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Pollution Source Identification and Suitability Assessment of Groundwater Quality for Drinking Purposes in Semi-Arid Regions of the Southern Part of India

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Abstract: The quality of groundwater plays an important role in human health, and it majorly influences the agricultural process in the southern part of India. The present study mainly focused on evaluating the quality of groundwater used for domestic purpose in semi-arid regions of the southern part of India. The samples were collected in 36 locations, covering the entire investigation zone. The collected samples were analyzed for various physical and chemical characteristics of groundwater and compared with the world health organization standards. The entropy-weighted water quality index (EWQI) of the groundwater revealed that 16.67% of the samples required primary-level treatment before they could be used for drinking purposes. About 72.23% of the samples were in the good-to-medium category for drinking purposes, as was identified through weighted overlay analysis. The ionic relationship plot was used to identify the source of contamination and it revealed that carbonate weathering and anthropogenic activities are the primary sources of groundwater contamination. The present results show the contaminated zones and offer more helpful solutions to strengthen the water management policy in the study region.

Keywords: groundwater; EWQI; contaminated zone; anthropogenic activities; environment; GIS

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1. Introduction

Groundwater plays a vital role in human health and in the water supply system for the purpose of domestic, irrigation and industrial usage over the world [1]. Due to increases in demand for fresh water, the rapid increase in population, industrialization and urbanization activities are the key factors contributing to groundwater contamination [2]. Gravel, sand, sandstone and fractured rocks holding groundwater are called aquifers [3]. Groundwater flows through the interconnected voids and spaces below the Earth's surface. The natural outcomes of groundwater are classified as springs and are discharged into rivers, lakes and streams [3]. Groundwater is widely spread throughout the world and can be found almost everywhere. Groundwater tables are classified as either shallow or deep. Sources of groundwater are recharged by rain and melting snow. Recently, the world has started to face increased water demand due to the absence of surface water and the over

extraction of groundwater. In India, around 85% of rural and 50% of urban people depend on groundwater for domestic uses such as drinking, cooking and bathing [4–7].

In many regions of the world, groundwater sources are the most significant supply of drinking water, especially in regions with restricted or contaminated surface water sources. The nature of groundwater, especially shallow groundwater, is changing due to human activity. Groundwater is less subject to bacterial contamination than surface water due to the fact that the dirt and rocks through which it streams screen out the majority of the microorganisms [8]. In many emerging nations, accessibility of water has turned into a basic and critical issue as it is difficult to supply the required amount of water for their daily needs. In a detailed report by UNICEF in 2023, more than 892 million people still practice open defecation worldwide, and more than 1300 children (less than age of five) die every day due to water borne diseases and the consumption of unsafe drinking water [9]. Compliance with drinking water quality norms is of extraordinary importance on account of the ability of water to spread illnesses throughout large populations of people. Albeit the norms differ from one spot to another, the goal is to decrease the chance of spreading water borne illnesses as much as possible, as well as to make the water pleasant to drink, meaning that it should be safe for consumption and an attractive prospect [10]. The existence of groundwater is not uniform throughout the country. The variation in the rate of precipitation has majorly influenced the chemical properties of geology and geomorphology, finally dominating the nature of groundwater quality. Unconstrained and over extraction of groundwater has further aggravated the issue and has provoked a sharp reduction in the groundwater level. A large number of shallow wells have become dry. Thus, proficient assessment and arranging of groundwater resource the board is vital to resolve these issues [11–13].

Both Remote Sensing (RS) and Geographic Information System (GIS) are important methods and tools for use in understanding the ecological modifications due to man-made and nature disasters. For better preparation of ecological administration, the land use/land cover map is vital because it assists us with understanding the effect of these progressions on the ecosystem [14,15]. The existence of groundwater is reliant upon a few features, namely, precipitation, topography, land use/land cover and geomorphology. The over extraction of groundwater and inadequate rainfall intensity results in a shortage of groundwater. Consequently, systematic arranging is needed for the legitimate usage of and the executives of groundwater. Remote sensing and GIS have helped us to discover new wellsprings of groundwater-accessible zones. Hydrogeochemical studies are considered significant strategies for identifying and controlling the influencing processes of groundwater with the presence of minerals in the aquifer system. Groundwater composition in the study area was affected by chemical leaching from anthropogenic activities, dissolution, precipitation and the ion-exchange process of minerals in the aquifers. Once the groundwater is polluted, it may stay in an uncommon or even in dangerous condition for a very long time, even hundreds of years. It is truly challenging to recognize the extent of water quality issues [16]. In the present study area, groundwater investigation required data, such as lithological variations, precipitation intensity, geomorphic set up, surface water conditions and geographical changes. These boundaries and sample locations were identified during routine fieldwork. With the progression of remote detecting innovation, it is feasible to diminish the quantum of field investigation. The present research focused on analyzing the quality of groundwater for drinking purposes in the study area.

2. Materials and Methods

2.1. Study Area

The study area lies between the latitude of 10°0′00″ N and 10°15′00″ N, and the longitude of 77°40′00″ E and 77°55′00″ E in the southern part of Dindigul district, Tamil Nadu, India. It covers an area of 481.73 sq.km. The climatic conditions and weather of the study area are tropical and semi-arid throughout the entire zone of the study region. The annual average and minimum temperatures recorded are 28.6 °C and 19.7 °C, respectively,

throughout the year. The study region received 417.9 mm of precipitation during the northeast monsoon. About 75% of the investigation zone was covered by crystalline groups of rocks and fundamentally covered by quartzite ranging between 5 and 50 m thick and combined with magnetite, garnet, diopside, biotite and quartz.

