Geochemical Evaluation and Potability of Groundwater in a Hard Rock Terrain: A Case Study from the Karaipottanar Sub-Basin, Southern India

Sangunathan Ulaganathan
University of Madras
Sridhar Sithu Govindasamy Dinakaran
University of Madras
Chidambaram Sabarathinam
Kuwait Institute for Scientific Research
Thivya Chandrasekar
thivya@nct.ac.in

National College (Autonomous)
Suresh Gandhi
University of Madras
Manikandan Nagarathinam
University of Madras
Shanmugasundaram Arumugam
Malankara Catholic College

Research Article

Keywords: Karaipottanar sub-basin, Groundwater quality, hydrogeochemistry and principal component analysis

Posted Date: November 10th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-7929214/v1

Additional Declarations: No competing interests reported.

GEOCHEMICAL EVALUATION AND POTABILITY OF GROUNDWATER IN A HARD ROCK TERRAIN: A CASE STUDY FROM THE KARAIPOTTANAR SUB-BASIN, SOUTHERN INDIA

Sangunathan Ulaganathan[1], Sridhar Sithu Govindasamy Dinakaran [1], Chidambaram Sabarathinam[2], Thivya Chandrasekar[3*], Suresh Gandhi[4], Manikandan Nagarathinam[5], Shanmugasundaram Arumugam

[1]Department of Applied Geology, University of Madras, Guindy Campus, Chennai, India.
[2]Water Research Center, Kuwait Institute for Scientific Research, Kuwait
[*3]Department of Geology, National College (Autonomous), Tiruchirappalli, India.
[4]Department of Geology, University of Madras, Guindy Campus, Chennai, India.
[5]Department of Geography, University of Madras, Guindy Campus, Chennai, India.
[6]Department of Geology, Malankara Catholic College, Kanyakumari, India.
*Corresponding author: thivya@nct.ac.in

ABSTRACT

Groundwater serves as the primary source of water for domestic, agricultural, and industrial use in many countries. Effective water resource management requires the implementation of strategies to protect aquifers from contamination. Monitoring groundwater quality is crucial for ensuring environmental sustainability and public health, as it provides essential data for informed decision-making. The geochemical characteristics of groundwater significantly influence the suitability and sustainability of aquifer systems as water sources. This study aims to evaluate the groundwater chemistry of a hard rock aquifer in the Karaipottanar sub-basin, Tamil Nadu, India, and to assess its suitability for drinking, domestic, agricultural, and industrial applications. A total of 44 groundwater samples were collected from various geological formations like charnockite, fissile hornblende biotite gneiss, granitic/acidic rocks, and alluvial deposits. Physicochemical parameters such as pH, total dissolved solids (TDS), and major ions were analyzed and compared with the Bureau of Indian Standards (BIS, 2012) guidelines. The Drinking Water Quality Index (DWQI) was employed to evaluate the water's fitness for human consumption. To assess irrigation suitability, analytical tools such as the Wilcox diagram, USSL diagram, Sodium Adsorption Ratio (SAR), and Permeability Index (PI) were used. For domestic and industrial suitability, the Langelier Saturation Index (LSI), Ryznar Stability Index (RSI), and Corrosivity Ratio (CR) were applied and interpreted based on standard classifications. Hydrogeochemical processes were further investigated using Gibb's and Piper trilinear diagrams. Additionally, Principal Component Analysis (PCA) was conducted to identify the underlying relationships among groundwater quality parameters and to understand the complexity of the hydrogeochemical system in the study area.

KEYWORDS: Karaipottanar sub-basin, Groundwater quality, hydrogeochemistry and principal component analysis.

