



RESEARCH ARTICLE

# Assessment of groundwater quality and irrigation suitability for crop production using hydrochemical parameters in a coastal region of Tamil Nadu, India

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## Abstract

Quality irrigation water is essential in semi-arid and coastal regions for sustainable crop production. The quality of irrigation water has deteriorated nowadays due to indiscriminate use of chemical fertilizers and overexploitation of groundwater. Therefore, the study assessed groundwater quality of the Nainarkoil block of Ramanathapuram district, Tamil Nadu, where agriculture is the predominant economic activity. A total of 50 geocoded samples were collected and analysed for hydrochemical parameters, including pH, electrical conductivity (EC), major cations (sodium (Na<sup>+</sup>), potassium (K<sup>+</sup>), calcium (Ca<sup>2+</sup>) and magnesium (Mg<sup>2+</sup>)) and anions like (CO<sub>3</sub><sup>2-</sup>, HCO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>). Irrigation quality indices like sodium percentage, Kelly's Index, sodium adsorption ratio, permeability index and residual sodium carbonate were computed to determine overall suitability for irrigation. The Geographic Information System tool ArcGIS was employed to create a spatial distribution map of quality parameters, which offers a clear visual representation of groundwater characteristics. The results revealed wide variations in suitability with several locations exhibiting elevated salinity and hardness. Eighty percent of samples exceeded the allowable limits for pH and EC respectively. Where 56 % and 64 % of locations had Ca<sup>2+</sup> and Mg<sup>2+</sup> concentrations respectively, above the limit. Na<sup>+</sup> and K<sup>+</sup> ions surpassed the limits of WHO in 78 % and 26 % of samples respectively. Regarding anions, 76 %, 54 % and 68 % of the samples crossed the limits for CO<sub>3</sub><sup>2-</sup>, HCO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup> respectively. According to the findings, the majority of groundwater samples exceeded the WHO's standard limits, which are not appropriate for irrigation, crop production and findings highlight the need for regular monitoring and sustainable water management practices.

**Keywords:** correlation matrix; GIS tools; groundwater; hydrochemical parameters; quality Indices

## Introduction

Water is one of the most important natural resources on earth since it determines the existence of life and serves as an essential component for humanity (1, 2). Groundwater and surface water have always been highly valued and distinctive sources of freshwater for household, industrial and agricultural purposes (3). Water quality is crucial for sustainability and environmental health, especially in areas that are rapidly industrializing and intensifying their agriculture (4). Water quality refers to the chemical, physical and biological characteristics of water that determine its suitability for various uses. In agricultural contexts, key chemical parameters include salinity, nutrient content and toxic ions, while physical factors such as pH and electrical conductivity are critical indicators. The availability of good-quality water is essential for the sustainability of socioeconomic growth (5). The quality of

groundwater used for irrigation is mainly determined by its water type, the proportion of salt and dissolved solids present in it (6). The steadily rising food demands of a growing population have played a significant role in expanding irrigation practices (7). Crop yields are increased when irrigation water quality is high under standard soil and water management techniques. However, poor irrigation water quality can reduce soil permeability, which in turn decreases crop productivity by limiting the availability of good-quality water to plants (8).

Around 2.5 billion people worldwide depend only on readily available groundwater for household requirements and irrigation (9). India is home to 16.60 % world's population, 2.2 % of its land and 4 % of the world's water resources (10). Tamil Nadu contains 6 % of India's population, 4 % of the country's total land area, but it only has 2.5 % of India's water resources (11). India is

the highest user of groundwater in the world, with an estimated yearly use of over 250 billion m<sup>3</sup>, which is more than 25 % of the world's total use (12). Based on WHO reports, in India, 65 % of the rural and 36 % of the urban population do not consume good quality drinking water (13). Rapid urbanization and agricultural operations lead to changes in rivers' natural hydrological conditions, which is reflected in the deterioration of water quality. The situation is critical in coastal areas, where water quality is assumed to be affected by land cover alterations (14). Several agricultural sites near the coast have been abandoned due to groundwater salinity (15). To effectively use and protect important water sources and to forecast changes in groundwater environments, it is essential to understand the hydrochemical parameters of groundwater, such as pH, electrical conductivity (EC), major anion (CO<sub>3</sub><sup>2-</sup>, HCO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup>) and cation (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup>) concentrations (16).

Therefore, understanding the quality of groundwater helps us to determine its suitability for drinking and agricultural use. In the current scenario, the use of GIS and remote sensing has significantly expanded in the evaluation of water quality. GIS is a tool for mapping water quality and power to screen, which is used as a database framework to create water quality maps based on component focus estimations (17). Using GIS as a decision support system to map the water quality parameters can serve as a helpful foundation for making prompt and accurate management choices (18). This study assesses the groundwater quality in the Nainarkoil block of the Ramanathapuram district of Tamil Nadu, India. This is a semi-arid coastal region where agriculture is the primary livelihood, since these locals heavily depend on groundwater for irrigation. So,

this research highlights the groundwater quality in the Nainarkoil block for its suitability to irrigation and crop production.

### Study area

The study examines the quality of the groundwater in the Nainarkoil block of Ramanathapuram district, Tamil Nadu, India (Fig. 1). This district is located in the southern part of Tamil Nadu, which is a vital region for agriculture. The research area's geological coordinates are 78°10' to 79°27' E longitudes and 9°05' to 9°50' N latitudes. The mean minimum temperature ranges from 19.5 °C-24.8 °C, while the mean maximum ranges from 29.2 °C-37.8 °C. The typical temperature ranges from 19.5 °C-24.8 °C at the lowest and from 29.2 °C-37.8 °C at the highest. March is the month with the largest variation between the mean maximum and mean minimum temperatures. The district receives an average annual rainfall of 827.0 mm, with 67.4 mm in winter, 122.7 mm in summer, 135.3 mm during the south-west monsoon and 501.6 mm during the northeast monsoon (19).

### Materials and Methods

Fifty groundwater samples, widely used for agricultural purposes, were randomly collected from bore wells and stored in 1 L polythene bottles. The sampling points are indicated in Fig. 1. Water flushing for 5-10 min was conducted before the collection of water samples. To remove all impurities and contaminants, the bottles were immersed in water containing 10 % HNO<sub>3</sub> and pre-rinsed with distilled water. To stop evaporation, all sample bottles were sealed tightly. The standard procedure for estimation of water quality parameters such as pH, EC, Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, CO<sub>3</sub><sup>2-</sup>,