2.2. Sample Collection and Analysis

In simple random sampling, a proper number of wells are chosen from the total population of accessible wells. Selection of the sample location is carried out in such a way that each well has an equivalent possibility of being selected (Figure 1). The impact of the population depends on the incentive behind the sample collection and monitoring. Random sampling is utilized when extrapolations on a river-basin-wide scale (e.g., water quality contour maps) are to be made, since it is accepted in the present circumstance that open wells and bore wells are found randomly throughout the study region. The collected samples were transferred and analyzed according to American public health association (APHA) standards [16]. All the groundwater samples were analyzed for physical and chemical characteristics to assess the groundwater for drinking purposes. Significant particles comprising the physical characteristics of pH, electrical conductivity, total dissolved solids, total hardness were measured during field visits, and major cations including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) and the major anions bicarbonate (HCO_3^{-}), sulfate (SO_4^{2-}), chloride (Cl^{-}), nitrate (NO_3^{-}) and fluoride (F^{-}) were analyzed following the standard procedure recommended by (APHA, 2017).

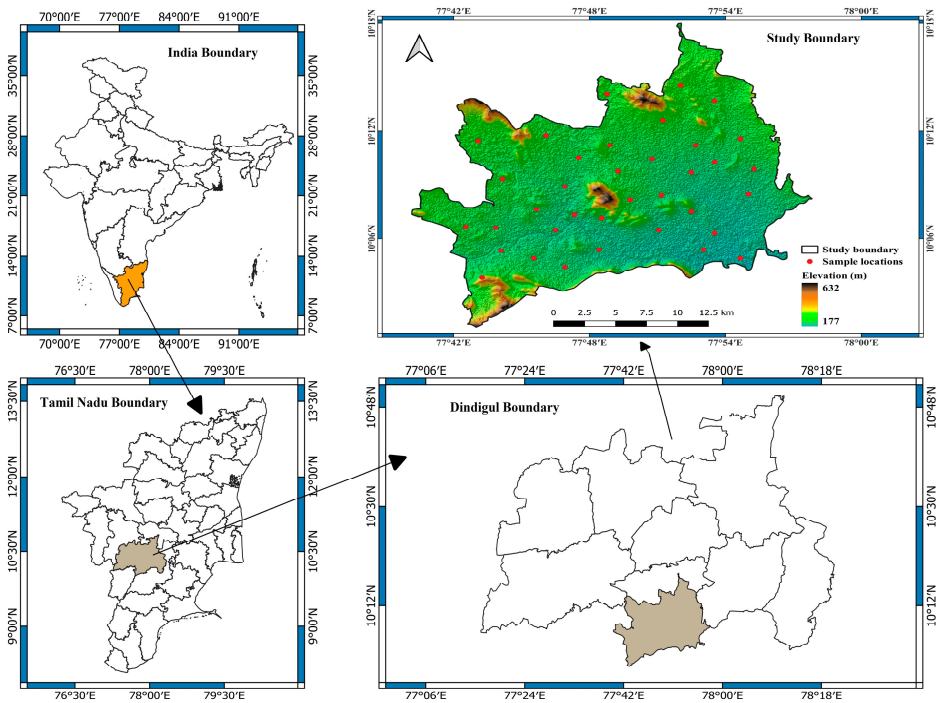

Figure 1. Groundwater sample collecting the location and topography of the study area.

2.3. Entropy Water Quality Index (EWQI)

The EWQI is the methodology for assessing water quality via entropy value including different hydrochemical parameters. The water quality index (WQI) value of the groundwater gives detailed information on the groundwater quality and influencing parameters that alter the nature of the water [17]. The modified or entropy water quality index (EWQI), also called the upgraded or further-developed WQI, evolved as a more accurate version of the WQI. Using this model, the tendency ordinarily presented by parameter weight is incredibly limited [18]. The EWQI has been portrayed as a powerful, fair, legitimate, exact

and dependable index for evaluating drinking water quality across the globe. In order to calculate the EWQI of groundwater samples, the following steps were followed:

Step 1. Assessing the matrix (X).

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots x_{1n} \\ x_{21} & x_{22} & \cdots x_{2n} \\ \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots x_{mn} \end{bmatrix}$$

Step 2. Standard grade matrix (Y).

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots y_{1n} \\ y_{21} & y_{22} & \cdots y_{2n} \\ \vdots & \vdots & \vdots \\ y_{m1} & y_{m2} & \cdots y_{mn} \end{bmatrix}$$

Step 3. Entropy information (ej).

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} P_{ij} ln P_{ij} \quad (1)$$

Step 4. Weighted entropy (wj).

$$w_j = \frac{(1 - e_j)}{\sum_{i=1}^{n}(1 - e_j)} \quad (2)$$

Step 5. Quality rating scale (qi).

$$q_i = \frac{C_j}{S_j} \times 100 \quad (3)$$

$$EWQI = \sum_{j=1}^{n} w_i q_i \quad (4)$$

2.4. Weighted Overlay Analysis (WOA)

Using multi criteria techniques in the water management field is the most effective way to identify the contaminated zone and source of pollution, and it provides an indication of how to take remedial measure in the specific region. In the present study, weighted overlay analysis (WOA) was used to identify the suitability of groundwater for drinking purposes in the study area [19,20]. In WOA, weight is assigned to each parameter based on their importance and influence in the stable equilibrium of the groundwater chemistry. In the current study, high weightage was assigned to Ca^{2+}, Mg^{2+}, NO_3^- and F^-, medium weightage was assigned to Na^+, K^+, Cl^-, SO_4^{2-} and HCO_3^-, and low weightage was assigned to pH, TDS, TH and EC [21]. Moreover, the weightage was assigned based on the geological formation and source of contamination in study area.