INTRODUCTION

In many arid regions, groundwater is a key source of water that serves a wide variety of industrial, agricultural, and domestic needs (Tian et al. 2023; Davraz Aysen & Batur, Burcu 2021). Spatial analysis, and descriptive statistics in groundwater quality due to regional geologic conditions and anthropogenic causes necessitate evaluation before use, especially for human consumption (Sharma et al. 2023). Specifically, the degree of urbanization changes the functioning of natural ecosystems, upsets the ecological balance, and promotes the emergence of novel qualitative traits (James 2024). The particular microclimate conditions seen in metropolitan areas play a significant role in the transformation of soil. Drinking water, household uses, agricultural needs, and industrial processes all rely heavily on groundwater in the modern world (Das & Mukhopadhyay 2020). Reintroducing wastewater to the hydrologic cycle contributes to groundwater contamination as well (Chen et al. 2021). Extensive use of fertilizers, agrochemicals, sewage/drain water, and mining activities on crucial aquifers are recognized as major threats to groundwater quality (Adesiji et al. 2023). The chemical quality of groundwater must be understood and monitored since it is a good alternative to surface water for drinking, home, industrial, and agricultural use. (WHO 2004).

Numerous studies in a wide variety of locations around India have conducted numerous studies on water quality (Chidambaram et al 2022; Ramachandran et al. 2021; Asare-Donkor and Adimado 2020; Malakootian et al. 2020; Sangunathan et al. 2016). Since water is essential to life on Earth, it is important to pay close attention to the challenges and opportunities presented by its abundance, scarcity, and deterioration (Alsabti et al 2023; Thilagavathi et al. 2021; Zaidi et al. 2019; Sridhar et al 2017; Shanmugasundharam et al. 2017; Jenefer et al 2016; Sakthivel et al. 2016; Kanagaraj et al. 2014). As SDG-6 of the United Nations' sustainable development goals clearly states that providing access to clean water is a top priority. While progress is being made towards the SDGs, there are still areas with insufficient data, retarding the development of sustainable management strategies (UN-Water 2023).

This study will focus on the hard rock aquifer region of the Karaipottanar sub-basin. For domestic agricultural and drinking water demands, groundwater is the primary lifeline of the region. Recent research has gained focus on hard rock aquifers due to groundwater scarcity and interactions with the aquifer matrix (Tanvir Hassan, Maciek W. Lubczynski 2024; Thivya et al. 2016; Dewandel et al. 2010), Hard rock aquifers require a thorough evaluation of water quality change. Further, the quality of the groundwater is mainly depending on the residence time in the aquifers as well as the lithological conditions (Samuel Kojo Abanyie et al. 2023). Hence the study aims to determine the current status of groundwater quality, suitability for various utility purposes, the drinking water quality index, and the process governing the groundwater chemistry of the region.

Statistical analysis plays a crucial role in interpreting groundwater chemistry data. It helps in identifying patterns, trends, and relationships within the data, allowing for meaningful interpretations and informed decision-making (Ramachandran et al. 2020; Rehman et al. 2016; Singaraja et al. 2014; Manimaran et al. 2025; Chidambaram et al. 2008). Multivariate analysis of groundwater chemistry data often comprises multiple variables, and multivariate techniques help uncover complex relationships among them. Principal Component Analysis (PCA) is commonly used to reduce the dimensionality of the dataset and identify dominant factors contributing to the variation (Ravikumar et al. 2023; Garcia et al. 2020: Prasanna et al. 2010; Zuur et al. 2007). Cluster analysis or classification techniques like discriminant analysis can aid in grouping similar samples or identifying distinct groundwater types (Jing Yang et al. 2020; Morsi et al. 2015; Valdes et al. 2007).

The Drinking Water Quality Index (DWQI) is a tool used to assess the overall quality of drinking water by considering different factors. It helps determine if the water is safe to drink and identifies any potential health risks. The specific parameters included in DWQIs can vary depending on where you are and what research has been done. In Canada, the Canadian Council of Ministers of the Environment (CCME 2001) has a Water Quality Index that looks at various chemical components and uses a scoring system to assess health risks, aesthetics, and regulatory limits. In India, they have standards for drinking water quality set by the Bureau of Indian Standards (BIS 2012), but they don't have a specific DWQI. Instead, researchers in India have developed different indices to evaluate water quality, taking the standards into account. One common method used for DWQI is the weighted arithmetic index, which assigns weights to different parameters based on their importance. Scores are calculated for each parameter based on how they compare to guidelines, and these scores are then combined to get an overall index value (El Osta et al. 2022; Rumuri and Manivannan 2020; Thivya et al. 2013; Rajesh et al. 2019).