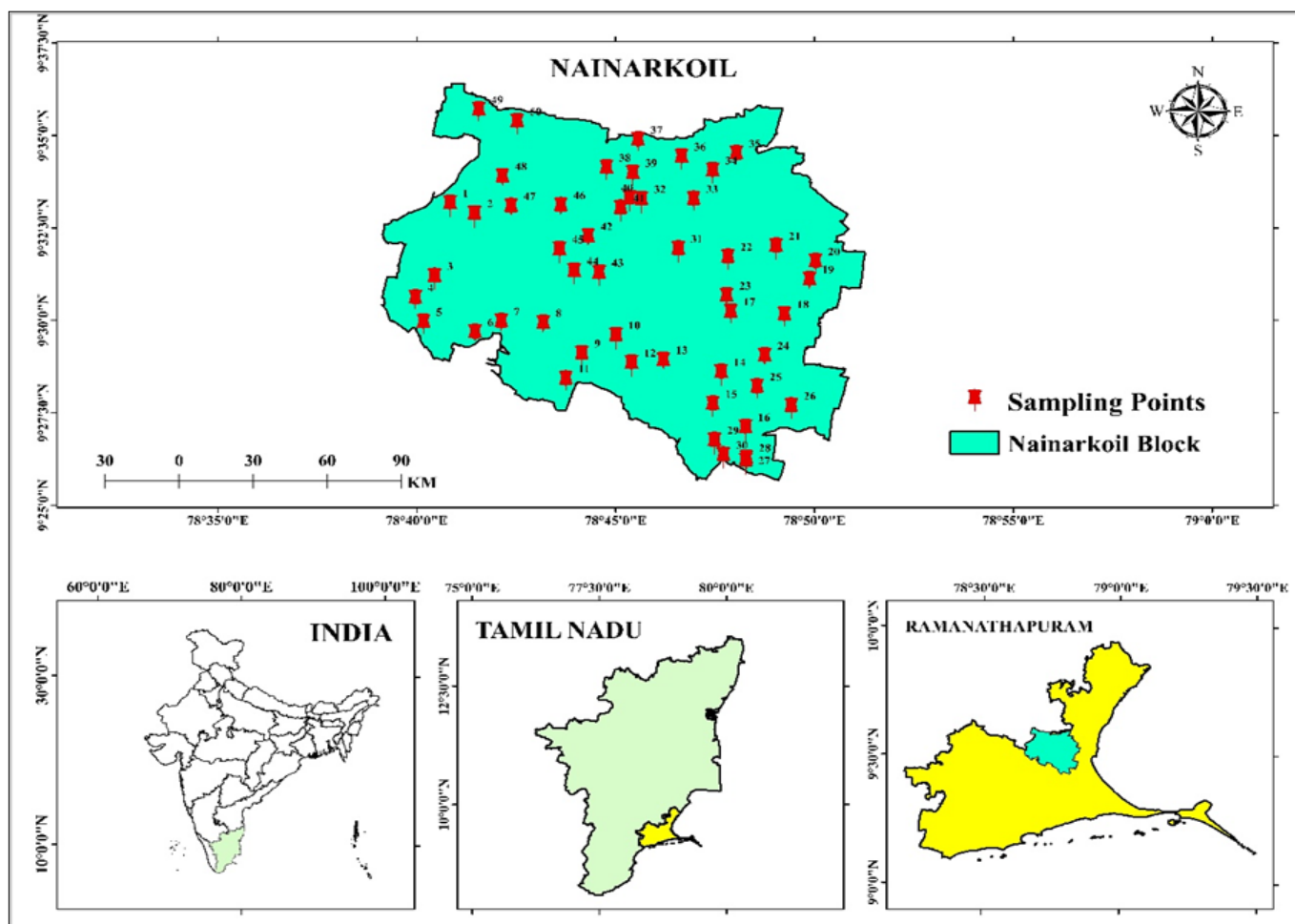


Fig. 1. Study area with 50 sampling points.

HCO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup> was followed. A calibrated pH meter was used to assess pH and a conductivity meter was used to measure EC. The Versenate titration method was used to quantify Ca<sup>2+</sup> and Mg<sup>2+</sup> and flame photometry for the analysis of Na<sup>+</sup> and K<sup>+</sup>. Titration with H<sub>2</sub>SO<sub>4</sub> was done by utilizing phenolphthalein and methyl orange indicators for the determination of CO<sub>3</sub><sup>2-</sup> and HCO<sub>3</sub><sup>-</sup>. To measure Cl<sup>-</sup>, argentometric titration using AgNO<sub>3</sub> was followed, while barium chloride was used in the turbidimetric method to quantify SO<sub>4</sub><sup>2-</sup> (20). Relevant irrigation quality indices, including sodium percentage (Na %), Kelly's index (KI), sodium adsorption ratio (SAR), permeability index (PI) and residual sodium carbonate (RSC), were then calculated using the obtained data. The suitability of irrigation was assessed using ArcGIS diagrams.

The irrigation quality parameters, such as Na %, KR, SAR, PI and RSC, were calculated by using Eqn. (1-5) and are expressed in meq/L.

$$\text{Na \%} = \frac{(\text{Na} + \text{K}) \times 100}{(\text{Ca} + \text{Mg} + \text{Na} + \text{K})} \quad (1)$$

$$\text{KI} = \frac{\text{Na}}{(\text{Ca} + \text{Mg})} \quad (2)$$

$$\text{SAR} = \frac{\text{Na}}{\sqrt{\frac{(\text{Ca} + \text{Mg})}{2}}} \quad (3)$$

$$\text{PI} = \frac{(\text{Na} + \sqrt{\text{HCO}_3})}{(\text{Ca} + \text{Mg} + \text{Na})} \times 100 \quad (4)$$

$$\text{RSC} = (\text{CO}_3 + \text{HCO}_3) - (\text{Ca} + \text{Mg}) \quad (5)$$

### Preparation of spatial distribution map

ArcGIS 10.8 was used to generate spatial distribution maps illustrating groundwater quality indicators. Users can view, analyse and understand data with ArcGIS, which helps them make well-informed decisions on urban planning and environmental management (2). The major elements that promote the quality of groundwater in the investigated area were classified by using spatial distribution in the ArcGIS software. These maps offer a clear visual representation of the variations in groundwater characteristics throughout the research region (1).

### Statistical analysis

Statistical approaches for water quality involve data analysis and interpretation to evaluate variability and trends in water parameters, facilitating the monitoring and identification of possible concerns (21). Table 1 presents the minimum, maximum, mean and standard deviation values of the analysed parameters.

**Table 1.** Statistical analysis of hydrochemical parameters for groundwater samples

Parameters	Minimum	Maximum	Average	SD
pH	7.16	8.73	7.92	0.39
EC (µS/cm)	620	19120	4781.4	4772.74
Na (mg/L)	71.27	2073.7	541.74	453.11
K (mg/L)	0	195.5	16.19	36.47
Ca (mg/L)	14	646	110.16	125.24
Mg (mg/L)	15.8	1018.17	207.27	265.5
CO <sub>3</sub> (mg/L)	0	426	51.42	62.89
HCO <sub>3</sub> (mg/L)	207.4	1268.8	542.78	235.97
Cl (mg/L)	35.5	6390	1273.17	1591.3
SO <sub>4</sub> (mg/L)	5.76	151.68	42.59	33.91

## Results and Discussion

Water quality results were compared with WHO standards to assess suitability for irrigation (22) (Table 2).

### Electrochemical properties

The pH distribution of groundwater samples in the research area is depicted in Fig. 2a. The pH determines whether water is basic or acidic. The pH of irrigation water samples ranged from 7.16 to 8.73, with an average of 7.92. The pH level of the 92 % groundwater samples was found to be acceptable limit (6.5-8.5) of WHO and the remaining samples lie in the range of slightly alkaline. The increased pH level might be due to the presence of calcareous aquifers (23).

