

A comprehensive water quality index based on analytical hierarchy process

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ABSTRACT

The popular water quality index (WQI) and the recently developed integrated water quality index (IWQI) were used to evaluate the potability of 32 groundwater samples collected from Nalagarh valley, Himachal Pradesh, India. But their analytical results were surprisingly contrasting. While WQI classified 14 of the samples as 'excellent' and 17 as 'good', IWQI put all of them under 'unsuitable' category. This led to the development of a new index, called 'comprehensive water quality index (CWQI)', on the basis of analytical hierarchy process (AHP). Unit weights and sub-index values of both relaxable (that have both acceptable and permissible limits) and non-relaxable (that have only one guideline value) parameters were considered in the calculation process. Two segments were calculated: P_{CWQI} (positive CWQI) and N_{CWQI} (negative CWQI) with their scores varying between 0 and 1 and 0 and (-0.840), respectively. Grading of water quality from drinking perspective was done essentially with N_{CWQI} scores, such as 'excellent' (when $N_{CWQI} = 0$), 'good' ($N_{CWQI} = 0$ to -0.21), 'marginal' ($N_{CWQI} = -0.21$ to -0.42), 'poor' ($N_{CWQI} = -0.42$ to -0.63), 'very poor' ($N_{CWQI} = -0.63$ to -0.84) and 'un-acceptable' ($N_{CWQI} = <-0.84$). In fact, when $N_{CWQI} = 0$, higher the P_{CWQI} , better the water quality. When two water samples had the same N_{CWQI} score, they were graded by their respective P_{CWQI} score. When two water samples had the same magnitudes of P_{CWQI} and N_{CWQI} , they were graded equally. On the basis of this classification, groundwater in majority of the study area was classified under 'good' category for drinking purposes in absence of an alternative source of water. Compared to WQI and IWQI, CWQI proved itself to be a robust and comprehensive technique for assessing the groundwater quality. It was hence recommended to be used universally for groundwater quality assessment.

1. Introduction

The United Nations defined framework for 17 sustainable development goals (SDGs) in 2015 with Goal No. 6 focusing on access to clean water and sanitation for all. But as of 2020 after a span of five years, about two billion of the global population still lack access to safely managed drinking water (WHO (World Health Organisation) (2022)). Water is an issue that concerns all aspects of human development, including health, agriculture, education, economic productivity, and even peace and stability of a country (Naik, 2017). Therefore, any step toward improvement in access to clean fresh water has the potential to solve a myriad of developmental barriers. This contribution is an attempt toward this direction, and therefore has global implications.

Water quality monitoring is a fundamental tool in the management of freshwater resources (Bartram and Balance, 2006). The concept of

water quality monitoring originated in Germany in 1850 (Wepener et al., 2006). The objective that time was to evaluate the purity of water on the basis of certain harmful indicator microorganisms. In 1912, for better safeguard of the river ecosystem and public health, the 8th report of the Royal Commission on Sewage Disposal, established by the British Government in 1898, mentioned about specific water quality parameters, such as ammoniacal nitrogen, oxygen absorbed from permanganate and dissolved oxygen, in sewage discharges (Johnstone and Horan, 1996; Calvert, 2013). Subsequently in 1978, Bolton et al. (1978) developed the river water classification system. Many countries adopted this classification for appraisal of water pollution, albeit for a limited number of parameters, such as for smell, turbidity, suspended matter, microorganisms, etc.

Conventionally, water quality is evaluated by comparing the concentration levels of the physical, chemical and biological parameters with their respective guideline values. When concentrations of one or

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Nomenclature		MCLG	Maximum Contaminant Level Goal
<i>List of acronyms</i>		ML	Maximum Limit
AHP	Analytical hierarchy process	MPL	Modified permissible limit
AL	Acceptable limit	NSF	National Sanitation Foundation
CI	Consistency index	N_{CWQI}	Negative comprehensive water quality index
CR	Consistency ratio	N_f	Number of variables
CWQI	Comprehensive water quality index	PL	Permissible limit
DL	Desirable limit	P_{CWQI}	Positive comprehensive water quality index
GM_n	Geometric mean	SDGs	Sustainable Development Goals
q_i	Quality rating of the i^{th} parameter	SI	Sub-index
IWQI	Integrated water quality index	W_i	Unit weight of the i^{th} parameter
K	Constant of proportionality	W_n	Normalized eigenvector (weights)
MCDM	Multi-criteria decision analysis method	WQI	Water quality index

two parameters exceed their prescribed limits, it often becomes difficult to recommend or reject a water body on the basis of the conventional approach (Mohebbi et al., 2013; Mukate et al., 2019; Noori et al., 2019; Jha et al., 2020). To overcome such a dilemma, convergence of a large set of data to a single indicator value that provides comprehensive information about the water quality without diluting the prescribed standards becomes essential (Kumar et al., 2015; Herojeet et al., 2016; Madhav et al., 2018; Matta et al., 2020).

1.1. Water quality index (WQI) as a solution

Water quality index (WQI) is a mathematical equation that helps incorporation of large datasets of multiple water quality parameters to a single numerical score that defines the suitability of a source water for drinking purposes (Tiwari and Mishra, 1985; Rao, 1997; Stambuk-Giljanovic, 1999; Mishra and Patel, 2001; Reza and Singh, 2010; Shivasharanappa et al., 2011; Kushtagi and Srinivas, 2012; Mohebbi et al., 2013; Naubi et al., 2016; Raju et al., 2016; Krishan et al., 2016a; Krishan et al., 2016b; Singh et al., 2020a; Keesari et al., 2020; Sharma et al., 2021; Lata and Rishi, 2021; Sangwan et al., 2021; Matta et al., 2022). Horton (1965) pioneered the WQI model by assigning weights to selected parameters and aggregating their sub-index (SI) values in a continuous additive approach to compute a final indexing score. Since then, various workers worldwide have developed many WQI models on the basis of this pioneering concept (Lumb et al., 2011; Sutadian et al., 2016; Krishan et al., 2016b; Kachroud et al., 2019; Noori et al., 2019; Jha et al., 2020).

Most WQI models follow four distinct steps: (i) parameter selection, (ii) standardization of the water quality parameters expressed in different units (iii) weight assignment to individual parameters to calculate their sub-index (SI) values, and (iv) aggregation of the SI s to obtain a final index value (Abbasi and Abbasi, 2012; Bharti and Katyal, 2011; Rajkumar et al., 2020; Raju et al., 2015). The confusion and difficulty faced by many workers while using different WQIs are: (i) different water classifications for the same WQI model, (ii) application of different WQIs to the same dataset leading to different categories of the same water source, and (iii) worker's discretion in choosing a particular WQI model based on one's convenience (Kachroud et al., 2019).

1.2. The problem in assigning weights in WQI

The process of assigning weight to an individual parameter is carried out through addition and division methods by generating either a relative weight or a unit weight. Relative weight is assigned on a scale of one to four (1–4) based on the relative importance of a chemical parameter in water quality assessment (Horton, 1965; Mohan et al., 1998; Vasanthavigar et al., 2010), while unit weight of a parameter is inversely

proportional to its guideline value (Tiwari and Mishra, 1985). Few WQI models prefer equal weights to be assigned to all parameters, while most others prefer assignment of unequal weights since each parameter has its own influence on the overall water quality. The sensitivity of an index can be affected by heavily weighted parameters, so it becomes essential that each parameter is weighed on the basis of the ultimate usage of water, such as for drinking, domestic or irrigation purposes, since each usage has its own quality standards.

The final WQI score of a water sample is highly dependent on the cumulative SI values of its chemical parameters, and SI of a particular parameter is equal to its quality rating multiplied by its unit weight. Therefore, since the unit weight of a chemical parameter is inversely proportional to its prescribed guideline value, a parameter with a lower guideline value (for example F^-) will have a higher unit weight and a higher SI value than a parameter with a higher guideline value (i.e., NO_3^-) that shall have a lower unit weight and a lower SI value. This will happen even though both the chemical parameters (viz., F^- and NO_3^-) have equal importance in water quality assessment (Rajkumar et al., 2020). This discrepancy has been described with greater details in section 2.3.1.

1.3. Other techniques for assigning weights and the analytical hierarchy process (AHP)

Organisation for Economic Co-Operation and Development (OECD (Organisation for Economic Co-Operation and Development) (2008)) has identified two processes for determining the weight of a chemical parameter, such as (i) statistical-based techniques (principal component analysis and factor component analysis) and (ii) participatory-based processes (Delphi method and analytical hierarchy process). Statistical-based techniques are less promising than the participatory-based processes because of their complexity; often insignificant parameters are heavily weighted due to their statistical importance (Böhringer and Jochem, 2007; Zardari et al., 2015).

Delphi method in the participatory-based processes is based on the opinions of experts and stakeholders through several rounds of questionnaires to reach a consensus. Therefore, it is a relatively time-consuming and expensive process (Hartwich, 1999; Franklin and Hart, 2007; Semiromi et al., 2011; Almeida et al., 2012; Sutadian et al., 2017). The analytical hierarchy process (AHP), on the other hand, uses multi-criteria decision analysis method (MCDM) that involves calculations through geometric, division and arithmetic methods besides using the ideas and opinions of the experts and stakeholders who share their knowledge and experience about the specific parameters. It is one of the most promising techniques to generate relative weights of parameters through pair-wise comparison of matrices. Therefore, it reduces the speculation of errors and false assignment of weight to a particular parameter (Kumar et al., 2017).

Many quantitative and qualitative studies in various fields apply AHP to achieve reliable results (Sutadian et al., 2016). Ocampo-Duque et al. (2006) applied AHP for establishing weights in the Fuzzy Water Quality Index (FWQI) while assessing water quality of the Ebro River, Spain. Karbassi et al. (2011) used AHP to modify the original weight of a WQI developed by the National Sanitation Foundation (NSF) while assessing water quality of the Gorganrood River, Iran. Do et al. (2013) and Sarkar and Majumder (2021) while working on the water quality status of the Jingmei and Xindian Rivers, Taipei, Taiwan, and Haora River, Tripura, India, respectively, successfully applied AHP to design a network of sampling stations and plan sampling frequency by assigning multiple weights on different variables.

1.4. Objective of this study

There is a dearth of literature available on the application of AHP in

groundwater quality studies. An attempt has been made in this contribution to develop a comprehensive water quality index (CWQI) based on AHP to assess the groundwater quality of the Nalagarh valley, Himachal Pradesh, India. The assessment results of CWQI have been compared with those of WQI (Tiwari and Mishra, 1985) and the recently developed integrated water quality index (IWQI) (Mukate et al., 2019) (discussed in section 2.3) to examine its accuracy and reliability.