STUDY AREA

The region picked for the study is the Karaipottanar sub-basin, with most of it situated in Namakkal districts southeast and a small portion in Trichy district's northwest. The basin has an area of 1116 km^2 and is located between latitudes 10°56' and 11°23'N and longitudes 78°06' and 78°28'E (Fig. 1). The Cauvery River, which flows through the Archaean crystalline granitic gneisses, fissile hornblende biotite gneisses, and charnockite, originates in the Kolli Hills (Fig. 2). There are pockets of lateritic bauxite, recent alluvial deposits, and colluvium at the foothills along the stream. Crystalline rocks that have been worn and fractured as well as colluvial deposits make up the basin's aquifer system. The geomorphology of this location includes alluvial plains, structural hills, residual hills, valley fills, pediments, and undulating plains. The region has a tropical climate and experiences more NE monsoon rain than the SW monsoon, with temperatures ranging from 260 °C to 320 °C (CGWB 2008). In 2016, this region received 353 mm of rain on average per square kilometer. The worn and fractured granite gneiss, granite, charnockite, and other associated rocks are represented by the hard, cemented, and crystalline rocks of the Archaean age. In the worn mantle and the fractured zones, ground water occurs in phreatic conditions and semi-confined circumstances. Depending on the geographic circumstances, these aquifers can have maximum saturation thicknesses of up to 20 m. When there are phreatic conditions, groundwater occurs (Jain et al. 2007).