2.5. Saturation Index (SI)

SI is an effective method to identify the source of groundwater pollution in the study region. It calculates the ratio of the ionic activity product (IAP) to the respective thermodynamic reaction constant (Ksp) in the stable equilibrium of groundwater [22,23]. Increases in the Earth's temperature play a vital role in the dissolution of minerals and alter the nature of the groundwater quality. SI values of less than 0 indicate undersaturation, greater than 0 represent oversaturation and equal to 0 indicate a stable equilibrium of the groundwa-

ter [24]. In the present study, PHREEQC V.3 geochemical software recommended by United States Geological Survey (USGS) was utilized.

$$SI = \frac{K_{IAP}}{K_{SP}} \tag{5}$$

2.6. Chloro-Alkaline Indices (CAI)

Many factors such as infiltration of rainfall through the soil medium, movement of water through the parent rocks, waste from the municipal, irrigation field and anthropogenic activities primarily influence the quality of groundwater [24,25]. Calculating the CAI value of groundwater samples helps us to identify the interaction of groundwater and mineral present in the parent rocks (lithological alternation of groundwater chemistry) [26]. It is a widely used method to represent the effect of the reaction between rocks and water in the study region. The following formula was used to calculate the CAI value:

$$\mathrm{CAI-I} = \frac{\mathrm{Cl^-} - (\mathrm{Na^+} + \mathrm{K^+})}{\mathrm{Cl^-}} \tag{6}$$

$$CAI - II = \frac{Cl^- - (Na^+ + K^+)}{SO_4^{2-} + HCO_3^- + CO_3^{2-} + NO_3^-} \tag{7}$$

3. Results and Discussion

3.1. Hydrochemistry Characteristics of Study Region

3.1.1. pH

The concentration of hydrogen ions in the chemical composition of groundwater plays a vital role in deciding the quality of water for drinking and irrigation purposes [27,28]. In the present study, the concentration of pH ranges from 6.93 to 8.25 with a mean of 7.71. All the samples fell under the acceptable limit recommended by the WHO, 2011 (Figure 2a). The infiltration of rainwater and the ion-exchange process in the aquifers were the primary sources of hydrogen ions in the study region.

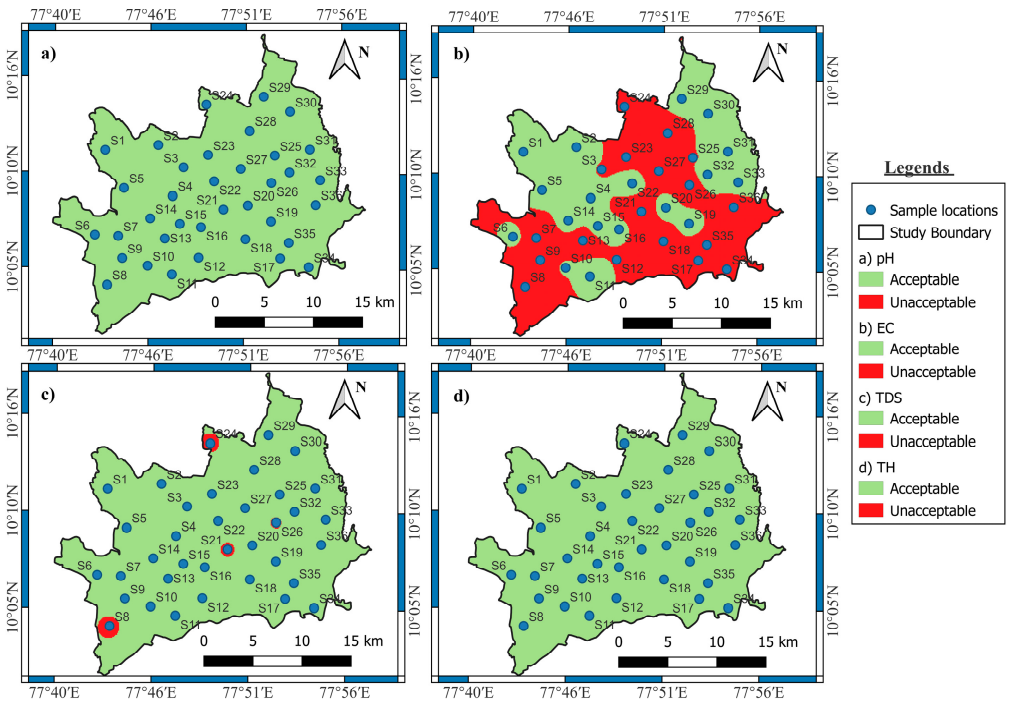

Figure 2. Spatial analysis of (**a**) pH, (**b**) EC, (**c**) TDS and (**d**) TH.

3.1.2. Electrical Conductivity (EC)

A value of electrical conductivity of groundwater shows a measurement of water capability to pass electricity flow and it is depending on the concentration of ions in the chemical composition of groundwater [29,30]. In the present study, the concentration of EC ranges from 132.88 to 3164.00, with a mean of 1623.46. Overall, 45.95% of samples exceed an acceptable concentration of EC in groundwater (Figure 2b). An excess quantity of dissolved salts and inorganic natural minerals present in the aquifer system increased the electrical conductivity of the water in the study area.

3.1.3. Total Dissolved Solids (TDS)

The sum of inorganic salts and other organic salt in groundwater is called total dissolved solids [31]. The major salts, namely cations, are calcium, magnesium, sodium and potassium; the major anions include carbonate/bicarbonate, sulphate, chloride and nitrate. The excess quantity of TDS affects the taste and increases the odor of the groundwater [32]. In the present study, the concentration of TDS ranged from 73.70 to 1885.63 mg/L, with a mean of 913.36 mg/L. A total of 11.11% (four samples) contained the excess concentration of TDS in groundwater (Figure 2c). In the study region, the identified sources of excess TDS in groundwater were the infiltration of surface runoff, sewage disposal, modern agriculture activities and industrial effluents disposal in the southeast and east zones of the study region.

