Evaluation of different WQI methods for drinking water assessment with a case study of groundwater from Vizianagaram District, AP, India.

Abstract

Application of Water Quality Index (WQI) to assess the water quality for drinking water suitability and intensity of contamination is in practice worldwide. Many WQI methods have been in use since their conceptualization, and some are country-specific or use-specific. A generalized and widely acceptable method that can project ground truths in non-dimensional numerical form to evaluate the water quality, especially for drinking uses, is lacking. Complexity and disagreement among different methods are adding to incongruence among the scientists. The concept and a simple calculation method WQI are deliberated. Five different WQI methods using water chemistry results of Vizianagarm District are discussed. The WQI output obtained from these methods displays discrepancies in the proper projection of water quality. Some samples show similarities in WQI values obtained from two to four methods. However, the suitability status of water for drinking purposes could not be precisely ascertained from these indices. Since the water chemistry results and WQI values are incompatible, the output from these methods could be red herring. Few issues are identified among the studied methods which need improvisation. The use of ideal value in the weighted arithmetic index method and arbitration in assigning Weight for each parameter gives scope for speculation. Non-uniformity in the categorization of water and the suitability statuses of drinking water are discouraging factors. The WQI is an effective tool in screening the vast database for identifying and addressing the issues in water quality. Since drinking water standards and water supply are government-sponsored, an institutional intervention is required to standardize the WQI computation procedure. Such an initiative is necessary for the practical application of water quality data to contain water-borne diseases.

Keywords: Drinking water specifications; Parameter; Water chemistry; Weightage; Sub-index; Normalization;

Introduction

Water quality assessment has become an integral part of water resource studies. It is slowly evolving as a specialized subject, and researchers across the globe are focusing on these topics.

New challenges in this domain are emerging due to rapid water quality deterioration and detection of unknown elements or toxic synthetic compounds. In addition, advances in analytical chemistry and diagnostic techniques in medical sciences could link certain carcinogenic diseases to water contamination. Regular or more frequent water quality monitoring of drinking water sources is gaining ground rapidly by including additional parameters and observation points. In this process, voluminous water chemistry data is generated periodically. Many countries are adopting different water quality index methods for early detection of unsuitable or contaminated water sources, which help in prioritizing the remedial and preventive measures. In general, the method involves synthesizing a numerical value using water analysis results, standard or threshold values, and assigning Weight to each tested parameter. Some of the WQI methods formulated by several national and international organizations are Weight Arithmetic Water Quality Index (WAWQI), National Sanitation Foundation Water Quality Index (NSFWQI), Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI), Oregon Water Quality Index (OWQI). In addition, several countries have begun developing composite indices of water quality to describe the state of their domestic waters (Iuliana Paun 2016). Some examples rea America (Cude 2001), Taiwan (Liou et al. 2004), Argentina (Pesce and Wunderlin 2000), Australia (ISC 2005), Canada (Khan et al.2003; Lumb et al. 2006; CMME 2001), and New Zealand (Smith 1989, 1990).

The concept of indexing water quality measurements by determining a dimension-less digit to define the chemical load was in practice for a century, and it was refined from time to time by different researchers and Govt. agencies. Nevertheless, rapid strides in this direction have been made in the past half a century. In 1965, Horton introduced a mathematical equation for determining a unique index number to define water quality and named it WQI (Horton 1965). Then, Brown et al. (1970 and 73) proposed a new National Sanitation Foundation Water Quality Index (NSFWQI). In later years of the 20th century, a few more researchers and Govt. agencies of different countries proposed different versions of WQI (and different names).

Nevertheless, they focused on assessing water quality for suitability to aquatic life and recreational purposes (Prati and Pesarani 1971, Inhaber, 1974; Ott 1978; Landwehr 1979; Steinhart et al., 1982; Tyson and House 1989; Smith 1990; SAFE 1995). Some researchers and countries proposed different WQIs considering a different set of parameters. Some of these indices are used worldwide (Sanjoy Shil et al., 2019). Since the year 2000, the evolution of WQI formulae and their application has taken a giant leap. The rating functions for various parameters were added, equations for water quality sub-indices were proposed, and multiple factors were considered. Furthermore, statistical tools were also applied (Cude 2001; Swamee and Tyagi 2000; Environment Canada 2005; Saeedi et al., 2010).

Though many methods are available for detraining, WQI results differ and do not display the actual status of water quality. Moez Kachroud et al. (2019), while reviewing the main WQI calculations, noted - contradictions observed in the final result when, on the same database, the WQI is calculated by different methods. Despite the continuous efforts by academicians and scientists across the globe, a widely acceptable WQI method for potable water quality assessment could not be developed. Shweta Tyagi et al. (2013) emphasized the dire need to develop a new and globally accepted "Water Quality Index" in a simplified format, which may be used at large and represent the reliable picture of water quality. Lack of universal acceptability and standardization is hampering the broad applicability of water quality indexing. However, since the different characteristics of natural waters exist, the water quality indices may be regionalized and directed to the use for which that water is intended. Therefore, there is a need for authenticated country/region and use specific WQI estimation procedures for optimum utilization of the indices in water quality assessment.

An attempt is made through this Paper to evaluate five different WQI methods with a case study. The water chemistry results of Andhra Pradesh state government observations wells of Vizianagaram district are used for determining WQI applying the five methods. The district is selected as it represents a typical Precambrian hydrogeological tertian. Srinivas Rao et al. (2020)assessed groundwater water quality for part of the district applying of Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) method. This work is initiated with the hypothesis that no two WQI methods are in agreement, and none of the methods are helpful in precisely identifying the water unsuitable for drinking purposes. It is also aimed to draw the attention of Govt. agencies and research institutions to standardize the WQI computation procedure for drinking water assessment.