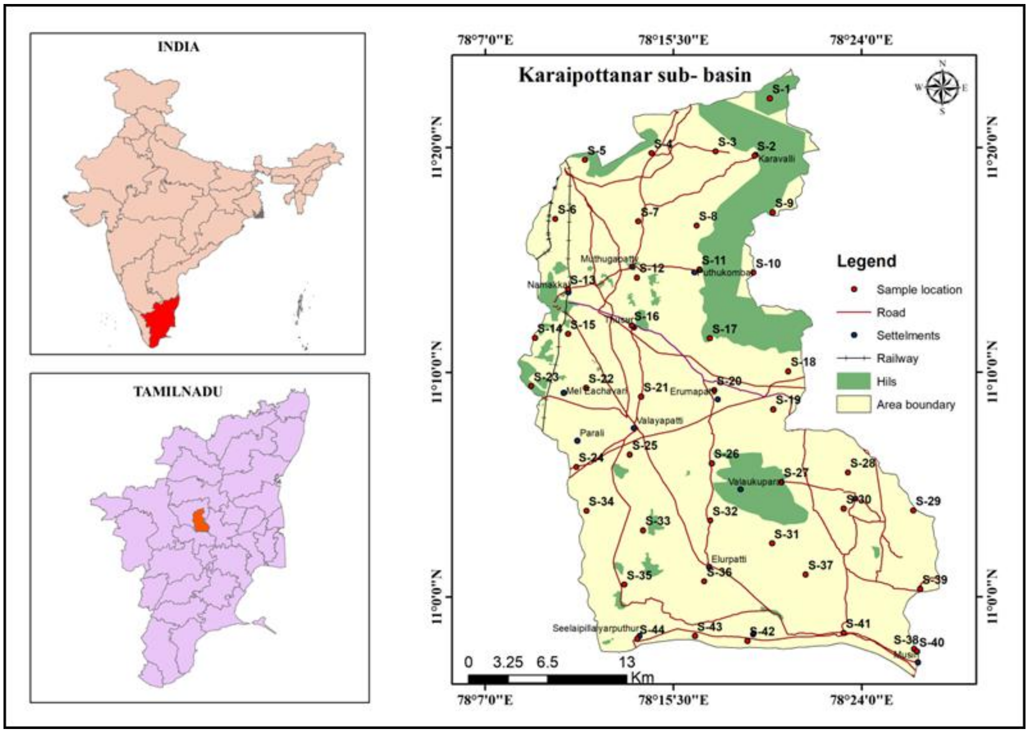

Fig.1 Study area with sample location

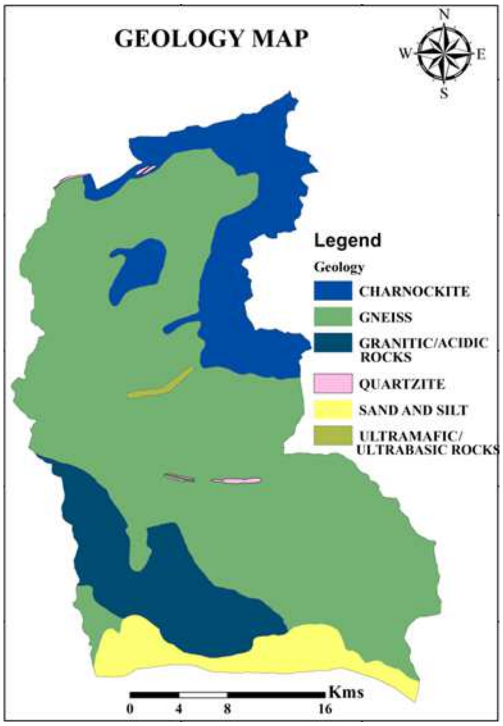

Fig. 2 Geology map of study area.

MATERIAL AND METHODS

To evaluate the groundwater quality and hydrogeochemical properties of aquifers, groundwater sampling and sample procedures are essential instruments. These instruments need to be looked at as soon as possible because water is dynamic. A total of 44 samples from the bore well and open well were collected for this study. The standard solutions were made in a sterile laboratory setting using analytical-grade chemicals and deionized water. Plastic bottles were cleaned by soaking in a 10% HNO_3 solution, flushing with de-ionized water, and dried in an oven. Prior to collection, the plastic bottles were rinsed them thoroughly with the water that was being sampled. The pH of the sample in the field itself was measured using an electronic pH meter. Standard buffer solutions (pH 4, 7, and 10) were used to calibrate the pH meter (PCSTestr 35) before each set of samples. Using a digital multi-parameter probe, the electrical conductance (EC) and total dissolved solids (TDS) of groundwater were measured. The probe's calibration standard was KCl solution (1413 S/cm). With the exception of HCO_3^-, which was measured using the titration method, all main cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (Cl^-, SO_4^{2-}, NO_3^-, and F^-) were measured using ion chromatography (Metrohm AG-8883 Basic IC Plus) (APHA 1998) Standard Merck chemicals were used for the chemical analysis of water samples. The following calculation was used to determine the analysis's error percentage as a percentage. The error rate was discovered to be no more than 5% (Domenico and Schwartz 1998). The spatial distribution diagram for a particular parameter was done using the interpolation approach and prepared using Arc GIS 10.3, and One of the most widely used interpolation techniques for analyzing groundwater quality data is the IDW (Dinpashoh et al. 2019; Biazar et al. 2019). The irrigation quality diagram was determined using Aquachem 5.5 (User Manual, 2005). Software called SPSS 11.5 (Statistical Package for Social Science) was used to locate the primary processes that influence the chemical composition of groundwater.

GROUNDWATER CHEMISTRY

Due to its significance in describing the natural system, comprehending contamination migration, and developing remediation methods, geochemistry plays a considerably larger part in groundwater studies (Ya-ci Liu et al. 2014; Deutsch and Siegel 1997). This topic discusses the geochemical distribution that influence of the-quality of the groundwater.

Piper diagram

The compositional trends of chemical data of groundwater were processed on a Piper diagram (Piper 1944), as illustrated in Fig. 3. According to this diagram, the Ca-Mg-Cl, Na-Cl, Ca-HCO_3, and Ca-Na-HCO_3 types of samples are the most prevalent among those plotted in a variety of hydrochemical facies of the research region. However, the hydrogeological state of the groundwater in the research area suggests a pattern begins with a Ca-HCO_3 type, moves through Ca-Cl and Ca-Mg-Cl types, and ends with a Na-Cl type, or from a Ca-HCO_3 type it may also possible to directly to a Na-Cl type. Mineral dissolution, an interaction between rock water and the recharge of freshwater, are suggested by the Ca-HCO_3 and Ca-Cl water types (Mondale & Singh, 2012). The presence of mixed Ca-Mg-Cl water suggests the mixing of high salinity water, potentially from surface contamination sources like irrigation return flow, followed by ion exchange processes (Rumuri and Manivannan, 2020; Ayuba et al., 2017; Panda et al., 2022). The Na-Cl water type indicated the influence of high residence time of groundwater, where sodium in groundwater results from cation exchange between groundwater and lithological materials (Rajendiran et al., 2023; Chotpantarat and Thamrongsrisakul, 2021). Additionally, it may be attributed to anthropogenic factors, with salts from sewage source interacting with groundwater (Ibrahim et al., 2024).