3.1.4. Total Hardness (TH)

The total hardness of groundwater was measured by the sum of natural minerals such as calcium and magnesium and it expressed by the concentration of multivalent cations as $CaCO_3$ [33]. In the present study, the concentration of TH ranged from 21.76 to 379.22 mg/L, with a mean of 140.90 mg/L. All the samples fell under the acceptable limit recommended by the WHO, 2011 (Figure 2d). The processes, namely rock–water interaction, weathering of parent rock and ion exchange, highly dominate the quality of groundwater in the study area.

3.1.5. Calcium (Ca^{2+})

Calcium is one of the major chemical characteristics in groundwater and a significant parameter in determining the hardness of water [34]. It helps to stabilize the pH of water and gives a good taste to water. In the view of human health, calcium strengthens bones and teeth [35,36]. It also helps to maintain blood pressure, reduce blood clotting, promote good muscle function, reduce heart problems and improve nerve functions. In the present study, the concentration of Ca^{2+} ranged from 15 to 201 mg/L, with a mean of 62.18 mg/L. Only two sample locations exceeded the acceptable limit of calcium in groundwater (Figure 3a). Quartz, limestone and dolomite are found in a few areas in the southwest and southern parts of the study area as the major sources of elevated concentrations of calcium in groundwater [37]. Natural sources such as the weathering of parent rock and ion exchange are significant sources of calcium in groundwater and highly dominate the quality of the groundwater in the study area.

3.1.6. Magnesium (Mg^{2+})

Magnesium is another essential mineral that is required in order to maintain the proper functioning of human health [38]. It helps to maintain the stable equilibrium of water; excess amounts of magnesium, however, slowly react with other minerals [39]. The consumption of magnesium through water helps to regulate the cardiovascular and immune system in the human body. In the present study, the concentration of Mg ranged from 0.26 to 82.05 mg/L, with a mean of 32.10 mg/L. All the samples fell under the acceptable limit of Mg concentration (Figure 3b). Quartz, limestone and dolomite are found in a few parts of the southwest and southern parts of the study area, and are the major sources of elevated concentrations of magnesium in groundwater. Natural sources such as

the weathering of parent rock and ion exchange are significant sources of magnesium in groundwater; these highly dominate the quality of the groundwater in the study area.

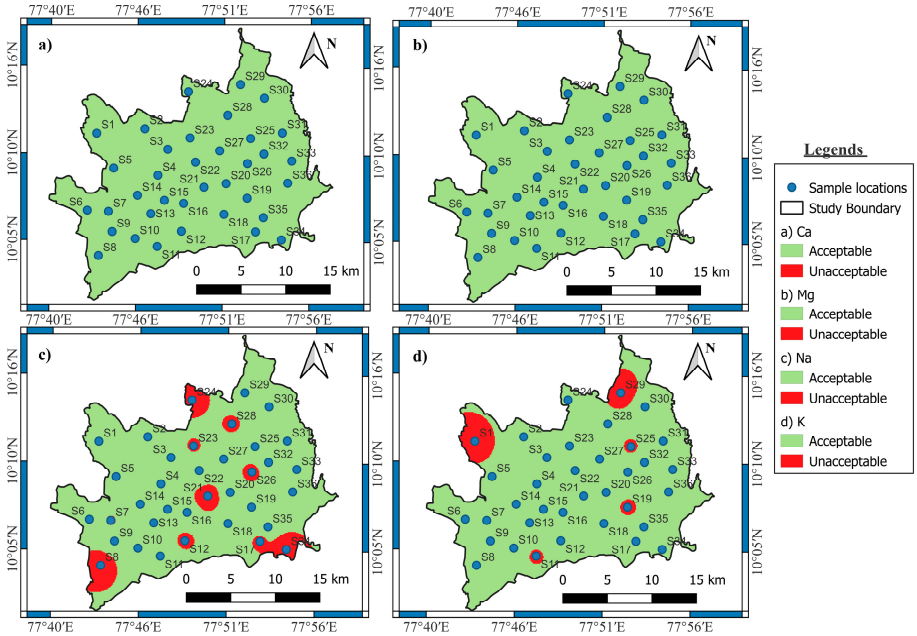

Figure 3. Spatial analysis of (**a**) Ca^{2+}, (**b**) Mg^{2+}, (**c**) Na^{+} and (**d**) K^{+}.

3.1.7. Sodium (Na^{+})

Sodium is an important chemical parameter present within groundwater in the environment [40]. The presence of sodium helps to regulate and maintain blood pressure, as well as to control the level of fluid and muscle function [41]. An adequate level of sodium in water prompts crop growth and improves the agricultural yield. In the present study, the concentration of Na^{+} ranged from 3 to 376.00 mg/L, with a mean of 143.39 mg/L. About 27.78% of samples were contaminated due to excess concentrations of sodium (Figure 3c). Anthropogenic activities such as roadside salt, runoff water infiltrate into ground level, sewage disposal, municipal waste disposal and the utilization of excess quantities of fertilizers in agricultural fields were identified as primary sources of excess concentrations of sodium in the groundwater in the study area.

3.1.8. Potassium (K^{+})

Potassium is a mineral that is commonly found in groundwater, and it helps to maintain a stable equilibrium of the chemical composition of groundwater [42]. The concentration of potassium in groundwater is an important parameter by which to assess the quality of groundwater [43]. In the present study, the concentration of K^{+} ranges from 0 to 23.00 mg/L, with a mean of 7.01mg/L. Only 19.44% of the study area was contaminated due to higher concentrations of potassium (Figure 3d). The nature of the soil and rock in the study region is rich in potassium, which releases into the aquifer system. Anthropogenic activities such as municipal waste disposal and usage synthetic fertilizers were identified as sources of potassium in the study area.

