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Research Article

Hydrogeochemical and GIS Analysis of Groundwater Quality for Drinking and Irrigation Purposes in Kuzhithuraiyar Sub-Basin, Kanniyakumari District, Tamil Nadu, India

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A hydrogeochemical analysis was conducted to find the suitability of the groundwater for drinking and irrigation purposes in the Kuzhithuraiyar sub-basin, Kanniyakumari district, Tamil Nadu, India. 48 groundwater samples were collected from the different locations of the study area during both the pre- and postmonsoon periods. This study assesses the groundwater quality for drinking and irrigation purposes based on the analytical results, water quality index, Wilcox plot, and irrigation parameters such as electrical conductance, Kelly's ratio, sodium absorption ratio values, magnesium hazards, bicarbonate, and the residual sodium carbonate index. The pH values ranged from 8.5 to 6.5, suggesting generally acceptable conditions. TDS concentrations range from 24 to 1277 mg/L, whereas EC values range from 37.50 to 1996 μS/cm. It is observed from the collected samples that the premonsoon water samples TDS' values were exceeded the recommended TDS limits than postmonsoon samples. Water quality indices indicate that 50% of premonsoon samples and 48% of postmonsoon samples are suitable for drinking. In total, 10% of samples are admissible to a doubtful category before and after the monsoon, 6% are good to permissible during the monsoon, and 84% are good to permissible. Kelly's ratio shows that 56% and 48% of samples collected during the post- and premonsoon are suitable for irrigation, respectively, whereas the remaining samples are not. Due to magnesium hazards, 40% and 44% of pre- and postmonsoon samples are not suitable for irrigation. Overall, the postmonsoon samples exceeded the permissible TDS limit (1000 mg/L) by 10% and the premonsoon samples by 6. 13% of samples obtained after the monsoon and 19% collected before the monsoon have a potential salinity greater than three, indicating that these samples are unacceptable. The sustaining water quality and mitigating possible hazards in the Kuzhithuraiyar sub-basin require continuous monitoring and focused measures.

1. Introduction

Groundwater is extensively used in dry and semiarid regions for industrial, agricultural, and residential uses [1–3]. People's health and socioeconomic development are impacted by the water quality [4, 5]. 97% of the earth's water is found in the oceans and it is too salty to drink, grow crops, or be used for most industrial purposes. Fresh water makes up 3% of the earth's water supply. Approximately 68 percent of fresh water on Earth is found in glaciers and icecaps, while just over 32 percent is found in groundwater [5, 6]. The incorrect application of agricultural chemicals, rapid industrialization, poor waste management, and needless water extraction are just a few of the numerous causes of ion imbalance in the water quality [5]. A solid understanding of hydrochemistry is necessary to assess the quality of groundwater used for irrigation and drinking [7–9].

When choosing a water quality fit for household use, the water quality index (WQI) is helpful. In India, weighted arithmetic and integrated WQIs are frequently used to evaluate surface and groundwater because they produce results with greater precision [10, 11]. Both natural and artificial activities that cause a decline in the groundwater quality can further restrict the use of groundwater resources. Natural and human activities can decrease the groundwater quality, limiting its utility. Geological, weathering, and microbial processes can pollute groundwater with minerals and pollutants. Groundwater concentrations can rise as minerals such as arsenic or fluoride dissolve from geological formations, making it unsuitable for certain uses. Agriculture, industry, and improper waste management harming the groundwater quality. Chemicals and heavy metals from industrial processes can pollute groundwater. Nitrates and other agrochemicals from excessive fertilizer and pesticide usage can damage groundwater [12, 13]. A vast amount of groundwater (million cubic meters) is used in agriculture for plant growth and yield [12–14]. Depleting the water table level due to excessive groundwater usage without adequate recharging is a significant threat to the sustainability of agriculture. The type of aquifer utilized, its salinity, and its TDS all affect the quality of irrigation water [14–17]. Both human health and agricultural productivity are negatively impacted by water quality [8, 18].

There is a consistent flow of tourists into the Kanyakumari district, which could lead to overextraction of groundwater. As a result, certain coastal pockets may experience a drop in water levels [19–21]. Wells drawing heavily from tertiary aquifers and coastal alluvium during summer may cause saline water intrusion into freshwater areas [22]. Urbanization, industrialization, and agricultural activities in the Kanniyakumari district in Tamil Nadu, India, are some elements that influence the water quality. Analyses and comparisons with standard permitted limits were conducted on the water quality indicators, including turbidity, total dissolved solids (TDS), electrical conductivity (EC), pH, hardness, nitrite, sulfate, phosphate, bacteriological examinations, and fecal coliform [23].

The research gap in this context is the need for a more detailed investigation into the factors contributing to groundwater quality degradation in the Kanniyakumari district. There is an opportunity to delve deeper into the impact of tourism, urbanization, industrialization, and agricultural practices on the water quality. Additionally, further research could explore effective strategies for sustainable groundwater management, especially in the face of potential overextraction and saline water intrusion. Detailed studies on the specific aquifers, their salinity, and the associated effects on the irrigation water quality may also provide valuable insights. Moreover, assessing the long-term consequences of groundwater depletion on agriculture and human health could require a more comprehensive investigation.

The main objective of the present study is to examine the suitability of the groundwater for drinking and irrigation purposes. Chloroalkaline indices, hydrochemical facies, and statistical analysis—Pearson's correlation, salinity, and sodium hazards, total ionic concentration, permeability index, Wilcox's plot, Doneen's plot, USSL plot, and Piper trilinear plots and water quality index were used to assess the suitability of the groundwater. The study's findings can directly impact the health and well-being of the local population by identifying potential contaminants or hazards in the groundwater that could pose health risks upon consumption. Analyzing the suitability of groundwater for irrigation purposes helps ensure sustainable agricultural practices, which are crucial for the livelihoods of farmers and the local economy. So far, no detailed study using this comprehensive methodology has been found in this area.

