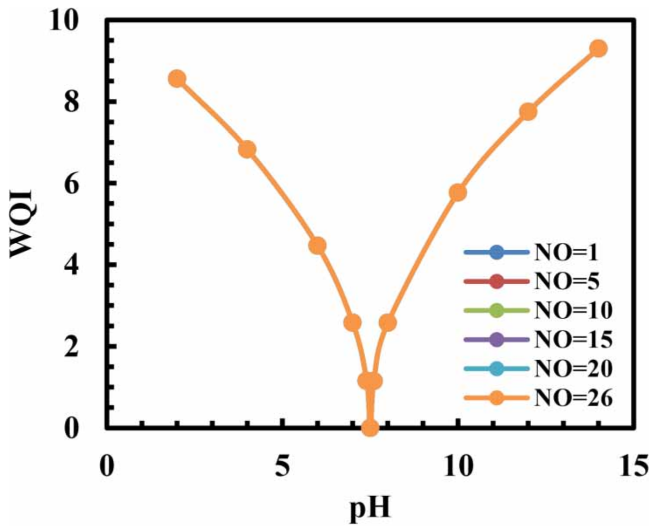


Figure 11 | Effect of pH on WQI for different parameter numbers, M1WQI.

standards. It is found that our developed model gives the same WQI values irrespective of the standard used (condition 8 is satisfied).

Table 4 contains the summary that shows that M1WQI is the only model that has passed all the necessary conditions. This means the M1WQI model can be employed globally irrespective of standards, such as WHO, GoB, USEPH, and so on, and for any intended water use, such as drinking, irrigation, recreational, industrial, and so on.

DISCUSSION

The results of the present work (Table 4) indicated that all tested WQI models are suffering from the well-known problems of WQI models. These problems are rigidity, subjectivity, ambiguity, eclipsing, and uncertainty that result from all steps followed in developing any WQI model. However, the severity of these problems differs from one model to another. Moreover, a comparison of the results of the present work with that of the previous works (Abrahão *et al.* 2007; Singh & Kamal 2014; Majeed 2018; Ebenezer & Yahans 2022; Mariana & Arini 2022; Hop *et al.* 2023; Liang *et al.* 2023; Wang *et al.* 2023) indicated that

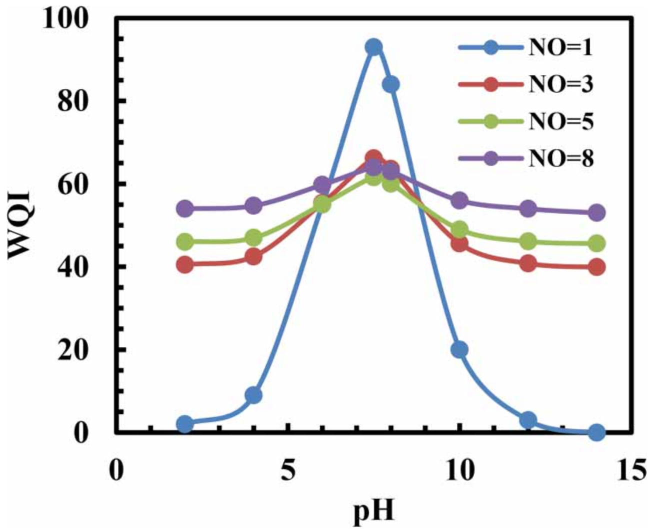


Figure 12 | Effect of pH on WQI for different parameters number, NSF.

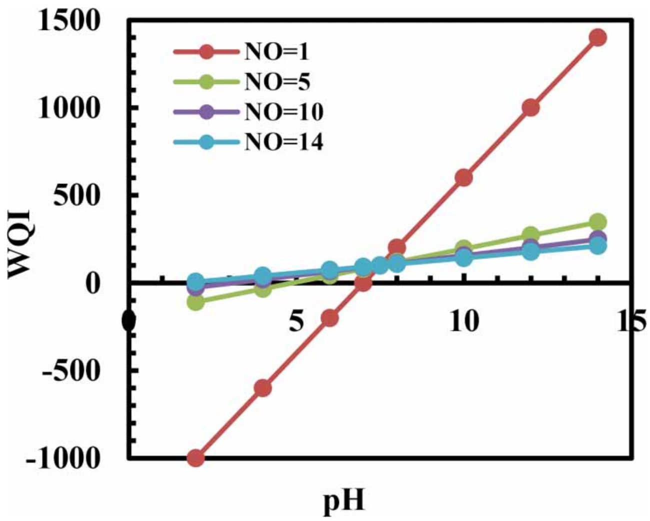


Figure 13 | Effect of pH on WQI for different parameter numbers, Ramakrishna.