3.1.9. Chlorides (Cl^{-})

Chlorides are generally distributed chemical parameters of groundwater in nature, and are found as part of a combination of sodium, potassium and calcium [44]. In the present study, the concentration of Cl^{-} ranged from 15.00 to 681.00, with mean of 259.80 mg/L. A few sample locations (two samples) contained an unacceptable limit of chloride in the groundwater (Figure 4a). A high concentration of chloride leads to an increase in the electrical conductivity of water and also increases its corrosive nature [45]. The sources of

excess chloride in the study region include weathering of rocks, soil, salt-rich rock stratum and geogenic processes.

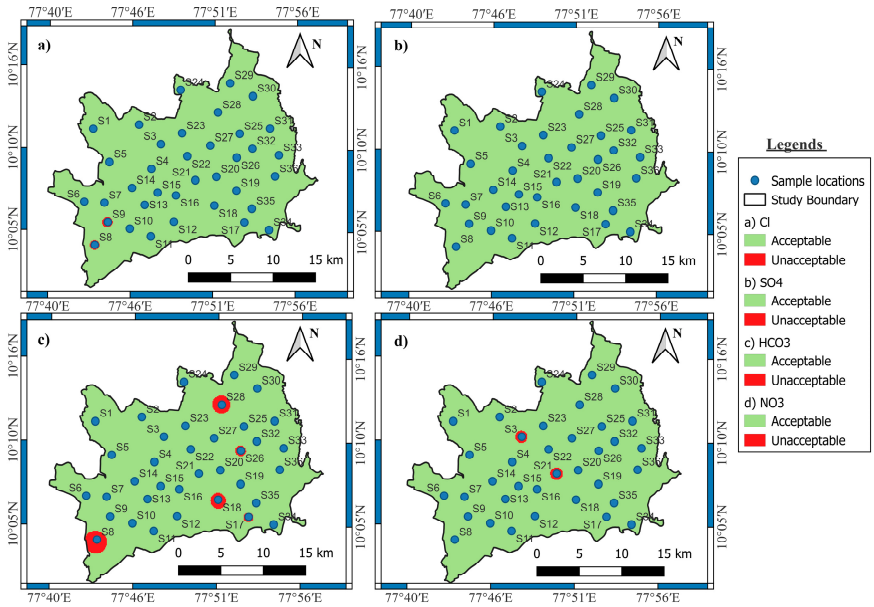

Figure 4. Spatial analysis of (**a**) Cl^-, (**b**) SO_4^{2-}, (**c**) HCO_3^- and (**d**) NO_3^-.

3.1.10. Sulphate (SO_4^{2-})

Sulphate is naturally present in groundwater due to the dissolution of minerals and atmospheric deposition [46]. In the present study, the concentration of SO_4^{2-} ranged from 1.00 to 400.00 mg/L, with a mean of 63.48 mg/L. The concentration of sulphate in all the sample locations was acceptable for drinking purposes (Figure 4b).

3.1.11. Bicarbonate (HCO_3^-)

Bicarbonate is a significant parameter used to assess the quality of groundwater for drinking purposes. The concentration of bicarbonate reveals the presence of organic matters in the aquifer system [47,48]. In the present study, the concentration of HCO_3^- ranged from 84.46 to 772.73 mg/L, with a mean of 391.35 mg/L. Seven sample locations (19.44%) in study area were found to be contaminated due to higher concentrations of potassium (Figure 4c). The results revealed that the dissolution of minerals in the aquifer system along with rock–water interactions are the primary source of contamination in the study area.

3.1.12. Nitrate (NO_3^-)

Nitrate is the most significant chemical characteristic of groundwater. The presence of nitrate plays a vital role in quality in both groundwater and in human health [49]. In the present study, the concentration of NO_3^- ranged from 6 to 70.00 mg/L, with a mean of 20.05 mg/L. Four of the sample locations had higher concentrations of nitrate in the groundwater (Figure 4d). The major sources of contamination were anthropogenic activities such as the usage of excess quantity of fertilizers, modern agriculture methods, leachates from the surface runoff, sewage disposal and leachates from municipal waste dumping yards [50].

3.1.13. Fluoride (F^-)

The excess concentration of fluoride in groundwater causes serious health issues in humans and it affects the stable equilibrium of the groundwater [50]. In the present study, the concentration of F^- ranged from 0.30 to 1.97 mg/L, with a mean of 0.99 mg/L. Four of the sample locations had higher concentrations of fluoride in the groundwater (Figure 5). Elevated concentrations of fluoride were identified in the study region due to poor calcium

interaction, few volcanic minerals, lithological structure and silicate weathering in the parent rock or aquifer system; compared with anthropogenic activities, these concentrations were very low.