2. Materials and Methods

2.1. Study Area. The study area is located on the western side of Kanniyakumari district, Tamil Nadu, India (Figure 1). The basin has a unique advantage in terms of rainfall during both the southwest and northeast monsoon seasons. Gathering secondary data sources involves creating thematic geology maps (source: Geological Survey of India Map) and soil (source: National Bureau of Soil Survey and Land Use Planning Map). These maps were then digitized using ArcGIS before that these data were properly georeferenced and projected. The study area has a heterogeneous geology with igneous, sedimentary, and metamorphic rocks. Geomorphology includes alluvial plains, coastal plains, denudational hills, peneplains, and structural hills. The study area can be divided into four significant landforms: hills, plains, valleys, and coastal belts. In a hilly region, gravelly soil is found, and the crops in this region include rubber, nutmeg, cloves, and pineapple, followed by plains and valleys where red loamy soil covers are found with the paddy, tapioca, banana, coconut, etc., crop pattern. In the coastal regions, sandy soil is found and cashew nuts, coconut, mango, and tamarind are the major crops. Permeable and fissured formations can be found beneath the study area. Worn, fissured, and fractured crystalline rocks coexist in the examined region with semiconsolidated and unconsolidated strata to produce the critical aquifer system. These rock types are made up of limestone and sand stone and play an important role in the groundwater occurrence in the present study area. Phreatic type of groundwater aquifers found in sand dunes near the point where the Kuzhithuraiyar river joins the Arabian Sea and in worn, broken, and fissured crystalline rocks [21]. The water table is worn and semirestricted to constrained conditions in these rock fracture and fissure zones at 8–18 m depths below the surface. Dunes have water levels of 4–8 m below the surface [24].

2.2. Sampling and Analysis. The water samples were collected during both the pre- and postmonsoon seasons in 2022. The concentrations of the major anions and cations in the groundwater, along with the pH, EC, and TDS, were determined by standard procedures using 48 samples collected across the basin (Figure 1). An ion electrode was employed to measure the EC and pH. To obtain TDS, multiply EC by 0.64. The titrimetric method was used to analyze anions such as Cl^-, CO_3^-, and HCO_3^-, as well as cations such as Ca^{2+} and Mg^{2+}. We used a flame photometer to observe Na^+ and K^+ and a spectrophotometer to look at SO_4^- and NO_3^-. All physicochemical parameters were compared with WHO standards [25]. The following equation was used to determine the normalized charge balance index [26–28]:

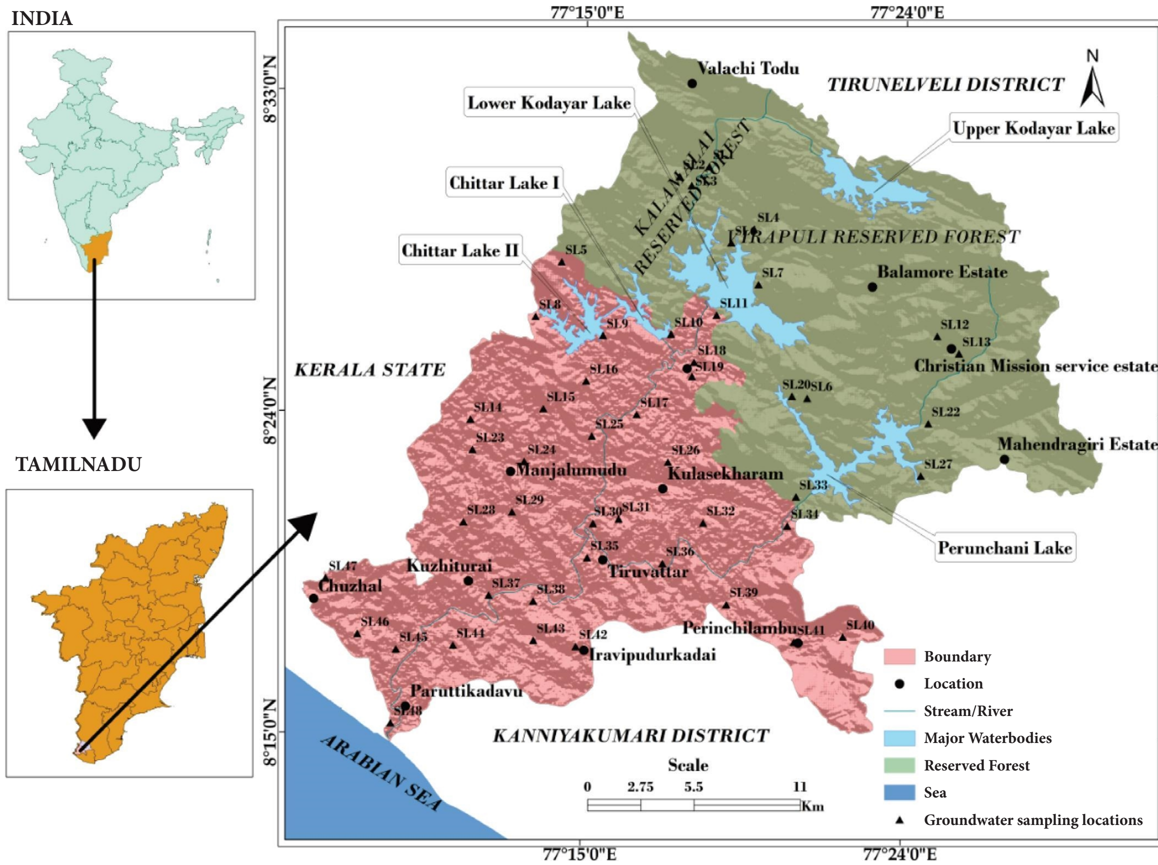


Figure 1: Location map along with sampling locations, Kuzhithuraiyar sub-basin.

$$\text{NCBI} = \frac{\Sigma T_Z^- - \Sigma T_Z^+}{\Sigma T_Z^- + \Sigma T_Z^+}, \quad (1)$$

where ΣT_Z^+ is the total sum of cations in epm and ΣT_Z^- is the total sum of anions in epm.

2.3. Water Quality Index (WQI). The WQI is a quantitative measure used to evaluate the overall quality of groundwater. This report offers a compilation of water quality criteria assessed in groundwater samples, which can aid in comprehending and conveying the overall condition or appropriateness of the water for different purposes, such as drinking, irrigation, industrial use, or preservation of the environment. Every parameter in the current study has a distinct weight based on how significant they are to groundwater quality for drinking purposes [29, 30]. A rank between 1 and 5 is assigned for all the hydrogeochemical parameters. pH and TDS are ranked highest because of their importance in water chemistry. Chloride is ranked lowest due to its low impact on the water quality. The relative weight (W_i) is calculated using the following formula:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}. \quad (2)$$

The quality rating scale (q_i) is determined using the following formula:

$$q_i = \frac{C_i}{S_i} x\, 100, \quad (3)$$

where C_i is the concentration of groundwater parameter and S_i is the drinking water standard based on WHO [25].

