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Development and evaluation of a water quality index for groundwater quality assessment in parts of Jabalpur District, Madhya Pradesh, India

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ABSTRACT

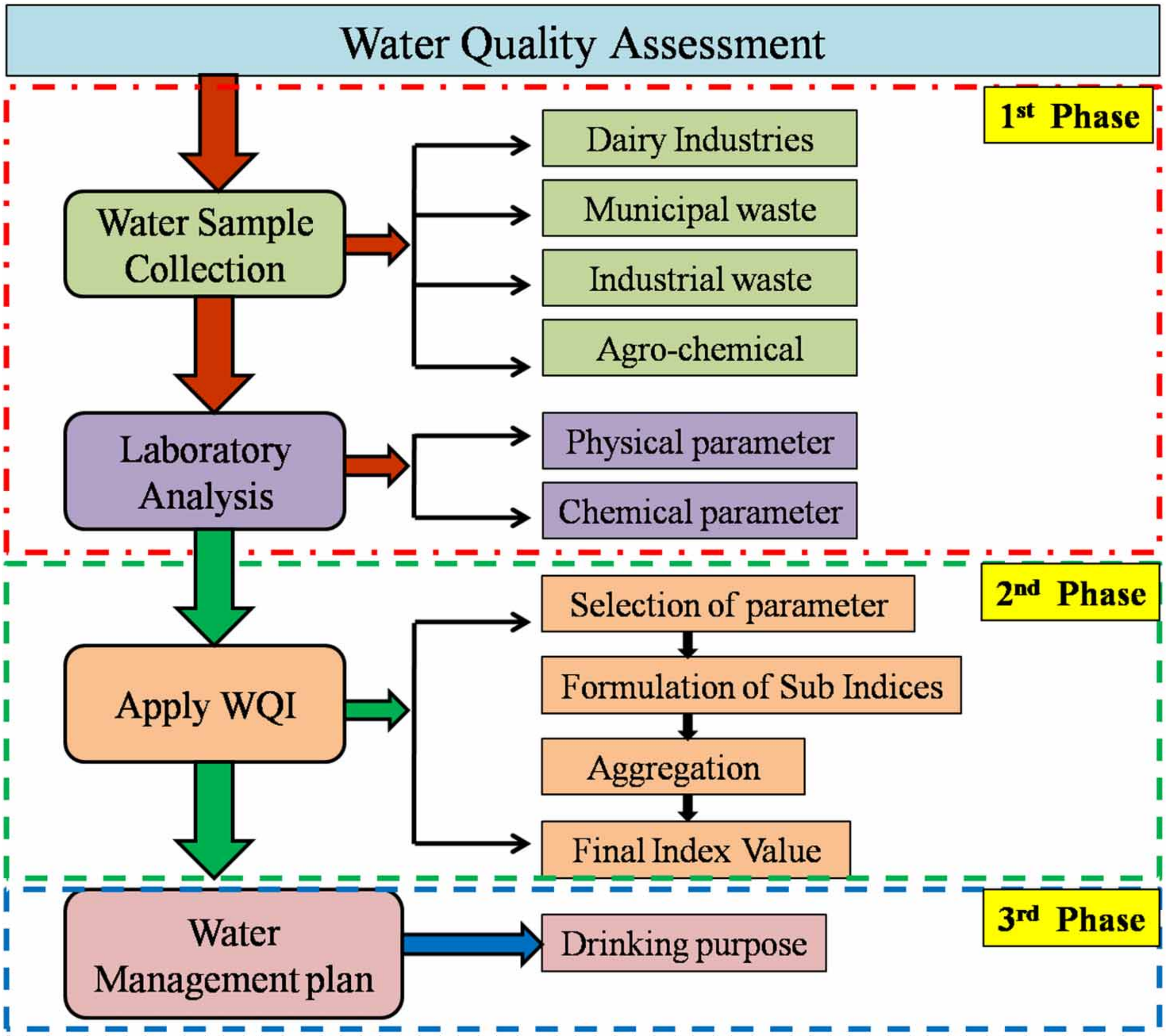
Groundwater is an important source for drinking water supply in Jabalpur District, Madhya Pradesh, India. An attempt has been made in this work to understand the suitability of groundwater for human consumption. The parameters of pH, Electrical Conductivity (EC), Copper (Cu), Chromium (Cr), Sulphate (SO_4), Iron (Fe), Nitrate (NO_3), Chloride (Cl), Total Hardness (TH), Total Alkalinity (TA), and Sodium (Na) were analyzed to estimate the groundwater quality. The water quality index (WQI) has been applied to categorize the water quality, which is quite useful to infer the quality of water for the people and policy makers in the concerned area. The WQI in the study area ranges from 17.90 to 176.88. According to the WQI rating, sites 1, 3, and 4 are not appropriate for drinking water or have low water quality and site 2 has moderate drinking condition, whereas site 5 has excellent drinking condition. The current study suggests that the groundwater of the area with deteriorated water quality needs treatment before consumption.