Material and Methods

Study area: Vizianagaram district is one of the north-coastal districts of Andhra Pradesh. It lies between $17^o15'$ and $19^o15'$ of the northern latitude and 83^o 00' to 83^o 45' of the eastern longitude (Fig. 1). The district can be divided into two distinct natural physical divisions, plain and hilly regions. The hilly region is mainly covered with densely wooded forest and comes under the tribal tract of the district. Since it is hilly terrain, its elevation is also uneven. The plain portion of the district is a well-cultivated area. The rivers drain the district of Nagavali, Gosthani, Suvarnamukhi, Champavathi, Vegavathi, and Gomukhi, which pass through hilly regions and plains. The district's climate is characterized by high humidity all the year with oppressive summer and good seasonal rainfall. The mean daily maximum temperature is about 35^oC, and the mean minimum is 27^oC during hot weather. In the coldest months, the mean daily maximum temperature is about 28^o C, and the mean daily minimum is about 18^o C. The Normal annual rainfall for the district is 1131 mm. The district mostly gets rainfall during both the southwest and northeast monsoon seasons. The average rainfall during southwest monsoon months from June to September amounts to 71% of the annual rainfall. Northeast monsoon months from October to December constitute 11 % of the annual rainfall.

Hydrogeology: The district is mainly occupied by the Khondalite and Charnockite suite of rocks and Granite gneisses(consolidated rocks) belonging to the Achaean age. These rocks are intruded by Quartzites and capped by Laterites at a few places. Alluvial formations of the Recent to Sub-recent age occur along the flood plains of the rivers flowing through the district. Groundwater occurs under water table to semi-confined conditions in the consolidated rocks and is tapped using dug wells and bore wells down to depths ranging from 5 to 10 m and 30 to 80 m, respectively. The yields of dug wells range from 20 to 40 m^3/day, while discharge in bore wells varies from 0.5 to 5 lps (liters per second). The aquifers of Alluvial formations are exploited through shallow tube wells (Filter point wells), which range in depth from 10 to 30 m with discharge ranging from 0.5 to 5.5 lps.

Hydrochemistry: Groundwater samples were collected from 47 bore wells (Piezometers) distributed throughout the Vizianagaram district in post-monsoon 2019 (Fig. 1). These wells were exclusively developed for monitoring purposes by Andhra Pradesh State Ground Water and

Water Audit Dept. (GW&WAD). The groundwater quality parameters like pH, EC, TDS, carbonate, bicarbonate, chloride, fluoride, sulfate, nitrate, sodium, potassium, calcium, magnesium, and Total hardness (TH) were analyzed in Water Quality Level-II laboratory, Visakhapatnam, GW&WAD following the standard methods prescribed by the American Public Health Association (APHA, 2017). The pH is determined using a pH meter with a glass electrode; EC is measured using a digital EC meter of cell constant 1 $cm^{-}1$. A flame photometer is used for Na^{+}, and K^{+} determination where color produced is characteristic of respective alkali metal and has proportionate color intensity with concentration. Mg^{2+} is estimated through titration against EDTA (subtracted from Ca^{2+} titer value) with ammonia buffer and EBT indicator. Ca^{2+} is determined through titration against EDTA with NaOH buffer and ammonium purpurate indicator. Titration against HCl (molarity 0.02N) with phenolphthalein indicator is used for CO_3^{2-} and methyl orange indicator is used for HCO_3^{-}. Titration against $AgNO_3$ with potassium chromate indicator is used for Cl^{-}. F^{-} is tested using an ion-selective electrode and TISAB. SO_4^{2-} is measured with a Nephelo-turbidity meter involving barium sulfate suspension formation with barium chloride reagent. NO_3^{-} is estimated with a UV-VIS spectrophotometer. TH is calculated using the following formula (Eq No. 1), in which all parameters are taken in meq/L units. M S Excel is used for water chemistry data analysis as well as WQI calculations.

$$TH = (Ca+Mg)*50 \quad \text{Eq. No. 1}$$

WQI methods

General concept and calculation procedure

Since the concept of indexing water quality results evolved, it underwent a continuous transformation from theoretical perception to formulae. Following the tenets of original principles, researchers proposed different equations and input factors for determining the WQI. Broadly, it involves synthesizing water chemistry data with an assigned weight and ratio of parameter content and standards, resulting in an output of dimensionless numerical value for a sample. Normalized and concise outcomes in the form of digital information, which can be connected to field scenarios with ease, make the WQI an attractive option for hydrochemistry the world over. In the process of fine-tuning the WQI calculations, many methods, as well as equations, evolved. Usually, WQI is determined in three to five stages-

Stage 1: Assigning Weight (wi) to each tested parameter based on its importance in human health and relative calculating weights (Wi). In general, wi rang between 1 and 5 with ascending rate of importance in the water quality evaluation.

$$Wi=wi/\sum wi \qquad \text{Eq. No. 2}$$

E.g.

Parameter	TDS	Ca	Mg	HCO_3	NO_3	F	Sum
wi (arbitrary value)	5	3	2	1	5	4	$\sum wi = 20$
Wi ($wi/\sum wi$)	0.25	0.15	0.1	0.05	0.25	0.20	1

Stage 2: % calculation of ratio (qi) of concentration of each tested parameter (Ci) and its standard (drinking water standard or threshold value) value (Si). Si is a crucial input that would address the regional or country-specific water quality issues.

$$qi = (Ci/Si)*100 \qquad \text{Eq. No. 3}$$

E.g.

Parameter	TDS	Ca	Mg	HCO_3	NO_3	F
Concentration (Ci)	1480	72	88	270	44	0.33
Standard value (Si) BIS DWS-IS 10500: 2012 - Permissible Limit in the Absence of Alternate Source (Choose the Standards as per	2000	200	100	500	45	1.50

requirement)						
qi	74	36	88	45	97	22

Stage 3: Determination of sub-index for each parameter (SIi) which is the product of relative Weight (Wi) for each parameter and proportionate parameter (qi)

SIi=Wi*qi Eq. No. 4

E.g.