2. Materials and methods

2.1. Study area

Nalagarh, a narrow intermontane valley, with a geographical area of about 250 km² in the State of Himachal Pradesh, India has been taken as the study area (Fig. 1). Himachal Pradesh is a sub-Himalayan hilly State with a strong focus on industrialization in recent years. Within this State,

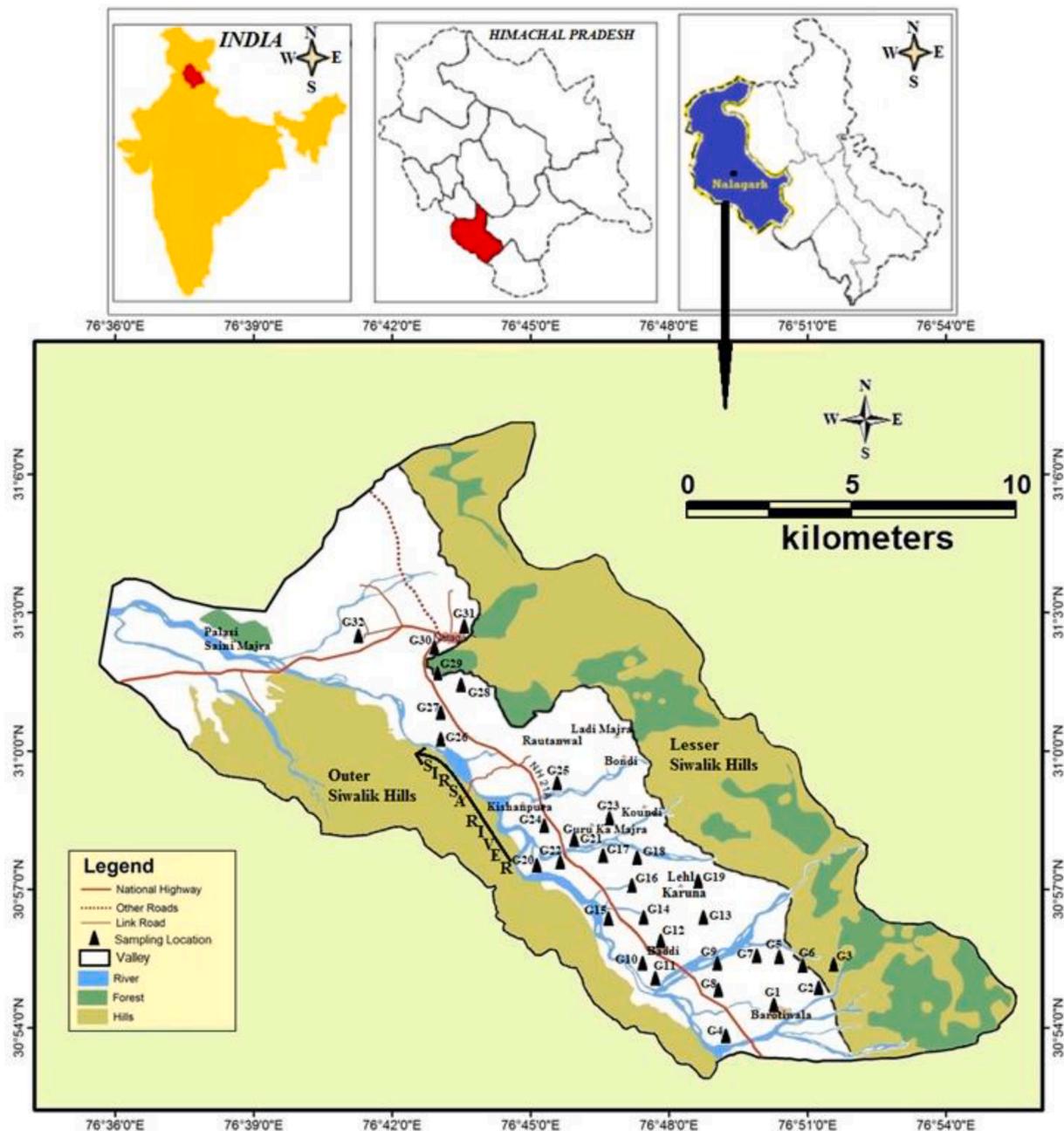


Fig. 1. Groundwater sampling locations in Nalagarh valley, Himachal Pradesh, India.

Nalagarh valley has the highest concentration (~70 %) of both large scale and medium scale industries (Government of Himachal Pradesh (GoHP) (2012)). The designated industrial zone is called Baddi-Barotiwala-Nalagarh (BBN) Industrial Belt where about 12 different categories of industries are in operation (Herojeet et al., 2013; Herojeet et al., 2015).

There also are numerous open-cast mining operations active in the area for quarrying limestone, minerals, stones, riverbed boulders, sand, etc. Popular subsidies granted by the State in recent years have attracted many industries from the neighboring and southern States to shift to Nalagarh valley. Many fertile agricultural lands are turning into industrial areas causing an environmental chaos (Government of India (GoI) (2012)). About 55 % of industrial units do not even possess valid permits for their operation (Anonymous, 2014). As per a 2007 report prepared by the BBN Authority, about 72 % of industrial units are operating in BBN without Effluent Treatment Plants (ETP) making the groundwater vulnerable to pollution (Kamaldeep et al. (2011). Rajkumar et al. (2019), Rajkumar et al. (2020), Rajkumar et al. (2022) give a detailed account of the environmental status in Nalagarh valley.

This contribution assesses the pollution menaces in the groundwaters of the Nalagarh valley, and critically examines the WQI (Tiwari and Mishra, 1985) that has been conventionally used historically and the recently developed IWQI (Mukate et al., 2019), both of which have been used in this valley. Also, it proposes a new indexing method that not only satisfies the limitations of these indices but also classifies the collected water samples into various water classes depending on their usability.

2.2. Sampling and laboratory investigations

Groundwater samples were collected in May (premonsoon) and October (postmonsoon) 2012 from 32 different sampling locations (shallow borewells) of Nalagarh valley (Fig. 1). Samples were collected in good quality (HDP) plastic bottles (1000 mL) with cover locks using Whatman filter paper no. 42 (to remove suspended particles).

Water samples were acidified with HNO₃ to maintain pH ~2 in the field for the analysis of metal constituents. They were then preserved in laboratory at 4 °C until their analysis. Physical parameters, namely pH and electrical conductivity (EC), were examined onsite (Hanna HI98194). Total dissolved solids (TDS) were computed as TDS = EC * 0.64. Standard protocol was followed for analysis of the chemical parameters, namely TH (total hardness), Ca²⁺, Mg²⁺, Na⁺, and K⁺, HCO₃⁻, SO₄²⁻, PO₄³⁻, F⁻, Cl⁻ and NO₃⁻ (American Public Health Association (APHA) (2005)).

Mapinfo Professional 6.5 was used for digitization purposes. Vertical mapper 3.0 was used to generate spatial interpolation maps of various water quality indices and groundwater parameters. Minitab 17 was applied for computing various statistical parameters. MS office (Excel) 2010 was used for the application of AHP procedures. The supplementary (suppl.) Table S1(a and b) shows the analytical results. Detailed procedures for sampling and methods of analysis of the chemical parameters are given by Rajkumar et al. (2022).

2.3. Limitations of WQI and IWQI

The conventional WQI developed by Tiwari and Mishra (1985), recently developed IWQI by Mukate et al. (2019), and the newly proposed 'comprehensive water quality index (CWQI)' have been applied in this study to appraise the groundwater quality.

2.3.1. Water quality index (WQI)

The WQI model developed by Tiwari and Mishra (1985) used the following mathematical Eq. (1) to determine the classification of groundwater suitability for drinking purposes. This has been referred thus by many workers, such as Lumb et al. (2011), Kachroud et al. (2019), Das and Sarkar (2021), Matta et al. (2018), Matta et al. (2021), etc.

$$WQI = \text{antilog} \frac{\sum_{i=1}^n W_i \log q_i}{\sum_{i=1}^n W_i} \quad (1)$$

where, W_i = the unit weight and q_i = quality rating of the i^{th} parameter.

In the first step, water quality rating (q_i) is computed for each parameter as in Eq. (2):

$$q_i = \frac{(V_{\text{actual}} - V_{\text{ideal}})}{(V_{\text{standard}} - V_{\text{ideal}})} \times 100 \quad (2)$$

where, V_{actual} = measured value of the i^{th} parameter, V_{ideal} = the ideal value, which is taken as zero, except for pH (ideal value = 7) and DO (ideal value = 14.6), and V_{standard} = its standard value as recommended by the water quality guidelines.

In the second step, the unit weight (W_i) is calculated using the Eq. (3):

$$W_i \propto \frac{1}{S_n} \Rightarrow \frac{K}{S_n} \quad (3)$$

where, K (constant of proportionality) = $\frac{1}{\frac{1}{S_{s1}} + \frac{1}{S_{s2}} + \frac{1}{S_{s3}} + \dots + \frac{1}{S_{sn}}}$ and S_n = standard/acceptable guideline value as per the Bureau of Indian Standards (BIS (Bureau of Indian Standards) (2012)).

The WQI water classification is presented in Table 1. But there are certain limitations in this conventional WQI equation:

- (i) Eq. (1) for computing the final WQI value is complex and not user-friendly due to frequent use of logarithm and antilogarithm tables.
- (ii) The model does not clearly specify what it meant by the standard value, i.e., whether it was the desirable or permissible or maximum permissible limits of the BIS prior to BIS (Bureau of Indian Standards) (2012) or the guideline value of the previous versions of the WHO (World Health Organization) (2017). Nevertheless, BIS does not have any term 'desirable' in its quality criteria now; it has been replaced with the term 'acceptable'. Therefore, for this contribution, V_{standard} has been taken as the acceptable limits of the BIS (Bureau of Indian Standards) (2012) or guideline values of the WHO (World Health Organization) (2017) where BIS acceptable limits are not available.
- (iii) Also, assumption of a value of zero for V_{ideal} (V_i) is not correct since in nature a zero value for a chemical parameter is simply not possible due to rock-water interactions and many other environmental dynamics.
- (iv) As already pointed out in section 1.2, even if two parameters are equally important in water quality assessment, a parameter with a lower guideline value shall have a higher unit weight and a higher SI value (therefore, more important) than a parameter with a higher guideline value. This has been explained further in the following paragraph taking F⁻ and NO₃⁻ as examples.

The calculation of unit weight (W_i) of a chemical parameter in WQI is inversely proportional to its prescribed standard value, i.e., $W_i \propto \frac{1}{S_n} \Rightarrow \frac{K}{S_n}$. The constant of proportionality (K) value for all 13 parameters in this study is 0.769 (i.e. $K = \frac{1}{1.3} = 0.769$ where 1.3 is sum total of the individual unit weights of all 13 chemical parameters). F⁻ has an acceptable limit of 1.0 mg/L and NO₃⁻ has a guideline value 45 mg/L by BIS (Bureau of Indian Standards) (2012). Then, the unit weight of F⁻ = $\frac{K}{S_n} = \frac{0.769}{1} = 0.769$ and that of NO₃⁻ = $\frac{K}{S_n} = \frac{0.769}{45} = 0.017$, which is 45 times less than that of F⁻. If a water sample has F⁻ and NO₃⁻ contents of 2.0 mg/L and 90 mg/L, respectively, the quality rating will be 200 for both of them as per Eq. (2), but the SI for F⁻ shall be 153.8 (i.e., 200×0.769) and for NO₃⁻, it will be 3.4 (i.e., 200×0.017), since SI of a particular parameter = quality rating \times unit weight. The final WQI value of a water sample is highly dependent on the SI value, and normally gets skewed toward the

drinking purposes. The sub-index thus becomes zero, i.e.,

$$SI_1 = 0 \tag{5}$$

The concept of excellence in water quality is defeated in this process. Since BIS (Bureau of Indian Standards) (2012) does not list any desirable limit (DL), assuming that what IWQI considers DL is actually acceptable limit (AL), a chemical parameter with a value above the prescribed AL is only conditionally suitable for drinking purposes, i.e., in the absence of an alternative source of potable quality of water (BIS (Bureau of Indian Standards) (2012); Health Canada, 2017; USEPA (U.S. Environmental Protection Agency) (2012); WHO (World Health Organization) (2011); WHO (World Health Organization) (2017)). Therefore, categorizing a water sample as excellent when the concentrations of some of its chemical parameters are above the acceptable limits is simply erroneous.

The issue is more complicated in case of non-relaxable parameters when IWQI considers a value which is only 20 % less than the value of the permissible limit as the limit for excellent category, while, in fact, this value should be significantly much lower in magnitude. For example, in case of nitrate, a value lying between 0 and 36 mg/L (i.e., 20 % deficit of the permissible limit of 45 mg/L) is considered excellent, while for such a categorization of water quality, the nitrate value should actually be much lower. For example, the United States of America, under the authority of the Safe Drinking Water Act (SDWA), has set the Maximum Contaminant Level Goal (MCLG) for total nitrate at 10.0 mg/L (Water Quality Association (WQA), 2013). Therefore, considering the sub-index $SI_1 = 0$ in such cases (i.e. when nitrate value approaches 36 mg/L) gives only a false impression on the final score of IWQI.

Case II: When the i^{th} parameter content is less than desirable limit, i.e., $P_i \leq DL$, then SI_2 is computed as (Eq. (6)):

$$SI_2 = \frac{DL - P_i}{DL} \tag{6}$$

Case III: When the P_i value is more than the MPL, i.e., $P_i \geq MPL$, then SI_3 is calculated using Eq. (7):

$$SI_3 = \frac{P_i - MPL}{MPL} \tag{7}$$

Two water samples having Mg^{2+} concentrations (P_i) of 14 mg/L and 102 mg/L and F^- values (P_i) of 0.7 mg/L and 1.7 mg/L, respectively, are used here to explain the errors in the calculations of SI_2 and SI_3 above. The DL/AL in case of Mg^{2+} is 30 mg/L and the permissible limit (PL) in absence of an alternative source is 100 mg/L. Thus, the quality rating of SI_2 ($Mg^{2+} = 14$ mg/L) is 0.533 (i.e., $\frac{(30-14)}{30}$), and SI_3 ($Mg^{2+} = 102$ mg/L) is 0.186 (i.e., $\frac{(102-86)}{86}$), where $MPL = (PL - 20\% \text{ of } (PL - DL)) = (100 - 20\% \text{ of } (100 - 30)) = (100 - 14) = 86$ mg/L. This calculation indicates that a water sample with an Mg^{2+} concentration of 102 mg/L above MPL value of 86 mg/L has a superior quality due to a lower SI value of 0.186 than a water sample with Mg^{2+} concentration of 14 mg/L (i.e. below DL/AL) that has a SI value of 0.533. IWQI's logic looks unconvincing and it surely has a problem in SI calculation.