Key words: groundwater, principal component analysis (PCA), water quality, WQI

HIGHLIGHTS

- WQI values in sites 1, 3 and 4 are 106.99, 176.88, 161.25, showing that the groundwater is not suitable for drinking purposes.
- WQI value in site 5 is 17.90, showing that water is fit for drinking purposes.
- Principal component analysis reveals that four parameters are responsible for the high values of WQI.
- The outcome of the study will be helpful in formulating effective drinking water management measures for residents in the Jabalpur region, India.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The purity of water is essential to all living beings. For example, precipitation, weathering and soil erosion, as well as human-induced variables such as human exploitation of water resources, can all affect the quality of a region's surface water (Meshram *et al.* 2020a, 2020b, 2021a, 2021b). This includes both natural and anthropogenic factors. It is a big problem because of the rapid growth of human population, rapid industrialization, unplanned cities, pollution moving down from the hills to the lowlands, and the excessive use of fertilizers and pesticides in farming (Ouyang *et al.* 2006).

Groundwater is an important natural water resource that has long been used for drinking and irrigation, particularly in dry and semi-arid climates (Ramakrishnaiah *et al.* 2009; Li *et al.* 2018; Adimalla & Qian 2019; Ram *et al.* 2021). Groundwater is important as it can be directly used for potable water (via desalination) and industrial applications (Panagopoulos 2021a, 2021b, 2021c). Despite the fact that groundwater is frequently thought to be the cleanest of all inland water supplies, studies reveal that it is not fully free of contamination, albeit it is expected to be free of suspended solids. The underlying problem with groundwater is that once it has been contaminated, it is impossible to regain its purity. As a result, there is a need for, and apprehension about, groundwater quality conservation and management (Said *et al.* 2004). Because water quality is dependent on a number of factors, it is widely acknowledged that there are no straightforward explanations for its degradation. Many metrics have significant correlations, and the cumulative effect of their interconnection shows water quality. To assess groundwater quality, the concentrations of many physicochemical parameters in industrial areas are measured and compared with drinking water standards (de França Doria 2010). Groundwater contamination, drinking and irrigation water quality, and geochemical occurrence and distribution have all been investigated all over the world (Narsimha & Sudarshan 2013; Khan & Jhariya 2017; Adimalla & Venkatayogi 2018; He & Wu 2018; Li *et al.* 2018; Zhang *et al.* 2018).

In order to better understand the water quality and ecological status of the studied systems and identify potential factors/ sources that influence water systems, a variety of applied mathematics techniques, such as Cluster Analysis (CA), Principal Component Analysis (PCA), Factor Analysis (FA), and Discriminant Analysis (DA), help interpret advanced information matrices and provide a useful tool for reliable water resource management (Simeonov *et al.* 2004). Multivariate statistical methods have been used to define and evaluate surface and freshwater quality, which is important because they can be used to show how natural and anthropogenic sources can change over time and space (Helena *et al.* 2000).

