Geochemical and multivariate assessment of groundwater resources of Churachandpur sub-division of Manipur, India

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Abstract
Hydrogeochemical and multivariate assessment of groundwater samples of the Churachandpur sub-division of the state of Manipur was carried out to study its suitability for potable and irrigational uses. The study extensively discusses the underlying hydro-geochemistry using multivariate geostatistical tools for physicochemical parameters of 35 spatially distributed groundwater samples during pre- and post-monsoon seasons. In situ parameters (pH, TDS, DO, EC, salinity, ORP) were assessed in field conditions, and it was found that few samples exceed concentration than the prescribed standards. Both positive and negative ORP values and low DO levels of the samples indicate oxidizing and reducing aquifers due to recent unstable geologic formations. Although the concentration of Cl−, SO4\(^{2-}\), and NO3\(^{-}\) is well within desirable levels, the concentration of F\(^{-}\) and As\(^{3+}\) of a few samples exceeds the prescribed standard. The water quality index of the groundwater samples signifies that more than 50% of samples are unsuitable for potable uses for both seasons. The geochemical analysis indicates that most of the water is Ca–Mg–Cl–HCO\(_3\) type followed by Mg–Ca–Cl–HCO\(_3\) types in both the seasons and dominated by the rock-weathering geochemical process. Multivariate analysis and geostatistical mapping highlight the spatial variability of water quality parameters and possibilities of the occurrence of geogenic contaminants in the aquifers of the study area.

Keywords Geochemistry · Groundwater · Aquifer · Arsenic · Fluoride

Introduction
India is a major groundwater-dependent country, and around 90% of groundwater is extracted for irrigation use (Coyte et al. 2018). The usefulness of groundwater resources is dependent on their availability, accessibility, and quality (Kresic 1997). Accessibility to quality groundwater determines the human health, socioeconomic condition, and overall development of a region and is influenced by several natural and anthropocentric factors (Alam 2019, 2017; Choudhury et al. 2011; Mahanta et al. 2009, 2011). Anthropogenic activities, such as over-exploitation of groundwater resources, excessive use of chemical fertilizer, pesticides, and dumping of solid and industrial waste, can deteriorate the groundwater quality (Todd 2003). Recent studies have revealed geogenic contaminants in the region’s aquifers and their dissolution to groundwater due to hydrogeochemical interactions (Alam et al. 2020a; Mukherjee et al. 2015; Mahanta et al. 2015, 2011; Bhattacharya et al. 2012. The hydrogeochemical interactions are influenced by various geochemical reactions and dissolution processes such as oxidation–reduction reactions, precipitation, sorption, hydrogeological conditions, and climatic factors (McSween et al. 2003; Drever 1997). Thus, assessing basic ions in groundwater can extensively explain the hydrogeochemical interaction in the aquifer formations, dissolution of contaminants, and water types of a region (Prusty et al. 2003; Drever 1997). The present study attempts to assess spatiotemporal groundwater quality and geochemical properties of groundwater sources in the region using various water quality indices multivariate and geochemical tools to ensure sustainable groundwater resources for the region’s overall development.
Study area

The study was carried out in the Churachandpur sub-division, located in the hilly terrain of the south-western part of the state of Manipur (India) between the coordinates 93° 35′–93° 55′ E and 24° 15′–24° 40′ N (Fig. 1). The region is part of hilly terrain and Khuga river valley, which is a southern extension of Manipur valley with higher population density. Agriculture and rice cultivation is the primary source of livelihood of the people in the area. More than 90% of the total geographical location of the region is covered by the forest and very rich in forest biodiversity with endemic, rare floral species (MSAPCC 2013). The majority of the people in the study area depend on the spring water, dug wells, tube wells as a source of their potable water apart from limited public water supply from rivers and streams (CGWB 2013).