Parameter	TDS	Ca	Mg	HCO3	NO3	F	Sum (∑SIi)
Wi	0.25	0.15	0.1	0.05	0.25	0.20	
qi	74	36	88	45	97	22	
Sli	18.50	5.40	8.80	2.25	24.25	4.44	63.60

Stage 4: Calculation of WQI - Summation of all Sri…n of each sample (SIi)

WQI=∑Sri…..n Eq. No. 5

Stage 5: Categorization of each sample based on the criteria. (Adopted by Brown et al ., 1970, Raychaudhuri et al., 2014, Asit and Surajit 2015)

E.g.

WQI Value	Water quality	No. of water samples	% of water samples
<50	Excellent		
50-100	Good	1	

101-200	Poor		
201-300	Very Poor		
>300	Unsuitable		
Total			

Results and Discussions

Variations in different WQI methods

The above example is an aggregation of the arithmetic equation, and different researchers proposed certain modifications to the equations considering geometric and harmonic series (Saeedi et al., 2009). Divergent results of WQI emerge even by adopting a given method by different scientists, which could be due to the scope for arbitration in considering the weights (wi) for each parameter, choosing the drinking water standards (Si), as well as criteria for categorization. To substantiate the hypothesis, five different commonly used and simple methods of WQI calculations are deliberated. The formulae developed or used by the respective researchers are presented in Table 1, demonstrating that discordance among these methods exists at the weights level or choosing the weight value. A similar attempt was made by Landwehr and Deininger in 1976 for surface water and brought out the merits and demerits of five different WQI methods. The latest attempt by Moez Kachroud et al. (2019) was made to illustrate the discrepancies in different WQI methods applying the same database.

Weighted arithmetic index (Brown et al., 1970 and 1973): In the Weighted arithmetic index (WAQI) method, also referred to as NSFWQI, the relative Weight (Wn) of each tested parameter is determined by apportioning the drinking water specifications. Water quality rating (Qn) for each parameter is calculated using the ideal value (Vi), which is at the prudence of the researcher. WQI is arrived at by dividing the product sum of relative Weight and quality rating with the sum relative Weight (Supplemental material 1). Brown et al. (1970) proposed the method was the initial attempt to bring the theoretical assumption into equation form using the Delphi technique. Subsequently, this method underwent few changes, and some scientists attempted to simplify it. Though many options for estimating WQI are available, the WAQI method is commonly used. Many researchers are not assigning any value or using 0 for the excellent value (Vi) for the tested parameter (except pH or Dissolved Oxygen) in the calculations; thus, the formula is losing relevance (Rawat et al., 2017; Prasad et al., 2019). RoohollahNoori et al. (2019) have pointed out NSFWQI is widely used with non-original rather than original model inputs.

Groundwater quality index (Saeedi et al., 2009): The groundwater quality index (GWQI) developed by Saeedi et al. (2009) is one of the simplest methods in practice for groundwater quality assessment. It includes only two steps; in the first step proportion of observed concentrations (Ci) of a few principal parameters to the maximum admissible concentration (Si) in water quality standards is calculated as the standard value of the parameters. In the second and final step, aggregate the product of all the standardized values and Weight of participation (Wi) of each parameter (Supplemental material 2). The parameters' Weight or Weight of participation is assigned according to the judgment of water quality experts and some studies on the importance of each drinking water component(Saeedi et al., 2009). The Weight (wi) considered for each parameter as well as equations for deriving the GWQI are not mentioned by the authors leading to speculation and non-acceptance. The classification of water based on GWQI proposed by the authors is different from the general practice (Table 1). It is high (GWQI >0.15), low (GWQI <0.04), and suitable (0.04 <GWQI <0.15).

WQI (Raychaudhuri et al., 2011 and 2014): This WQI method differs from others in deciding the weightage (wi). The authors have proposed Weight (wi) based on the number of samples' compliance with drinking water specifications. Weights of 5, 4, 3, 2, 1 are assigned to the parameters when 0-20, 21-40, 41-60, 61-80, and 81-100 % of samples are within the permissible limit of drinking water standards (DWS) respectively (Raychaudhuri et al., 2011). Nitrate may be assigned the maximum Weight of 5 (irrespective of compliance) due to its paramount importance in water quality assessment. The rest of the steps involved in the computation of WQI are the same as discussed in the General concept and calculation procedure (Supplemental material 3). The assigning weights based on compliance to DWS lacks scientific support and are statistical based rather than rationale. This weightage system is site-specific, and a generalized model could not be evolved from such a procedure.

WQI (Asit and Surajit 2015): The WQI method adopted by these researchers is the most popular one; in this, the weights (wi) are assigned according to their relative importance in the overall quality of water for drinking purposes (Asit and Surajit 2015). Many researchers have different perceptions about the drinking water specification and their significance to human health. Therefore, they assign varied weightage (wi) values for each parameter discussed in subsequent paragraphs (Rawat et al., 2017; Hamlat and Guidoum 2018; Prasad et al., 2019; Shah Jehan et al., 2020). These authors supported the simple arbitrary approach of choosing wi values for the tested chemical constituents ranging from 1 to 5 (in increasing order of importance) based on their relative importance in the water quality evaluation. The wi assigned to each of the parameters are in general agreement with many other researchers. Other steps in arriving at WQI are similar to the general WQI method (Supplemental material 4). Researchers and professionals often use this method by assigning different wi values based on the site-specific requirements and demands from epidemiology and environment inputs (Singh et al., 2017; Hamed et al., 2018; Adimalla et al. 2018).

Integrated water quality index (Shrikant et al., 2019): A radical change in the calculation of WQI is proposed by Shrikant et al. (2019) and called it an integrated water quality index (IWQI). In this method, the permissible limits(PL) of drinking water specifications of India DWS (BIS 2012) are modified by subtracting 20% of the range between permissible and desirable limits (DL) and termed it as modified permissible limits (MPL). The authors brought out three stages of sub-indexing (SI) for categorizing the water with the presumption that the values which are less than the minimum required concentration (<DL) and above MPL will affect the water quality. In contrast, the values between DL and MPL can be supposed as excellent for drinking.