Various researchers have investigated the contamination sources of river water using PCA and FA approaches. Simeonov *et al.* (2003), for example, used PCA to examine the association between a variety of parameters in order to assess water quality in northern Greece. PCA has been found to be a useful tool for analyzing huge datasets and developing analytical methodologies. To investigate the causes of parameter change, Shrestha & Kazama (2007) divided participants into groups based on regional and seasonal features. Although all approaches allow for dimensional reduction, Factor Analysis (FA), Cluster Analysis (CA), and Discriminant Analysis (DA) are commonly employed when the goal is to examine and understand the relationship between the variables, whereas PCA is commonly used when the goal is to focus on data reduction while losing some perception. At a dumpsite, Amadi (2011) used FA to discern between natural and anthropogenic causes of groundwater pollution. CA was used by Azhar *et al.* (2015) and Fathi *et al.* (2018) to group similar sample stations together based on system characteristics. FA reduces data by locating hidden variables (factors) that explain covariance, allowing the original parameters to be stated as a linear combination. Zeinalzadeh & Rezaei (2017) created a two-parameter index that beat the National Sanitation Foundation Water Quality Index (NSFWQI) in detecting changes in river conditions by using PCA to extract the most important indicators from water samples taken from the Shahr Chai River in Iran. Many researchers have considered the use of PCA approaches in a variety of domains (for example: Vega *et al.* 1998; Yu *et al.* 1998; Morales *et al.* 1999; Perkins & Underwood 2000; Bordalo *et al.* 2001; Gangopadhyay *et al.* 2001; Voutsa *et al.* 2001; Bengraïne & Marhaba 2003; Ouyang 2005).

Jabalpur is a region in Madhya Pradesh State (MP), where groundwater is a major water resource for drinking, domestic and agricultural purposes. No efforts have been made to understand the comprehensive evaluation of groundwater quality using the PCA approach in this region. Therefore, groundwater quality in this area is vital in determining the suitability of water for drinking purposes. Thus, the objective of the study is to calculate the WQI of groundwater in order to assess its suitability for human consumption using the PCA approach in the study area. It is expected that the outcome of the study will be helpful in formulating an effective drinking water management measure for residents in the Jabalpur region.

2. MATERIALS AND METHODS

2.1. Study area and data source

The location of Jabalpur (MP) was selected for the present analysis. The research was conducted on four point sources and one non-point wastewater source. The point sources are site 1 (dairy industries), sites 2–3 (municipal waste) and site 4 (industrial waste), and site 5 is a non-point source of agro-chemicals. Jabalpur is located on the Kymore plateau and Satpura hills in the agro-climatic area of 23 °9′ N latitude and 79 °58′ E longitude, at an altitude of 411.78 metres above mean sea level, and has a sub-tropical, sub-humid climate. Summers are hot and dry, and winters are cold and rainy. The temperature at this site can drop below freezing in the winter and exceed 46 °C in the summer, making the environment quite severe (Figure 1).

2.2. Water sampling

The groundwater samples were carried out during the premonsoon (February) period in 2018. A total of 280 groundwater samples were collected from existing hand pumps, bore wells, or open wells and stored in thoroughly prewashed high-quality polyethylene bottles at 4 °C until analysis. The samples were collected at 8:00 AM and 1:00 PM daily from the five sites.