Materials and methods

Assessment of in situ parameters

As per the standard procedures, the groundwater samples were collected from 35 spatially distributed locations, including dug wells, shallow tube wells, and natural springs. Samples were collected in properly rinsed HDPE bottles from different sampling sites after sufficiently flushing the source and preserved with a few drops of 0.2 N HNO3 for further laboratory analysis of ions (APHA 2005). In situ parameters including temperature, pH, EC, DO, Salinity, TDS, ORP were assessed with the help of field testing electrodes and sensors (Eutech, Extech, Hanna). Field testing kit Arsenator (Wagtech) and ion meter (Thermo) were used to determine As3+ and F− concentration, respectively, in the field condition. The geographic coordinates of the sampling locations were recorded using a GPS handset (Garmin, Etrex 30).

Assessment of basic parameters and ions

The preserved samples were further brought to the laboratory and analysed to determine the basic ions and confirm the presence of geogenic contaminants (such as As3+ and F−). The samples were analysed using standard procedures of titrimetric, gravimetric, spectrophotometric, and ion chromatographic (IC) methods as described in standard procedures of APHA (2005).

Water quality index

Based on WHO standards, potability uses of groundwater sources were appraised using water quality indices (WQI) (WHO 2011). WQI is a combined mathematical water quality rating determined based on the overall influences of water quality parameters for specific uses and purposes. WQI was determined by assigning different weights (Wi) to water quality parameters according to their significant impacts on the overall water quality, and relative weights (Wir) are calculated as per the given equation (Ramakrishnaiah et al. 2009):

\[ W_i = \frac{W_i}{\sum W_i} \]  

where i is the number of water quality parameters under consideration for evaluation of WQI. As per the WHO guidelines and standards, the water quality rating scales (Qi) of each parameter are determined using the following equation:

\[ Q_i = \left( \frac{C_i}{S_i} \right) \times 100 \]  

where \( C_i \) represents the measured concentration of parameters and \( S_i \) represents the drinking water quality standards according to WHO (2011). Then, the sub-indices (SIi) of each parameter are evaluated using the following equation:

\[ SI_i = W_i \times Q_i \]  

The cumulative WQI is then calculated using the following summation of sub-indices (SIi)

\[ WQI = \sum SI_i \]  

The calculated WQI is then used for classification for status drinking water as unsuitable (WQI > 300); very poor (200 < WQI < 300); poor (100 < WQI < 200); good (50 < WQI < 100) and excellent (WQI < 50) (Alam et al. 2020b).

Geochemical assessment

Geochemical classification and water type of the groundwater samples can be determined through graphical plots between major cations and anions in the form of a trilinear diagram (Piper 1953). This is a prominent geochemical tool that categorizes the groundwater types or geochemical facies of water samples. Further, Gibb’s plots between cationic and anionic ratios as a function of TDS are widely used to assess and identify the dominant geochemical processes (precipitation, rock, and evaporation dominance) that govern the dissolution of ions in groundwater (Gibbs 1970).

Multivariate analysis

Multivariate statistical analysis of groundwater quality parameters was carried out to simplify and identify
complex hydrogeochemical relationships between parameters. The Pearson’s correlation ($r$) coefficient matrix represents the co-variability/correlation between the water quality parameters. The $t$-test was applied to observe the seasonal variability between the water quality parameters considering the assumption of normality at the significance level of $p$-value smaller than 0.05 ($p < 0.05$). In addition, the principal component analysis (PCA) and hierarchical cluster analysis (CA) were carried out to establish the geochemical interactions and grouping of water quality parameters based on their similar characteristics (Alam et al. 2020b).

**Irrigation water quality**

The concentration of EC, TDS, and irrigation water quality indices such as sodium absorption ratio (SAR), residual sodium carbonate (RSC), sodium percentage (%Na), Wilcoxon diagram, USDA classification, and permeability index (PI) is generally used for assessing salinity and alkali hazards of irrigation water. An increase in the percentage of sodium increases the SAR of the soil that represents the alkali hazards. These values can be evaluated using the following equations (concentrations of ionic species in meq/l)

\[
\%Na = \frac{(Na + K)}{(Ca + Mg + Na + K)} \times 100
\]

\[
SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}
\]

The RSC is the factor that regulates the impacts of carbonate ($CO_3^{2−}$) and bicarbonate ($HCO_3^{−}$) of the water on soil. The higher RSC value signifies more scope for sodium absorbability by soil. Mathematically, RSC can be expressed as

\[
RSC = (CO_3^{2−} + HCO_3^{−}) − (Ca^{2+} + Mg^{2+})
\]