SI_1 = 0:If the observed value ith parameter (Pi) is above DL but less than MPL, that isPi = >DL and <MPL.Pi is the water quality of ith parameter.

SI_2= (DL-Pi)/DL: If the value of the ith parameter is less than the desirable limit (Pi<DL), then use SI_2.

It is presumed that if the parameter content is less than the (<DL) Acceptable limit (Requirement as mentioned BIS DWS), then it is not suitable for human consumption.

SI_3= (Pi-MPL)/MPL: If Pi is greater than the modified permissible limit (MPL), that is Pi>MPL, then follow the SI_3 for calculation. The benchmark (PL) is reduced to facilitate pre-emptive action.

IWQI = the sum of all sub-indices (SI) of each sample.

The researchers suggest a varied classification criterion using the index values, which range from 1 to 5 (akin to 50 to 300) classes (Excellent, Good, Marginal, etc.). An explanation for each class is regarding suitability for drinking, as is the case with other methods (Supplemental material 5).

The unique features of this method are the simplicity in calculations, provision for considering the deficit ion content, no scope for arbitration or human judgment. Though the normalization of tested parameters and standard values is considered, weightage is ignored. Thus ranking of chemical constituents and samples will be missing if all parameters strength lies between >=DL and <= MPL. They are reducing the PL of BIS DWS to MPL for IWQI calculation, which has legal sanctity. It does not reflect the accurate intensity of deviation from the standard.

Case study

Water chemistry results containing content of 10 parameters of 47 groundwater samples are used to calculate the WQI applying the above discussed five methods to demonstrate the applicability and efficacy of these methods. The WQI methods selected are generally used by many scientists and professionals. They have logical similarities, easy to calculate, and do not require multiple sets of data. The Indian drinking water standard - BIS DWS-IS 10500: 2012 - Permissible Limit in the Absence of Alternate Source is used as a benchmark to assess the water quality. The K, Na, and CO_3 were not used in the WQI computation as BIS does not specify any limits for these ions. Detailed calculations of each method are presented as Supplemental materials 1 to 5, and summary results and chemical analysis data are provided in Table 2. The parameters above requirement (Acceptable limit) and permissible limit of BIS DWS are displayed distinctly (highlighted in yellow and red, respectively) for ready reference. Similar marking is done for the samples classified as good and poor quality based on WQI values. A cursory look at the final WQI output indicates certain parity among four methods (2 to 5), especially in the case of the highly contaminated samples (Table 2).

The method suggested by Brown et al. (1970) is different by identifying the only sample (Sample No. 16) which has high fluoride content (2.51 mg/l) as of poor quality. Surprisingly many samples having parameters content above acceptable and permissible limits were classified as an excellent category. However, the WQI score is high for samples having a fluoride concentration of about 1 mg/l (Supplemental material 1 and Table 2). Lack of provision for assigning the weights for each parameter and double apportioning (1/Sn and K/Sn) the standards could be reasons for poor water quality projection. The provision for providing the ideal value (Vi) while normalizing the test results (Qn- the quality rating) is considered only for pH (7) by many researchers (Bora and Goswami 2016; Rawat et al., 2017; Prasad et al., 2019). The F- content controls the WQI result as it has the most dominating unit weight (Wn) because it is calculated by a value inversely proportional to the recommended standard value (1/1.5). The low denominator value, when compared with other parameters, has enhanced the Wn for F^- leading to its high-quality rating (Sample No. 28). Though 10 samples are not suitable for drinking purposes, categorization based on WQI values of the method indicates only one sample as of poor quality (Table 3). The WQI is only 27.80 for a highly contaminated sample (Sample No. 24), with 8 out of 10 parameters much above PL. In contrast, for sample 18, which has all the parameters much below AL, the WQI is 26.10 (Table 2). Contradictory output and poor projection of water quality results in WQI values are discouraging the broad application of this method.

The GWQI method identified two highly contaminated samples as poor, and most of the samples with parameters concentration above requirement (acceptable limit) of BIS DWS as good. Classification of water samples based on the GWQI values suggested by Saeedi et al. (2009) is different from the rest of the methods, which is marginally modified for this study (Table 3). The GWQI value is <0.30 in samples having all the examined parameters within the required (acceptable limit) of BIS DWS. Samples with 4 to 5 parameters content above the required (acceptable limit) of BIS DWS have 0.31 to 0.50 GWQI. Those with >0.78 GWQI value have two parameters above the permissible limit of BIS DWS apart from five parameters above the requirement (acceptable limit) of BIS DWS (Supplemental material 2 and Table 2). The GWQI values are low because normalized parameters are not converted into a percent (tested value/standard value of each parameter) like many other methods. The Weight of participation of each parameter (Wi) proposed by Saeedi et al. (2009) is adopted with minor changes to suit BIS DWS. Due to the lack of information on Weight (wi) assigned to the parameters, the Wi factors are used directly. Wi values are not available for NO_3 and F as the authors have not considered these ions. The Weight of participation (Wi) specified for K (0.04) and Na (0.06) are used for NO_3 and F, which is not in concurrence with the significance of NO_3 and F in drinking water. Similarly, the authors accorded high Wi the alkaline earths, which may not be apt for other areas.

The hindrance to applying the GWQI method was felt due to the non-availability of information on wi, the calculation procedure of Wi and qn, and equations. A general categorization pattern of water samples akin to other popular methods would make the GWQI more acceptable. Another drawback is not accounting for low pH (<6.50). The GWQI method is simple, and the values display the near-truth status of water quality. It can find wide acceptability provided certain ambiguities are resolved.