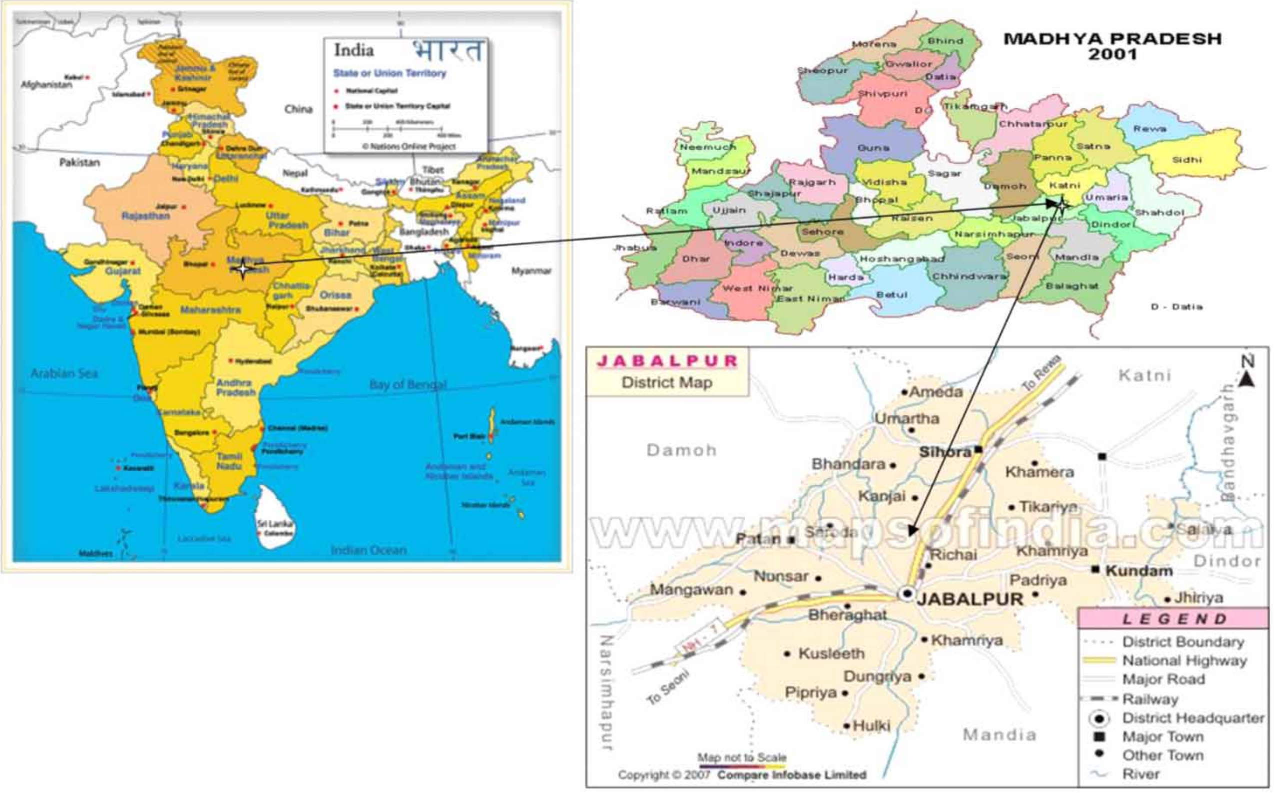


Figure 1 | Location map of the study area.

2.3. Determination of properties of water

The 11 variables examined for the water sample were pH, EC, Cu, Cr, SO_4, Fe, NO_3, Cl, TH, TA, and Na. Table 1 lists the water quality metrics and their abbreviations. All water samples were analyzed using standard procedures recommended by the American Public Health Association (APHA 1992).

2.4. Principal component analysis

To perform the statistical analysis, SPSS 14.0 was used. With a large dataset of interrelated variables, PCA is an excellent method for attempting to explain variation by using a small number of unbiased variables (Simeonov *et al.* 2003). The eigenvalues and eigenvectors of the original variables are extracted from the covariance matrix using the PCA method. By

Table 1 | Water quality parameters and their abbreviation

Parameters	Abbreviation	Unit
pH		–
EC	Electric conductivity	(dS/m)
Cu	Copper	(mg/l)
Cr	Chromium	(mg/l)
SO_4	Sulphate	(mg/l)
Fe	Iron	(mg/l)
NO_3	Nitrate	(mg/l)
Cl	Chloride	(mg/l)
TH	Total hardness	(mg/l)
TA	Total alkalinity	(mg/l)
Na	Sodium	(mg/l)

multiplying the unique correlated variables with an eigenvector, which is a set of coefficients, we get uncorrelated (orthogonal) variables (PC). As a result, the PCs are linear weighted combinations of the distinct variables. The PC keeps track of the most important aspects of the data collection, as well as enabling data reduction with little data loss (Vega *et al.* 1998). It is a powerful pattern-recognition technique that tries to explain the variation of a large number of connected variables by breaking them down into a smaller number of unrelated variables (principal components). PCA is a method for extracting a collection of independent linear combinations of study parameters in order to capture as much variability as possible in a dataset (Panigrahi *et al.* 2007). PCA can be calculated using Equation (1):

$$f_{ij} + f_{i1}z_{i1} + f_{i2}z_{i2} + \cdots \ldots\ \ldots\ \ldots f_{im}z_m + e_{ij} \tag{1}$$

where $j =$ measured variable, $f =$ factor loading, $z =$ factor score, $e =$ residual term accounting for errors, $i =$ sample number, and $m =$ total number of factors.