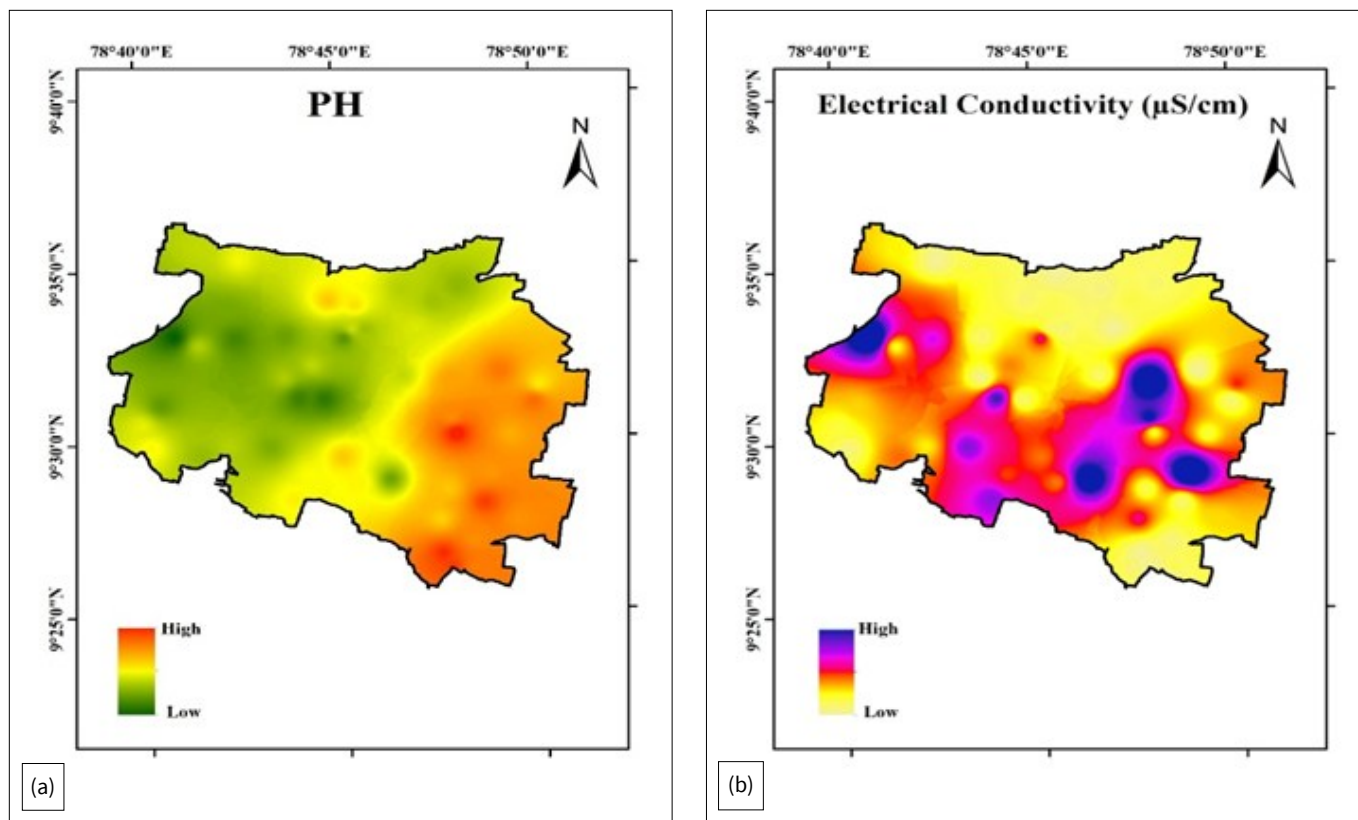
There is a greater variation in electrical conductivity in the villages of the Nainarkoil block study area (Fig. 2b). The salt content of groundwater is indicated by EC measurements. The average EC is 4781.4 µS/cm, with a range of 620 to 19,120 µS/cm. EC exceeded the WHO's maximum allowed level (1400 µS/cm) in 80 % of samples. Higher EC can be linked to groundwater samples with high salinity and mineral content that are the result of geochemical processes such as ion exchange, evaporation and silicate weathering (24).

### Cations in the groundwater samples

Na<sup>+</sup> and K<sup>+</sup> are widely distributed across the study area, which is depicted in the geographical distribution map (Fig. 3a, b). The average Na<sup>+</sup> content of groundwater in the research region is 541.74 mg/L, with a range of 71.27 to 2073.7 mg/L. Alarmingly, 78 % of the samples had sodium levels surpassing the WHO's recommended limit of 200 mg/L. The natural dissolution of Na-rich minerals in the aquifer or man-made factors, such as overuse of fertilizers containing Na might be the causes of elevated Na<sup>+</sup> levels in groundwater (25). K<sup>+</sup> level ranges from 0 to 195.5 mg/L, with an average of 16.19 mg/L. Potassium concentrations exceeding the WHO threshold of 12 mg/L were detected in 26 % of the samples.

**Table 2.** Comparison of parameters with the WHO's standard

Parameters	WHO standards permissible limit	No of samples exceeding WHO limits	% of samples exceeding WHO limits
pH	6.5-8.5	4	8 %
EC (µS/cm)	1400	40	80 %
Na (mg/L)	200	39	78 %
K (mg/L)	12	13	26 %
Ca (mg/L)	75-200	28	56 %
Mg (mg/L)	50-150	32	64 %
CO <sub>3</sub> (mg/L)	0.0	38	76 %
HCO <sub>3</sub> (mg/L)	500	27	54 %
Cl (mg/L)	200-600	34	68 %
SO <sub>4</sub> (mg/L)	200-400	50	100 %



**Fig. 2.** Spatial distributions of (a) pH and (b) EC.

The higher concentration of potassium may be due to the presence of rock materials. The coastal belt of Ramanathapuram district was documented for the dominance of sodium in irrigation water, as per the reports submitted by (26).

$\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  cation changes are illustrated in the geographic distribution map (Fig. 3c, d). The calcium and magnesium levels of groundwater samples ranged from 14 mg/L to 646 mg/L and 15.8 mg/L to 1018.17 mg/L, with averages of 110.16 and 207.27 respectively. The  $\text{Ca}^{2+}$  level is higher than the allowable limits in 28 samples out of 50. The desired limit of 75 mg/L-200 mg/L is exceeded by 56 % of the samples. In 64 % of the samples (i.e. 32 samples), the  $\text{Mg}^{2+}$  concentration was found above the permissible limits (50 mg/L-150 mg/L). Conversely, reduced quantities of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  may result from reverse cationic exchange with  $\text{Na}^+$ , in these  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were replaced by  $\text{Na}^+$  in groundwater can adversely affect crop yield by increasing salinity (4).

#### Anions in the groundwater samples

$\text{CO}_3^{2-}$  content of the groundwater depends on the amount of dissolved carbon dioxide, temperature, pH, cations and other dissolved salts. The  $\text{HCO}_3^-$  content of waters is the actions of the carbonate equilibrium that keep the  $\text{HCO}_3^-$  content of natural waters within a reasonable range (27). The groundwater samples  $\text{CO}_3^{2-}$  concentrations in groundwater samples (Fig. 4a) varied from 0 to 426 mg/L. Only 24 % of the samples (12 out of 50) were found within the limit, while the remaining 76 % (38 samples) surpassed it. The  $\text{HCO}_3^-$  content (Fig. 4b) in the groundwater samples ranged from 207.4 mg/L to 1268.8 mg/L. Forty percent of the samples are under the WHO's permitted limit of 500 mg/L, while 54 % samples surpassed the limit.