Similarly, the permeability index determines soil’s ability to transmit water and air (Doneen 1964), and mathematically, it can be defined as given below:

\[
PI = \frac{(Na^+ + \sqrt{HCO_3^{−}})}{(Ca^{2+} + Mg^{2+} + Na^+)} \times 100
\]

where the ionic concentrations are expressed in meq/l. The US Salinity Laboratory’s (USSL 1954) diagram is widely used to classify and rate the irrigation water into 16 classes based on plotting between alkali hazards (SAR) and salinity hazards (EC) (Wilcox 1955).

**Results and discussion**

Statistical summary and descriptive statistics of twenty (20) physicochemical parameters of 34 spatially distributed groundwater samples are presented in Table 1. The table describes the minimum, maximum, average, standard deviation, and coefficient of variation (CV) to show the variability of groundwater physicochemical parameters, including in situ parameters and significant ions such as $F^−$ and $As^{3+}$.

**Evaluation of in situ parameters**

The majority of water quality parameters for both PM and PoM were found within the acceptable range except few samples that exceed WHO the prescribed standards (Table 1). During the PoM season, some samples show acidic characteristics due to the infiltration of overland water from heavy precipitation. TDS values in both seasons show exceeding amounts with an average of 300.3 ppm and 272.9 ppm during PM and PoM, respectively. High EC concentration in both the seasons and their strong correlation with TDS ($r > 0.97$ at $p < 0.05$) signifies the dissolution of inorganic lithophilic ions from the aquifer matrix of the study area. This is further ascertained by the high degree of a strong correlation between EC, TDS, and salinity concentrations in both seasons ($r > 0.95$ at $p < 0.05$). The groundwater quality parameters also exhibit significant spatiotemporal variability in concentrations in both seasons, indicating the seasonal influence of subsurface runoff. Low DO levels and negative ORP values of the samples indicate reducing aquifer conditions or may be due to microbial activity and shallowness of the aquifer (CGWB 2013). The ORP values, which range from −94 to 215 mV and −68 to 211 mV during PM and PoM, respectively, justify the existence of both oxidizing and reducing aquifers in the region. The 70.7% and 66.7% samples show hard to very hard category hardness due to the presence of both carbonate and non-carbonate hardness (Table 2). Arsenic ($As^{3+}$) and fluoride ($F^−$) in a few groundwater samples indicate that the aquifers in the study area are not free from arsenic and fluoride-bearing aquifers. The geostatistically interpolated map (Fig. 2) shows the possible spatial distribution of fluoride in the aquifer of the study area for both PM and PoM. The interpolated maps indicate the presence of potential Fluoride bearing aquifers in the central and southern portion of the study area during both seasons.

**Water quality index (WQI)**

The WQI values evaluated for the groundwater samples of the study area indicate that most of the samples fall in
the category of poor to unsuitable during both PM (64.7%) and PoM (52.9%) seasons (Table 3). It was observed that WQI is mainly influenced by the presence of geogenic contaminants like Fluoride and other water quality parameters like EC, TDS, TH. The geostatistical interpolation maps for WQI (Fig. 3) for the study area indicate poor WQI in the central portion of Churachandpur town mainly due to rapid urbanization, overexploitation of groundwater, and other anthropogenic influences. Poor and unsuitable WQI indicates possibilities of public health threats to the region if the population is more inclined to use groundwater resources in the future.

Geochemical analysis

The normalized inorganic charge balance (NICB) (ΣZ⁺−ΣZ⁻)/ΣZ⁺ + ΣZ⁻), i.e. the extent of deviation between the total cations (Ca²⁺, Mg²⁺, Na⁺, K⁺) and anions (SO₄²⁻, NO₃⁻, Cl⁻, HCO₃⁻) expressed in meq/l for each set of samples, was assessed and found in the accepted range of ± 10% (Domenico and Schwartz 1990). The Piper (1953) trilinear diagrams and Durov’s diagram were used to evaluate the geochemical facies of groundwater considering significant cations and anions (Figs. 4 and 5). These graphical plots represent the major water types of the study area that are