The subindex (S_i) is calculated using the following formula:

$$S_i = W_i q_i, \quad (4)$$

where W_i is the relative weight and q_i is the quality rating scale

The water quality index is calculated using the following formula:

$$WQI = \sum_{i=1}^{n} W_i q_i, \quad (5)$$

where WQI is the water quality index.

2.4. Hydrogeochemical Parameters. Many hydrogeochemical characteristic changes will occur through the water's ionic interaction. These have been identified through the parameters below.

2.4.1. Chloroalkaline Indices. The ion exchange process constantly alters the chemical composition of the groundwater. Ions undergo exchange as groundwater flows through geological strata [31]. When water encounters minerals that contain ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}), these ions can replace other ions that are already in the water. Calcium and magnesium ions can substitute sodium and potassium ions that are attached to minerals in the aquifer. The ion exchange mechanism has a profound impact on the chemical composition of water. Chloroalkaline indices measure this process, which relies on stativity, groundwater flow, and other aquifer processes. It is possible to calculate the chloroalkaline indices (CAI-1) and (CAI-2) [32] by using the following formulas:

$$\mathrm{CAI\,1} = \frac{\mathrm{Cl}^- - \left(\mathrm{Na}^+ + \mathrm{K}^+\right)}{\mathrm{Cl}^-}, \quad (6)$$

$$\mathrm{CAI\,2} = \frac{\mathrm{Cl}^- - \left(\mathrm{Na}^+ + \mathrm{K}^+\right)}{\mathrm{SO}_4^{2-} + \mathrm{CO}_3^{2-} + \mathrm{HCO}_3^- + \mathrm{NO}_3^-}. \quad (7)$$

Positive chloroalkaline indices 1 and 2 indicate a direct ion exchange process, while negative values indicate a reverse ion exchange process.

2.4.2. Groundwater Classification. Groundwater hydrochemical facies are categorized according to their unique compositions and features. These classifications help people understand the chemical composition of groundwater, identify its sources, and evaluate its possible uses and risks. Hydrochemical facies of groundwater can be determined using the following equations proposed by [33]:

$$r1 = \frac{\mathrm{Na}^+ - \mathrm{Cl}^-}{\mathrm{SO}_4^{2-}}, \quad (8)$$

$$r2 = \frac{\left(\mathrm{K}^+ + \mathrm{Na}^+\right) - \mathrm{Cl}^-}{\mathrm{SO}_4^{2-}}, \quad (9)$$

$r1$ greater than 1 is categorized as Na^{2+}-SO_4^{2+} type of water, and r1 less than 1 is categorized as Na^{2+}-HCO_3^- type of water. The meteoric genesis index indicates that deep meteoric percolation occurs when values are less than 1, while shallow meteoric percolation occurs when values exceed 1 [33].

2.4.3. Parameters Responsible for Irrigation Suitability. The quality of water and soil productivity is altered by the chemical ions such as K^+, Na^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, and HCO_3^- [14]. Elevated concentrations of sodium in irrigation water, particularly when paired with bicarbonate, can lead to soil sodicity. Sodic soil is substantial in salt. When irrigation water contains high salt levels, especially when paired with bicarbonate, soil can become sodic. This causes excessive salt saturation in the soil, which can harm the plant development and structure. Sodic soils have low fertility, permeability, and drainage, which reduces agricultural production [34, 35]. Sodicity is crucial to the health of soil and agriculture; thus, readers must grasp it. SAR stands for the sodium adsorption ratio, which measures the proportion of sodium compared to other ions such as calcium and magnesium. Soil structure deterioration, less water infiltration, and detrimental impacts on plant growth can occur due to increased soil dispersion and decreased water availability [36]. Soil dispersion occurs when water or wind erosion breaks down aggregates of soil into smaller particles. Soil dispersion breaks down the soil structure, separating the particles and making them more prone to erosion and compaction [36]. Furthermore, these ions enhance the soil structure and hinder the sodium-induced soil dispersion. Ensuring sufficient calcium and magnesium in the soil facilitates optimal aeration, root development, and water penetration. Potassium is crucial for numerous physiological processes in plants [37]. Optimal quantities of potassium in irrigation water can enhance the crop yield and quality. Potassium is a vital nutrient for plant growth as it is necessary for various physiological activities. The presence of bicarbonate ions in the soil can lead to an elevation in alkalinity, which, in turn, can influence the pH of the soil and potentially affect the availability of nutrients.

2.4.4. Sodium Adsorption Ratio (SAR). The suitability of irrigation water and its possible effects on plant growth and soil structure were evaluated using the SAR of irrigation water. The quantity of sodium in irrigation water is determined by comparing it with other positively charged ions, such as magnesium and calcium [38] developed the (10) of the SAR,

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\sqrt{\left(\mathrm{Ca}^{2+} + \mathrm{Na}^{2+}/2\right)}}. \quad (10)$$

Four classes can be classified according to the sodium adsorption values. They are as follows: (1) Less than 10 indicates excellent. (2) 10 to 18 indicates good. (3) 18–26 indicates doubtful. (4) Greater than 26 indicates unsuitable. The lower the value, the higher the infiltration rate, whereas the higher the value, the lower the infiltration rate.

2.4.5. Residual Sodium Carbonate (RSC). RSC can be surpassed by Na^+ adsorption in soil, which aids in accumulating Ca^{2+} and Mg^{2+} caused by excessive CO_3^{2-} and HCO_3^- in groundwater [14]. RSC is calculated using the following equation coined by [39]:

$$\mathrm{RSC} = \left(\mathrm{HCO}_3^+ + \mathrm{CO}_3^{2-}\right) - \left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right). \quad (11)$$

Three classes are characterized based on the values of RSC, i.e., low or good (<1.25), medium or doubtful (1.25 to 2.5), and high or unsuitable (>2.5).

2.4.6. Soluble Sodium Percentage. Increased irrigation water sodium levels replace calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions with sodium (Na^+), lowering soil percolation and infiltration [40–42]. The following equation was used to calculate the Na%:

$$Na\% = \frac{Na^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} * 100. \quad (12)$$

Five classes are categorized based on the sodium percentage. They are as follows: excellent (<20%), good (20 to 40%), permissible (40 to 60%), doubtful (60 to 80%), and unsuitable (>80%). It is inversely related to the infiltration of soil.