In the study region, Cl<sup>-</sup> ranges from 35.5 mg/L to 6390 mg/L with an average of 1273.17 mg/L (Fig. 4c). According to WHO

(22). The ideal limit of Cl<sup>-</sup> is 200-600 mg/L and 68 % of the samples have levels over this threshold. Numerous factors, including weathering, the leaching of sedimentary rocks and soil, household and municipal effluents, can contribute to the presence of Cl<sup>-</sup> in groundwater (28).  $\text{SO}_4^{2-}$  levels in groundwater samples in the research region ranged from 5.76 mg/L to 151.68 mg/L, with an average of 42.59 mg/L (Fig. 4d). In groundwater,  $\text{SO}_4^{2-}$  are often found as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{Na}^+$  salts. High  $\text{SO}_4^{2-}$  concentrations in water are caused by anthropogenic activities, the buildup of soluble salts in the soil and the use of excessive amounts of  $\text{SO}_4^{2-}$  fertilizers (18) and fertilizer leaching can also raise  $\text{SO}_4^{2-}$  levels in groundwater (29).

#### Irrigational quality indices

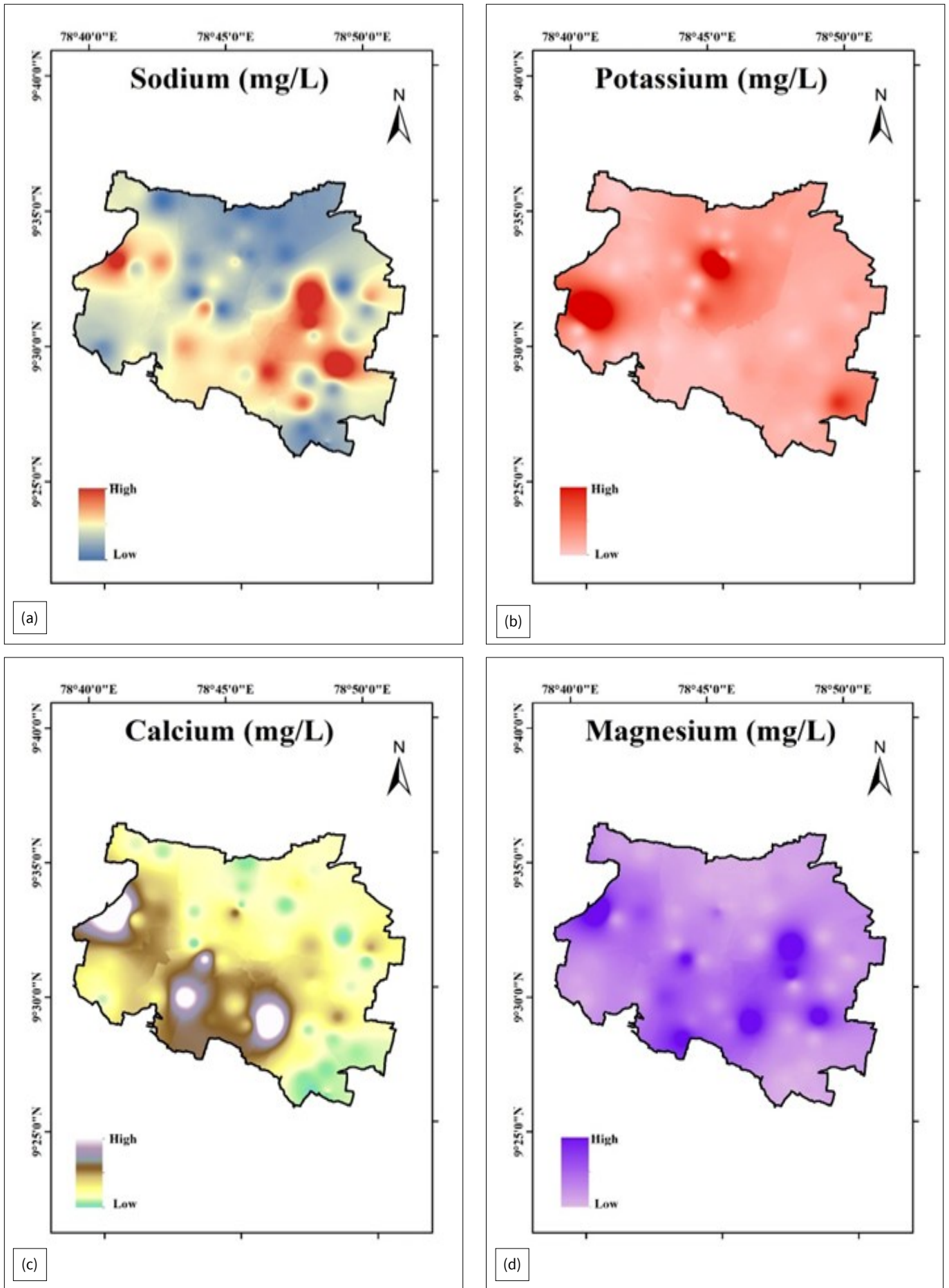
WHO standards for irrigation quality indices are depicted in the Table 3.

##### Sodium percentage

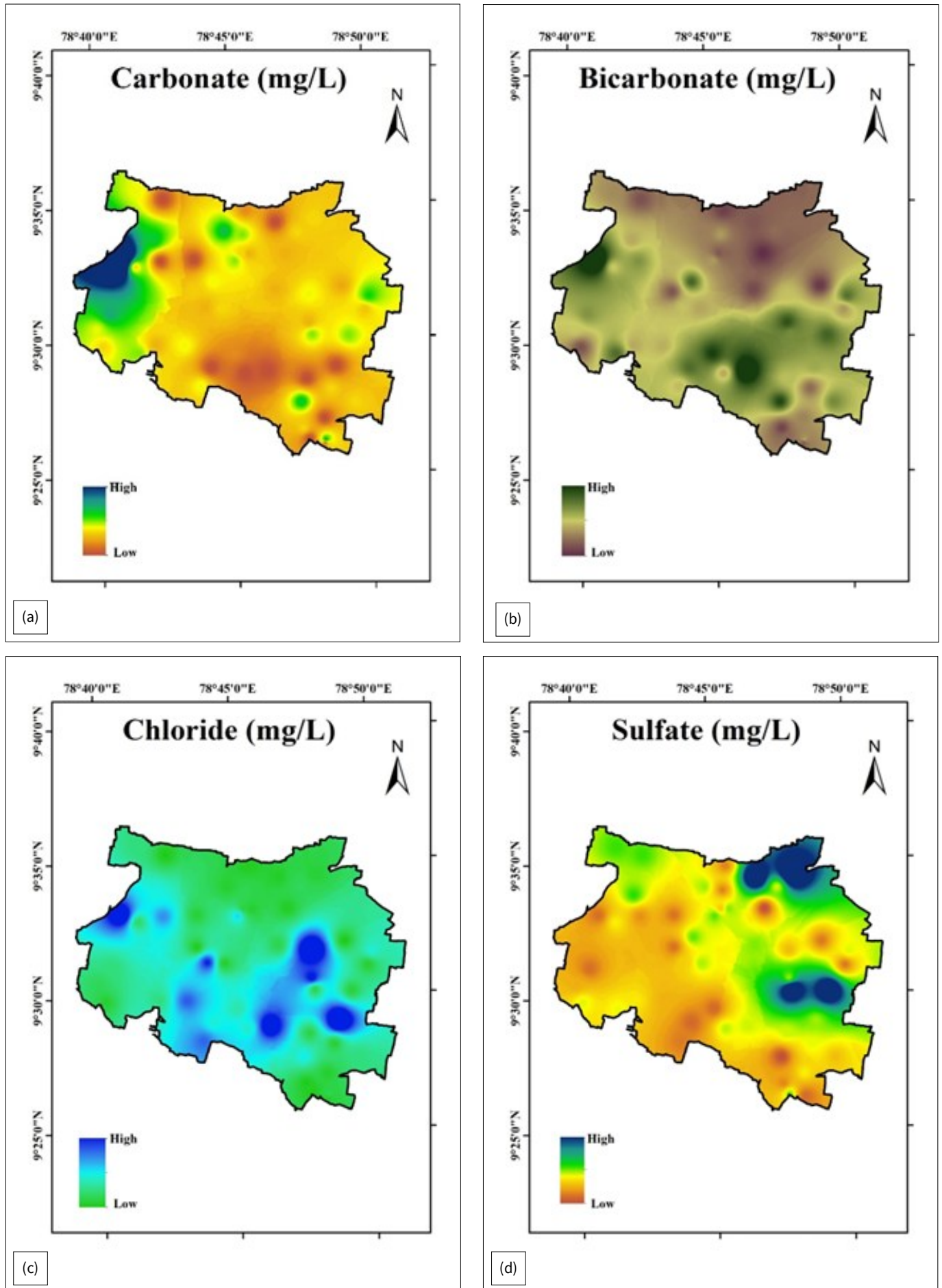
Groundwater divided into 5 groups according to  $\text{Na}^+$  content and electrical conductivity (30). The water is unsuitable for agricultural use since the salt content is more than 60 %. In several samples of the Nainarkoil block of Ramanathapuram district, the levels of  $\text{Na}^+$  were found to be higher than the normal (based on  $\text{Na}^+$  %). Based on  $\text{Na}^+$  % (Fig. 5a), the samples were classified as excellent (6 sites), good (13), permissible (20), doubtful (9) and unfit (2). Most of the samples are in the good to acceptable range and they are suitable for irrigation and crop production. Among the cations,  $\text{Na}^+$  was the most prevalent ion among the many other cations found in the water. This is due to silicate weathering and dissolution of soil salts deposited by the impacts of evaporation and anthropogenic human activities, in addition to intense agricultural activities and poor drainage conditions (31).