Similarly, in case of F^- , the sub-index rating of SI_2 ($F^- = 0.7$ mg/L) is 0.3 (i.e., $\frac{(1-0.7)}{1}$) and SI_3 ($F^- = 1.7$ mg/L) is 0.214 (i.e., $\frac{(1.7-1.4)}{1.4}$), where 1.4 is $MPL = (PL - 20\% \text{ range (i.e. PL - DL)}) = (1.5 - 20\% \text{ of } (1.5 - 1.0)) = 1.5 - (20\% \text{ of } 0.5) = 1.5 - 0.1 = 1.4$. This confirms that a water sample with F^- concentration of 0.7 mg/L below the DL/AL of 1.0 mg/L is of inferior quality due to a higher SI rating value of 0.3 than a water sample with F^- concentration of 1.7 mg/L that has a SI rating value of 0.214. IWQI's logic in SI calculations is again defeated.

With all these limitations, the final IWQI is computed by summation of each individual sub-index (SI) value of the chemical parameters in a water sample, as shown in Eq. (8), and categorization of water classes is done as per Table 1.

$$IWQI_i = \sum_{j=1}^n SI_{ij} \tag{8}$$

where, SI_{ij} = the sub-index value of i^{th} sample and j^{th} water quality parameter.

Therefore, the overall results of IWQI are scientifically biased and may misinterpret the final water quality status of a geographical area since calculation of the individual SI values are of doubtful authenticity.

2.3.3. Development of a comprehensive water quality index (CWQI)

A new index, called Comprehensive Water Quality Index (CWQI), has been developed to assess the groundwater quality status for physicochemical parameters. This index overcomes the limitations of the conventionally used water quality index (WQI) and integrated water quality index (IQWI) developed by Tiwari and Mishra (1985) and Mukate et al. (2019), respectively, for groundwater.

Two terms, such as relaxable parameters and non-relaxable parameters, are used in vogue by both BIS (Bureau of Indian Standards) (2012) and WHO (World Health Organization) (2017) while considering the health significance of a parameter for drinking purposes. CWQI uses acceptable limits (BIS (Bureau of Indian Standards) (2012)) for both relaxable and non-relaxable parameters or guideline values (WHO (World Health Organization) (2017)) for non-relaxable parameters as the threshold limits for computing the water quality rating for physicochemical parameters. The guideline values of WHO (World Health Organization) (2017) have been used only when BIS (Bureau of Indian Standards) (2012) does not specify acceptable/permissible limits (in absence of an alternate source) for certain parameters, such as for EC, Na^+ , K^+ and HCO_3^- .

Thus, the quality rating or sub-index (SI) of a parameter is calculated accordingly to understand the actual contribution of a particular parameter on the overall water quality of a water sample. The following steps explain the computation of CWQI; "also shown in Fig. 2".

2.3.3.1. Assignment of weight on selected water parameters using multi-criteria decision analysis method (MCDM). Saaty (1980) developed the AHP technique as one of the multi-criteria decision analysis methods to assess the relative weight of selected parameters/factors/indicators based on the objectives of a study. This technique has sound methodology to integrate various opinions and judgments and is easy to apply on many complex and diverse variables by following a stepwise hierarchical grading procedure for the decision making process (Saaty, 1989; Forman and Gass, 2001; Shen et al., 2015). It has been successfully used worldwide in different research spectrum related to banking (Kamil et al., 2014), education (Bodin and Gass, 2004), energy (Ishizaka et al., 2016), medicine (Kuruoglu et al., 2015), food sector (Jennings et al., 2016; Gorane and Kant, 2016; Sun, 2015) and various construction and developmental projects (Oddershede et al., 2007). Recently, many workers applied AHP for establishing the relative weights of variables for assessing groundwater potential mapping (Jha et al., 2010; Singh et al., 2018), groundwater vulnerability zonation (Kumar et al., 2017; Kumar et al., 2019) and similar water resource studies (Chakraborty and Kumar, 2016; Tallar and Suen, 2016; Sutadian et al., 2017).

Four distinct steps, as follows, have been used in this contribution for developing CWQI for groundwater using AHP.

- (i) Preparation of a hierarchical structure of selected parameters (physical, cations, and anions as indicators) depending on the expected pollution sources, land use and land cover and other developmental activities.
- (ii) Establishment of pair-wise comparison of matrices among the parameters and assignment of weights in a 1–9 point scale to the defined variables based on their importance in the evaluation of water quality.

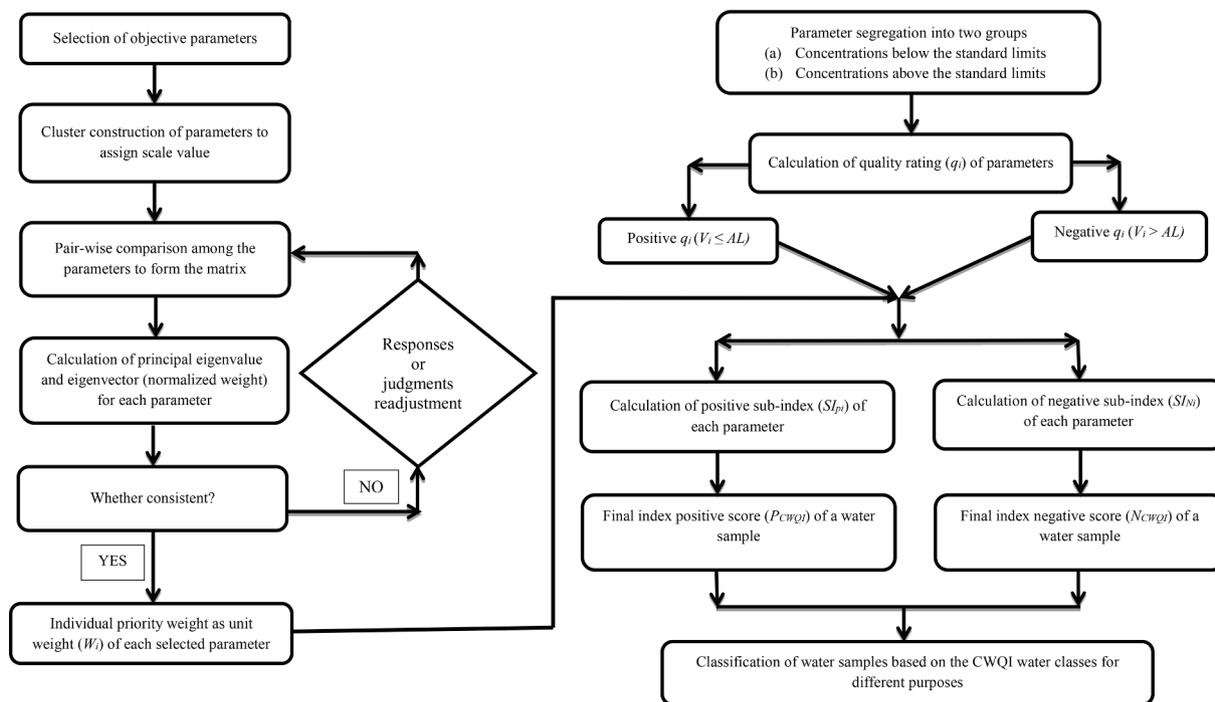


Fig. 2. Development steps of CWQI using AHP pathways for establishing the weights of the chemical parameters.

- (iii) Computation of the matrices using geometric mean to obtain the normalized weights of all input variables.
- (iv) Calculation of the consistency index (CI) and consistency ratio (CR) to validate the judgment of assigning a value to a specific parameter.

These steps are further explained as follows:

Step i: Thirteen parameters have been grouped in three cluster levels (a) physical parameters (pH, EC, TDS), (b) chemical parameters, namely

cations (TH, Na⁺, K⁺, Ca²⁺, Mg²⁺), and anions (HCO₃⁻, Cl⁻, SO₄²⁻), and (c) health risk parameters (NO₃⁻, F⁻), as shown in Fig. 3. The first two clusters (C1 and C2) include the aesthetic characteristics of water for drinking, domestic, irrigation and industrial purposes. The third cluster (C3) is generated as health-based indicator, especially for drinking purposes.

The criteria for formation of these clusters are based on the opinions of the local inhabitants during the course of field investigations and sample collection, inputs from the peers and other water quality

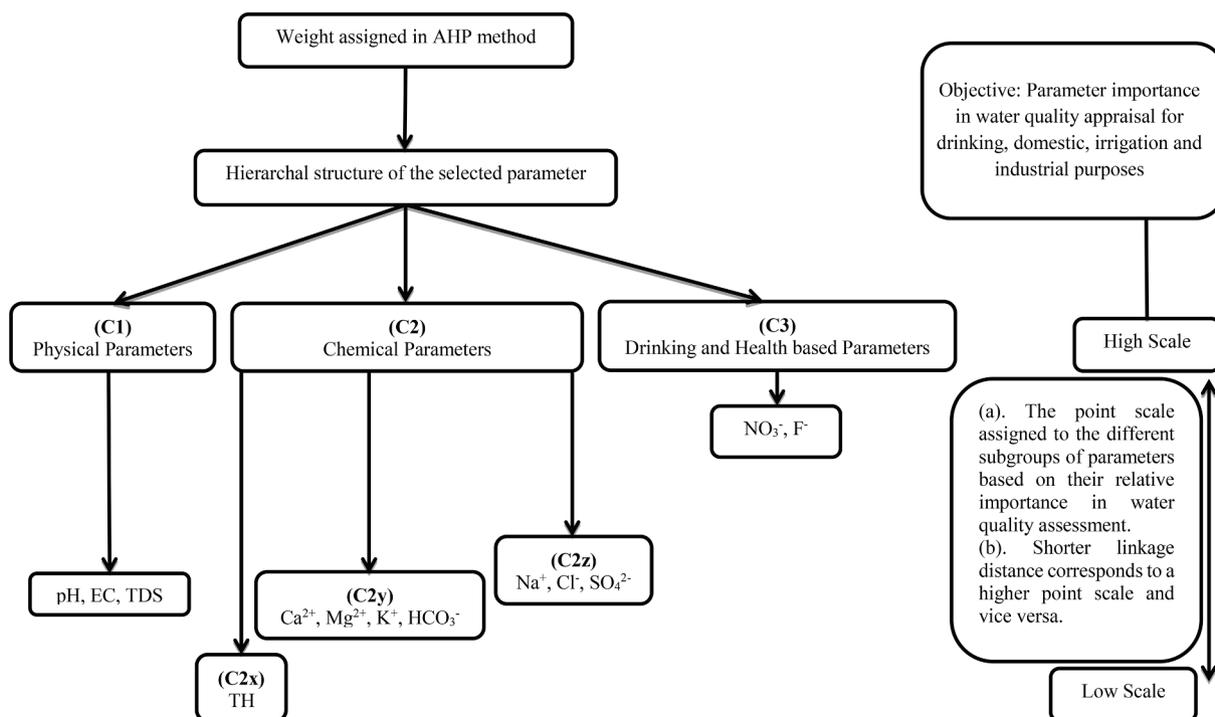


Fig. 3. Hierarchical structure of different clusters formed by the 13 selected parameters.

researchers as well as published articles on these parameters as sources of groundwater contamination. The clusters C1 and C3 have only one subgroup each, and different parameters present in these subgroups have same importance. On the other hand, the parameters representing C2 are further divided into three subgroups, i.e., C2x (TH), C2y (Ca²⁺, Mg²⁺, K⁺, HCO₃⁻) and C2z (Na⁺, Cl⁻, SO₄²⁻), where the parameters belonging to each subgroup have equal significance in assessment of water quality and therefore same point scale is assigned to each subgroup (Table 2).