2.5. Water quality index

The Water Quality Index (WQI) is a mathematical method for obtaining a single number to reflect water quality from several water quality measures, created by Horton (1965). Water quality can be assessed by employing a number of commonly used water parameters, such as BOD (Biological Oxygen Demand), temperature, turbidity and conductivity (Kankal *et al.* 2012). Water quality parameters are measured using the WQI, which provides a way to construct a numerical expression that may be used to describe water quality (Miller *et al.* 1986). Using a chosen method or model, the water quality index reduces water quality data to a common scale and aggregates it into one value. All water quality criteria are taken into account in the WQI calculation, which is based on the appropriateness of surface and groundwater for their intended use. The following three processes are the most frequently linked with developing any index:

i. Parameter selection.
ii. Assignment of weightage to all parameters.
iii. Aggregation of sub-indices (or parameter) to produce a final index.

Parameter selection: Parameter selection necessitates three steps. The first step is Principal Component Analysis, which identifies the most meaningful parameters that best represent the entire data collection, allowing for data reduction with minimal loss of original information (Helena *et al.* 2000). After varimaxally rotating the initial factor loading matrix, an attempt is made to arrange the parameters into factors and to exclude those with no substantial linkages to rotated factors or components. In step 3, the covariance explained by each component and its percentage contribution to the overall covariance of the components are determined for rotating loading matrices of factors.

Assignment of weightage to all parameters: A higher weight value indicates that the parameter is more significant. The most difficult aspect of determining the weight of each parameter is that various people may have varying viewpoints. Different parameters are assigned weights based on the designed proportional factors.

Aggregation of sub-indices (parameter) to produce a final index: The process of merging and simplifying a group of water quality parameters is known as aggregation. The following equation describes the WQI aggregation function:

$$WQI = \sum (P1 * w_{P1}) + (P2 * w_{P2}) + (P3 * w_{P3}) + (P4 * w_{P4}) \tag{2}$$

where $P1$, $P2$,….. $Pn =$ water quality parameters; w_{P1}, w_{P2}……..$w_{Pn} =$ weightage of the corresponding parameter.

The above-mentioned water quality metrics are described in depth below, with findings displayed in Table 2.

3. RESULTS AND DISCUSSIONS

3.1. Water quality parameter

The findings of the groundwater sample analysis are shown in Table 2. According to this data, the pH of the water samples ranges from 7.42 to 7.61. These statistics are within the WHO's (World Health Organization) safe limits. Site 2 has the highest average EC value (1.66 dS/m), which is considered high by the USSL (United States Salinity Laboratory). Site 1 comes in second (1.27 dS/m). The lowest EC value (1.03 dS/m) was obtained at site 5. As a result, all of the samples were classified as high. Copper levels in sites 1 through 5 are 0.26 mg/l, 0.13 mg/l, 0.90 mg/l, 0.40 mg/l, and 0.12 mg/l, respectively. The

Table 2 | Physico-chemical properties of water samples

	Location				
Parameter	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
pH	7.50	7.58	7.61	7.42	7.50
EC (dS/m)	1.27	1.66	1.16	1.11	1.03
Cu (mg/l)	0.26	0.13	0.90	0.40	0.12
Cr (mg/l)	0.08	0.07	0.23	0.08	0.04
SO_4 (mg/l)	43	12	60	47	18
Fe (mg/l)	0.92	0.39	0.48	0.52	0.29
NO_3 (mg/l)	1.86	4.8	0.71	0.45	0.62
Cl (mg/l)	42	36	50	75	45
TH (mg/l)	300	240	235	280	260
TA (mg/l)	717	790	900	710	520
Na (mg/l)	488	380	520	130	128

copper concentration in all water tests, according to WHO, is within the permitted range. The highest concentration of Cr is found at site 3 (0.23 mg/l). Sites 1 and 4 (0.08 mg/l), site 2 (0.07 mg/l), and site 5 (0.04 mg/l) have the lowest Cr values.