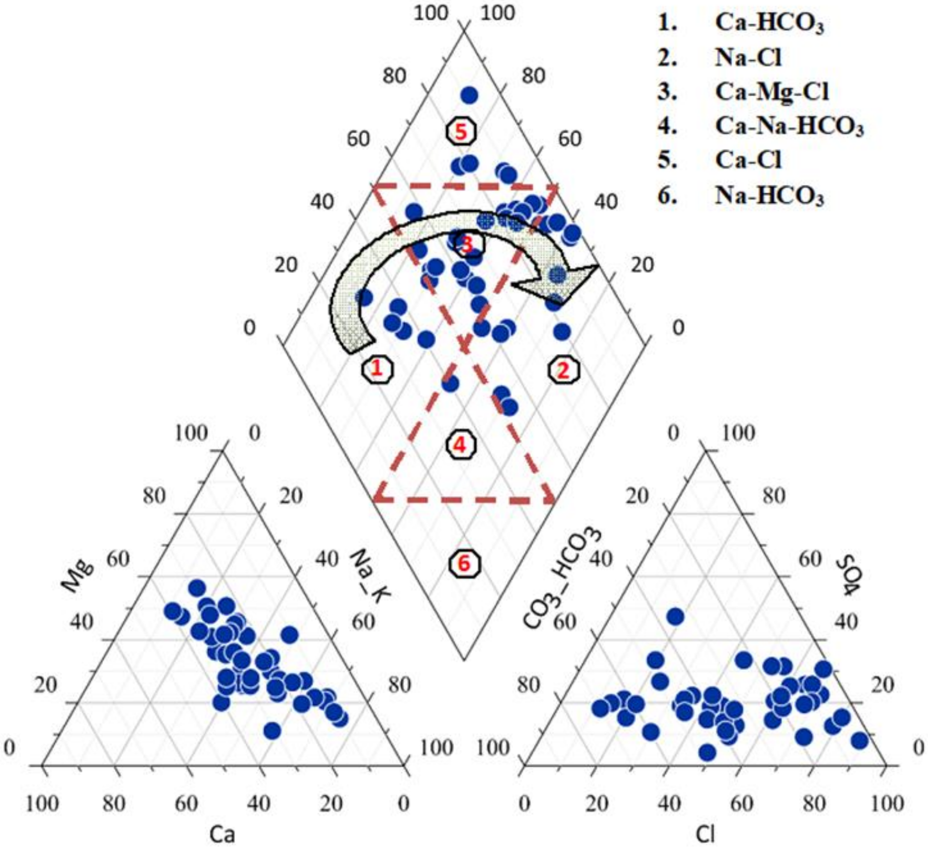

Fig. 3 Piper trilinear plot for groundwater samples

Gibbs diagram

Gibbs (1970) has studied the mechanisms that govern the principal dissolved components of the chemical composition of groundwater. In his method, Gibbs (1970) suggested identifying and quantifying the interactions between rocks and water, precipitation, and evaporation. The samples that fall between the rock weathering and evaporation dominance zones inside the plot area make up the majority of the samples in the anion plot (Fig. 4). Anthropogenic activities that raise Na^+ and Cl^- and thus TDS, such as the use of agricultural fertilizers and irrigation return flows, also have an impact on evaporation. High TDS content shows that evaporation and crystallization processes are normally in charge of controlling the surface water in these places (Thivya et al. 2013; Gibbs 1970). This reveals unequivocally that anthropogenic activity, rather than a natural source, determines and predominates the change in groundwater's chemical makeup in some parts of the research area (Gupta & Kumari, 2022; Karanth 1991).