The longer arrow lines (linkage distance) connecting to each subgroup parameters from their respective clusters are indicative of lower point scale and vice versa. The double sided arrow line (↔) on the right side in Fig. 3 indicates the range of point scale with respect to the relative importance of parameters in water quality appraisal for drinking, domestic, irrigation and industrial purposes. For example, C3 (NO₃ and F⁻) has minimum linkage distance which corresponds to higher point scale. The subgroup C2x (TH) has the maximum linkage distance from the main cluster and therefore represents a lower point scale.

Step ii: The indicator parameters were assigned a value between 1 and 9 on the basis of the public opinions and expert suggestions in order to construct a pair-wise matrix. The pair-wise matrix compares and evaluates the contribution of each of the paired parameters independently for easy judgment and decision-making process (Rezaei-Moghaddam and Karami, 2008). The constructed pair-wise comparison among selected water parameters is formed as a squared matrix, and the diagonal matrix of the same parameters is always unity (Fig. S1). Table S2 illustrates the point scale 1 – 9 and the weight assigned to each indicator parameter on the basis of their relative importance.

Step iii: The objective of assigning weight to each variable (water quality parameter) in matrix X on the basis of its relative importance (Table S2) is to generate the principal eigenvalue. The principal eigenvalue is calculated by the nth root of products between the principal eigenvectors of all variables (column) with respect to the criteria or alternative variable (row-wise) of the matrix algebra X. The normalized eigenvector is computed by the ratio of the geometric mean of the criteria or alternative variables of pair-wise comparison matrix by the summation of geometric mean of all variables (Saaty 1980; Bhushan and Rai 2004). The summation of principal eigenvectors must be unity, i.e., $\sum_{n=1}^{N_f} W_n = 1$, where $W_n > 0$.

The geometric method of aggregating different weights is more consistent than the arithmetic method in pair-wise comparison matrix (Forman and Peniwati, 1998). The arithmetic method has eclipsing problem as higher individual weights often dominate the other lower individual weights and vice versa (Ishizaka et al., 2011). This limitation creates overestimation of variable weights in absolute priorities due to simple aggregation. Therefore, the normalized eigenvector (weights) is calculated by the geometric mean method using the following formula (9):

$$W_n = \left(\frac{GM_n}{\sum_{n=1}^{N_f} GM_n} \right) \tag{9}$$

where, GM_n indicates the geometric mean of the i^{th} row of judgment matrices and N_f the total number of variables/parameters of the i^{th} row and are expressed as.

$$GM_n = \sqrt[N_f]{a_{1n}a_{2n}a_{3n} \dots a_{nN_f}} \tag{10}$$

Steps iv: Best judgments (weights) assigned to the variables are necessary to validate whether they are consistent or not. Saaty (1980) proved that the principles of the transitive attribute (i.e. $a_{ij} \cdot a_{jk} = a_{ik}$) must be achieved for judgement in consistency, which is denoted by λ_{max} value closer to N_f number of variables. Therefore, λ_{max} is the largest eigenvalue equal to or greater than N_f order of the square matrix X. Consistency Index (CI) is calculated as shown in Eq. (11):

Table 2
Results of pair-wise comparison matrix of thirteen parameters for the present study.

Parameters	Assigned Weight	pH	EC	TDS	TH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	Cl ⁻	F ⁻	NO ₃ ⁻	SO ₄ ²⁻	Geometric Mean (A1)	Normalized Weight (A2)	Consistency Check (A3 = A1* ^N A2)	λ (A3/A2)	Consistency Index (CI)	Consistency Ratio (CR)
pH	4	1.000	1.000	1.000	1.333	1.000	1.000	0.800	1.000	1.000	0.800	0.444	0.444	0.800	0.857	0.063	0.816	13.058	0.0051	0.0033
EC	4	1.000	1.000	1.000	1.333	1.000	1.000	0.800	1.000	1.000	0.800	0.444	0.444	0.800	0.857	0.063	0.816	13.058		
TDS	4	1.000	1.000	1.000	1.333	1.000	1.000	0.800	1.000	1.000	0.800	0.444	0.444	0.800	0.857	0.063	0.816	13.058		
TH	3	0.750	0.750	1.000	1.000	0.750	0.600	0.750	0.600	0.750	0.600	0.333	0.333	0.600	0.643	0.047	0.612	13.056		
Ca ²⁺	4	1.000	1.000	1.000	1.333	1.000	1.000	0.800	1.000	1.000	0.800	0.444	0.444	0.800	0.857	0.063	0.816	13.058		
Mg ²⁺	4	1.000	1.000	1.000	1.333	1.000	1.000	0.800	1.000	1.000	0.800	0.444	0.444	0.800	0.857	0.063	0.816	13.058		
Na ⁺	5	1.250	1.250	1.250	1.667	1.250	1.250	1.000	1.250	1.250	1.000	0.556	0.556	1.000	1.071	0.078	1.020	13.058		
K ⁺	4	1.000	1.000	1.000	1.333	1.000	1.000	0.800	1.000	1.000	0.800	0.444	0.444	0.800	0.857	0.063	0.816	13.058		
HCO ₃ ⁻	4	1.000	1.000	1.000	1.333	1.000	1.000	0.800	1.000	1.000	0.800	0.444	0.444	0.800	0.857	0.063	0.816	13.058		
Cl ⁻	5	1.250	1.250	1.250	1.667	1.250	1.250	1.000	1.250	1.250	1.000	0.556	0.556	1.000	1.071	0.078	1.020	13.058		
F ⁻	9	2.250	2.250	2.250	3.000	2.250	2.250	1.800	2.250	2.250	1.800	1.000	1.000	1.800	1.928	0.141	1.836	13.061		
NO ₃ ⁻	9	2.250	2.250	2.250	3.000	2.250	2.250	1.800	2.250	2.250	1.800	1.000	1.000	1.800	1.928	0.141	1.836	13.061		
SO ₄ ²⁻	5	1.250	1.250	1.250	1.667	1.250	1.250	1.000	1.250	1.250	1.000	0.556	0.556	1.000	1.071	0.078	1.020	13.058		
																$\sum_{n=1}^{N_f} W_n = 1.000$				$\lambda_{max} = 13.061$

$$CI = \frac{\lambda_{max} - N_f}{N_f - 1} \quad (11)$$

Further, λ_{max} is calculated using Eq. (12):

$$\lambda_{max} = \sum_{n=1}^{N_f} \frac{(XW)_n}{N_f W_n} \quad (12)$$

where, W is the priority weight (eigenvalue column).

Saaty (1980) produced random consistency index (RCI) values for N dimension matrix, as shown in Table S3. Consistency ratio (CR) is computed as the ratio of consistency index (CI) and random consistency index (RCI) value as shown in Eq. (13):

$$CR = \frac{CI}{RCI} \quad (13)$$

Saaty (1980) suggested that CR value must be less than 0.10, so that the set of judgment values shall have valid consistency for the pair-wise comparison matrix. Perfect consistency exists if the CR value exactly equals to 0 (zero). If the CR value exceeds 0.10, readjustment of responses in the pair-wise comparison matrix is necessary to rectify the inconsistency. On the basis of all above steps, the final weight assigned to each quality parameter for calculation of CWQI is presented in Table 2.

2.3.3.2. Calculation of quality rating. The quality rating (q_i) of a chemical parameter is defined as the numerical difference between its acceptable limit (AL) and its measured value divided by the AL as expressed in Eq. (14).

$$q_i = \frac{AL_i - V_i}{AL_i} \quad (14)$$

This is, in fact, a normalized quality rating where, V_i = the actual concentration of a measured parameter (i^{th}) and AL = acceptable limit of the parameter as per the BIS (Bureau of Indian Standards) (2012) standards.

In a case where the acceptable limit of a parameter is not given by the BIS (Bureau of Indian Standards) (2012), the WHO (World Health Organization) (2017) guideline value for the parameter is used, i.e., for EC, Na^+ , K^+ and HCO_3^- . There are two segments of the quality rating calculation on the basis of the concentration of the i^{th} parameter:

- (i) When the concentration of the i^{th} parameter is below or equal to the acceptable limit, i.e., $V_i \leq AL$: In such a case, the water sample shall have negligible or no health implications and q_{1i} will be a positive value.
- (ii) When the measured value of the i^{th} parameter exceeds the acceptable limit, i.e., $V_i > AL$: In this case, the water sample in question may have an immediate or long term health effect and q_{2i} will be a negative value.

2.3.3.3. Final computation of CWQI. The quality rating (q_i) of a chemical parameter is multiplied by its corresponding relative weight (W_i) to generate a sub-index (SI_i) value, as follows:

$$SI_i = q_i \times W_i \quad (15)$$

where, W_i is, in fact, the normalized unit weight of the i^{th} parameter.

Therefore, CWQI, for parameters from 1 to m , is computed as:

$$CWQI = \sum_{i=1}^m SI_i \quad (16)$$

Rao (2012) suggests that if the measured values of the chemical parameters in a water sample satisfy the potable water standards, they may not pose any health implications. Therefore, if the measured values are within their prescribed limits, the CWQI calculated will be a positive

comprehensive water quality index (P_{CWQI}). On the contrary, if a measured value of a chemical parameter is above its prescribed limit, it may pose health risks to humans, and the index thus calculated will be a negative comprehensive water quality index (N_{CWQI}) for the parameter.

If m number of parameters are analysed in a water sample, where m_1 numbers have $V_i \leq AL$ and m_2 numbers have $V_i \geq AL$, then the water sample will be represented by both positive comprehensive water quality index (P_{CWQI}) and negative comprehensive water quality index (N_{CWQI}) as shown in Eqs. (17) and (18):

$$P_{CWQI} = \sum_{i=1}^{m_1} SI_{pi} \quad (17)$$

$$N_{CWQI} = \sum_{i=1}^{m_2} SI_{Ni} \quad (18)$$

where, m is the number of parameters ($m_1 + m_2$) of the water sample, SI_{pi} is the positive sub-index of the i^{th} parameter and SI_{Ni} is the negative sub-index of the i^{th} parameter that are calculated using the following equations.

$$SI_{pi} = q_{1i} \times W_i \quad (19)$$

$$SI_{Ni} = q_{2i} \times W_i \quad (20)$$

Both SI_{pi} and SI_{Ni} are calculated independently for different parameter concentrations below or above the acceptable limits or guideline values of BIS (Bureau of Indian Standards) (2012) and WHO (World Health Organization) (2017), respectively, and aggregated separately to obtain a pair of P_{CWQI} and N_{CWQI} scores to understand the actual water quality of a particular water sample. A N_{CWQI} score shall be represented by a negative (-) symbol.

2.3.3.4. Grading of water quality as per CWQI. Grading of water quality in a water sample depends on the magnitude of mineralization in the sample in real-time. Many researchers have developed water quality indices to determine quality status in a water sample using physico-chemical and heavy metal parameters (Horton, 1965; Brown et al., 1971; Tiwari and Mishra, 1985; Backman et al., 1998; Mohan et al., 1996; Edet and Offiong, 2002; Rao, 2012; Mohebbi et al., 2013; Mukate et al., 2019; Rajkumar et al., 2020). The grading of water classes is based on the numerical scores of the indices that vary widely in a range of classes depending on a worker's discretion.

However, for CWQI, the development process of water classes is entirely different and is focused on the standard limits of water quality of the chemical parameters rather than the empirical values of the indices. The principle behind considering the water quality standards for classification in CWQI is because the physicochemical quality of a water sample for human consumption is usually assessed based on the prescribed limits of the parameters present, the violator parameters, if any, and the essential health significance of the drinking water. This brings the usage of relaxable and non-relaxable parameters defined before.

Generally in a water sample, when the measured value of a chemical parameter is above the acceptable limit (whether it's a relaxable or non-relaxable parameter), it is rendered unsuitable for drinking purposes and is thus rejected. But in this study, all the groundwater samples, irrespective of the parameters, whether they are within or above the regulatory limits of the BIS (Bureau of Indian Standards) (2012) and WHO (World Health Organization) (2017), are carefully examined while appraising the applicability of the proposed index.