In the third method, three samples were categorized as poor water (WQI >100), with three or more parameters above the PL limit of BIS DWS. Index values almost truly reflect the intensity of ionization and the samples having specific parameters beyond PL obtained >71 scores. Samples with all the parameter concentration less than the requirement (Acceptable limit) of BIS DWS has <30WQI value, and it varies between 30 and 70 for samples that have one or more parameter above the AL (Supplemental material 3 and Table 2). Unlike other methods, Raychaudhuri et al. (2014) relied on compliance of samples to BIS DWS for determining wi. This method does not account for low pH (<6.50), but it is considered. The quality rating (qi) is calculated for all the samples for both <6.50 and>8.50 pH. The WQI values are reduced by about 10 if qi is computed in either of the categories (samples with < 6.50 or >6.50). This method did not distinguish the samples unsuitable for drinking purposes (above PL of BIS DWS) with high WQI values (>100). Compliance with BIS DWS shows that seven samples (15%) are above PL and 33 samples (70%) above AL. In contrast, WQI classification indicates that only two samples are of poor quality, all fit drinking uses (Table 3). Irrespective of the epidemiologic importance of parameters concerning drinking purposes same (1) weightage (wi) is accorded to each parameter because of the compliance procedure adopted by the authors. The process camouflages the actual water chemistry of analyzed samples. The method is site-specific and is not popular among scientists.

The fourth method is very much like the third one, except the procedure used for assigning the Weight for each parameter (wi) is different, chosen according to its relative importance in the water quality for drinking purposes. The authors have assigned low (2) wi to TH, Ca, and Mg; 3 to HCO_3 and Cl; 4 to pH, TDS, SO_4, and F; only NO_3 is assigned a weight of 5. K, Na, and CO_3 are not considered as BIS DWS not specified any limits. The wi pattern followed is in agreement with other researchers and realistic to epidemiological concerns. Though wi assigned for each parameter is higher than that of the third method, the relative Weight (Wi) on average is almost the same; thus, the WQI values and categorization of samples are similar in both the WQI methods (Supplemental material 4 and Table 3).In the Asit and Surajit (2015) method, the WQI values are marginally higher (~3%) in all but 7 samples. They are lesser by 4% (in 7 samples) than the values obtained using the method suggested by Raychaudhuri et al. (2014). The average WQI value of 47 samples is 60 and 62 in the third and fourth methods, respectively (Table 2). This method could not differentiate the samples by categorization based on two different (AL and PL) criteria of BIS DWS. The samples having at least (ignoring pH) one parameter above PL have >65 WQI values. Many researchers use this WQI method due to the flexibility of allocating wi to each parameter independently based on the local conditions (Krishna et al., 2014 and 2015; Singh et al., 2017; Abbasnia et al. 2018; Shah Jehan et al., 2020). The classification proposed by the authors is also in tune with other popular methods. The broad scope for discretion in choosing wi for want of norms is the major setback for the method. Adopting this method by different researchers for the same water chemistry data produces varied WQI values due to a lack of standardization or authenticated practice in assigning Weight to tested parameters in concurrence with health concerns.

The fifth method put forth by Shrikant et al. (2019) is distinctly different from others and suggests a radical change in water quality assessment for drinking purposes. The WQI values obtained from the method exhibit two highly mineralized water samples (along with 2 to 4 methods) and five samples which have ion content lesser than the required (acceptable limit) of BIS DWS as poor waters (not suitable for drinking). Though specific samples have more than one parameter above PL and a few above AL, they are categorized as excellent (<1) and good water (1-2), which could be misleading (Supplemental material 5 and Table 2). The authors followed the Requirement (Acceptable limit) criteria mentioned in column 3 of Table 1 to 3 of (BIS DWS) IS 10500: 2012 Indian Standard drinking water-specification. They interpreted water with chemical constituents less than the AL limit as poor water since it does not contain ion concentration to the required level. Theoretically, it may be correct, but practically it is challenging to implement, and BIS DWS did not specify. Another initiative of Shrikant et al. (2019) to modify the PL (to MPL) may not be acceptable since BIS DWS are legal documents. The IWQI values (1 to5) and unusual pattern of water classification (2-3: Marginal: Acceptable for Domestic) is another hurdle in practicing the method (Table 3). Despite these shortcomings, the IWQI model is straightforward and contains limited scope for bias. No provision for weightage based on the parameter importance in the context of health significance in drinking water results in treating all tested parameters on par.

Assigning Weight (wi) to parameters

Ranking the parameters based on their epidemiological significance in drinking water constitutes crucial input in water quality assessment for potable water through WQI. Various water quality indices in practice follow different procedures in deciding the ranking. However, the most common and simple one is to assign Weight (wi) in the form of a numerical score between 1and 5 in increasing order of importance. Chemical quality criteria for drinking water are considered based on toxicity to human health apart from physiological and regional climatic conditions. These factors will also govern the ranking pattern of parameters in calculating the indices for drinking water quality evaluation. To upkeep, the sanctity of drinking water standards and actual projection of water quality status freedom for grading the tested parameters are provided in WQI estimation. Since the methodology of WQI is still in evolving stage, a robust weight pattern is yet to be developed. Many researchers followed different grading models based on their wisdom and available inputs, which add ambiguity in the outcome of WQI, which is illustrated in Table 4 along with citations. Experiment with the case study data is carried out by changing the weights of each parameter and calculating WQI values for different weight patterns (Supplemental material 6a). The results indicate a minor variation in WQI values among five patterns (SD values vary from 2.27 to 4.16), and samples with border values of categorization are classified into neighboring categories, e.g., sample no. 12, 27, and 28 (Supplemental material 6b). The mean WQI values obtained using different wi patterns (wi1-wi2; wi2-wi3 etc.) are almost similar(mean values vary from 55 to 62 and SD is 2.66) though assigned wi values differs significantly. Changing the weightage between 1 and 5 or vice versa for any of the parameters or assigning the highest (5) or lowest (1) rank to all parameters is not making a notable distinction in WQI output. Instead, assigning different weights between 1 and 5 shows some variations in WQI. The freedom of assigning weights depending on the health significance, local conditions, and input from interdisciplinary literature can be left to researchers until statutory agencies standardize the wi pattern. Moez Kachroud (2019) made a similar inference that weighting factors are poorly determined and suggested weighting should be decided according to water use. Accordingly, a Universal WQI cannot be defined.