2.4.7. Kelly's Ratio. Kelly's ratio of less than 1 means the water is suitable for irrigation. At the same time, water is unsuitable for irrigation if it is greater than 1. Kelly's ratio was calculated using the following formula proposed by [43] and modified by [44]:

$$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}}. \quad (13)$$

2.4.8. Permeability Index (PI). The interconnectivity of the grains, which is impacted by ongoing groundwater agriculture, is directly correlated with PI. Utilizing groundwater abundant in Mg^{2+}, Ca^{2+}, Na^{+}, and HCO_3^{-} can Diminish Soil Permeability. It Was Calculated Using the following equation coined by [45]:

$$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}} * 100. \quad (14)$$

The values can be classed into three types: Class I good (>75%), Class II doubtful (25–75%), and Class III unsuitable (<25%).

2.4.9. Magnesium Hazard. In water, calcium and magnesium often remain in equilibrium. The excess magnesium content in water harmfully affects the crop yield. Magnesium hazard for irrigation water has been calculated using the following equation developed by [46]:

$$\text{Magnesium ratio} = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} * 100. \quad (15)$$

If the magnesium ratio exceeds 50, it is considered harmful and unsuitable for irrigation [47].

2.4.10. Potential Salinity. Salinization is the process of salt buildup in the soil, which can negatively impact soil fertility, plant growth, and agricultural output. Potential salinity can be calculated using the following formula proposed by [45]:

$$PS = Cl^{-} + 0.5 * SO_4^{2-}. \quad (16)$$

Potential salinity less than 3 is defined as suitable and greater than 3 is defined as unsuitable for irrigation.

2.4.11. Total Dissolved Solids. TDS measures the number of dissolved solids in water. TDS in water originates from a diverse range of natural and human-related sources. Weathering and disintegrating rocks and minerals with water flow through geological formations are examples of natural sources. Water interacts with rocks and soil, dissolving various minerals, including calcium, magnesium, sodium, potassium, bicarbonates, chlorides, sulfates, and other similar substances. Anthropogenic pollution arises from multiple causes, such as industrial discharges, agricultural runoff, sewage effluents, and human activities introducing contaminants into waterways [48, 49]. TDS is classed into three types: suitable (<450 mg/L), doubtful (450 to 2000 mg/L), and unsuitable (>2000).

2.4.12. Correlation Matrix. A correlation matrix, specifically Pearson's correlation matrix, examines the interrelationship among various variables inside a dataset. Using this tool, you can effectively ascertain the magnitude and orientation of linear correlations or interdependencies among variables. Pearson's correlation coefficient, represented as "r," allows for quantifying the intensity and orientation of the linear association between two continuous variables. The variable "r" can take on values from −1 to +1 [50]. A correlation coefficient +1 indicates a flawless linear link, implying that if one variable increases, the other similarly increases in direct proportion. A correlation coefficient −1 implies a strong negative linear relationship, where one variable consistently increases, while the other consistently declines in proportion [50]. In general, a correlation coefficient near zero suggests the absence of a linear association between the variables. When analyzing water quality, variables such as pH, EC, and TDS and major cations (such as calcium, magnesium, sodium, and potassium) and anions (such as chloride, sulfate, and bicarbonate) can be examined using a correlation matrix with Pearson's correlation coefficient.

3. Results and Discussion

3.1. Drinking Water Quality Analysis. The results show that the Kuzhithuraiyar sub-basin has pH values ranging from 6.5 to 8.5. The range of EC is 37.50 μS/cm to 1996 μS/cm. TDS concentrations range from 24 to 1277 mg/L. The current cation and anion trends are as follows: $Cl^{-} > HCO_3^{-} > SO_4^{2-} > NO_3^{-} > CO_3^{-}$ and $Na^{+} > Ca^{2+} > Mg^{2+} > K^{+}$. Kodumkulam and Villusari have 317 mg/L and 3 mg/L of sodium levels, respectively. The calcium concentration ranges from 2 mg/L at Kodayar to 92 mg/L at Edavar. Magnesium concentrations at Edavar and Kodayar range from 58.32 mg/L to 1.22 mg/L. At Viricode, potassium levels are 37 mg/L, and at Churur, they are 1 mg/L. Edavar's chloride value ranges from 624 mg/L to 4 mg/L. Bicarbonate values range from 366 mg/L at Kodumkulam to 4.97 mg/L at Vilamalai, averaging 90.96 mg/L. The concentration range of sulfate is 77 mg/L at Edavar and 1 mg/L at Karod. At Vavarai, nitrate concentrations are 18 mg/L, and at Netta, they are 0.05 mg/L. At Manalodai, the range of carbonate is 0 to 4.33 mg/L. The ionic concentration is closer to the coastline tract in the southwestern section than in other places. This leads to an interaction between salinity and ions. The drinking water standards are compared with the WHO standards [25]. The spatial distribution map of major ions is shown in Figures 2(a)–2(j).