Drinking water containing more than 400 mg/l of sulphate has a harsh, medicinal taste and can cause gastrointestinal discomfort and catharsis. SO_4 concentrations in water samples from sites 1 to 5 were 43 mg/l, 12 mg/l, 60 mg/l, 47 mg/l, and 18 mg/l, respectively. These SO_4 levels are all within the WHO's acceptable limit. The highest Fe content was found at site 1 (0.92 mg/l), followed by site 4 (0.52 mg/l). The lowest Fe measurement was for site 5 (0.29 mg/l). According to the WHO, the iron concentration in all water samples is below the permitted threshold. As a result of sewage percolation beneath the surface, nitrate is a pollutant present in groundwater. Natural water contains organic nitrate sources, as well as industrial and agricultural contaminants. The highest NO_3 concentration was found at site 2 (4.8 mg/l). Site 1 came next (1.86 mg/l), and site 4 had the lowest NO_3 value (0.45 mg/l). The nitrate amounts in all water tests, according to WHO, are within permissible levels.

Chloride levels in water samples from sites 1 to 5 are 42 mg/l, 36 mg/l, 50 mg/l, 75 mg/l, and 45 mg/l, respectively. According to the WHO, the chloride concentration in all water tests is within the permissible range. A high concentration of chlorine in groundwater makes it hazardous to human health (Pius *et al.* 2012; Sadat-Noori *et al.* 2014). The greatest TH value (300 mg/l) was found at site 1. Site 4 was next (280 mg/l), and site 3 had a TH value of 235 mg/l. All of the water samples have overall hardness levels that are below the WHO's tolerable limit. The main sources of alkalinity in natural water are hydrogen sulphide, carbonate, and bicarbonate. In and of itself, alkalinity is not harmful to people. Total alkalinity values at sites 1 through 5 were 717 mg/l, 790 mg/l, 900 mg/l, 710 mg/l, and 520 mg/l, respectively. The TA levels in water samples from sites 1 to 4 were higher, whereas readings from site 5 were below the WHO's authorized range.

Greater salt levels have been associated with cardiovascular disease and pregnancy-related toxaemia in women, according to the National Academy of Science. The maximum concentration of Na (520 mg/l) is found at site 3. The following two locations are site 1 (488 mg/l) and site 2 (380 mg/l). Site 5 has the lowest Na concentration (128 mg/l). Water samples from sites 4 to 5 were confirmed to be within the WHO's permitted range. According to WHO guidelines, water samples from sites 1 to 3 had higher salt levels. The high concentration of Na indicates weathering of rock-forming minerals and dissolution of soil salts present therein due to evaporation (Stallard & Edmond 1983). The high Na concentration in groundwater may be related to the mechanism of cation exchange (Kim & Yun 2005). Table 3 shows the mean, standard deviation, and coefficient of variation for the water samples that were chosen.

3.2. Principal component analysis (PCA)

In a preliminary assessment prior to doing the precept evaluation, a Pearson correlation matrix was used to ensure the relationship between physicochemical metrics. Table 4 shows the Pearson correlation matrix. The correlations between

Table 3 | Statistics of water quality parameters of groundwater samples

Parameters	Mean	SD	CV (%)
pH	7.52	0.07	0.89
EC	1.25	0.22	17.75
Cu	0.36	0.29	79.46
Cr	0.10	0.07	66.63
SO_4	36.00	18.15	50.40
Fe	0.52	0.22	41.37
NO_3	1.69	1.64	96.78
Cl	49.60	13.49	27.19
TH	263.00	24.42	9.28
TA	727.40	124.21	17.08
Na	329.20	169.93	51.62