![Fig. 1 The geographical location and sampling points of the study area](image-url)
distinctly categorized as Ca–Mg–Cl–HCO$_3$ type followed by Mg–Ca–Cl–HCO$_3$ type water where concentrations of F$^-$ were found to be higher due to co-precipitation process of F$^-$ with Mg-rich calcite resulting in increased concentration of Mg$^{2+}$. Some samples with geochemical facies of Ca–Mg–Cl–SO$_4^{2-}$ types of water represent younger alluvial sediments of fluvio-lacustrine origin (Fig. 5). The Gibbs diagram (Fig. 6) indicates the chemical weathering of rock-forming minerals as a significant geochemical process that governs the dissolution of ions in groundwater.

### Table 1 The summary and descriptive statistics of the water quality parameters during PM and PoM seasons

| Parameters                      | Min   | Max    | Avg    | SD     | CV (%) | WHO Standards |
|---------------------------------|-------|--------|--------|--------|--------|---------------|
|                                | PM    | PoM    | PM     | PoM    | PM     | PoM           |
|                                | PM    | PoM    | PM     | PoM    | PM     | PoM           |
| Temp. (°C)                      | 20.0  | 20.9   | 29.30  | 30.10  | 23.39  | 23.39         |
| pH                              | 6.13  | 5.65   | 7.95   | 8.50   | 7.16   | 7.16          |
| TDS (ppm)                       | 80.00 | 70.0   | 620.0  | 730.0  | 300.9  | 272.9         |
| EC (µS)                         | 160.0 | 90.0   | 1230   | 1020   | 593.8  | 146.2         |
| ORP (mV)                        | −94.0 | −68.0  | 215.0  | 211.0  | 162.2  | 146.2         |
| DO (ppm)                        | 2.06  | 1.47   | 6.44   | 7.45   | 4.60   | 4.06          |
| Salinity (ppt)                  | 100   | 100    | 400    | 500    | 210    | 200           |
| Ca$^{2+}$ (mg/l)                | 31.91 | 34.6   | 408.9  | 414.9  | 177.1  | 169.1         |
| Mg$^{2+}$ (mg/l)                | 5.00  | 7.50   | 155.0  | 140.0  | 43.01  | 37.49         |
| TH as CaCO$_3$ (mg/l)           | 45.0  | 45.0   | 320.0  | 315.0  | 159.6  | 151.1         |
| Na$^+$ (ppm)                    | 14.01 | 12.0   | 92.10  | 114.1  | 46.67  | 45.49         |
| K$^+$ (ppm)                     | 4.19  | 2.16   | 144.8  | 235.0  | 27.47  | 38.17         |
| Cl$^-$ (mg/l)                   | 9.98  | 4.99   | 194.6  | 54.89  | 67.51  | 27.59         |
| HCO$_3^-$ (mg/l)                | 29.6  | 20.0   | 109.6  | 119.7  | 60.7   | 60.0          |
| SO$_4^{2-}$ (mg/l)              | 0.60  | 0.70   | 2.36   | 1.80   | 1.17   | 1.21          |
| NO$_3^-$ (mg/l)                 | 0.59  | 0.55   | 718.4  | 356.1  | 32.04  | 8.60          |
| PO$_4^{3-}$ (mg/l)              | 0.02  | −0.04  | 7.16   | 9.46   | 1.97   | 2.44          |
| F$^-$ (ppm)                     | 0.10  | 0.10   | 1.30   | 1.10   | 0.61   | 0.55          |
| As$^{3+}$ (ppb)                 | bdl   | bdl    | 50.00  | 50.00  | 3.82   | 3.82          |

**BDL** Betlow detection limit

### Table 2 USGS hardness classification of groundwater samples during PM and PoM seasons for the study area

| Hardness classification | Hardness as CaCO$_3$ (mg/l) | Percentage (%) of samples |
|------------------------|-----------------------------|---------------------------|
|                        | PM                          | PoM                       |
| Soft                   | 0–60                        | 9.1                       |
| Moderately hard        | 61–120                      | 18.2                      |
| Hard                   | 121–181                     | 30.3                      |
| Very hard              | > 180                       | 42.4                      |