Groundwater quality assessment for drinking purposes

The water chemistry results of Vizianagaram, when compared with BIS DWS (less than a requirement; Acceptable limit), display that only 6 samples are suitable for drinking uses. If the PL is considered as a benchmark, 12 samples are suitable for drinking uses. The Rural Water Supply and Sanitation Department (RWS & S) survey indicates that about 25% of the area is under the non-potable category due to the high concentration of nitrate and total hardness (DSR-Vizianagaram Dist. 2018). The different WQI methods used to assess the suitability of water for drinking purposes could not present the prevailing water quality conditions with regards to BIS DWS (sample no. 6, 9, 10, 13, 19, 23, 31, 38). However, water quality status is fairly represented in the WQI values (Table 2). The degree of difference or extent of deviation among DWS and WQI values is very high. The classification scheme of all the examined methods is inappropriate for assessing drinking water suitability. The excellent (Class A or 1) and good (Class B or 2) categories can be considered as suitable for drinking, but all the methods have classes like poor and very poor or, in some methods, marginal and poor (Class C and D or 3 and 4 respectively). The last class (E or 5) is categorized as unstable for drinking purposes. It is incongruent with the suitability criteria of drinking water specifications. The potability of water grouped as poor and very poor classes is questionable. Few methods explained marginal (Class C or 3) water as acceptable for domestic and poor (Class D or 4) as unsuitable for drinking.

In contrast, the last category (Class E or 5) is labeled as Unacceptable or Unsuitable, which is somewhat perplexing and misleading (Table 3). Moez Kachroud et al. (2019) noted that despite using the same variables, the classification from each index differs, especially in the evaluation for drinking water. In conjunction with DWS, the WQI methods must be refined, particularly in third-world countries, so that index values could raise red flags in the database to facilitate immediate focus on the problem areas. Since the research for a more valuable and universal water quality index is going on, the water agencies, users, and water managers in different countries may use and adapt the available WQI methods with minor modifications to meet their needs (Shweta Thyagi et al., 2013).

Conclusions

Evaluation of five WQI methods indicates certain commonalities and diversities in principles engraved in these methods. Normalization of tested parameter values with selected standards is commonly followed, whereas rating parameters by assigning relative weightage and categorization varies in different methods. Despite weightage being a strategic input in indexing water quality, the present practice leaves broad scope for discretion. Its standardization by statutory organizations is required to minimize or avoid assumptions and to authenticate the WQI results. It is essential since WQI is primarily applied to assess water quality for drinking uses by Govt. Agencies. WQI score and classification criteria need to be rationalized in tune with the drinking water suitability criteria. Precise use of DWS in WQI calculations is to be ensured to withstand legal scrutiny, and the output can also use the output. Though researchers are making enormous efforts in refining and popularizing the WQI, a consensus approach for presenting ground truth through indices is yet to be achieved. Institutional intervention at WHO or country-level is required to standardize the methodology, accord legal status to WQI, and emphasize its parallel use with DWSto ensure safe drinking water for maintaining good human health.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly used products in our area of research and country. There is no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for litigation but knowledge advancement. The producing company did not fund the research. Instead, the personal efforts of the authors funded it.

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Table 1. Steps involved and formulae of five different methods used for WQI calculations.

		Weighted arithmetic index (after Brown 1970).	GWQI (after Saeedi et al., 2009).	WQI (after Raychaudhuri et al., 2014).	WQI (Asit and Surajit 2015).	Integrated water quality index (after Shrikant et al., 2019).
Steps	Symbols	Method - 1	Method - 2	Method - 3	Method - 4	Method - 5

1	wi/wi & K	1/∑(1/Sn)		wi based on compliance to DWS	wi based health significance	Range = Permissible limit (PL) Desirable limit (DL)
2	Wi	K/Sn	Parameters' weight	wi/∑wi	wi/∑wi	Modified Permissible Limit (MPL)=Permissible Limit (20%Range)
3	qn	100 [(Vn-Vi)/Sn-Vi)]	(Ci/Si)x100	(Ci/Si)x100	(Ci/Si)x100	SI_1=0; SI_2=(Dl-Pi)/DL; SI_3=(Pi-MPL)/MPL
4a	Sri	∑qn*Wn/∑Wn	SIi=Wi*qi	SIi=Wi*qi	SIi=Wi*qi	
4b	WQI	WAI = ∑(qn*Wn/sum (Wn)	GWQI=∑ Sri	WQI= ∑ Sri	WQI=∑ Sri	IWQI =∑ SI3 to SI5
5	Classification	<50 : Excellent	<0.50 : Excellent	<50 : Excellent	<50 : Excellent	<1.00 : Excellent
		51 to 100: Good	0.50 to 1.00: Good	50 to 100: Good	50 to 100: Good	1.00 to 2.00: Good
		101 to 200: Poor Water	1.00 to 2.00: Marginal	101 to 200: Poor Water	100 to 200: Poor Water	2.00 to 3.00: Marginal
		201 to 300: Very Poor Water	2.00 to 3.00: Poor	201 to 300: Very Poor Water	200 to 300: Very Poor Water	3.00 to 5.00: Poor
		>300: Water Unsuitable For Drinking	>3.00: Water Unsuitable	>300: Water Unsuitable For Drinking	>300: Water Unsuitable For Drinking	>5.00: Water Unsuitable

Table 2. Water chemistry results and WQI values were obtained from different methods.