##### Kelly's index

Irrigation water sources were categorized by using Kelly's index



**Fig. 3.** Spatial distribution maps of (a) Sodium ( $\text{Na}^+$ ), (b) Potassium ( $\text{K}^+$ ), (c) Calcium ( $\text{Ca}^{2+}$ ), (d) Magnesium ( $\text{Mg}^{2+}$ ).



**Fig. 4.** Spatial distribution of (a) Carbonate ( $\text{CO}_3^{2-}$ ), (b) Bicarbonate ( $\text{HCO}_3^-$ ), (c) Chlorine ( $\text{Cl}^-$ ), (d) Sulphate ( $\text{SO}_4^{2-}$ ).

**Table 3.** WHO standard for irrigation quality indices

Parameters	WHO standards permissible limit	No of samples fall within this WHO limits	% of samples fall within this WHO limits
Na%	<20 Excellent	6	12%
	20-40 Good	13	26%
	40-60 Permissible	20	40%
	60-80 Doubtful	9	18%
	>80 Unfit	2	4%
KI	<1.0 Suitable	27	54%
	>1.0 Unsuitable	23	46%
SAR	0-10 Excellent	0	0%
	10-18 Good	5	10%
	18-26 Doubtful	6	12%
	>26 Unfit	39	78%
PI	>75 Class I	36	72%
	25-75 Class II	14	28%
	<25 Class III	0	0%
RSC	<1.25 Good	36	72%
	1.25-2.5 Doubtful	5	10%
	>2.5 Unfit	9	18%

(Fig. 5b). Index of 1 L of water Kelly's indicates that it is unsuitable for irrigation since it displays an excessive amount of salt. Water is considered to be appropriate for agricultural irrigation, having a Kelly's index of less than 1. Twenty-seven samples (54 %) are appropriate for irrigation and crop production in the study region, while 23 samples (46 %) are not suitable. Groundwater samples taken from several villages (nearly half of the locations) in Nainarkoil block are deemed inappropriate for irrigation purposes based on Kelly's index, which indicates that water quality in most places is unsuitable for farming. Practices like soil cleaning, vitrification, encapsulation of regions by impermeable vertical and horizontal layers, electrokinesis and permeable barrier systems in groundwater are some of the physical and chemical remediation techniques used to clean up groundwater (32).

#### Sodium absorption ratio (SAR)

The sodium adsorption ratio (SAR) is one of the important indicators for evaluating the quality of water, especially for irrigation. SAR computes the ratio of Na<sup>+</sup> concentration to Ca<sup>2+</sup> and Mg<sup>2+</sup> and provides information on the possibility of Na buildup in soils (33). The Na absorption ratio calculation (Eqn. 3) has been used to classify the quality of the groundwater samples in the research region. A category of good was observed in only 10 % of the total samples (5 sites) indicating healthy favourable conditions for crop development and yield (Fig. 5c). Meanwhile, 12 % of the samples (6 sites) were doubtful for irrigation (hazards of medium Na) and SAR >26 was found in 78 % (39 locations) of the groundwater samples. The plant may experience osmotic consequences as a result of the excessive salinity.

#### Permeability index (PI)

There are 3 types into which the permeability index (Fig. 5d) can be divided into 3 groups: Class I, Class II and Class III (34). One of the basic physical characteristics of soils that permits water to pass through them is permeability. Soil permeability is frequently impacted by the prolonged use of high amounts of salt, Ca, Mg and HCO<sub>3</sub> water. Furthermore, by reducing permeability and altering the makeup of the earth's substance, a higher salt level modifies the physical properties of soil. Eqn. 4 has been used to calculate the permeability index, which is represented in mg/L. A permeability index value of >75 indicates that it is safe (Class I). With a value range of 25 mg/L-75 mg/L (Class II) it is quite safe and the water is unsuitable for irrigation if the PI value is less than 25