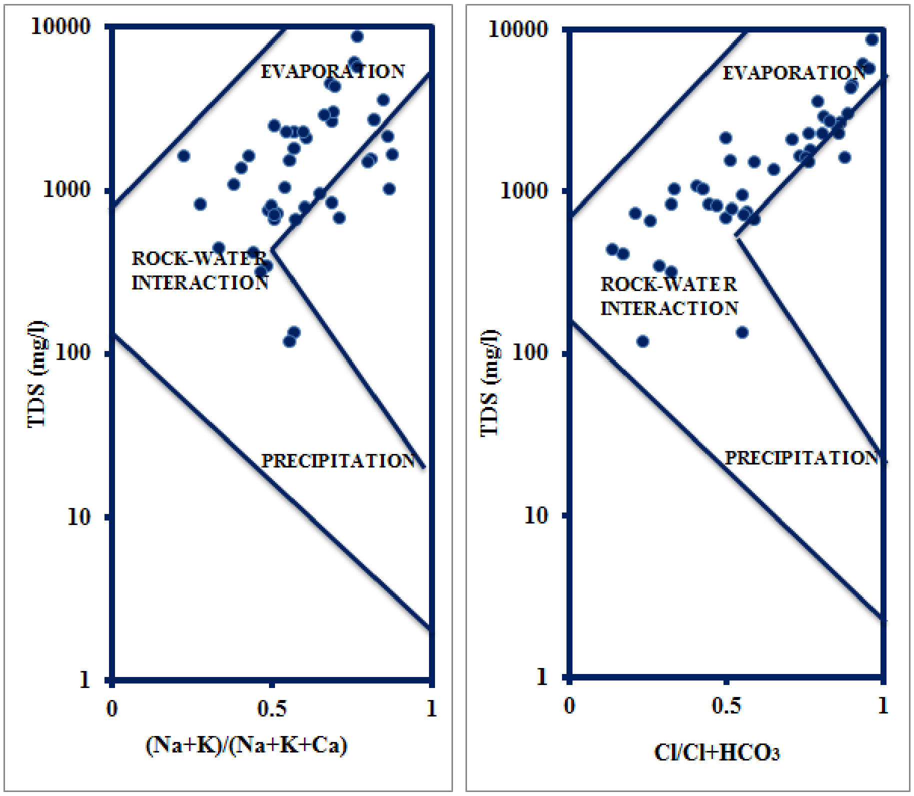

Fig. 4 Gibbs plot for the groundwater samples

GROUNDWATER QUALITY FOR DRINKING

The chemical composition of the host rock has largely influence the chemistry of groundwater. The results of the groundwater analysis were used as a tool to identify the mechanisms and processes that affected the chemistry of the groundwater in the study area. To assess the quality of groundwater for drinking, irrigation, domestic, and industrial use, physico-chemical factors have been considered. The minimum, maximum, average, standard deviation, and BIS or WHO recommended values for each parameters are shown in Table 1, along with the numbers of samples that fall outside the acceptable range. The average pH of the groundwater, which ranges from 6.0 to 8.7, was 7.8, indicating a slight alkalinity. Generally, pH variations in the research area have not been linked to any significant health problems. Mineral dissolution and pipe line corrosion will both be exacerbated by low and high pH levels (WHO 2003). The pH in majority of the samples are within acceptable limits.

The average TDS in groundwater was 1872 mg/L, with a range of 117 mg/L to 8553 mg/L. Kolli Hills' surroundings have the lowest TDS content, while the basin's center has the highest concentration (Fig. 5). It is indicated that ions are dissolved from the source rock into the groundwater as part of the weathering processes in the aquifer media due to the long-term interaction with the groundwater of the area (Ramesh 2008). In sixteen of the samples, the TDS is higher than the BIS 2012 suggested limits for drinking of 2000 mg/L.