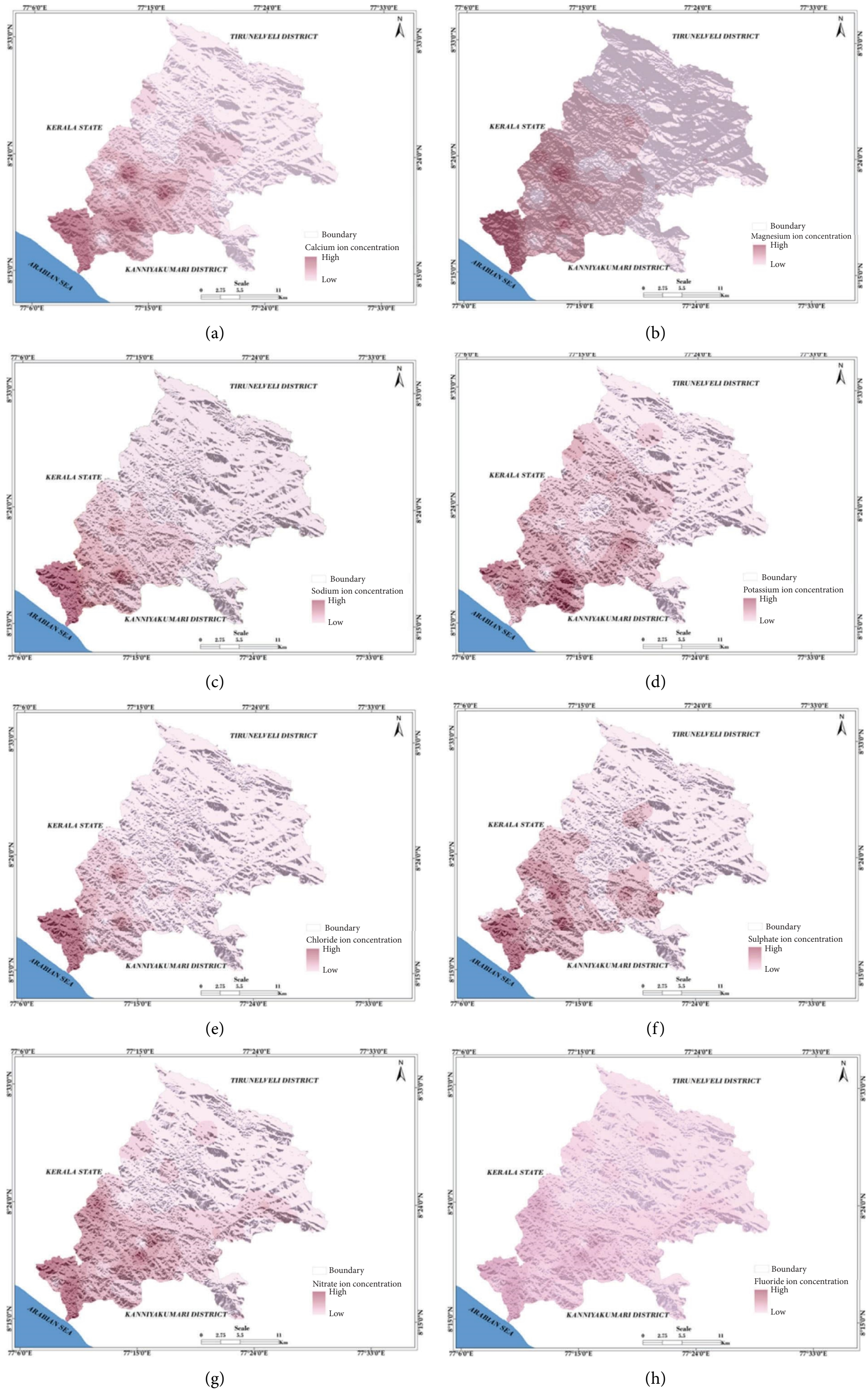
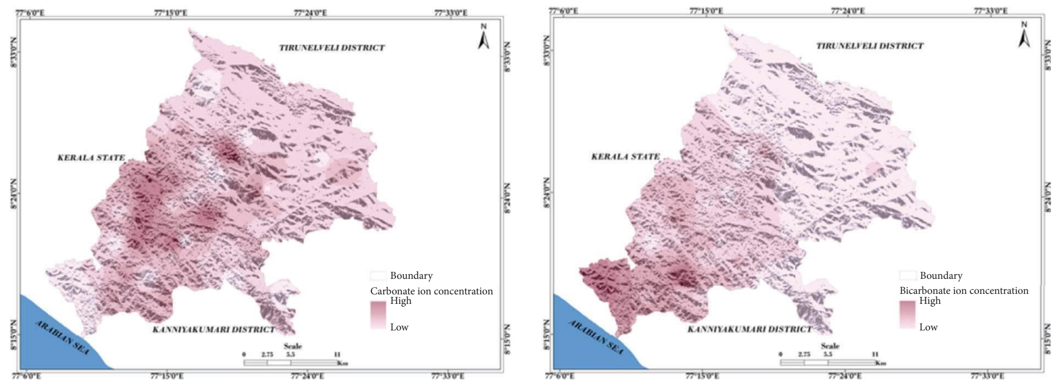


Figure 2: Continued.



(i) (j)

Figure 2: Spatial distribution of (a) calcium, (b) magnesium, (c) sodium, (d) potassium, (e) chloride, (f) sulfate, (g) nitrate, (h) fluoride, (i) carbonate, and (j) bicarbonate, Kuzhithuraiyar sub-basin.

The pH ranges between 6.5 and 8.5 in all samples collected before and after the monsoon. The average EC limit was exceeded by 29% of samples in the postmonsoon period and 46% in the premonsoon period. The salinity index of the groundwater samples was computed using electrical conductivity measurements. High-salinity (class 3) water is the perfect irrigation solution for crops that can withstand medium and high salt levels. Low- to moderate-salinity (classes 1 and 2) water does not cause significant harm to soil or crops [51]. The salinity index shows that 8% of samples are highly saline, and 92% are low to moderately saline. The TDS value indicates that 10% and 15% of samples during the post- and premonsoon periods, respectively, exceed the limit. Drinking water with a TDS of 1000 mg/L is permissible [8, 51]. Samples taken before or after the monsoon had a 6% higher calcium content than samples taken during the monsoon. Samples taken before and after the monsoon showed 2% and 10%, respectively, more magnesium than the regulatory limit. Sodium concentrations before and after the monsoon are 8% greater than the allowed limit. Potassium contents increased by 23% and 14% in the postmonsoon and premonsoon seasons, respectively. The chloride concentration was higher in 10% of the premonsoon samples and 8% of the postmonsoon samples. All samples had carbonate, bicarbonate, nitrate, and fluoride concentrations within permissible limits (Table 1).

3.1.1. Water Quality Index. The relative weights in Tables 2 and 3 show the calculation and results of the water quality index. According to the WQI value, water is categorized as follows: 0–25 is excellent, 25–50 is good, 50–75 is moderate, 75–100 is poor, and more than 100 is very poor for household use and drinking. The water quality index during premonsoon is 50% and 48% during postmonsoon. The water quality index results show that all the samples are good for drinking during both monsoons.

3.2. Ionic Suitableness for Irrigation Evaluation. The Indian coast can be classified into two categories based on the geomorphic setup: (a) east coast and (b) west coast. The vast coastal plains and sedimentary deposits along the east coast have given way to creating clearly defined deltaic plains at the river mouths [52]. The west coast is mostly rocky, with tidal creeks, and exposed rock [53]. The Kuzhithuraiyar, or Thamirabarani, is confluences on the west coast near Thengapattanam. The ionic interactions in the samples are identified through the chloroalkaline indices and meteoric genesis index. It shows that more than 50% of samples show reverse ion exchange processes and deep meteoric percolation, while 50% show the direct ion exchange and shallow meteoric percolation. The irrigation suitability of the water samples is calculated using standard formulas, and their results are given in Table 3.