When all measured values of the parameters are equal to or below the acceptable limits/guideline values, i.e., $V_i \leq AL$, and $V_i = 0$ or below the detectable level in water sample, the score of the positive comprehensive water quality index (P_{CWQI}) will range from 0 to 1. Water samples with higher score of P_{CWQI} shall indicate superior water quality and the N_{CWQI} will be zero. On the other hand, in a case when the concen-

trations all of the chemical parameters are above the acceptable limits, i. e., $V_i > AL$, in a water sample, then N_{CWQI} shall have negative score and $P_{CWQI} = 0$.

The maximum limit (ML) of the water class will be calculated based on the permissible limits (PL) of all selected relaxable parameters used for assessing a water sample for drinking purposes in the absence of an alternate source, assuming that the concentrations of the parameters are equal to PL ($V_i = PL$). Therefore, the P_{CWQI} score ranges from 0 to 1 and N_{CWQI} score will be between less than 0 and less than ML. Water sample with higher magnitude of N_{CWQI} score will have more adverse effect on water quality.

It is important to note here that the ML value will depend entirely on the number of relaxable physicochemical parameters considered for quality assessment. Non-relaxable parameters (single limiting value) will not be considered for calculation of ML. When $N_{CWQI} < ML$, the water sample needs to be rejected irrespective of P_{CWQI} score. The illustrative examples for calculating the P_{CWQI} , N_{CWQI} and ML are presented in Table 3. The water classification based on CWQI scores accordingly is given in Table 4.

3. Results and discussions

3.1. General assessment of groundwater for drinking purposes

Table S1 (a and b) lists all the analytical data of the 32 water samples collected from the study area during premonsoon and postmonsoon seasons. Table 5 presents their descriptive statistics such as the range, mean \pm SD (standard deviation) and percentage above their respective guideline values as per BIS (Bureau of Indian Standards) (2012) and WHO (World Health Organization) (2017). Fig. S2 (a – m) shows the spatial distribution maps of these parameters for premonsoon and postmonsoon seasons. The pH values in both seasons vary between 7.17 and 8.5 and 7.03 – 8.07, respectively, indicating slightly alkaline nature of groundwater. Out of the 14 different analysed parameters, only six parameters, namely EC, TH, Ca^{2+} , Mg^{2+} , K^+ and F^- , exceed their acceptable limits in these samples although they lie within their respective permissible limits (in absence of an alternate source) (BIS (Bureau of Indian Standards) (2012); WHO (World Health Organization)

(2017)). In case of EC and F^- , only one sample in each case (G31 for EC and G13 for F^-) exceeds its guideline value (BIS (Bureau of Indian Standards), 2012; WHO (World Health Organization), 2017), and that again only during the premonsoon season. In the sampling location G20, K^+ value exceeds its permissible limit (12 mg/L) (WHO (World Health Organization), 2017; BIS (Bureau of Indian Standards), 2012) during the postmonsoon season.

About 66 % and 47 % of groundwater samples in both premonsoon and postmonsoon seasons, respectively, show their TDS values exceeding their acceptable limit of 500 mg/L (BIS (Bureau of Indian Standards), 2012). This reflects dissolution of minerals or salts from the soil as well as anthropogenic activities (Kumar et al., 2015b; Sethy et al., 2016). However, their maximum concentrations do not exceed 900 mg/L. High TDS contents give rise to water hardness which is reflected in the total hardness (TH) concentrations exceeding their acceptable limit of 200 mg/L (BIS (Bureau of Indian Standards), 2012) in 97 % of the water samples in premonsoon and 84 % in the postmonsoon season. Even one sample (G31) during premonsoon and three samples (G10, G12, and G31) during postmonsoon season exceed their permissible limit of 600 mg/L (BIS (Bureau of Indian Standards), 2012).

In fact, TH is attributed to high concentrations of dissolved Ca^{2+} and Mg^{2+} with other anions in groundwater (Herojeet et al., 2016). While Ca^{2+} concentrations exceed the acceptable limit of 75 mg/L in about 41 % and 53 % of water samples during premonsoon and postmonsoon seasons, respectively, almost all water samples exceed the acceptable limit of Mg^{2+} , i.e., 30 mg/L, in both these seasons. In one water sample during premonsoon and in five water samples during postmonsoon seasons, Mg^{2+} concentrations are above the permissible limit of 100 mg/L. The excess dissolution of Mg^{2+} ion normally occurs in an aquifer when calcium ions undergo both supersaturation and precipitation (Hem, 1991; Singh et al., 2020b). In the study area, higher Mg^{2+} concentrations may be due to weathering and dissolution of sandstone and dolomite rocks, leaching of chemical fertilizers and pesticides and indiscriminate disposal of untreated industrial effluents (Herojeet et al., 2013, 2016; Keesari et al., 2014; Rajkumar et al., 2022). Although no health impact of hard water has been observed in the Nalagarh Valley so far, prolonged consumption of such water may cause increased incidences of artery calcification, urolithiasis, gastrointestinal irritation

Table 3
Model calculations for P_{CWQI} , N_{CWQI} and maximum limit (ML) in CWQI.

Parameter	BIS (2012)		Weights (W_i) (Value is obtained from Table 2, Column #17:A2)	Calculation for CWQI for sample # G31 (postmonsoon)			Calculation for Maximum Limit (ML)		
	Acceptable limit (AL)	Permissible limit* (PL*)		V_i (from Table S1b)	$q_i = \frac{AL - V_i}{AL}$	$SI_i = q_i \times W_i$	$V_i = PL^*$	$q_i = \frac{AL - V_i}{AL}$	$SI_i = q_i \times W_i$
pH	6.5–8.5		0.063	7.320	0.139	0.011	NR		
EC	1500**		0.063	1348.000	0.101	0.008	NR		
TDS	500	2000	0.063	875.000	-0.750	-0.059	2000.000	-3.000	-0.189
TH	200	600	0.047	772.000	-2.860	-0.089	600.000	-2.000	-0.094
Ca^{2+}	75	200	0.063	79.050	-0.054	-0.003	200.000	-1.667	-0.105
Mg^{2+}	30	100	0.063	169.080	-4.636	-0.292	100.000	-2.333	-0.147
Na^+	200**		0.078	51.900	0.741	0.058	NR		
K^+	12**		0.063	3.000	0.750	0.047	NR		
HCO_3^-	500**		0.063	140.000	0.720	0.022	NR		
Cl^-	250	1000	0.078	31.810	0.873	0.068	1000.000	-3.000	-0.234
F^-	1	1.5	0.141	0.240	0.760	0.107	1.500	-0.500	-0.071
NO_3^-	45		0.141	3.480	0.923	0.130	NR		
SO_4^{2-}	200	400	0.078	26.35	0.868	0.068	400.000		-0.068
						$P_{CWQI} = 0.52$			$ML = N_{CWQI} = -0.840$
						$N_{CWQI} = -0.44$			

Note: (1) In case of pH, the value range of 6.5–8.5 is considered as a single guideline value.

(2) pH, EC, Na^+ , K^+ , HCO_3^- and NO_3^- are non-relaxable (NR) parameters which are not considered in computation of ML value due to a single limiting value (i.e., guideline value) of water quality standards (BIS, 2012 and WHO, 2017).

* In absence of an alternate source.

** Indicates WHO (2017) standards since BIS (2012) didn't prescribe any limits for these parameters.

Table 4
Water classification by CWQI as per the maximum limit (ML) value of relaxable parameters.

CQWI ranges			Water Class	Uses
P_{CWQI} score	N_{CWQI} score	N_{CWQI} numerical score		
$0 \leq P_{CWQI} \leq 1.0$	$N_{CWQI} = 0$	$N_{CWQI} = 0$	Excellent	<ul style="list-style-type: none"> Direct use for all purposes (drinking, domestic and irrigation).
$0 \leq P_{CWQI} \leq 1.0$	$0 > N_{CWQI} \geq \frac{ML}{4}$	$0 > N_{CWQI} \geq -0.21$	Good	<ul style="list-style-type: none"> Conditional use for drinking purposes, but only if all measured parameters are within their permissible limits. Direct domestic and irrigation uses.
$0 < P_{CWQI} \leq 1.0$	$\frac{ML}{4} > N_{CWQI} \geq \frac{2ML}{4}$	$-0.21 > N_{CWQI} \geq -0.42$	Marginal	<ul style="list-style-type: none"> Prior treatment necessary for drinking purposes. Direct domestic and irrigation uses.
$0 < P_{CWQI} \leq 1.0$	$\frac{2ML}{4} > N_{CWQI} \geq \frac{3ML}{4}$	$-0.42 > N_{CWQI} \geq -0.63$	Poor	<ul style="list-style-type: none"> Unfit for drinking. May be used for other domestic and irrigation purposes.
$0 < P_{CWQI} \leq 1.0$	$\frac{3ML}{4} > N_{CWQI} \geq ML$	$-0.63 > N_{CWQI} \geq -0.84$	Very Poor	<ul style="list-style-type: none"> Unfit for drinking and domestic uses. May be used for irrigation of salt-tolerant crops.
$0 < P_{CWQI} \leq 1.0$	$N_{CWQI} < ML$	$N_{CWQI} < -0.84$	Unacceptable	<ul style="list-style-type: none"> Unfit for drinking, domestic and irrigation purposes. May be used for industrial purposes, such as for cleaning of machinery, raw materials, cooling etc.

Table 5
Descriptive statistics of the analytical results and their comparison with the BIS (2012) and FAO (1994) standards.

Parameter	BIS (2012) Standards		FAO (1994) Standards (range for irrigation use)	Summary of the analytical results during the premonsoon season				Summary of the analytical results during the postmonsoon season					
	AL	PL		Range	Mean \pm SD	% (and no.) of samples above BIS (2012) Standards		Range	Mean \pm SD	% (and no.) of samples above BIS (2012) Standards			
						AL	PL			AL	PL		
Physical parameters													
pH	6.5–8.5		6.5 – 8.4	7.17 – 8.5	7.57 \pm 0.35	NIL		3.0 (1)	7.03 – 8.07	7.41 \pm 0.23	NIL		NIL
EC	1500 ^a		0 – 3000	500 – 1513	908.72 \pm 284.08	3.0 (1)		NIL	443 – 1348	819.45 \pm 270.71	NIL		NIL
TDS	500	2000	0 – 2000	324 – 992	588.78 \pm 185.35	65.6 (21)	NIL	NIL	284 – 875	530.03 \pm 175.49	46.9 (15)	NIL	NIL
TH	200	600	—	206 – 622	306.38 \pm 86.95	96.9 (31)	3.0 (1)	—	186 – 772	384.19 \pm 155.33	84.4 (27)	9.4 (3)	—
Major cations													
Ca ²⁺	75	200	0 – 400	35.32 – 157.28	74.01 \pm 28.23	40.6 (13)	NIL	NIL	27.55 – 138.59	80.26 \pm 31.09	53.1 (17)	NIL	NIL
Mg ²⁺	30	100	0 – 60	20.64 – 137.20	56.70 \pm 21.70	90.6 (29)	3.0 (1)	62.5 (20)	31.72 – 172.82	74.16 \pm 36.72	84.4 (27)	15.6 (5)	46.88 (15)
Na ⁺	200 ^a		0 – 920	12.0 – 99.90	35.02 \pm 22.02	NIL		NIL	9.10 – 62.50	30.11 \pm 12.09	NIL		NIL
K ⁺	12 ^a		—	0.90 – 8.80	2.44 \pm 1.51	NIL		—	0.40 – 19.00	2.09 \pm 3.20	3.0 (1)		—
Major anions													
HCO ₃ ⁻	500 ^a		0 – 610	60.0 – 196.00	118.94 \pm 28.66	NIL		NIL	62.00 – 204.00	130.00 \pm 28.44	NIL		NIL
Cl ⁻	250	1000	0 – 1063	2.98 – 38.77	14.56 \pm 9.21	NIL	NIL	NIL	3.94 – 39.76	15.84 \pm 9.64	NIL	NIL	NIL
F ⁻	1	1.5	0 – 20	0.06 – 1.20	0.22 \pm 0.21	3.0 (1)	NIL	NIL	0.05 – 0.50	0.20 \pm 0.11	NIL	NIL	NIL
NO ₃ ⁻	45		0 – 45	0.49 – 6.27	3.08 \pm 1.52	NIL		NIL	0.00 – 18.92	3.93 \pm 4.26	NIL		NIL
SO ₄ ²⁻	200	400	0 – 960	9.98 – 27.01	13.22 \pm 3.30	NIL	NIL	NIL	9.69 – 26.48	13.37 \pm 3.99	NIL	NIL	NIL
PO ₄ ³⁻	–	–	0 – 6	0.01 – 0.95	0.18 \pm 0.19	–	–	NIL	0.01 – 0.05	0.03 \pm 0.01	–	–	NIL

Abbreviations: AL = acceptable limit; PL = permissible limit in absence of an alternate source.