### Multivariate analysis

#### Correlation coefficients ($r$)

Pearson’s correlation coefficients ($r$) between the water quality parameters and WQI are presented in Table 4. The high degree of significant correlation between various parameters such as EC, TDS, and Salinity shows very high co-variability ($r$ at $p < 0.05$) within them, indicating typical inorganic ion load in the groundwater samples during both seasons. Similarly, Salinity, TDS, Na$^+$, Ca$^{2+}$, and Cl$^-$ show a high degree of correlation, indicating the probable presence of halite-aquifer and Na and Ca-hardness of water. A strong and moderate correlation between TH, Cl$^-$ and salinity suggests the presence of non-carbonate hardness in the groundwater of the study area. The WQI exhibits moderate correlation with F$^-$ indicative of the higher concentration of F$^-$ influencing potability of the groundwater samples. The positive correlation of WQI with EC, salinity, TDS, Cl$^-$, TH, Ca$^{2+}$, Mg$^{2+}$ during both seasons signifies that these parameters deteriorate the drinking water quality.
Principal component analysis (PCA)

The three principal components (PCs) for both PM and PoM samples are presented in Table 5 (with eigenvalue > 1), which accounts for 61.24% (PM) and 62.4% (PoM) of variances in the hydrogeochemical variables and interactions. During pre-monsoon PC-1 (37.4%), PC-2 (50.5%), PC-3 (61.24%) account for variances within the samples. Similarly, during post-monsoon season PC-1 (35.4%), PC-2 (53.4%), PC-3 (62.4%) account for variances within the variables. It is fairly distinct that during both PM and PoM seasons, about 35.7% of variances of the data are highly

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**Table 3** The WQI of the study area during PM and PoM seasons

| Sl No. | Water quality | WQI range | Number of samples | Percentage (%) of samples |
|--------|---------------|-----------|-------------------|---------------------------|
|        |               | PM       | PoM              | PM           | PoM         |
| 1      | Excellent     | 0–50     | 3                | 5            | 8.8         | 14.7         |
| 2      | Good          | 50–100   | 9                | 11           | 26.5        | 32.4         |
| 3      | Poor          | 100–200  | 12               | 8            | 35.3        | 23.5         |
| 4      | Very poor     | 200–300  | 6                | 3            | 17.6        | 8.8          |
| 5      | Unsuitable    | Above 300| 4                | 7            | 11.8        | 20.6         |

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Fig. 2 The map showing the spatial distribution of fluoride concentration in the study area during a PM and b PoM seasons
Fig. 3  The map showing the spatial distribution of WQI in the study area during a PM and b PoM seasons

Fig. 4  Piper diagram showing the major groundwater types of the study area during a PM and b PoM seasons
correlated with EC, salinity, TDS, Ca\textsuperscript{2+}, Na\textsuperscript{+}, TH, and Cl\textsuperscript{−}. Similarly, PC-2 indicates 24.6% of variances in the variables are correlated with pH, DO, and F\textsuperscript{−} during PM and F\textsuperscript{−}, Cl\textsuperscript{−}, during PoM. These variations can be attributed to heavy precipitation and the shallow aquifer of the region (CGWB 2013).

Cluster analysis (CA)

The water quality parameter that determines the hydro-geochemical characteristics of the study area was analysed using hierarchical cluster analysis (CA). The CA indicates three major water quality parameters that determine the WQI and hydrogeochemical characteristics of the groundwater samples, i.e. groups I, II, and III (Fig. 7 and Table 6). The group exhibits considerable spatial variability of water quality parameters due to the inconsistency and variability of the aquifers formations. A higher concentration of Ca\textsuperscript{2+}, EC, TDS, ORP, and TH indicates the presence of inorganic ions and non-carbonates hardness of water due to the possibility of dissolution from halite-dominated aquifers. Groups II and III represent more non-carbonate types of hardness as HCO\textsubscript{3}\textsuperscript{−} concentrations are comparatively lesser. Moreover, the WQI of the samples indicates the influence of higher concentrations of EC, TDS, TH and the presence of alkaline earth metals ions.