All samples are excellent and safe, according to the residual sodium concentration (RSC) and sodium absorption ratio (SAR). Figure 3 plots the SAR and EC measurements acquired from the USSL. It is possible to decrease the permeability and structure of the soil by increasing the amount of salt in the soil [54]. Groundwater in the C4-S2, C4-S3, C4-S4, and C4-S1 categories cannot be used for irrigation in most soil types except those with high permeability [55]. On the other hand, C3-S1 water can only be used for irrigation in semitolerant crops [56]. The USSL diagram indicates that the three samples taken before the monsoon and the four samples taken after the monsoon belong to the C3-S2 category, which denotes moderate salinity and mild alkali threats. The research area has low to medium alkalinity and low to high salinity.

Premonsoon samples with cation and sodium concentrations show that 21% of them are good and 2% and 6% are excellent, 44% of premonsoon and 48% of postmonsoon samples are acceptable, and 33% of premonsoon and 23% of postmonsoon samples are doubtful. The soil infiltration rate and Na% are antagonistic [14]. This antagonistic relationship is often observed in soils with high levels of sodium. High sodium levels can lead to the dispersion of soil particles, causing the formation of a compacted soil structure with reduced pore spaces. This compacted structure hinders water movement through the soil, resulting in a lower infiltration rate. Sodium ions can harm soil structure,

Table 1: pH, EC, TDS, and cation and anion concentration of groundwater samples of Kuzhithuraiyar sub-basin.

Parameter	Desirable limit	Postmonsoon		Premonsoon		Postmonsoon samples (%)		Premonsoon samples (%)	
		Min	Max	Min	Max	Within limit	Exceeding limit	Within limit	Exceeding limit
pH	6.5–8.5	6.9	8.5	6.5	8.5	100	—	100	
EC	300 μS/cm	39.06	1523.44	37.5	1996.88	71	29	54	46
TDS	500 mg/L	25	975	24	1278	90	10	85	15
Ca	75 mg/L	2	104	2	92	98	2	94	6
Mg	30 mg/L	1.22	43.74	1.22	58.32	98	2	90	10
Na	200 mg/L	2	230	3	317	92	8	92	8
K	10 mg/L	0.1	38	1	37	77	23	86	14
Cl	250 mg/L	4	411	4	624	92	8	90	10
SO_4	200 mg/L	1	72	1	77	100	—	100	—
CO_3	—	0	1.47	0	4.33				
HCO_3	—	4.98	317.2	4.97	366	—	—	—	
NO_3	45 mg/L	0.1	23	0.05	18	100	—	100	
F	1.0 mg/L	0.05	0.76	0.05	0.86	100	—	100	

Table 2: Relative weight of the parameter.

Parameters	Min	Max	Average	STD	WHO standards [25]	Weight (w_i)	Relative weight (W_i)
pH	8.5	6.9	7.80	0.32	6.5 to 8.5	5	0.138889
TDS	975	25	213.17	247.09	500–1500	5	0.138889
Ca	104	2	18.38	21.43	75–200	2	0.055556
Mg	43.74	1.215	9.14	8.31	50–150	2	0.055556
Na	230	2	41.90	60.68	200	3	0.083333
K	38	0.1	7.03	7.29	12	2	0.055556
Cl	411	4	64.96	105.40	200–600	3	0.083333
SO_4	72	1	11.58	13.63	200–400	4	0.111111
CO_3	1.47	0	0.36	0.40	—	1	0.027778
HCO_3	317.2	4.98	66.23	65.03	300–600	3	0.083333
NO_3	23	0.1	4.98	5.20	50	2	0.055556
F	0.76	0.05	0.20	0.15	1.2	4	0.111111

influencing its permeability and reducing its ability to absorb and transmit water [57, 58]. The Wilcox diagram shows the salt and electrical conductance proportion before and after the monsoon (Figure 4). 10% of pre- and postmonsoon samples are classified as dubious, 6% as good to permissible, and 84% as permitted.

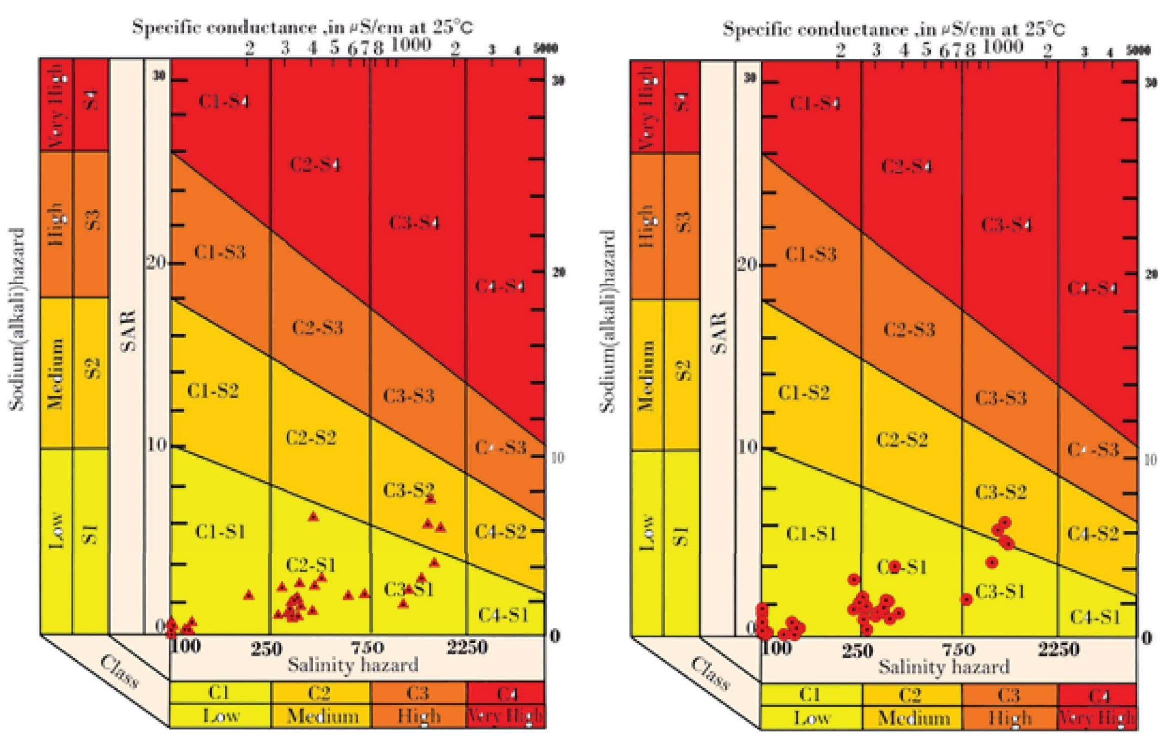
According to Kelly's ratio, 56% and 48% of samples during the post- and premonsoon periods are suitable for irrigation, and the remaining samples are unsuitable for irrigation. In this study, magnesium hazard shows that 40% and 44% of samples during pre- and postmonsoon are unsuitable for irrigation. Potential salinity of 13% of samples during postmonsoon and 19% of samples during premonsoon is greater than 3, indicating unsuitability for irrigation.