Sample No.	pH	TDS	TH	Ca^{2+}	Mg^{2+}	T A as HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	F^-	WAI (Brown et al., 1970)	GWQI (Saeedi et al., 2009)	WQI (Raychaudhuri et al., 2014)	WQI (Asit and Surajit 2015)	IWQI (Shrikant et al., 2019)

				mg/l											
1	7.00	1480	540	72	88	270	333	250	44	0.33	21	0.63	74	77	0.97
2	7.47	1485	600	160	49	300	380	200	25	0.21	14	0.63	71	72	0.94
3	6.95	226	100	24	10	110	19	28	1	0.58	30	0.18	31	34	5.06
4	7.65	1728	600	120	73	350	428	255	19	0.79	45	0.68	79	79	0.38
5	7.40	1287	440	56	73	400	285	147	10	0.28	17	0.50	61	61	1.24
6	7.45	643	200	40	24	220	124	85	1	0.70	38	0.30	43	46	2.04
7	7.40	1488	560	144	49	400	285	138	59	0.23	17	0.64	76	81	1.78
8	7.15	2657	1300	200	194	500	760	350	39	0.30	21	1.15	119	111	4.26
9	7.00	589	200	32	29	250	95	50	2	0.38	20	0.27	39	41	2.59
10	6.51	512	200	40	24	220	95	51	1	0.10	4	0.25	35	36	2.92
11	7.65	1256	500	128	44	250	333	170	37	0.17	13	0.57	67	70	1.01
12	7.03	794	360	64	49	250	143	81	15	0.26	15	0.39	50	51	1.92
13	7.31	605	260	16	53	200	143	45	4	0.15	9	0.30	41	42	2.84
14	7.37	1478	660	200	39	420	304	200	18	0.20	13	0.65	73	71	1.22
15	7.05	1853	640	96	97	550	428	250	9	1.00	55	0.71	82	81	0.51
16	8.10	1181	400	80	49	350	238	200	6	2.51	137	0.55	75	79	0.84
17	6.00	1590	800	168	92	550	428	120	2	0.12	6	0.69	73	66	2.03
18	7.55	455	200	40	24	150	95	62	2	0.48	26	0.27	39	42	2.83
19	7.36	506	260	40	39	150	95	77	3	0.93	50	0.32	45	48	2.03
20	7.40	1110	500	112	53	350	238	100	12	0.32	19	0.51	60	60	1.23
21	7.25	960	360	72	44	250	247	94	8	0.70	38	0.42	54	55	0.89
22	7.46	896	360	80	39	260	219	107	1	1.12	61	0.43	56	57	0.59
23	6.45	683	300	80	24	200	95	133	17	0.08	4	0.35	44	47	2.08
24	6.82	3802	1500	360	146	700	1045	600	63	0.39	28	1.48	149	143	7.47
25	7.50	1285	480	104	53	400	285	108	19	1.38	76	0.56	71	73	0.46
26	7.85	1408	500	128	44	400	285	175	18	0.30	19	0.57	67	68	0.82
27	7.32	938	300	56	39	250	143	294	2	0.04	3	0.41	50	52	1.65
28	7.00	253	100	24	10	50	19	84	9	1.00	53	0.21	36	41	4.60
29	7.30	774	360	64	49	200	143	150	8	0.18	11	0.39	49	50	1.65
30	6.88	1152	400	88	44	250	333	113	18	1.34	73	0.50	63	66	0.44
31	7.65	602	200	40	24	180	143	75	3	0.80	44	0.30	44	47	2.01
32	7.50	926	360	104	24	300	190	120	12	0.83	46	0.44	57	59	1.00
33	7.50	1206	440	120	34	250	333	125	13	0.83	46	0.51	62	64	0.55
34	7.35	1848	700	184	58	450	523	200	13	0.64	36	0.73	81	79	0.85
35	6.70	406	200	32	29	110	95	55	7	0.44	23	0.26	37	39	3.15
36	7.50	2052	640	96	97	400	475	350	37	0.99	57	0.78	91	94	0.59
37	6.53	165	100	16	15	60	29	20	1	0.17	8	0.15	26	28	5.79
38	7.30	676	260	48	34	250	124	110	2	0.62	33	0.34	46	48	1.70
39	6.45	406	200	56	15	150	48	45	13	0.13	6	0.25	35	38	3.67
40	7.20	240	140	40	10	100	29	34	1	0.19	10	0.20	30	33	4.99
41	7.50	2055	600	168	44	500	380	280	64	0.61	38	0.78	91	97	1.53
42	7.00	2080	640	96	97	400	475	320	60	0.35	23	0.78	90	94	1.90
43	7.74	789	360	104	24	270	133	100	7	0.76	42	0.41	54	55	1.40
44	6.45	182	100	24	10	70	19	25	5	0.24	11	0.16	27	30	5.71

45	6.47	110	60	16	5	40	10	22	3	0.12	5	0.13	23	27	6.64
46	9.17	2352	740	216	49	450	523	380	69	0.97	61	0.94	109	115	2.17
47	8.28	572	200	40	24	210	105	56	13.7	0.48	29	0.31	42	48	2.50

Note: Parameter concentration >=AL and <=PL highlighted in yellow; concentration >= to PL highlighted in red. WQI - Good category highlighted in yellow; Poor quality highlighted in red.

Table 3. Classification of water-based on different WQI methods.