Table 4 | Pearson correlation coefficients of physicochemical parameters under study

	pH	EC	Cu	Cr	SO_4	Fe	NO_3	Cl	TH	TA	Na
pH	1.0										
EC	0.40	1.0									
Cu	0.09	0.04	1.0								
Cr	−0.11	0.33	0.08	1.0							
SO_4	0.05	−0.07	−0.35	−0.80	1.0						
Fe	−0.75	−0.29	−0.44	0.22	−0.28	1.0					
NO_3	0.59	**0.61**	0.50	0.58	−0.48	−0.61	1.0				
Cl	0.27	−0.29	0.67	−0.48	−0.06	−0.33	0.02	1.0			
TH	−0.27	0.26	−0.03	−0.57	**0.68**	0.01	−0.40	0.01	1.0		
TA	0.11	**0.87**	0.07	0.23	0.17	−0.32	0.46	−0.42	0.50	1.0	
Na	**0.68**	0.21	−0.45	0.11	−0.19	−0.05	0.21	−0.06	−0.50	−0.21	1.0

Note: bold values show strong correlations of more than 0.60.

the physicochemical parameters under investigation revealed that EC has a strong (0.87) association with total alkalinity, while pH has a moderate (0.6) correlation with Na, EC with NO_3, Cu with chloride, and TH with SO_4. Grouping the traits into components and giving any physical significance is difficult at this time. As a result, in the next stage, the main component analysis is used. The correlation matrix is subjected to principal component analysis.

Table 5 summarizes the loadings, eigenvalues, and variance of each factor, as well as the overall cumulative variance of the variables. A factor with an eigenvalue greater than 1 was taken into account for this study. Using the Kaiser criterion, four distinct varimax factors (VF) were discovered, accounting for 94.62 percent of the entire variation in water quality.

The first VF, best represented by chromium, accounted for 31.39 percent of the total variance (Cr). VF2 was responsible for 24.38 percent of the total variance and had a significant impact on EC and TA. VF3 had a positive loading on pH and Na, and it accounted for 21.60 percent of the variance. VF4 had a significant loading on Cu and Cl, and explained 17.25 percent of the overall variance.

3.3. Derivation of the water quality index

As a starting point, we only include the first four principal components because they explain 94.62 percent of the total variance. Cr, TA, pH and Cu are selected from PC1 through PC4. Afterwards, the eigenvalues associated with each PC axis are ranked according to their importance in terms of the amount of variation they explain (i.e. PC1*31.39; PC2*24.38;

Table 5 | Varimax-rotated component matrix

	Component			
Parameter	**VF1**	**VF2**	**VF3**	**VF4**
pH	−0.04	0.22	**0.93**	0.27
EC	0.08	0.91	0.22	−0.05
Cu	0.23	0.10	−0.19	**0.94**
Cr	**0.91**	0.32	−0.09	−0.19
SO_4	−0.90	0.07	0.03	−0.12
Fe	0.23	−0.38	−0.53	−0.61
NO_3	0.54	0.59	0.40	0.42
Cl	−0.16	−0.41	0.13	0.81
TH	−0.77	0.37	−0.43	0.00
TA	−0.11	**0.98**	−0.10	−0.02
Na	0.20	−0.11	0.86	−0.35
Eigenvalues	3.45	2.68	2.37	1.89
Percentage of variance by component	31.39	24.38	21.60	17.25
Cumulative percentage of variance	31.39	55.77	77.37	94.62

Note: bold values show strong correlations of more than 0.90.

PC3*21.60; PC4*17.25), as shown in Table 5. Cr receives the most weight, whereas Cu receives the least weight (order of importance) (fourth order of importance) (Table 6).

$$WQI = \sum (Cr * w_{Cr}) + (TA * w_{TA}) + (pH * w_{pH}) + (Cu * w_{Cu}) \quad (3)$$

where Cr, TA, pH, Cu = water quality parameters. W_{Cr}, W_{TA}, W_{pH}, W_{Cu} = weightage of the corresponding parameter.