3.2.1. Pearson's Correlation Analysis. Pearson's correlation coefficient model, as presented in Tables 4 and 5, was employed to analyze the interrelationships among the physicochemical parameters. In pre- and postmonsoon, pH shows a positive correlation with bicarbonate (HCO_3^-) at a significant level ($p < 0.01$), indicating that as the pH levels increase, the concentration of bicarbonate in the water also tends to increase [56, 57]. EC, TDS, and most major ions, calcium, magnesium, sodium, potassium, chloride, and sulfate exhibit strong positive correlations among themselves ($p < 0.01$). This indicates a significant relationship, suggesting that these parameters increase or decrease in the groundwater samples. Chloride correlates positively with the concentrations EC, TDS, and most major ions, highlighting a consistent relationship among these parameters. The relationship between carbonate and other parameters appears weak or negligible as low or insignificant correlation coefficients indicate. Nitrate and fluoride seem to have very weak or little correlations with different parameters based on the provided correlation matrix [56, 57].

3.3. Discussion. In this study, pH, EC, TDS, and major cations (e.g., sodium, calcium, magnesium, and potassium) and anions (e.g., chloride, sulfate, bicarbonate, and nitrate) were found to be highly variable. The pH value ranges between 8.5 and 6.5, consistently within an acceptable range, indicating that the water is generally suitable for household and drinking use. According to the spatial distribution map, ionic concentrations vary with proximity to the coastline, which impacts interactions between salinity and ions. These variations illustrate the region's diverse geologic settings and anthropogenic influences, which may affect water quality [59, 60]. In both premonsoon and postmonsoon periods, a proportion of samples exceed the recommended TDS

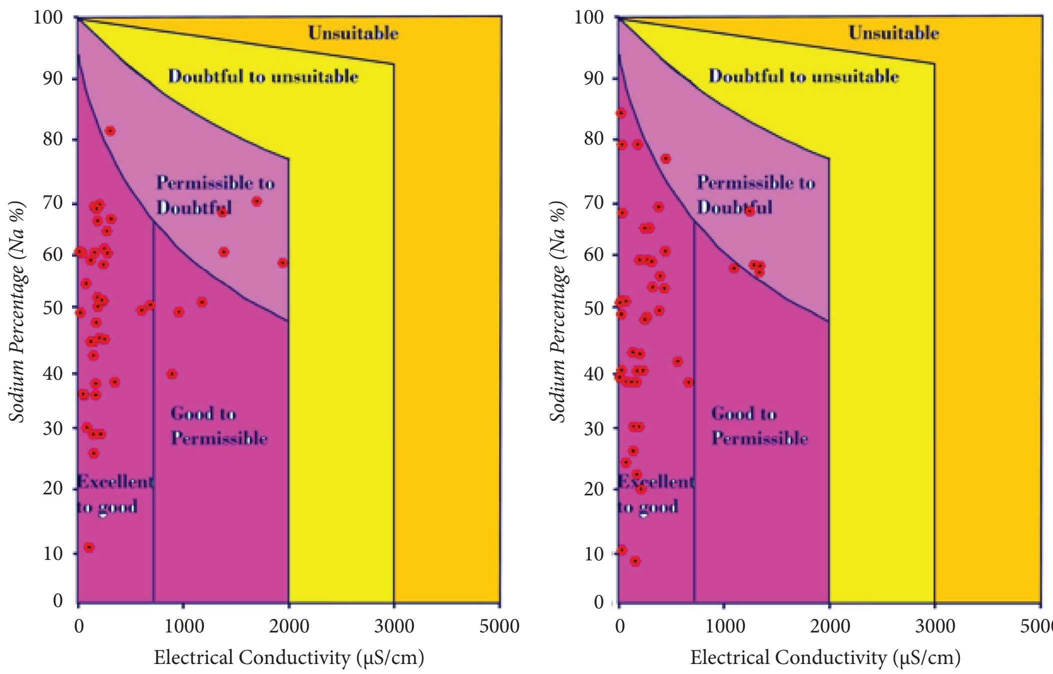
Table 3: Water quality index and irrigation suitability of the water samples of Kuzhithuraiyar sub-basin.

Parameter	Range	Water class	Samples in premonsoon	Samples in postmonsoon
Water quality index	0–25	Excellent	—	—
	25–50	Good	48	48
	50–75	Moderate	—	—
	75–100	Poor	—	—
	100	Very poor	—	—
Sodium adsorption ratio	<10	Excellent	48	—
	10–26	Good	—	—
	>26	Doubtful	—	—
RSC	<1.25	Good	48	—
	1.25–2.5	Doubtful	—	—
	>2.5	Unsuitable	—	—
Sodium percentage	<20%	Excellent	1	3
	20 to 40%	Good	10	11
	40 to 60%	Permissible	21	23
	60 to 80%	Doubtful	16	11
	>80%	Unsuitable	—	—
Kelly's ratio	<1	Suitable	23	27
	>1	Unsuitable	25	21
Permeability index	>75%	Good	37	35
	25 to 75%	Doubtful	11	13
	<25%	Unsuitable	—	—
Magnesium hazard	>50	Unsuitable	19	21
	<50	Suitable	29	27
Potential salinity	>3	Unsuitable	9	6
	<3	Suitable	39	42



(a) (b)

Figure 3: USSL diagram, Kuzhithuraiyar sub-basin, (a)pre monsoon and (b) post monsoon.



(a) (b)

Figure 4: Wilcox diagram, Kuzhithuraiyar sub-basin, (a) pre monsoon and (b) post monsoon.