Note: Unit in mg/L, except for EC (µS/cm) and pH.

^a Guideline value of the parameter by WHO (2017), since BIS (2011) does not provide any limit for this parameter.

and cardiovascular disorder in the long run (Durvey et al., 1991; WHO (World Health Organization) (2011); Sidhu et al., 2013; Jacintha et al., 2016).

3.2. General assessment of groundwater for irrigation purposes

Groundwater is the preferred source irrigation in the study area, since almost all surface water bodies, namely the perennial or ephemeral

streams, have already been contaminated by indiscriminate disposal of untreated domestic/industrial effluents. The soil texture is coarse in nature (sandy loam to clay loam) formed by the valley-filled deposits of alluvium that makes the land more fertile (Rajkumar et al., 2019). As per Food and Agriculture Organization (FAO) (1994), except for high concentrations of Mg^{2+} , groundwater is generally fit for agricultural purposes. About 63 % and 47 % of water samples exceed the FAO's permissible limit of 60 mg/L for Mg^{2+} in both premonsoon and postmonsoon seasons (Table 5, Fig. S3a).

Levy (2012) opines that Mg^{2+} and Ca^{2+} are divalent cations with similar chemical effects on soil's physical properties that help in maintaining healthy plant growth. But published literature reveals that high Mg^{2+} concentrations often cause Mg-induced Ca deficiency and also affect the hydraulic properties of soil, such as dispersion of clay particles, reduction of permeability, etc. (Franklin et al., 1991; Smith et al., 2015). On this, Food and Agriculture Organization (FAO) (1994) suggests that when the ratio of Ca^{2+}/Mg^{2+} is less than 1, the potential effect of exchangeable sodium and magnesium increases in soil. In the study

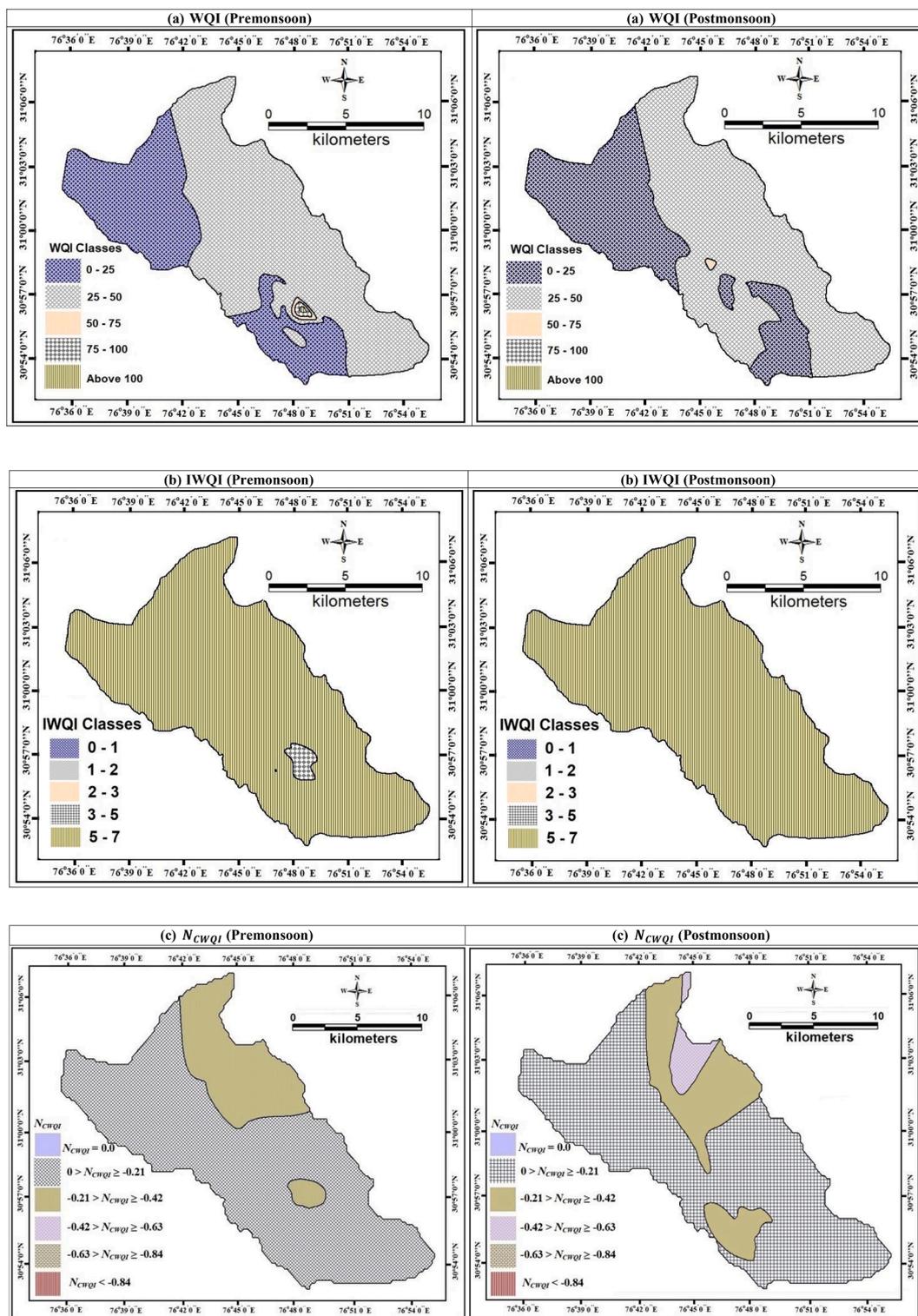


Fig. 4. Spatial distribution maps of (a) WQI, (b) IWQI, and (c) CWQI classifications for premonsoon and postmonsoon seasons.

area, the average Ca^{2+}/Mg^{2+} ratio of groundwater samples are 1.58 and 1.30 for premonsoon and postmonsoon seasons, respectively (Fig. S3b), and there is no report of decrease in yields of crops. Simson et al. (1979) infer that the Ca^{2+}/Mg^{2+} ratio between 0.5 and 30 does not affect crop yields. Therefore, possibly, the high Mg^{2+} concentration in groundwater samples have not shown any deleterious effect on plant growth and soil physical properties as yet due to ion balance stoichiometry with other cations and anions.

3.2.1. Groundwater quality classification based on WQI

The values of WQI vary from 17.46 to 104.24 for premonsoon and 14.56 – 52.26 for postmonsoon seasons [Tables 1; Table S4(a and b)].

Their spatial distribution is shown in Fig. 4a. The classification system of WQI, as explained in Table 1, puts 14 samples under excellent category (WQI value <25) in premonsoon and 13 samples in postmonsoon seasons, even if some parameters, such as TDS, TH, Ca^{2+} , and Mg^{2+} lie above the acceptable limits of BIS (Bureau of Indian Standards) (2012) in both seasons [Table S4(a and b)]. This goes against the conventional assumption that all chemical parameters must lie within their acceptable limits in an excellent water class (Rajkumar et al., 2020; Abtahi et al., 2015).

The numbers of groundwater samples falling under good water class ($26 < WQI > 50$) are 17 (premonsoon) and 18 (postmonsoon) having two to four parameters (TDS, TH, Ca^{2+} , and Mg^{2+}) lying above their

Table 6a

Ascending order of CWQI values and the corresponding WQI and IWQI values for groundwater samples (premonsoon).

Sl. No.	Sample No.	CWQI		Water Class	WQI		IWQI		Parameters above their regulatory limits	
		Score			Value	Water Class	Value	Water Class	Above acceptable limits (BIS, 2012)/ guideline values (WHO, 2017)	Above permissible limits (BIS, 2012)
		N_{CWQI}	P_{CWQI}							
1	G2	-0.01	0.60	Good	31.23	Good	6.08	Unsuitable	TH (206 mg/L), Mg^{2+} (36 mg/L)	
2	G8	-0.02	0.63	Good	23.89	Excellent	6.45	Unsuitable	TH (218 mg/L), Mg^{2+} (37.6 mg/L)	
3	G5	-0.02	0.58	Good	24.88	Excellent	6.00	Unsuitable	TH (228 mg/L), Mg^{2+} (39.4 mg/L)	
4	G10	-0.03	0.65	Good	19.56	Excellent	6.57	Unsuitable	TH (234 mg/L), Mg^{2+} (40.9 mg/L)	
5	G6	-0.03	0.59	Good	23.55	Excellent	5.96	Unsuitable	TH (238 mg/L), Ca^{2+} (79.1 mg/L), Mg^{2+} (38.8 mg/L)	
6	G16	-0.04	0.68	Good	17.46	Excellent	6.90	Unsuitable	TH (228 mg/L), Mg^{2+} (47.0 mg/L)	
7	G1	-0.05	0.66	Good	18.25	Excellent	6.69	Unsuitable	TH (220 mg/L), Ca^{2+} (135 mg/L)	
8	G4	-0.05	0.64	Good	19.22	Excellent	6.37	Unsuitable	TH (266 mg/L), Ca^{2+} (86.6 mg/L), Mg^{2+} (43.8 mg/L)	
9	G7	-0.05	0.60	Good	18.79	Excellent	6.03	Unsuitable	TH (260 mg/L), Ca^{2+} (90 mg/L), Mg^{2+} (41.5 mg/L)	
10	G26	-0.07	0.58	Good	26.53	Good	5.82	Unsuitable	TDS (516 mg/L), TH (282 mg/L), Mg^{2+} (54.7 mg/L)	
11	G9	-0.07	0.57	Good	17.61	Excellent	5.72	Unsuitable	TDS (548 mg/L), TH (272 mg/L), Ca^{2+} (119 mg/L), Mg^{2+} (37.3 mg/L)	
12	G23	-0.07	0.57	Good	44.54	Good	5.98	Unsuitable	TH (284 mg/L), Mg^{2+} (58.2 mg/L)	
13	G27	-0.07	0.56	Good	27.95	Good	5.80	Unsuitable	TDS (547 mg/L), TH (276 mg/L), Mg^{2+} (55.2 mg/L)	
14	G20	-0.07	0.50	Good	31.21	Good	5.00	Poor	TDS (670 mg/L), TH (244 mg/L), Mg^{2+} (46.6 mg/L)	
15	G17	-0.08	0.59	Good	17.59	Excellent	6.15	Unsuitable	TDS (532 mg/L), TH (282 mg/L), Mg^{2+} (57.7 mg/L)	
16	G22	-0.08	0.54	Good	36.74	Good	5.53	Unsuitable	TDS (592 mg/L), TH (290 mg/L), Mg^{2+} (54.1 mg/L)	
17	G14	-0.07	0.49	Good	24.21	Excellent	5.36	Unsuitable	TDS (840 mg/L), TH (216 mg/L), Mg^{2+} (40.4 mg/L)	
18	G24	-0.09	0.54	Good	43.57	Good	5.58	Unsuitable	TH (322 mg/L), Mg^{2+} (63.2 mg/L)	
19	G18	-0.10	0.54	Good	21.06	Excellent	5.55	Unsuitable	TDS (620 mg/L), TH (314 mg/L), Ca^{2+} (78.2 mg/L), Mg^{2+} (57.2 mg/L)	
20	G21	-0.10	0.54	Good	34.95	Good	5.52	Unsuitable	TDS (517 mg/L), TH (344 mg/L), Ca^{2+} (57.7 mg/L), Mg^{2+} (65.5 mg/L)	
21	G11	-0.11	0.54	Good	33.11	Good	5.50	Unsuitable	TDS (577 mg/L), TH (336 mg/L), Ca^{2+} (86.6 mg/L), Mg^{2+} (60.9 mg/L)	
22	G12	-0.11	0.54	Good	18.30	Excellent	5.43	Unsuitable	TDS (595 mg/L), TH (330 mg/L), Ca^{2+} (98.4 mg/L), Mg^{2+} (56.5 mg/L)	
23	G3	-0.14	0.54	Good	41.57	Good	5.59	Unsuitable	TDS (622 mg/L), TH (354 mg/L), Mg^{2+} (73.4 mg/L)	
24	G15	-0.14	0.48	Good	31.00	Good	4.98	Poor	TDS (742 mg/L), TH (342 mg/L), Ca^{2+} (89.2 mg/L), Mg^{2+} (61.7 mg/L)	
25	G13	-0.14	0.33	Good	104.24	Unfit	4.20	Poor	TDS (925 mg/L), TH (232 mg/L), Ca^{2+} (121.0 mg/L), F^- (1.2 mg/L)	
26	G25	-0.15	0.50	Good	45.78	Good	5.18	Unsuitable	TDS (706 mg/L), TH (352 mg/L), Mg^{2+} (74.4 mg/L)	
27	G28	-0.16	0.52	Good	32.24	Good	5.39	Unsuitable	TDS (684 mg/L), TH (390 mg/L), Mg^{2+} (79.2 mg/L)	
28	G32	-0.16	0.52	Good	18.05	Excellent	5.29	Unsuitable	TDS (738 mg/L), TH (374 mg/L), Ca^{2+} 88.3 mg/L, Mg^{2+} (69.7 mg/L)	
29	G29	-0.18	0.48	Good	35.15	Good	5.13	Unsuitable	TDS (826 mg/L), TH (386 mg/L), Mg^{2+} (76.5 mg/L)	
30	G30	-0.20	0.49	Good	33.21	Good	5.17	Unsuitable	TDS (844 mg/L), TH (386 mg/L), Mg^{2+} (83.9 mg/L)	
31	G19	-0.27	0.44	Marginal	31.88	Good	4.84	Poor	TDS (850 mg/L), TH (476 mg/L), Ca^{2+} (157 mg/L), Mg^{2+} (77.8 mg/L)	
32	G31	-0.37	0.43	Marginal	41.00	Good	5.57	Unsuitable	TDS (992 mg/L), EC (1513 μ S/cm)	TH (622 mg/L), Mg^{2+} (137.2 mg/L)