they are in excellent agreement. Careful inspection of Figures 3–14 indicated that, for the same data set, different models give different WQI values and rating categories. This finding agrees well with the results of the previous works in which WQI is calculated for the same set of data using many models. The results of these studies indicated each WQI gives a different value for WQI, and water quality for the same data set falls into different rating category.

A lot of researchers confirmed that no WQI model can be used globally and for all purposes (Van Helmond & Breukel 1997; Arief *et al.* 2016; Moez *et al.* 2019; Lazarus *et al.* 2023; Sandra *et al.* 2023).

The novelty of the present work is the development of a new WQIBA model (M1WQI) that overcomes all problems encountered in the previous models. This new model can be used globally, i.e. in all countries regardless of the standard used. Moreover, it can be used for any intended use of water, such as drinking, recreational, irrigation, or industrial. This is because the model is designed to reflect how far the water quality is beyond any standard.

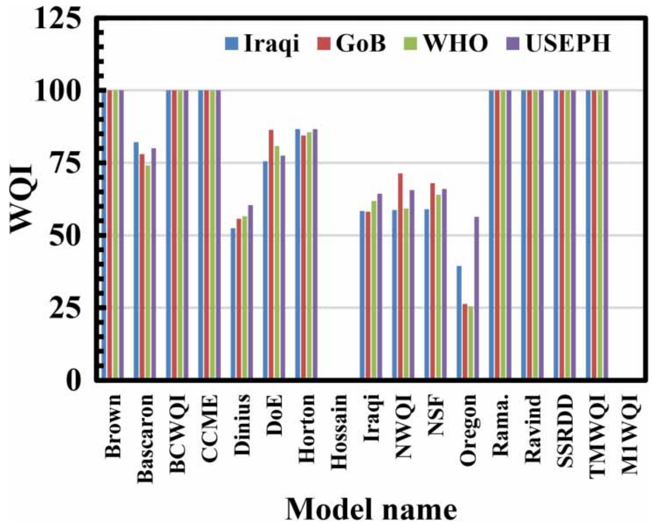


Figure 14 | Performance of the tested models with different standards, deviation% = 0.

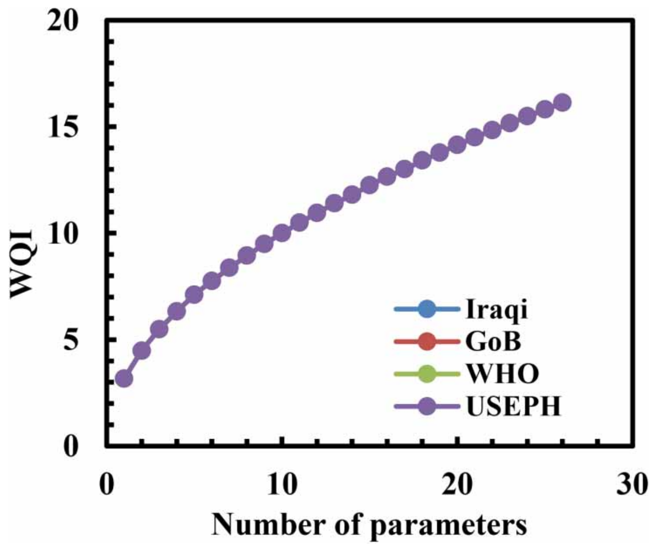


Figure 15 | Effect of parameter numbers on WQI for different standards on WQI for our model, (deviation% = 10%).