3.4. Water quality index

Water samples from each of the five sites were tested. The Water Quality Index (WQI) was developed for each site based on a large number of linked water quality factors. A WQI was developed based on the four water quality criteria (parameters). The classification of groundwater quality in relation to WQI is shown in Table 7. According to the findings, sites 1, 3, and 4 are plagued by water quality issues and are not appropriate for consumption. Site 2 is in poor drinking condition, while site 5 is in great drinking condition (Table 8). WQI values range from 17.90 to 176.887. It was discovered that groundwater in the majority of the research area is unfit for drinking due to excessive electrical conductivity, Na, and total alkalinity values exceeding the WHO permitted limit (2012).

Most respondents at the sample sites used shallow tube wells to obtain drinking water due to lower installation costs. Water from shallow tube wells has been shown to contain high quantities of iron and arsenic in some regions. As reported by Prusty & Farooq (2020) in coastal districts, water from both shallow and deep tube wells was salty. According to Yisa & Jimoh (2010), greater levels of iron and manganese are related to poor water quality. These characteristics are typical of unplanned

Table 6 | Order of importance of water quality parameters

Parameter	**Rotated factor**	**Square rotated**	**% covariance**	**Importance (%)**	**Order**	**Weightage**
Cr	0.91	0.83	31.39	26.05	1	1.20
TA	0.98	0.96	24.38	23.40	2	1.06
pH	0.93	0.86	21.60	18.58	3	0.94
Cu	0.94	0.88	17.25	15.18	4	0.80

Table 7 | Classification of groundwater quality according to WQI range

Akter *et al.* (2016)		Chaurasia *et al.* (2018)	
WQI Range	Type of water	WQI Range	Type of water
<35	Excellent	<50	Excellent
35–45	Good	50–100	Good water
45–55	Moderate	101–200	Poor water
55–65	Poor	201–300	Very poor
65–75	Very poor	>300	Not suitable for drinking water
>75	Not suitable for drinking water		

Table 8 | Computed water quality index values for sample sites

Location	WQI	Akter *et al.* (2016)	Chaurasia *et al.* (2018)
Site 1	106.9914	Not suitable for drinking water	Poor water
Site 2	52.12459	Moderate	Good water
Site 3	176.887	Not suitable for drinking water	Poor water
Site 4	161.2565	Not suitable for drinking water	Poor water
Site 5	17.9065	Excellent	Excellent

garbage dumping, agricultural run-off containing pesticides or fertilisers, and other environmentally detrimental activities that pollute surface water (Chapman 1996).

There were some limitations to the study. The data for this study was obtained during the premonsoon season (February). It would have been preferable to collect samples throughout the year, taking into account seasonality and well depth. We were unable to collect information on other WHO-recommended chemical parameters since they were outside of our area of work. Other WHO-recommended chemical parameters may be measured in the future.

4. CONCLUSIONS

This paper has highlighted an evaluation of groundwater quality for drinking purposes using water quality index studies in the study region. In this study, a statistical technique (PCA) was used to evaluate variations in groundwater quality. PCA analysis grouped 11 water quality parameters into four factors (Cr, TA, pH, and Cu) of similar water quality characteristics. Based on the obtained information, it is possible to design a future, optimal WQI, which could reduce the number of parameter estimations and associated costs. Principal component analysis helped us figure out what caused the water quality to change.

The WQI values range from 17.90 to 176.887. The high value of WQI at these sites has been found to be mainly from the higher values of EC, Na and total alkalinity (TA) in the groundwater. Water samples from sites 1, 2 and 3 are highly polluted in terms of Na, EC and TA while other elements are within permissible levels.

The water quality evaluation reveals that the groundwater in sites 1, 3, and 4 is unfit for drinking or has poor water quality, and the pollution load is rather significant in comparison with site 2. The groundwater quality in site 5 is suitable for drinking. According to the research, water quality monitoring and management should be prioritised in order to safeguard the groundwater resource from contamination and provide technologies to make groundwater suitable for residential and drinking uses.

FUNDING

Not applicable.

CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animals performed by any of the authors.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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