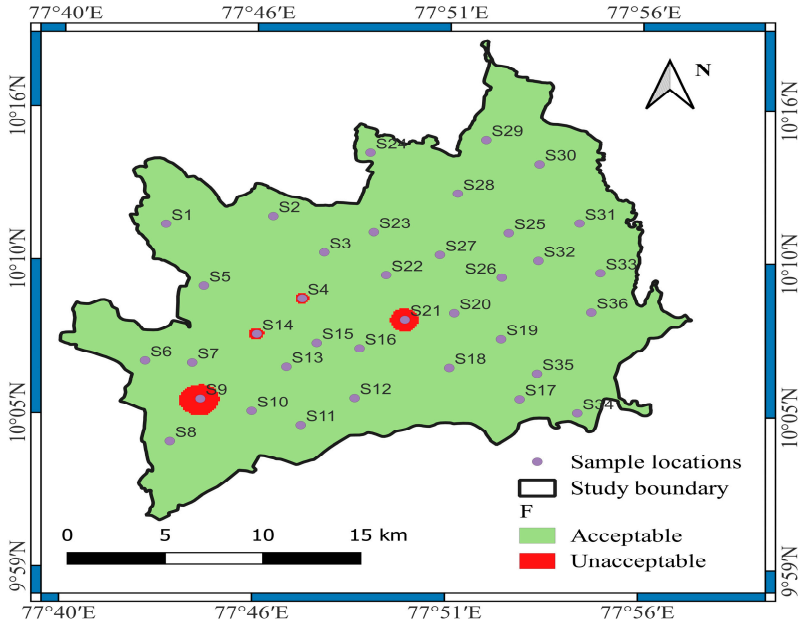

Figure 5. Spatial analysis of fluoride concentration in the study area.

3.2. EWQI

In the EWQI method, entropy information and weighted entropy are additional advantages when calculating the index values of groundwater quality for drinking purposes [51,52]. The value of EWQI in the present study ranged from 48.72 to 150.26, with an average of 85.65 in the study area. Overall, the water in 22.22%, 61.11% and 16.67% of the samples are of excellent, good and medium quality for drinking purposes, respectively (Table 1). The results revealed that a major part of the study region was contaminated and required an advanced level of treatment before use for drinking and other domestic purpose. Safety and remedial measures should be followed in contaminated zones in order to reduce the contamination and make the water safe for drinking uses.

Table 1. EWQI classification [53–55] of groundwater in the study area.

EWQI	Rank	Number of Samples	% of Samples	Class of Water	Purpose of Use
<50	1	8	22.22	Excellent	Fit for drinking purpose
50–100	2	22	61.11	Good	
100–150	3	6	16.67	Medium	Needs primary level of treatment before use
150–200	4	0	0	Poor	Needs advanced level of treatment before use
>200	5	0	0	Extremely poor	Unsuitable for drinking

3.3. Identification of Contamination Zone

In the present study, WOA was carried out by assigning weight to each parameter. The results of WOA shows that 27.77% of the sample locations were excellent, whereas 72.23% of the samples were in the good-to-medium category for drinking purposes (Figure 6). It indicates that south-west, south-east and a few samples in north are less contaminated due to anthropogenic activities such as agricultural waste disposal, using chemical fertilizers,

modern trends of agriculture activities, changed patterns of rainfall and agriculture practices found in the contaminated zones [56]. The excellent category of samples was found in the less populated and agriculture zones in the study area.

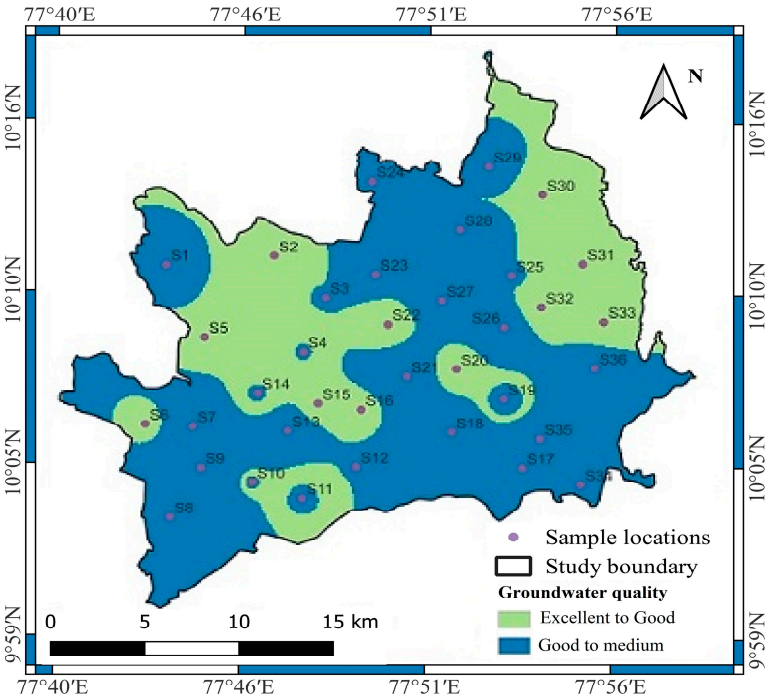

Figure 6. Weighted overlay analysis of groundwater suitability for drinking purposes.

3.4. Contamination Source Identification (CSI)

An elevated concentration of Na^+ and Cl^- ions indicates that the primary sources of contamination are rock–water interaction and mineral dissolution in the groundwater [57]. In the present study, 72.27% of the samples fell under the Cl^- ions and 27.73% of the samples fell under the Na^+ ions (Figure 7a). It confirmed the reverse ion-exchange process dominating the quality of the groundwater in the study area. This also reflects the influence of halite ion dissolution in the aquifer system. An excess amount of Cl^- confirmed that non-geogenic sources influenced the groundwater quality more than geogenic sources.