		WAI after Brown et al ., 1970; Method -1		WQI after Raychaudhuri et al., 2014; Method -3		WQI used by Asit and Surajit 2015; Method -4	
WQI value & (Class)	Water quality status	No. of water samples	% of water samples	No. of water samples	% of water samples	No. of water samples	% of water samples
<50 (A)	Excellent	39	83	21	45	19	40
51 to 100 (B)	Good	7	15	23	49	25	53
101 to 200 (C)	Poor Water	1	2	3	6	3	6
201 to 300 (D)	Very Poor Water	0	0	0	0	0	0
>300 (E)	Water Unsuitable For Drinking	0	0	0	0	0	0
Total		47	100	47	100	47	100
GWQI after Saeedi et al., 2009 (Modified): Method -2				IWQI after Shrikant et. al., 2019; Method -5			
WQI value	Class	No. of water samples	% of water samples	WQI value	Class & Explanation (w.r.t. to drinking water)	No. of water samples	% of water samples
<0.49	Excellent	26	55	<1	Excellent	13	28
0.5 to 0.99	Good	19	40	1–2	Good	13	28
1.00 to 1.49	Marginal	2	4	2–3	Marginal	11	23
1.50 to 1..99	Poor	0	0	3–5	Poor	5	11
2.00 to 3.00	Unsuitable	0	0	>5	Unsuitable	5	11
Total		47	100			47	100

Table 4. Different researchers adopted parameter weight (wi).

Parameters	Abbasnia et al. (2018) Factor Weight	Hamed et al. (2018) Weight (wi)	Singh et al. (2017) Weight (wi)	Adimalla et al. (2018) Weight (wi)	Krishna et al. (2014 and 2015) Weight (wi)	Saeedi et al. (2010) Modified to Weight (wi)	Das et al. (2017) Assigned Weight (AW)	Shah Jehan et al. (2020) Weight (wi)	Hamlat and Guidoum (2018) Weight (wi)
pH	3	3	4	3	4	1.00	2.54	4	4
EC (m S/cm)					4		3.22	4	4
TDS (mg/l)	5	5	4	5	5	0.75	2.75	4	0
TH as $CaCO_3$ (mg/l)	3		2	3			1.46		
Ca^{2+} (mg/l)	3	3	2	3	2	1.00		2	2
Mg^{2+} (mg/l)	2	3	1	3	1	0.75		2	1
K^+ (mg/l)	2	2	1	2	2	0.20		2	2
Na^+ (mg/l)	3	4	1	2	2	0.30	1.67	3	2
TA - HCO_3^- (mg/l)	2	1	3	3	3			1	3
Cl^- (mg/l)	3	5	3	4	3	0.50		4	3
SO_4^{2-} (mg/l)	4	5	4	3	4	0.50		3	4
NO_3^- (mg/l)	5		5	5	5		2.57		5
F^- (mg/l)	4		4	5					
PO_4^{3-} (mg/l)	1								1
Fe (mg/l)			4						

*mean of weight values from earlier publications

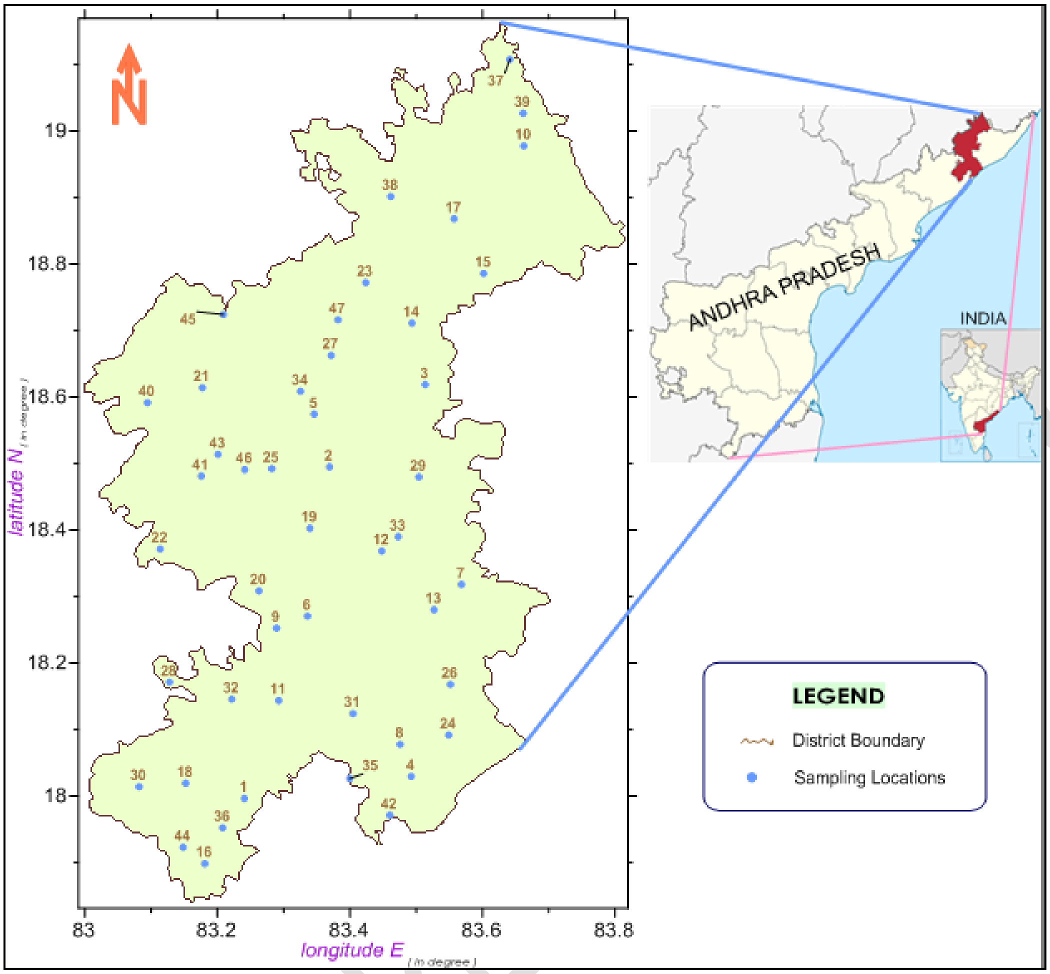

Fig. 1. Study area with sample locations.