Table 3 | Calculated WQI values when all parameters are at their standard and that calculated when only BOD or DO or COD is not at their standard

	WQI value for								
Model name	**Bascaron**	**BCWQI**	**Brown**	**CCME**	**DINIUS**	**DOE**	**Horton[a]**	**Hossain**	**Iraqi[b]**
Standard	72.32	99	100	99.18	56.4	75.52	83.33	0	64.5
BOD = 2 mg/L	71.77	98.89	85.213	98.41	54	78.38	87.8	−0.0231	69.2
Model name	**NSF**	**NWQI**	**Oregon**	**Ramakrishna**	**Ravindhranath[a]**	**SRDD**	**TMWQI**	**M1WQI**	
Standard	59.1	81	25.7	100	99.75	100	100	0	
BOD = 2 mg/L	63.1	82.4	26.3	96.15	96.4	82.81	99.96	0	

[a]DO = 8 mg/L.
[b]COD = 2 mg/L.

Table 4 | Summary of the test results

Condition No.	Bascaron	BCWQI	Brown	CCME	DINIUS	DOE	Horton	Hossain	Iraqi
1	No	Yes	No	Yes	No	No	No	Yes	No
2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4	No	Yes	No	Yes	No	No	No	Yes	No
5	No	No	No	No	No	No	No	No	No
6	No	No	No	No	No	No	No	No	No
7	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
8	No	Yes	No	Yes	No	No	No	Yes	No
Condition No.	**NSF**	**NWQI**	**Oregon**	**Ramakrishna**	**Ravindhranath**	**SRDD**	**TMWQI**	**M1WQI**	
1	No	No	No	No	Yes	No	Yes	Yes	
2	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	
3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
4	No	No	No	No	No	No	Yes	Yes	
5	No	No	No	No	No	No	No	Yes	
6	No	No	No	No	No	No	No	Yes	
7	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
8	No	No	No	No	Yes	No	Yes	Yes	

It is worth mentioning that selecting a limited parameter number has the advantage of reducing the cost and efforts required to assess water quality but this will lead to giving a picture that does not reflect the actual state of water quality, i.e. may give a good grade for water quality whereas it is poor since there is a great probability for the presence of other parameters exceed the permissible limit that is not included in the WQI calculation. On the other hand, selecting a large number of parameters has many disadvantages such as high cost and a lack of necessary laboratory equipment and specialists. This shortcoming is also eliminated by the developed model since it enables the calculation of WQI as if 26 parameters were included when actually only 5, 10, 15, or 20 parameters are employed.

CONCLUSIONS

The results indicated that all tested models suffer from the well-known WQI indices problems. None of these models can pass all of the logical conditions set by Bhargava (1985) and our suggested conditions. For example, BCWQI, CCME, and Hossain models failed to satisfy two of the logical conditions while TMWQI failed to satisfy three of the logical conditions and the Brown model failed to satisfy five of the logical conditions. This finding indicated that all of these models still suffer from one or more problems. Thus, there is a need for a universal model that can be applied to all countries regardless of the standard used. The utilized methodology applied to test many WQI models and to develop a new model is performed for the first time in the present work. The developed model can overcome all of these problems since the sub-index equation enables the exclusion of any parameter within the standard limit and the weight of each parameter depends on how far it is beyond the standard value. Moreover, the sub-index equation enables the sub-index value to be dependent on the ratio of the actual to standard value. This will eliminate the problems of the variations of the standard values of the parameters (for example, 0.001 for certain parameters to 1,500 for another parameter). The uncertainty problem encountered during parameter selection is also overcome through a suggested **F** factor. Since the calculated WQI using the developed model depends only on the deviation of the parameters from their standard values, the developed model can be applied universally regardless of standard (WHO, India, Jordan, and so on) and for any purpose (drinking, recreational, irrigation, industrial, and so on). The scientific value of the present work is the development of the new WQI model that overcomes all problems and hence it can be applied universally for all intended uses of water. This will also eliminate the effort required in all countries to study the previously available model and to decide which model is more suitable for the case at hand.

DATA

Full data of the present work are available at https://data.mendeley.com/drafts/mp5shwb237

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories, available at https://data.mendeley.com/datasets/mp5shwb237/1.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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