The Ca^{2+} + Mg^{2+} vs. $HCO_3{}^-$ graph represents the cation ion-exchange process or rock–water interaction and feldspar mineral dissolution in the groundwater chemistry. As for the status of groundwater in the study area, 56.66% of the samples fell above the 1:1 equiline, and 44.44% of the samples fell below the 1:1 equiline of Ca^{2+} + Mg^{2+} vs. $HCO_3{}^-$. It confirmed that a higher percentage of groundwater samples were dominated by the cation ion-exchange process [58]. It also indicates the dissolution of carbonate minerals from the aquifer in the study region (Figure 7b). The plot of Ca^{2+} + Mg^{2+} vs. $HCO_3{}^-$ + $SO_4{}^{2-}$ also confirmed that the presence of $HCO_3{}^-$ and $SO_4{}^{2-}$ (63.89% of samples) was associated with the soil system that majorly affects the nature of groundwater in the study area (Figure 7c). This was supported by plotting $HCO_3{}^-$ vs. Cl^- + $SO_4{}^{2-}$ graph, indicating that 61.1% of the samples (Figure 7d) fell below the equiline; this also confirmed that weathering and the influence of anthropogenic activities are the primary source of excess concentrations of ions in groundwater [59]. In particular, an excess amount of $HCO_3{}^-$ in the groundwater indicates that physical weathering of Na^+ and K^+ silicates along with anthropogenic activities of organic waste decomposition are significant sources of groundwater contamination in the study region.

$$\text{Halite dissolution (NaCl)} \rightarrow Na^+ + Cl^-$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^-$$

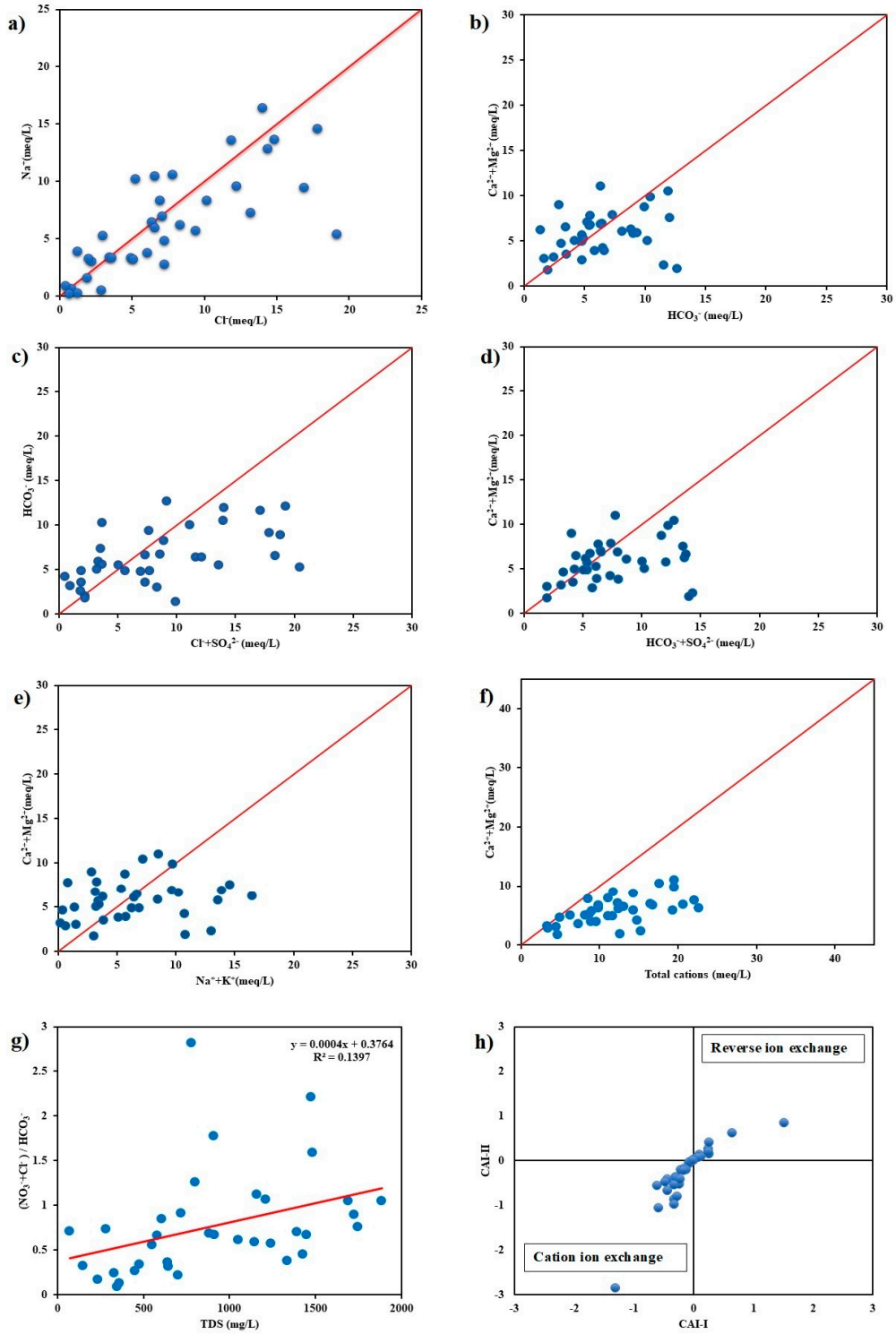

Figure 7. Ionic relation diagram of (**a**) Cl^- vs. Na+ (**b**) HCO_3^- vs. Ca^{2+}+Mg^{2+} (**c**) Cl^-+SO_4^{2-} vs. HCO_3^- (**d**) HCO_3^-+SO_4^{2-} vs. Ca^{2+}+Mg^{2+} (**e**) Na^++K^+ vs. Ca^{2+}+Mg^{2+} (**f**) total cations vs. Ca^{2+}+Mg^{2+} (**g**) TDS vs. (NO_3^-+Cl^-)/HCO_3^- (**h**) CAI-I vs. CAI-II.