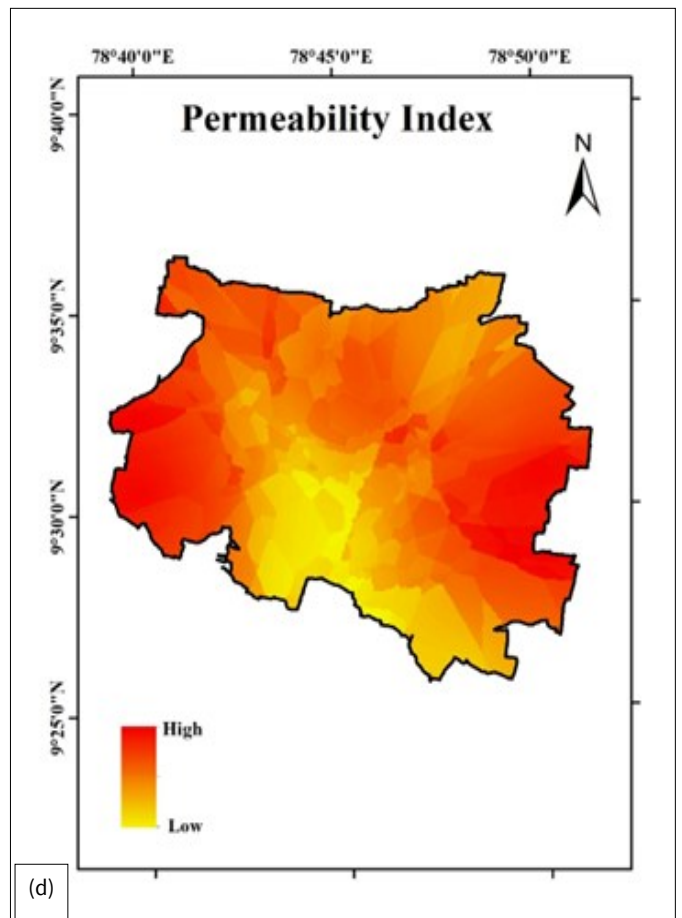
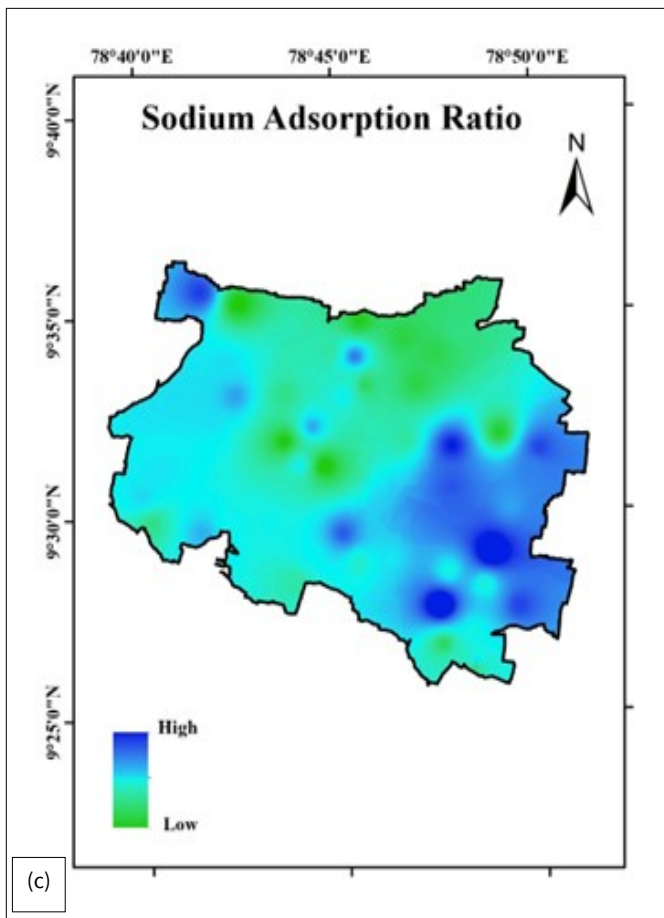
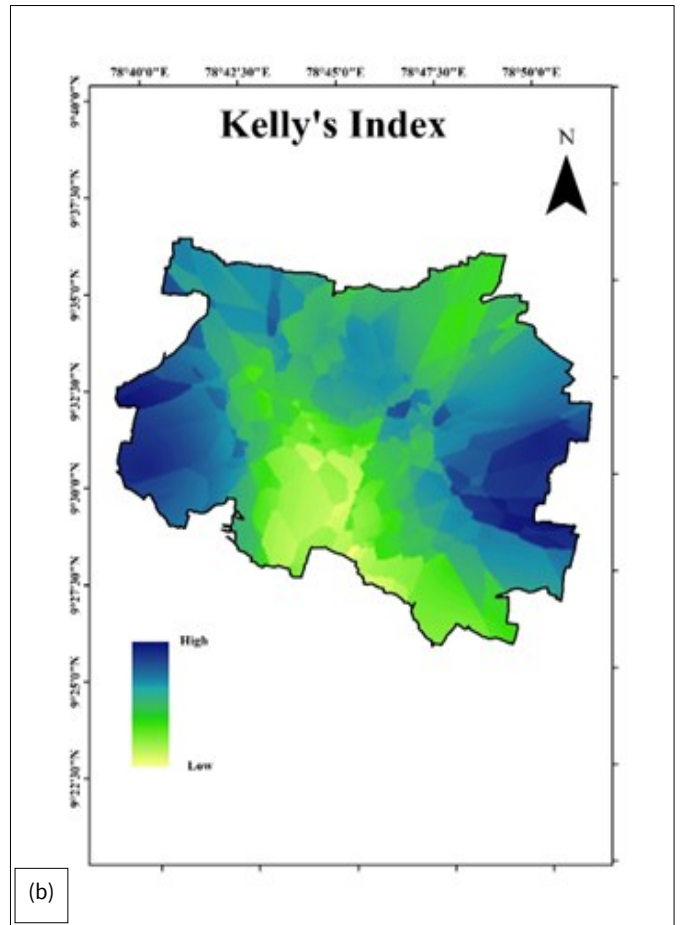
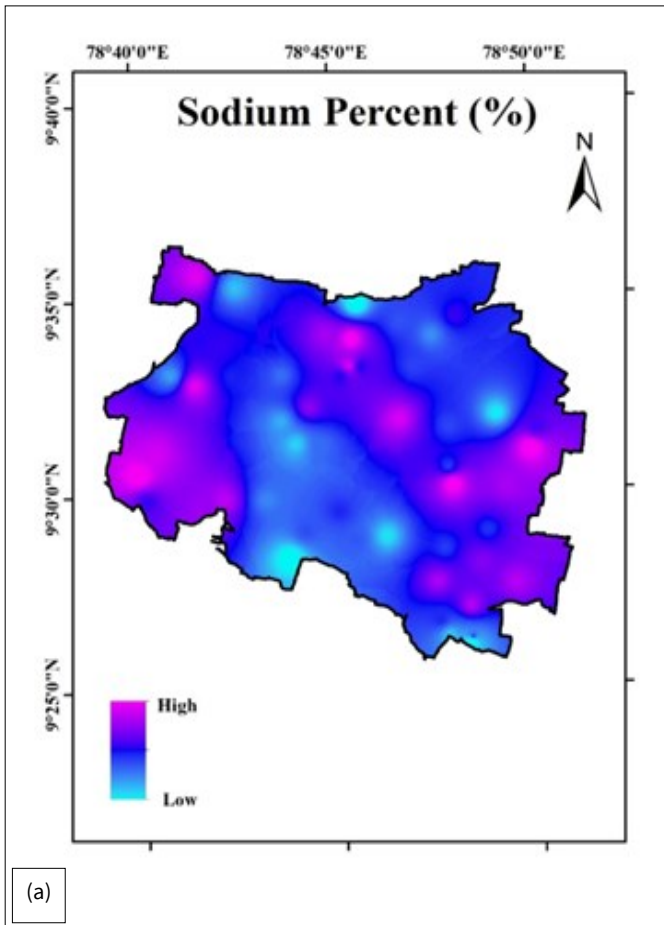
mg/L. In the research region, 36 sites (72 %) come under Class I and 28 % (14 sites) of samples are categorized in Class II. Therefore, it is recommended that farmers in this area use gypsum (CaSO<sub>4</sub>) while ploughing soil for field preparation, since it may improve soil structure and increase the capacity for water penetration (35).