Table 4: Correlation coefficient of analyzed parameters of Kuzhithuraiyar sub-basin during premonsoon.

	pH	EC	TDS	Ca	Mg	Na	K	Cl	SO_4	CO_3	HCO_3	NO_3	F
pH	1	0.192	0.192	0.189	0.213	0.178	0.132	0.196	0.116	0.413**	0.177	0.019	−0.082
EC		1	1.000**	0.941**	0.888**	0.979**	0.470**	0.975**	0.838**	−0.095	0.875**	0.489**	0.450**
TDS			1	0.941**	0.888**	0.979**	0.470**	0.975**	0.838**	−0.095	0.875**	0.489**	0.450**
Ca				1	0.879**	0.872**	0.408**	0.901**	0.796**	−0.060	0.872**	0.479**	0.520**
Mg					1	0.801**	0.327*	0.843**	0.883**	0.038	0.818**	0.472**	0.562**
Na						1	0.423**	0.974**	0.775**	−0.137	0.833**	0.395**	0.351*
K							1	0.380**	0.382**	0.078	0.439**	0.545**	0.221
Cl								1	0.796**	−0.168	0.767**	0.370**	0.343*
SO_4									1	−0.121	0.713**	0.431**	0.515**
CO_3										1	0.105	−0.102	0.048
HCO_3											1	0.441**	0.557**
NO_3												1	0.473**
F													1

Correlation is significant at the 0.01 level (2-tailed) **. Correlation is significant at the 0.05 level (2-tailed)*.

limits. Although most samples are within permissible limits, high TDS in some samples during both seasons raises concerns regarding its impact on water suitability for drinking and agriculture. Comparing the pre- and postmonsoon value ranges, the postmonsoon values are comparatively low due to the influence of precipitation, which dilutes the salinity in the water.

As a result of the analysis of cation and anion concentrations, it is apparent that their levels vary across different locations within the sub-basin. Elevated concentrations may negatively impact soil quality and crop growth in areas where sodium, calcium, magnesium, and potassium concentrations exceed the acceptable limits. The high sodium concentration in water affects the taste of drinking water. Excess sodium is toxic to some sensitive crops. Due to excess sodium in water, the soil acts as plastic in nature, affecting the soil's permeability. The mineral content of the surface soils and sediments determines where the F in groundwater comes from. Seawater intrusion is responsible for the concentration of chloride and sulfate in groundwater, whereas fertilizers and pesticides used in agricultural practices are responsible for the nitrate concentration.

During pre- and postmonsoon seasons, the WQI assessments indicate that the water quality is generally good for drinking. The results suggest that, despite some outliers in individual parameters, the water meets acceptable standards for household consumption. Correlation analyses using Pearson's correlation coefficient revealed significant relationships between water quality parameters. A positive correlation between pH and carbonate indicates that both

Table 5: Correlation coefficient of analyzed parameters of Kuzhithuraiyar sub-basin during postmonsoon.

	pH	EC	TDS	Ca	Mg	Na	K	Cl	SO_4	CO_3	HCO_3	NO_3	F
pH	1	−0.036	−0.036	−0.004	0.107	−0.064	−0.041	−0.077	0.064	0.645**	0.148	−0.197	0.079
EC		1	1.000**	0.933**	0.864**	0.986**	0.496**	0.984**	0.717**	−0.142	0.842**	0.685**	0.320*
TDS			1	0.933**	0.864**	0.986**	0.496**	0.984**	0.717**	−0.142	0.842**	0.685**	0.320*
Ca				1	0.836**	0.878**	0.365*	0.923**	0.747**	−0.008	0.784**	0.568**	0.442**
Mg					1	0.805**	0.313*	0.824**	0.711**	0.086	0.860**	0.468**	0.405**
Na						1	0.471**	0.979**	0.673**	−0.213	0.818**	0.685**	0.244
K							1	0.436**	0.228	−0.119	0.440**	0.474**	0.137
Cl								1	0.686**	−0.198	0.761**	0.655**	0.301*
SO_4									1	0.024	0.604**	0.299*	0.421**
CO_3										1	0.078	−0.319*	0.160
HCO_3											1	0.410**	0.333*
NO_3												1	0.020
F													1

Correlation is significant at the 0.01 level (2-tailed) **. Correlation is significant at the 0.05 level (2-tailed)*.

parameters increased simultaneously. Moreover, strong correlations between EC, TDS, and significant cations and anions suggest that these variables are interdependent, possibly affecting overall water quality. SAR, RSC, USSL diagram, and Kelly's ratio classify soils based on their salinity or alkalinity. The high salinity and potential salinity values in specific samples raise concerns regarding their suitability for agricultural use.

4. Conclusion

Different irrigation and drinking suitability metrics were used in the current study in the Kuzhithuraiyar sub-basin, leading to various interpretations. IDW spatial distribution analysis was performed using ArcGIS 10.8 software, which gave more ideas about the distribution of different ions in the study area. WQI shows good drinking water quality before and after monsoon season. EC and TDS readings indicate that most samples are drinkable. The samples close to the coast are highly salinized. This implies that crops with a medium to high tolerance to salt can only be cultivated adjacent to the shore. The SAR and RSC predict the sodium hazard, indicating a high infiltration rate in the research area. The USSL plot clearly shows that any soil can be used for irrigation with just a very minimal risk of exchangeable salt [61].

Five samples are shown on the Wilcox diagram to fall into the permitted to doubtful category pre- and post-monsoon. Seawater incursion from the Arabian Sea is reduced compared to the west coast of Tamil Nadu due to the structural features of the region having a significant role in controlling the seawater intrusion along the west coast. The geology of Kodumkulam and Chankurutti is a hard rock terrain of Garnet Biotite Sillimanite Graphite Gneiss. Vavarai, Edavar, and Vaikalur are sedimentary terrains very close to the sea of sand, silt, clay partings, sandstone with clay intercalations, and clayey sand.

Artificial recharge structures such as percolation ponds, check dams, and subsurface dykes in the coastal regions can be introduced. The high salinity of Vaikalur, Chankurutti, Vavarai, and Edavar villages was due to anthropogenic activities and the tsunami in 2004. Previous studies have shown that the salinity level has decreased comparatively due to the frequent rainfall in the study area. Even though Kodumkulam village is 13 km away from the seashore, the water is saline in this region due to anthropogenic activities such as habitat encroachment, contamination of surface water bodies, and poor maintenance of surface water bodies. In the village of Kodumkulam, it is remarkable that no steps have been taken to ensure excellent water sanitation. The surface water body, particularly a pond called Kodumkulam, which served as the village's primary water source, has now been converted into a domestic sewage collection pond. It needs to be adequately sanitized to raise the quality of the village's groundwater; otherwise, the health of the residents and habitats will be seriously jeopardized. So, the participation of every individual is required to improve the quality of the village.

Data Availability

All data supporting this study's findings are included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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