acceptable limits of BIS (Bureau of Indian Standards) (2012). Few samples even have violator parameters above their guideline values (WHO (World Health Organization) (2017)) and BIS permissible limits (in absence of an alternate source), such as G31 (EC, TH, Mg^{2+}) during premonsoon and G10, G12 and G31 (TH, Mg^{2+}) and G20 (K^+) during postmonsoon seasons. Only one sample, G24 (WQI = 52.26), falls in poor water class ($50 < WQI > 76$) during postmonsoon season. This sample shows TH concentrations of 566 mg/L, above the acceptable limit, and Mg^{2+} concentrations of 121.89 mg/L, above the permissible limit (Tables S1 and S4b). But it is interesting to note that during postmonsoon some other samples, such as G12 (27.46), G15 (31.26), G20 (39.41), and G31 (44.67) that fall in the good category have more number of violator parameters than G24. As a matter of fact, the water samples falling in poor water class should have more number of violator parameters than excellent/good ones. But this rule gets violated here.

Only one sample, i.e., G13 (WQI = 104.24), belongs to the unfit

water category during premonsoon (Table 6a; Table S4a) season. The sample G13 have same number of violator parameters (above acceptable limits) (TDS, TH, Ca^{2+} , F^-) as others, but shows high WQI value. This may be due to the presence of more than acceptable level of F^- (i.e., $F^- = 1.2$ mg/L) in it that has a high unit weight of 0.769. This also explains the difference in the WQI values between the unfit G13 during premonsoon and the poor water class G24 that has F^- concentration of 0.41 mg/L during postmonsoon season [Table S1(a and b)]. The higher unit weight of F^- (0.769) present in G13 during premonsoon period as compared to that of excess postmonsoon Mg^{2+} (unit weight = 0.026) in G24 directly impacts the sub-index values of F^- ($SI_{F^-} = 92.76$) and Mg^{2+} ($SI_{Mg^{2+}} = 10.55$).

In fact, the sample G31 (WQI = 41.00 premonsoon and 44.67 postmonsoon) is the only sample having higher number of parameters (TH and Mg^{2+}) above the BIS permissible limits, and technically, this sample should have more WQI value than that of G13 (104.24; premonsoon) in

Table 6b

Ascending order of CWQI values and the corresponding WQI and IWQI values for groundwater samples (postmonsoon).

Sl. No.	Sample No.	CWQI			WQI		IWQI		Parameters above their regulatory limits	
		Score	P_{CWQI}	Water Class	Value	Water Class	Value	Water Class	Above acceptable limits (BIS, 2012)/guideline values (WHO, 2017)	Above permissible limits (BIS, 2012)
1	G21	-0.01	0.67	Good	27.45	Good	6.03	Unsuitable	Mg^{2+} (35.94 mg/L)	
2	G22	-0.03	0.57	Good	31.95	Good	5.69	Unsuitable	TDS (519 mg/L), TH (238 mg/L), Mg^{2+} (39.6 mg/L)	
3	G32	-0.03	0.57	Good	14.56	Excellent	5.57	Unsuitable	TDS (656 mg/L), TH (216 mg/L), Mg^{2+} (35.67 mg/L)	
4	G6	-0.04	0.65	Good	19.76	Excellent	6.53	Unsuitable	TH (238 mg/L), Mg^{2+} (47.39 mg/L)	
5	G9	-0.04	0.62	Good	16.73	Excellent	6.13	Unsuitable	TH (252 mg/L), Ca^{2+} (83.48 mg/L), Mg^{2+} (41.12 mg/L)	
6	G19	-0.04	0.57	Good	22.22	Excellent	5.89	Unsuitable	TDS (745 mg/L), Mg^{2+} (31.72 mg/L)	
7	G1	-0.05	0.67	Good	17.69	Excellent	6.68	Unsuitable	TH (268 mg/L), Mg^{2+} (49.38 mg/L)	
8	G5	-0.05	0.62	Good	17.88	Excellent	6.17	Unsuitable	TH (266 mg/L), Ca^{2+} (81.05 mg/L), Mg^{2+} (45.13 mg/L)	
9	G7	-0.06	0.66	Good	18.28	Excellent	6.63	Unsuitable	TH (270 mg/L), Mg^{2+} (52.24 mg/L)	
10	G4	-0.07	0.66	Good	21.52	Excellent	6.57	Unsuitable	TH (290 mg/L), Mg^{2+} (54.55 mg/L)	
11	G8	-0.07	0.66	Good	19.98	Excellent	6.66	Unsuitable	TH (284 mg/L), Mg^{2+} (55.65 mg/L)	
12	G26	-0.07	0.59	Good	23.25	Excellent	5.87	Unsuitable	TDS (505 mg/L), TH (292 mg/L), Ca^{2+} (109 mg/L), Mg^{2+} (44.57 mg/L)	
13	G3	-0.07	0.56	Good	35.51	Good	5.74	Unsuitable	TH (298 mg/L), Ca^{2+} (85.78 mg/L), Mg^{2+} (51.78 mg/L)	
14	G2	-0.08	0.63	Good	30.44	Good	6.41	Unsuitable	TH (296 mg/L), Mg^{2+} (58.68 mg/L)	
15	G23	-0.08	0.62	Good	49.87	Good	6.46	Unsuitable	TH (288 mg/L), Mg^{2+} (61.65 mg/L)	
16	G17	-0.08	0.60	Good	17.40	Excellent	5.99	Unsuitable	TH (306 mg/L), Ca^{2+} (97.26 mg/L), Mg^{2+} (50.93 mg/L)	
17	G29	-0.10	0.57	Good	26.68	Good	5.76	Unsuitable	TDS (633 mg/L), TH (294 mg/L), Ca^{2+} (119 mg/L), Mg^{2+} (42.59 mg/L)	
18	G16	-0.13	0.68	Good	16.74	Excellent	6.87	Unsuitable	TH (362 mg/L), Mg^{2+} (78.24 mg/L)	
19	G11	-0.16	0.60	Good	35.26	Good	5.15	Unsuitable	TDS (559 mg/L), TH (388 mg/L), Mg^{2+} (87.95 mg/L)	
20	G27	-0.16	0.57	Good	31.84	Good	5.80	Unsuitable	TH (416 mg/L), Mg^{2+} (88.45 mg/L)	
21	G20	-0.16	0.51	Good	39.41	Good	5.76	Unsuitable	TDS (613 mg/L), TH (332 mg/L), Ca^{2+} 115.1 mg/L, Mg^{2+} (52.93 mg/L), K^+ (19 mg/L)	
22	G28	-0.21	0.52	Good	34.62	Good	5.37	Unsuitable	TDS (667 mg/L), TH (444 mg/L), Ca^{2+} (127 mg/L), Mg^{2+} (77.15 mg/L)	
23	G15	-0.23	0.57	Marginal	31.26	Good	5.85	Unsuitable	TDS (647 mg/L), TH (496 mg/L), Ca^{2+} (98.88 mg/L), Mg^{2+} (96.89 mg/L)	
24	G14	-0.24	0.55	Marginal	31.50	Good	5.62	Unsuitable	TDS (721 mg/L), TH (476 mg/L), Ca^{2+} (123.2 mg/L), Mg^{2+} (86.08 mg/L)	
25	G24	-0.25	0.58	Marginal	52.26	Poor	6.39	Unsuitable	TH (566 mg/L)	
26	G25	-0.25	0.51	Marginal	47.01	Good	5.24	Unsuitable	TDS (791 mg/L), TH (478 mg/L), Ca^{2+} (124.5 mg/L), Mg^{2+} (86.26 mg/L)	
27	G18	-0.26	0.61	Marginal	25.45	Excellent	6.39	Unsuitable	TDS (534 mg/L), TH (560 mg/L), Ca^{2+} (111.9 mg/L)	
28	G30	-0.27	0.52	Marginal	35.15	Good	5.57	Unsuitable	TDS (873 mg/L), TH (502 mg/L), Ca^{2+} (106.0 mg/L), Mg^{2+} (96.63 mg/L)	
29	G12	-0.29	0.60	Marginal	27.46	Good	6.65	Unsuitable	Ca^{2+} (93.21 mg/L)	
30	G13	-0.29	0.52	Marginal	47.96	Good	5.55	Unsuitable	TDS (797 mg/L), TH (528 mg/L), Ca^{2+} (138.6 mg/L), Mg^{2+} (95.05 mg/L)	
31	G10	-0.38	0.68	Marginal	32.64	Good	8.29	Unsuitable	TH (748 mg/L), Mg^{2+} (172.82 mg/L)	
32	G31	-0.44	0.52	Poor	44.67	Good	6.86	Unsuitable	TDS (875 mg/L), Ca^{2+} (79.05 mg/L)	
									TH (772 mg/L), Mg^{2+} (169.08 mg/L)	

which none of the violator parameters (TDS, TH, Ca^{2+} , F^-) exceed their permissible limits (Table S4a and b), but in reality, it does not happen so. This raises question on the index model methodology and water categorization by WQI. Possibly, its water classes are not good enough to properly characterize the actual groundwater quality in accordance to the regulatory limits.

3.3. Groundwater quality classification based on IWQI

The formulation of IWQI requires data arrangements for the computation of sub-index (*SI*) as described in section 2.3.2. It gives five water classes: excellent = excellent for drinking; good = good for drinking; marginal = acceptable for domestic; poor = not suitable for drinking; unsuitable = unacceptable. Groundwater with higher number of chemical parameters lying in between the desirable limits (DL) and modified permissible limit (MPL) belong to excellent water class with no effect on the water quality (i.e., *SI* = 0). But IWQI classification in Nalagarh valley does not allow any water sample to fall under excellent, good and marginal classes in both premonsoon and postmonsoon seasons [Tables 1; Tables 6a and 6b; Table S4 (a and b); Fig. 4b]. Only four groundwater samples (G13, G15, G19, G20) that fall under poor class in premonsoon season are not suitable for drinking, whereas all other samples fall under 'unsuitable' category in both the seasons.

Looking at the water samples individually more closely, it is observed that water samples belonging to poor water class, i.e., G13, G15 and G19, have nine chemical parameters under DL/AL and the remaining four parameters (TDS, TH, Ca^{2+} , Mg^{2+} or F^-) in between DL/AL and MPL during premonsoon season (Table 6a). These water samples should actually be categorized at least under 'good' category for all practical purposes, but categorizing them under 'poor' water class during premonsoon and 'unsuitable' category during postmonsoon seasons (Table 6b) does not look logical. The same problem arises even in other water samples in both the seasons. For example, in sample numbers G9, G11, G12, G18, G21 and G32, same parameters (TDS, TH, Ca^{2+} , Mg^{2+}) fall within DL/AL and MPL during premonsoon season, but IWQI classifies them under 'unsuitable' category for both drinking and domestic purposes [Tables 1; Table S4(a and b)]. Therefore, water classification under IWQI is of doubtful authenticity. Section 2.3.2 identifies many other problems associated with IWQI.