Furthermore, it is confirmed by plotting Ca^{2+} + Mg^{2+} vs. the Na^+ + K^+ graph that 50% of the sample was above and below the 1:1 equiline (Figure 7e). It indicates that cation ion exchange and the reverse ion-exchange process are the primary factors that influenced the quality of groundwater in the study area. The plot Ca^{2+} + Mg^{2+} vs. total cations of groundwater samples shows that all the sample fell under the total cation category (Figure 7f), indicating that the dominance of carbonate weathering and decomposition of organic

substances in the soil layers are the controlling factors of groundwater chemistry [60]. A major part of the study region covered by agriculture land and rich in agricultural activities, modern agriculture activities, usage of synthetic pesticides and fertilizers are the primary non-geogenic sources of contamination in the study area. This was confirmed by plotting $NO_3^- + Cl^- / HCO_3^-$ vs. total dissolved solid graph; this shows the linear relationship among the chemical parameter with an equation of y = 0.0004x + 0.3764, R^2 = 0.1397 (Figure 7g). It demonstrates that anthropogenic sources of contamination are rich in the southern part (agriculture field) of the study region. The chloro-alkaline index (CAI-I and II) of the groundwater indicates that 30.55% of the samples fell under the reverse ion-exchange process, and 69.45% of the samples fell under the cation ion-exchange processes (Figure 7h). This reveals that carbonate weathering and the dissolution of carbonate-rich minerals in the study area highly influenced the stable equilibrium of the chemical structure of the groundwater.

3.5. Effect of Evaporation Process on Groundwater Chemistry

Changes in climatic conditions lead to changes in the rainfall pattern and insufficient amounts of rainfall in the study area. Due to increases in the temperature of the Earth's surface, the evaporation process also influenced the chemical equilibrium of the groundwater [61–64]. In the present study, the saturation index (SI) was calculated to identify the effect of evaporation on the chemistry of the groundwater. The results shows that the SI values of anhydrite range from −1.69 to 0.72 with a mean of −0.28; 69.45% of samples have negative and 30.55 have positive values; the SI values of aragonite range from 1.91 to 3.57, with a mean of 2.75; all the samples have positive values; the SI values of calcite range from 2.05 to 3.71, with a mean of 2.90; all the samples have positive values; the SI value of dolomite ranges from 3.21 to 6.88, with a mean of 5.54; all the samples have positive value; the SI value of fluorite ranges from 0.63 to 2.92, with a mean of 1.67; all the samples have positive value; the SI value of gypsum ranges from −1.39 to 1.01, with a mean of 0.01; 47.23% of the samples have negative and 52.77% of samples have positive values; the SI value of halite ranges from 3.21 to 6.88, with a mean of 5.54; all the samples have negative value; the SI value of sylvite ranges from 3.21 to 6.88, with a mean of 5.54; all the samples have negative values (Table 2). The results show that aragonite, calcite, dolomite and fluorite minerals are oversaturated (precipitation), whereas anhydrite, gypsum, halite and sylvite minerals are undersaturated (dissolution) in the aquifer system (Figure 8). The SI value of each mineral confirmed that weathering of parent rocks and carbonate dissolution are significant sources of groundwater contamination in the study region.

Table 2. Saturation index of groundwater chemistry.

Minerals	Minimum	Maximum	Average
Anhydrite	−1.69	0.72	−0.28
Aragonite	1.91	3.57	2.75
Calcite	2.05	3.71	2.90
Dolomite	3.21	6.88	5.54
Fluorite	0.63	2.92	1.67
Gypsum	−1.39	1.01	0.01
Halite	-6	−2.67	−3.70
Sylvite	−5.56	0	−3.77

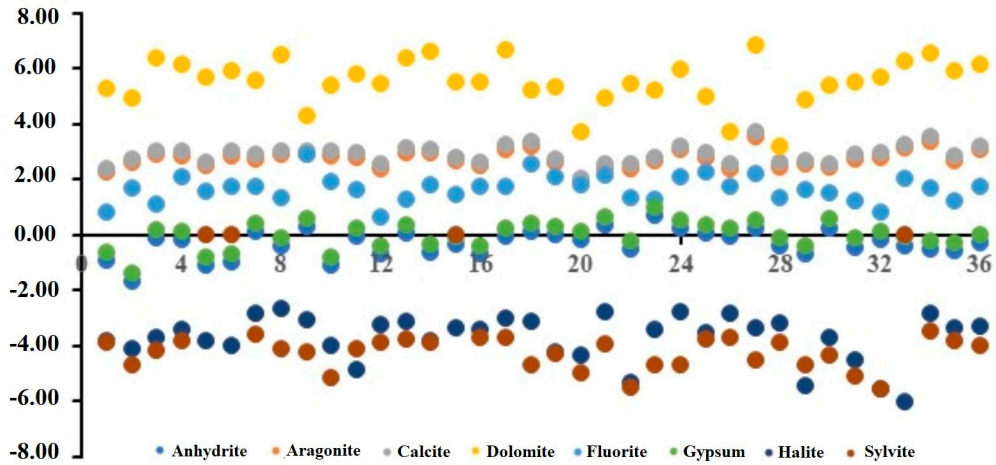

Figure 8. Saturation index of all minerals.

4. Conclusions

The present study aimed to assess the quality of groundwater for drinking purposes in semi-arid regions in the southern part of India. The study concluded that TDS, Ca^{2+}, Na^{+}, K^{+}, NO_3^{-} and Cl^{-} are the parameters highly influencing water quality in the study region. The present study identified that infiltration of surface runoff, sewage disposal, modern agriculture activities and industrial effluents disposal are the primary sources of excess TDS in groundwater. Moreover, anthropogenic activities such as roadside salt, runoff water infiltrate into ground level, sewage disposal, municipal waste disposal and utilization of excess quantity of fertilizers in agriculture fields are the identified primary sources of excess concentrations of sodium, potassium, nitrate and chloride in groundwater in the study area.

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