Irrigational water quality

Based on the concentration of EC, TDS, sodium percentage (%Na), and irrigational water quality indices (Table 7), the suitability of groundwater was assessed for agricultural use. Although the concentration of EC and salinity exhibits higher values, all the groundwater samples were found within permissible range to the excellent irrigational water quality category. The TDS concentration of the samples was found in the freshwater range (< 1000 mg/l). Similarly, the sodium percentages (%Na), SAR, PI, and RSC of all groundwater samples exhibit excellent to good category.
Fig. 6 The Gibbs diagram represents the rock-weathering as dominant geochemical processes during (a) PM and (b) PoM seasons for both cations and anions.
Table 4 Multivariate correlation between water quality parameters and WQI during (a) PM and (b) PoM seasons

|          | pH   | TDS  | EC   | ORP  | DO   | Salinity | Ca²⁺ | Mg²⁺ | TH as CaCO₃ | Na⁺   | K⁺   | Cl⁻     | HCO₃⁻ | SO₄²⁻ | NO₃⁻ | PO₄³⁻ | F⁻ | As₃⁺ | WQI   |
|----------|------|------|------|------|------|----------|------|------|-------------|-------|------|---------|-------|-------|------|-------|----|------|-------|
| (a) Pre-monsoon (PM) |      |      |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Temp     | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00      |      |      |             |       |      |         |       |       |      |       |    |      |       |
| pH       | 1.00 |      |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| TDS      | −0.10| 1.00 | 1.00 | 1.00 | 1.00 | 1.00      |      |      |             |       |      |         |       |       |      |       |    |      |       |
| ORP      | −0.11| 0.25 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| DO       | 0.06 | 0.26 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Salinity | −0.11| 0.23 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Ca²⁺     | 0.26 | 0.13 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Mg²⁺     | 0.01 | 0.42 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| TH as CaCO₃ | 0.10 | 0.16 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| TH as Na⁺ | 0.31 | 0.14 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Na⁺      | 0.11 | 0.21 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| K⁺       | 0.34 | 0.12 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Cl⁻      | 0.23 | 0.17 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| HCO₃⁻    | 0.54 | 0.16 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| SO₄²⁻    | 0.24 | 0.54 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| NO₃⁻     | 0.34 | 0.21 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| PO₄³⁻    | 0.24 | 0.13 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| F⁻       | 0.12 | 0.35 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| As₃⁺     | 0.21 | 0.23 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| WQI      | 0.23 | 0.41 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| (b) Post-monsoon (PoM) |      |      |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Temp     | 1.00 |      |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| pH       | 1.00 |      |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| TDS      | −0.20| 1.00 | 1.00 | 1.00 | 1.00 | 1.00      |      |      |             |       |      |         |       |       |      |       |    |      |       |
| ORP      | −0.20| 0.22 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| DO       | 0.20 | 0.22 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Salinity | −0.26| 0.96 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Ca²⁺     | 0.92 | 0.22 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Mg²⁺     | 0.17 | 0.17 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| TH as CaCO₃ | 0.26 | 0.17 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| TH as Na⁺ | 0.26 | 0.17 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Na⁺      | 0.17 | 0.17 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| K⁺       | 0.28 | 0.17 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| Cl⁻      | 0.14 | 0.14 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| HCO₃⁻    | 0.47 | 0.47 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| SO₄²⁻    | 0.48 | 0.48 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| NO₃⁻     | −0.11| −0.11|      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| PO₄³⁻    | 0.19 | 0.09 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| F⁻       | −0.08| −0.08|      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| As₃⁺     | −0.11| −0.11|      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
| WQI      | 0.08 | 0.08 |      |      |      |          |      |      |             |       |      |         |       |       |      |       |    |      |       |
irrigational water and signify safe irrigation water in both seasons (PM and PoM). The plots between salinity (EC) and alkali (Na) hazards (Fig. 8) illustrate that the samples are in the category of excellent to good followed by good to permissible, respectively. The USSLS diagram (Fig. 9) demonstrates the plots between alkali (sodium) and salinity (EC) hazards. It reveals that around 15.0% (PM) and 26.4% (PoM) samples fall in the category of C1-S1 (low-salinity and low-alkali hazards), followed by 35.3% (PM) and 32.4% (PoM) samples in the category of C2-S1 (medium-salinity and low-alkali hazards). The remaining 49.7% (PM) and 31.0% (PoM) samples fall in the category of C3-S1 (high-salinity and low-alkali hazard), respectively.