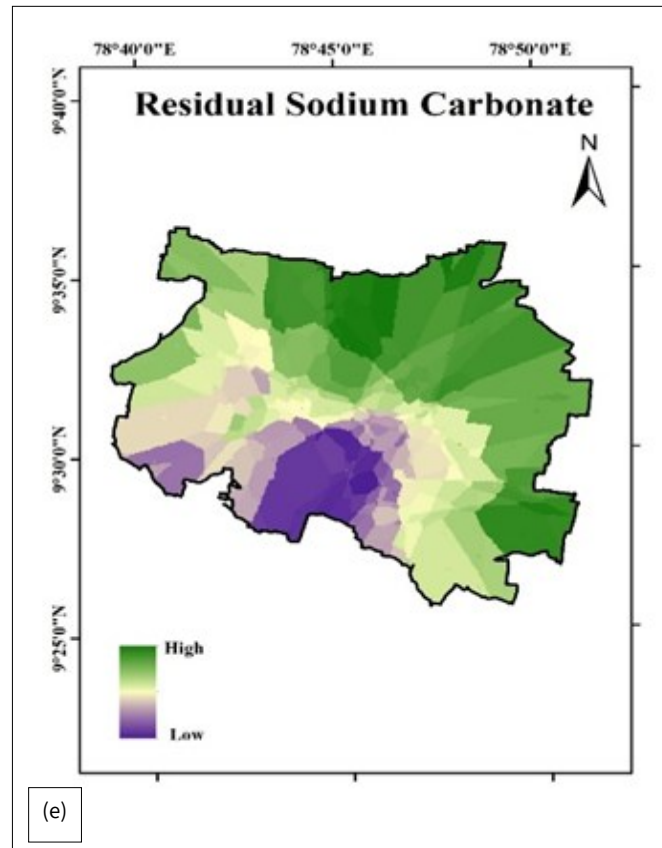
#### Residual sodium carbonate (RSC)

Various irrigation water classes are represented by the groundwater samples according to the RSC calculation (Eq. 2). CO<sub>3</sub><sup>2-</sup> and HCO<sub>3</sub><sup>-</sup> are the main ions that affect the quality of groundwater for agricultural usage. Natural earth elements like Ca, Mg, CO<sub>3</sub> and HCO<sub>3</sub> have a significant impact on the characteristics of water. The effects of CO<sub>3</sub> and HCO<sub>3</sub> in groundwater were evaluated using the RSC (Fig. 5e) value. The RSC is categorized as follows: A (less than 2.5 = Good), B (1.25-2.5 = Doubtful) and C (more than 2.5 = Unfit). A greater Na<sup>+</sup> adsorption concentration is the outcome of a higher RSC value in water. The water quality is unsuitable for agricultural use if the RSC value is more than 2.5 mg/L. However, results less than 1.25 mg/L show that agricultural water supplies are sufficient, while values between 1.26 mg/L and 2.5 mg/L signal that irrigation use is doubtful. In the study region, 72 % of the samples (36 sites) were excellent for irrigation, 10 % of the samples (5 locations) were doubtful and 18 % of the samples (9 locations) were found to be unsuitable for irrigation.

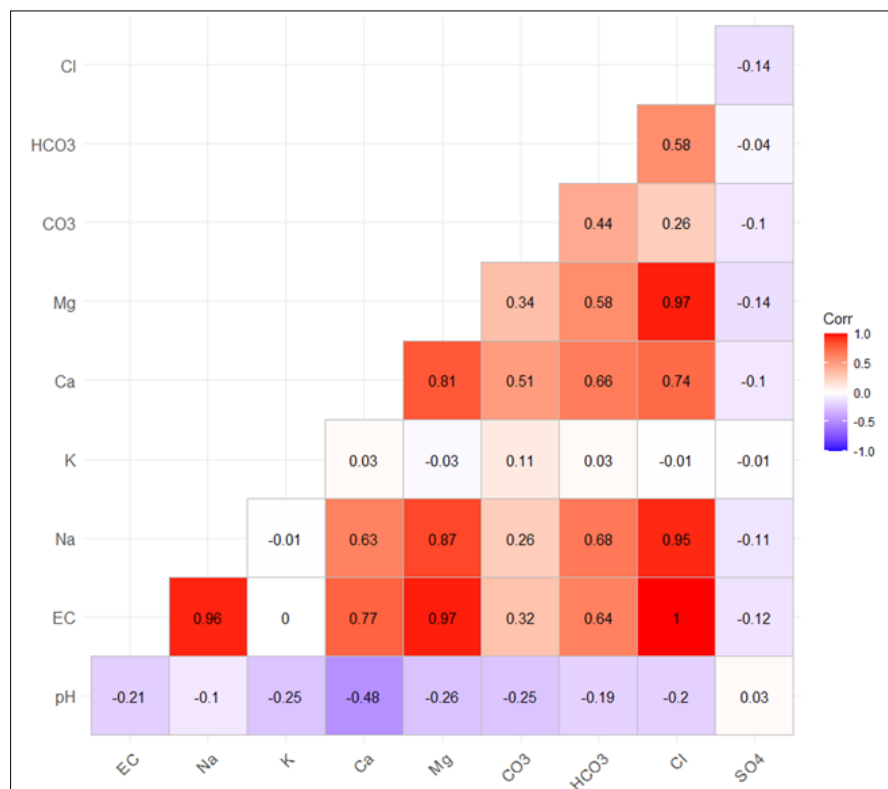
#### Correlation matrix

To illustrate the relation between various quality parameters, the correlation coefficient (r) model is used to analyse the relationships between the chemical parameters (Fig. 6). The range of correlation values is -1 to 1; A value of -1 denotes a high negative correlation, meaning that the variables fluctuate inversely. A positive correlation of 1 denotes an increase in both parameters at the same time (36). Strong correlations ( $r > 0.9$ ) and excellent correlations ( $0.9 \geq r \geq 0.5$ ) between different parameters have been shown to be significantly present in the correlation study of water quality parameters. The parameter pH doesn't have a strong correlation with other parameters. EC exhibited a strong positive correlation and significant association with Cl<sup>-</sup> (1), Mg<sup>2+</sup> (0.97), Na<sup>+</sup> (0.96), Ca<sup>2+</sup> (0.77) and HCO<sub>3</sub><sup>-</sup> (0.64), indicating that these ions significantly contribute to the salinity of groundwater. where EC has negatively correlated with pH (-0.21), higher salinity is slightly associated with lower pH. The Na<sup>+</sup> demonstrates positive correlation with EC (0.96), Cl<sup>-</sup> (0.95), Mg<sup>2+</sup> (0.87), HCO<sub>3</sub><sup>-</sup> (0.68) and Ca<sup>2+</sup>





**Fig. 5.** Spatial distribution of (a) Sodium percentage (Na %), (b) Kelly's Index (KI), (c) Sodium Absorption Ration (SAR), (d) Permeability Index (PI), (e) Residual Sodium Carbonate (RSC).