3.4. Groundwater quality classification based on CWQI

The newly proposed CWQI is calculated in two segments, i.e., P_{CWQI} (positive CWQI) and N_{CWQI} (negative CWQI), for each groundwater sample. Pre-treatment of the chemical parameters is necessary to ascertain their values below/above the acceptable and permissible limits (in absence of an alternative source) of BIS (Bureau of Indian Standards) (2012) as well as guideline values of WHO (World Health Organization) (2017). On the basis of Section 2.3.3, the ranges of P_{CWQI} and N_{CWQI} scores of the chemical parameters in the 32 water samples vary between 0.33 and 0.68 and (-0.01) - (-0.37) for premonsoon and 0.51 - 0.68 and (-0.01) - (-0.44) for postmonsoon seasons, respectively [Tables 6a and 6b, Table S4(a and b)]. The maximum limit (ML) of N_{CWQI} is -0.840 (Table 3). This has been calculated on the basis of the permissible limits (in absence of an alternative source) of the relaxable parameters only (i.e., TDS, TH, Ca^{2+} , Mg^{2+} , Cl^- , F^- and SO_4^{2-}).

It is important to mention here that while P_{CWQI} scores that vary always between 0 and 1 indicate potable water quality, water classes in CWQI are decided primarily on the magnitudes of N_{CWQI} scores of the relaxable chemical parameters. The lower the cumulative absolute scores of N_{CWQI} for these parameters, the better the water quality. When N_{CWQI} = 0, a higher P_{CWQI} score leads to better water quality. Wherever two N_{CWQI} scores are equal, grading is done on the basis of P_{CWQI} .

Six different classes, such as excellent, good, marginal, poor, very poor, and unacceptable, have been developed for grading water quality

based on the N_{CWQI} scores (Table 4). It is important to note here that in the study area, all 32 groundwater samples in both premonsoon and postmonsoon seasons have some parameters above their standard limits, i.e., acceptable and permissible limits (in absence of an alternate source) of BIS (Bureau of Indian Standards) (2012) and guideline values of WHO (World Health Organization) (2017). Even then, 30 groundwater samples fall under 'good' category and two samples (G19 and G31) under 'marginal' category during the premonsoon season. During postmonsoon period, 22 samples fall under 'good', nine under 'marginal' and one (G31) under 'poor' categories [Tables 1; Tables 6a and 6b; Table S4 (a and b); Fig. 4c]. Table 4 explains the human uses under different categories of water classification.

Water samples falling in 'good' category have chemical parameters above the acceptable limits of BIS (Bureau of Indian Standards) (2012)/guideline values of WHO (World Health Organization) (2017), but below their permissible limits (Table 6a). The marginal and poor categories of groundwater samples have parameters above their permissible limits/guideline values (Table 6b). There are certain exceptions, however for the water samples to be classified under marginal or poor category even if the chemical parameters are within their permissible limits/guideline values; for example, if a water sample has high concentrations of Mg^{2+} that has higher *SI* values. Because, the score of a particular sample is the *SIs* aggregation of the violator parameters, greater deviation of the parameter concentrations from their respective acceptable limits or guideline values leads to their having higher magnitude of N_{CWQI} scores. For example, during premonsoon season, the lowest graded 'good' category sample (G30) with N_{CWQI} score of -0.20 has three violators parameters, namely TDS, TH, and Mg^{2+} (Table 6a), and their corresponding *SIs* are -0.054 (TDS), -0.029 (TH), and -0.113 (Mg^{2+}) (Table S5a). During the same season, the sample G19 having the lowest magnitude of N_{CWQI} score under 'marginal' category (i.e., best graded under 'marginal' category) has four violators parameters with their *SIs* values as -0.055 (TDS), -0.043 (TH), -0.069 (Ca^{2+}), and -0.100 (Mg^{2+}) with a cumulative N_{CWQI} score of -0.27 (Table S5a, Table 6a). Similar examples in postmonsoon season can be the lowest graded sample (G28) among the 'good' category with an N_{CWQI} score of -0.21 and the best graded sample (G15) under 'marginal' category with an N_{CWQI} score of -0.23 (Table 6b, Table S5b). From these examples, it is noticed that among the violator parameters, the *SI* score of Mg^{2+} in absolute term is much more than those of the other parameters, thus having higher impact on the N_{CWQI} scores.

The beauty of CWQI is that it considers water as a valuable resource and assigns each water sample to certain uses depending on its N_{CWQI} score. For example, samples G10, G12, G18, G24 and G31 have some chemical parameters above their permissible limits. But despite this, these samples have been categorized under 'marginal' or 'poor' categories and assigned to some water uses (Table 4, Table 6b).

3.5. Comparison of groundwater quality classifications between WQI, IWQI and CWQI

A comparison of various grades assigned to the 32 groundwater samples by WQI, IWQI and CWQI has been made in Tables 6a and 6b for both premonsoon and postmonsoon seasons. During premonsoon period, 14 samples have been categorized as 'excellent' and 17 samples as 'good' in WQI, while in CWQI, 30 samples have been categorized as 'good'. The grading of water samples in WQI has been based on its index value, even if few parameters exceed their acceptable/permissible limits (in absence of an alternative source) prescribed by BIS (Bureau of Indian Standards) (2012). But a water sample in which few parameters exceed their acceptable limits should not be categorized as 'excellent' since groundwater in such samples can only be used for drinking in absence of an alternate potable source of water. In CWQI, a groundwater sample is categorized as 'excellent' only when no chemical parameter in it exceeds its acceptable limit. While CWQI does not categorise any sample as 'excellent' in this study, among the top 15 highly graded water samples

by CWQI under 'good' category during premonsoon season (Table 6a), WQI recognises 10 of them as 'excellent' and 5 as 'good'. Even lowest graded (marginal/poor) sample, G31, by CWQI is graded as 'good' in WQI in both premonsoon and postmonsoon seasons. Therefore, groundwater quality grading by WQI method is possibly of doubtful authenticity, since it does not strictly stick to the regulatory quality criteria.

Water quality grading is far stricter in IWQI compared to WQI. In both premonsoon and postmonsoon seasons, no water sample qualifies for drinking in Nalagarh valley (Tables 6a and 6b). Only four water samples in premonsoon season are categorized as 'poor', although it is not clear if these water samples could be used for some other purpose if not for drinking (Table 1). Among the top 15 top graded samples ('good' category) by CWQI during the premonsoon season (Table 6a), only one sample, G20, is categorized as 'poor' in IWQI, while all other 14 are 'unsuitable' for any human use. Again, one of the lowest graded samples, G19, ranked at 31 out of 32 samples by CWQI is categorised as 'poor' in IWQI, while the top graded sample, G2, that is categorized as 'good' by both WQI and CWQI, is graded as 'unsuitable' by IWQI (Table 6a). Similarly, during postmonsoon season, the best water sample (G21) graded as 'good' by both WQI and CWQI is classified as 'unsuitable' by IWQI (Table 6b). Therefore, grading done by IWQI is not consistent. Sub-section 2.3.2 discusses many other issues pertaining to IWQI that are of serious concern.

The discussion above concludes that CWQI is far superior to those of WQI and IWQI in giving six distinct water classes for various uses, i.e., for drinking, domestic, irrigation and industrial consumption. It considers the regulatory limits of both relaxable and non-relaxable chemical parameters and the water classification system is based on the quality ratings and unit weights of the major chemical parameters.

3.6. Limitations of the AHP models

Analytical hierarchy process is successfully applied to various quantitative and qualitative studies around the globe to solve complex problems by stepwise splitting/disintegrating them into sub-problems (clusters and subgroups). However, a major limitation of AHP is that while the parameters/variables considered in a particular model may explain the valuable relationship among them through hierarchal structure, the inclusion or exclusion of a specific/several parameter(s) may affect the entire information set-up of the hierarchical model structure and its outcome (Sharma et al., 2022). Analysis through AHP becomes more complex when the model represents multiple levels/layers of hierarchal structure (clusters and subgroups) and assigns different scales to the variables in each subgroup to compute stratified pair-wise comparison matrices.

Further, judgement by an expert sometimes does not eliminate the human subjectivity (bias) while assigning relative weights and calculating normalized weights of parameters through pair-wise comparison matrix. In other words, judgement of various experts may not fully guarantee that the final outcome would be an ideal solution by an AHP model (Sharma et al., 2022). Therefore, sensitivity analysis of AHP for validating through consistency ratio (CR) is desired. If the CR value exceeds 0.10, readjustment of responses in the pair-wise comparison matrix is necessary to rectify the inconsistency. In the present study, the CR value is 0.0033 (Table 2). It thus validates the accuracy of the AHP model for deriving the normalized weight for 13 parameters.

4. Summary and conclusions

Since its inception in 1965, there have been many modifications of the popular 'water quality index (WQI)'. But WQI has serious limitation in assigning unit weight of a chemical parameter besides having few other minor problems. Finding an appropriate unit weight of a chemical parameter is important since its magnitude multiplied by its quality rating decides the sub-index value of the parameter that decides its role

in determining the final water quality index of a water sample. While WQI offers a formula for determining the quality rating of a chemical parameter, its unit weight is proportional to its standard guideline value. So smaller the magnitude of a guideline value, higher the unit weight and vice-versa. Case of F^- and NO_3^- may be taken as an example.

To overcome this limitation, integrated water quality index (IWQI) was introduced in 2019. However, this model too has many serious problems, such as (i) not assigning any weight (unit/relative) to individual parameters, (ii) relying too much on BIS (Bureau of Indian Standards) (2012) desirable limits, which are, in fact, non-existent, (iii) modifying the permissible limits of both relaxable and non-relaxable parameters uniformly, (iv) considering the water samples with certain chemical concentrations above their acceptable limits under 'excellent' category, (v) concentrations of the chemical parameters above their permissible limits having lower sub-index values thereby indicating better water quality, etc.

The above discrepancies have been removed by the introduction of the comprehensive water quality index (CWQI) that has been devised on the basis of the analytical hierarchy process (AHP). The results were applied in the groundwaters of Nalagarh valley, Himachal Pradesh, India, as a case study. Both acceptable and permissible (in absence of an alternate source) limits of the relaxable parameters as per BIS (Bureau of Indian Standards) (2012) and guideline values of the non-relaxable parameters as per WHO (World Health Organization) (2017) were considered while grading the chemical quality of the groundwater samples. Two segments, P_{CWQI} and N_{CWQI} , were primarily calculated with P_{CWQI} varying between 0 and 1 and N_{CWQI} between 0 and -0.840 . Water quality is primarily graded on the basis of N_{CWQI} scores. Lower the absolute scores of the N_{CWQI} and higher the P_{CWQI} , better the water quality. When $N_{CWQI} = 0$, with a higher P_{CWQI} score, a water sample could be graded under 'excellent' category. Other categories were defined on the basis of N_{CWQI} scores varying between 0 and -0.21 for 'good', -0.21 and -0.42 for 'marginal', -0.42 and -0.63 for 'poor', -0.63 and -0.840 for 'very poor' and < -0.840 for 'unacceptable' quality of groundwater. Since water is a precious resource, each grade was assigned to certain uses. When two samples had the same N_{CWQI} scores, they were graded based on P_{CWQI} . When both N_{CWQI} and P_{CWQI} had equal magnitudes in these water samples, they were graded equally.

Until now, CWQI is possibly the best indexing method that offers an unbiased classification of groundwater quality. The concepts are based on logic and the quality criteria are defined by both BIS (Bureau of Indian Standards) (2012) and WHO (World Health Organization) (2017). Workers around the world can easily apply this method in their study areas. Although CWQI has been designed for evaluating groundwater quality, it can also be applied to assess surface water quality barring few essential parameters, such as dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, *Escherichia coli*, and total bacteria count.

CRedit authorship contribution statement

Herojeet Rajkumar: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft. **Pradeep K. Naik:** Writing – review & editing, Visualization, Validation, Supervision. **Madhuri S. Rishi:** Resources, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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