**Conclusion**

The study highlights significant spatial variability of WQI and hydrogeochemical characteristics of groundwater resources of the study area. The presence of geogenic contaminants (F−, As3+) in some groundwater samples in exceeding concentration indicates the possibility of contaminant aquifers. Moreover, exceeding EC, TDS, salinity, TH, Na+, and Cl− in groundwater samples signifies their influence on the overall groundwater WQI. It was found that more than 50% of samples of the region are in the category of poor to unsuitable potable water as per the WHO standard. The presence of F− concentration in 8.8% (PM) and 17.6% (PoM) samples exceeds the WHO permissible limit. The geostatistically interpolated map indicates possible fluoride-affected zones that contribute to unsuitable WQI in the habitations of the region. The geochemical evaluation demonstrates that the rock-weathering processes dominate the aquifers, resulting in Ca–Mg–Cl−–HCO3− type water followed by Mg–Ca–Cl–HCO3 types water. The principal component analyses indicate more than 60% variance in the hydrogeochemical variables of the study area and signify that the underlying geochemical process is highly correlated with EC, TDS, TH, Ca2+. But the irrigational water qualities were found to be suitable according to irrigational water quality indices indicating that groundwater is safe for agricultural uses.
**Table 5** Varimax-rotated factor loadings with Eigen values and % of variances for the groundwater quality parameters during PM and PoM seasons

| Parameters | Component | PM | PoM |
|------------|-----------|----|-----|
|            | PC-1 | PC-2 | PC-3 | PC-1 | PC-2 | PC-3 |
| Temp       | -0.21 | 0.47 | -0.31 | -0.28 | 0.66 | -0.28 |
| pH         | -0.20 | **0.81** | 0.12 | -0.26 | 0.65 | -0.24 |
| TDS        | **0.95** | 0.10 | 0.02 | **0.97** | 0.01 | -0.08 |
| EC         | **0.95** | 0.10 | 0.03 | **0.98** | -0.02 | -0.09 |
| ORP        | 0.39 | -0.17 | 0.26 | 0.27 | -0.39 | 0.40 |
| DO         | -0.29 | **0.78** | 0.07 | -0.15 | 0.39 | 0.58 |
| Salinity   | **0.92** | -0.01 | 0.08 | **0.95** | -0.09 | -0.08 |
| Ca²⁺       | **0.91** | 0.04 | 0.22 | **0.89** | -0.21 | -0.20 |
| Mg²⁺       | 0.52 | 0.33 | -0.26 | 0.25 | 0.09 | 0.42 |
| TH as CaCO₃ | **0.82** | 0.14 | -0.46 | **0.89** | 0.20 | 0.10 |
| Na⁺        | **0.78** | -0.01 | -0.45 | **0.93** | 0.19 | -0.09 |
| K⁺         | 0.64 | -0.10 | -0.08 | 0.71 | -0.23 | 0.23 |
| Cl⁻        | **0.78** | -0.25 | 0.24 | 0.29 | **0.86** | 0.06 |
| HCO₃⁻      | 0.26 | 0.02 | -0.49 | 0.48 | 0.41 | -0.50 |
| SO₄²⁻      | 0.04 | 0.23 | 0.76 | -0.10 | -0.44 | -0.60 |
| NO₃⁻       | 0.52 | 0.23 | -0.04 | 0.13 | 0.21 | 0.26 |
| PO₄³⁻      | 0.33 | -0.07 | 0.37 | 0.41 | -0.42 | -0.07 |
| F⁻         | 0.11 | **0.78** | -0.05 | 0.29 | **0.86** | 0.06 |
| As³⁺       | 0.52 | 0.24 | 0.56 | 0.30 | -0.013 | 0.40 |
| Eigenvalues | 7.08 | 2.51 | 2.04 | 6.741 | 3.411 | 1.78 |
| Variability (%) | 37.27 | 13.23 | 10.74 | 35.48 | 17.95 | 9.38 |
| Cumulative (%) | 37.27 | 50.51 | 61.24 | 35.48 | 53.43 | 62.81 |