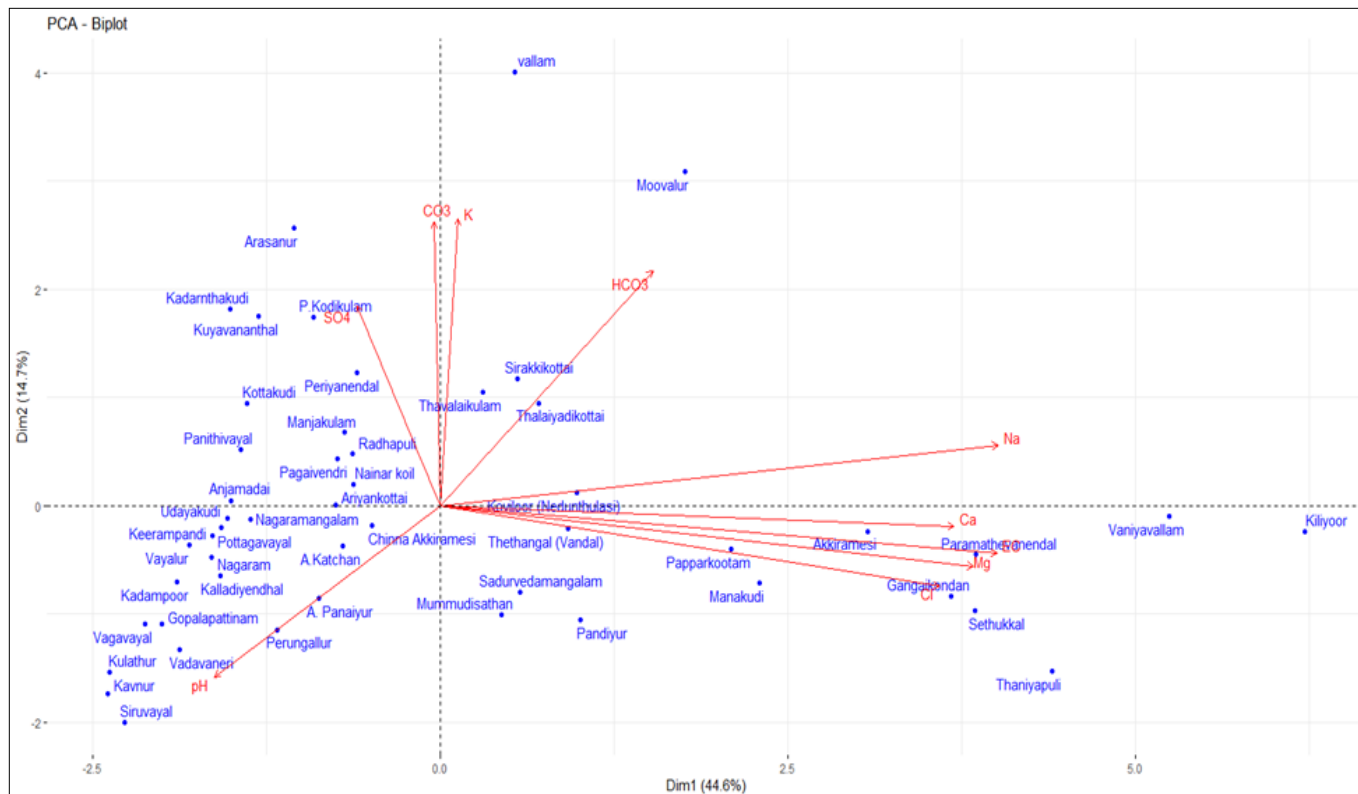


**Fig. 6.** Correlation matrix heatmap for the groundwater quality parameter.

(0.63). The high  $\text{Na}^+$  may slightly acidify the water.  $\text{Ca}^{2+}$  is highly correlated with  $\text{Mg}^{2+}$  (0.81),  $\text{Cl}^-$  (0.74) and moderately by positively with  $\text{HCO}_3^-$  (0.60) and  $\text{CO}_3^{2-}$  (0.51). If  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  often coexist, they will significantly contribute to water hardness.  $\text{Cl}^-$  exhibits a strong positive correlation with EC (1),  $\text{Na}^+$  (0.95),  $\text{Mg}^{2+}$  (0.97) and  $\text{Ca}^{2+}$  (0.74).  $\text{Cl}^-$  is a major contributor to salinity; excess can be toxic to crops.

#### Principal component analysis (PCA)

The PCA was employed to understand the spatial variation and dominant factors influencing the quality of irrigation water across 50 locations (Fig. 7). The analysis extracted two significant principal components Dim1 and Dim2, together explaining 59.3 % of the total variability. Dim1 (PC1) accounted for 44.6 % and was primarily associated with salinity-related variables including  $\text{Na}^+$ ,



**Fig. 7.** PCA analysis for irrigation quality parameters.

$\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$  and EC. The strong positive correlation among these variables suggests a common origin or influence likely from geochemical weathering, mineral dissolution or anthropogenic inputs such as the use of saline groundwater or fertilizers. Locations positioned on the right side of the PCA biplot, such as Kiliyoor, Vaniyavallam, Akkiramasi and Paramathevanendal, were characterized by high loadings of these salinity-indicating ions, highlighting their elevated salinity levels and potential risk for long-term agricultural sustainability. These areas are at risk of reduced crop productivity due to salt accumulation, requiring remedial strategies like  $\text{CaSO}_4$  application, improved drainage or the use of salt-tolerant crops.

On the other hand, Dim2 (PC2), which contributed 14.7 % of the variation, was largely influenced by  $\text{K}^+$ ,  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$  ions. These parameters are indicators of alkalinity and their dominance in some locations may point to the influence of  $\text{CO}_3$ -rich parent materials or alkaline groundwater systems. Sites such as Vallam and Moovalur, located at the top of the biplot, showed strong associations with these variables, indicating higher alkalinity levels. In contrast, locations on the left side of the biplot, such as Siruvayal, Kavnur and Vagavayal, displayed relatively low levels of salinity and alkalinity-related parameters but showed a slight dominance of pH, suggesting slightly more alkaline but less saline water. These areas are considered to have comparatively better-quality irrigation water suitable for most of the crops. The PCA biplot showed a negative correlation between pH and salinity indicators (EC,  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ), suggesting that increased salinity slightly lowers pH. This relationship may affect nutrient availability and crop performance.

## Conclusion

Based on the results, the groundwater pH ranged from neutral to slightly alkaline. In groundwater samples, EC values of only 24 % fell below the limits and 76 % exceeded the limit. Most

groundwater samples in the study area fall into the non-safe category for agricultural use because the concentrations of  $\text{Na}^+$  and  $\text{Cl}^-$  in the samples are greater than 200 mg/L in the research zone. And also, it was discovered that 4, 40, 28, 32, 39, 13, 38, 27 and 34 locations exceeded the allowable limits for pH, EC,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$  and  $\text{Cl}^-$  respectively. Furthermore, there were 9, 11, 14, 23 and 39 samples that exceeded the limits for RSC, Na %, PI, KI and SAR respectively. According to the findings, the majority of groundwater samples are not appropriate for agricultural irrigation. Excessive salt in irrigation water can decrease the soil's ability to absorb nutrients and affect plant osmotic activity. Therefore, it is recommended that farmers in this area apply  $\text{CaSO}_4$  when ploughing the soil in order to improve soil structure and increase the capacity for water penetration. These findings can be directly adopted by local stakeholders to address real-world water management challenges. In the research region, raising public awareness about the adverse effects of poor water quality on human health and agriculture, which are essential for effective water quality management and sustainable development.

Soil management should focus on the application of  $\text{CaSO}_4$  during ploughing to reduce sodium hazard, improve soil structure and enhance infiltration. Water management practices such as rainwater harvesting, farm ponds and groundwater recharge structures should be promoted to reduce dependence on poor-quality groundwater. In addition, drip irrigation offers an effective means of conserving water, minimizing salt accumulation in the root zone and improving leaching efficiency. Coupled with this, drip fertigation can ensure precise delivery of nutrients to the root zone, thereby improving nutrient uptake under saline conditions while reducing fertilizer wastage. The soils of this region exhibit some unique problems. So, the areas are mostly monocropped with rice grown during the rainy season (northeast - monsoon) and leaving the land fallow till the onset of the next season. Groundnut stands out as a viable crop to diversify the cropping system and increase land productivity in these locations.

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## Authors' contributions

SK conducted the survey, lab analysis, recorded data and wrote the research paper. AG conceptualized and supervised the work. ES and JP provided technical inputs to conduct the lab analysis. SK and SKK created thematic maps. RA, BS and AS assisted in manuscript writing and made corrections. AG supervised the overall preparation and finalized the manuscript. All authors read and approved the final version of the manuscript.

## Compliance with ethical standards

**Conflict of interest:** The Authors do not have any conflicts of interest to declare.

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