Bold indicates significant factor loadings

**Fig. 7** Dendrogram based on hierarchical cluster analysis shows the similar groundwater quality parameters and their contribution to WQI of the study area during **a** PM and **b** PoM seasons

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### Table 6  Groups showing similar types of groundwater quality parameters in the study area during PM and PoM seasons

| Group  | Water quality parameters                  | PM                        | PoM                        |
|--------|-------------------------------------------|---------------------------|---------------------------|
| Group I| Salinity; CO$_3^{2-}$, F$^-$, pH, SO$_4^{2-}$, PO$_4^{3-}$, DO, As$^{3+}$, Temp, K$^+$, Na$^+$, HCO$_3^-$, Mg$^{2+}$, Cl$^-$, NO$_3^-$ | Salinity; CO$_3^{2-}$, F$^-$, pH, SO$_4^{2-}$, PO$_4^{3-}$, DO, As$^{3+}$, Temp, K$^+$, Na$^+$, HCO$_3^-$, Mg$^{2+}$, Cl$^-$, NO$_3^-$ | |
| Group II| ORP, TH, Ca$^{2+}$, WQI                      | WQI, Ca$^{2+}$, TH, ORP | |
| Group III| EC, TDS                                      | EC, TDS                     | |

### Table 7  Various irrigational water quality indices during both PM and PoM seasons

| Parameters | Range | Groundwater class | Number of samples | Percent- age (%) of samples |
|------------|-------|-------------------|-------------------|-----------------------------|
| EC (µS/cm) (Richards 1954) | < 250 | Excellent | 5 | 10 | 14.7 | 29.4 |
| | 250–750 | Good | 18 | 20 | 52.9 | 58.8 |
| | 750–2000 | Permissible | 11 | 4 | 32.4 | 11.8 |
| | 2000–3000 | Doubtful | 0 | 0 | 0.0 | 0.0 |
| | > 3000 | Unsuitable | 0 | 0 | 0.0 | 0.0 |
| TDS (mg/l) (Freeze and Cherry 1979) | < 1000 | Freshwater | 34 | 34 | 100 | 100 |
| | 1000–3000 | Slightly saline | 0 | 0 | 0.0 | 0.0 |
| | 3000–10,000 | Moderately saline | 0 | 0 | 0.0 | 0.0 |
| | 10,000–35,000 | Highly saline | 0 | 0 | 0.0 | 0.0 |
| | > 35,000 | Brine | 0 | 0 | 0.0 | 0.0 |
| %Na (Wilcox 1955) | < 20 | Excellent | 23 | 16 | 67.6 | 47.1 |
| | 20–40 | Good | 11 | 18 | 32.4 | 52.9 |
| | 40–60 | Permissible | 0 | 0 | 0.0 | 0.0 |
| | 60–80 | Doubtful | 0 | 0 | 0.0 | 0.0 |
| | > 80 | Unsuitable | 0 | 0 | 0.0 | 0.0 |
| SAR (Bouwer 1978) | < 6 | No problem | 34 | 34 | 100 | 100 |
| | 6—9 | Increasing problem | 0 | 0 | 0.0 | 0.0 |
| | > 9 | Severe problem | 0 | 0 | 0.0 | 0.0 |
| PI (Doneen 1964) | < 60 | Suitable for irrigation | 34 | 34 | 100 | 100 |
| | > 60 | Unsuitable for irrigation | 0 | 0 | 0.0 | 0.0 |
| RSC (Eaton 1950) | > 1.25 | Unsuitable for irrigation | 0 | 0 | 0.0 | 0.0 |
| | < 1.25 | Safe for irrigation | 34 | 34 | 100 | 100 |
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Declarations

Conflict of interest This statement is to certify that there is no conflict of interest to declare. All Authors have seen and approved the manuscript being submitted. The article is the Authors’ original work, and it is not under consideration for publication or submitted for publication, nor has it been published in whole or in part elsewhere.
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