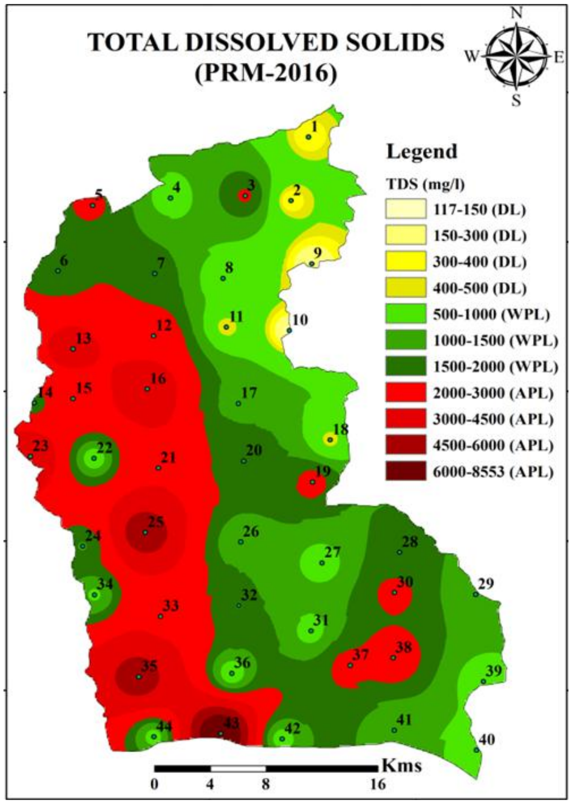

Fig. 5 Spatial distribution total dissolved solids

The average Ca concentration was 138 mg/L, and the range was from 9 mg/L to 490 mg/L, and twelve samples had higher concentrations than what is permissible for drinking. The high calcium concentration is more evenly distributed in the center of the research area. Due to the rain that falls in the research area, it helps to add the seepage of domestic sewage, agricultural run-off, and rock-water interaction in the groundwater (Ramachandran et al. 2025). Perhaps the central part of the study area is heavily influenced by carbonate weathering, which causes the dissolution of $CaCO_3$ and $CaMg (CO_3)$ present in the rocks and increases calcium and magnesium ions in the groundwater (Elango et al. 1992), both of which are induced by anthropogenic processes (Srinivasamoorthy et al. 2014).

The concentration of magnesium ranges from 10 mg/L to 328 mg/L. The concentration of magnesium is higher in the center of the study area, which could be due to magnesium dissolution from magnesium-bearing rocks in the area, most likely from ferro-magnesium minerals and dolomite precipitates (Hem 1985; Lidia Razowska 2014). The sodium concentration ranged between 12 and 1558 mg/L, with an average of 329 mg/L. It is in groundwater, with the highest concentrations in the central and southeast areas of the area. In general, sodium ions, which tend to reflect the abundance of the ions in various types of source rock and the rate at which the minerals are attacked in the feldspar-rich granitic terrain (Feth et al. 1964; Wali et al. 2024), Anthropogenically, it can infiltrate nearby domestic waste water (WHO 2003). The potassium concentration ranges from 1 mg/L to 579 mg/L with an average of 29 mg/L, and eleven samples exceed the required limit for drinking (Mathews 1982; Mohan et al. 2000). Due to the weathering of mica and orthoclase feldspar in the research area, where K^+ ions are produced during weathering and are generally used up in the creation of secondary minerals and some industrial input to groundwater, potassium may have been released from sources (Kannan et al. 2025). Cations are abundant in the following order: $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$. Seven samples from the research area have chloride levels that are too high. With a mean concentration of 658 mg/L, concentrations range from 10 mg/L to 3301 mg/L. Samples 16, 23, 25, 35, and 43 in the region show greater chloride amounts. High amounts of chloride in ground water samples from the study area could be the result of anthropogenic contamination from sources such as sewage, municipal waste, fertilizer, and road salt (Li D et al. 2021; Aghazadeh et al. 2017). Chloride is essentially a conservative metric that can be used to measure the amount of contamination from primary sources such as industrial and municipal discharge that enters naturally occurring fresh water (Ceilidh Mackie et al. 2022). Sulphate concentrations ranged from 10 mg/L to 2036 mg/L, with 282 mg/L serving as the average. Ten numbers of the samples there were above the permissible limit for drinking. The area with the highest concentration of sulphate is in the center, particularly in samples 16 and 43. Due to its high oxygen content, rainwater dissolves sulphate from sulfate-containing minerals such as sulphide ore, gypsum, and anhydrite, as well as from industrial waste and agricultural chemicals that seep into the groundwater (Chunlu Jiang et al. 2022; Amjad 2010). The range of nitrate values was from 2187 to 33 mg/L, with thirteen samples exceeding the allowable limit for drinking (BIS 2012). Bicarbonate concentrations range from 37 mg/L to 793 mg/L, with 298 mg/L being the average. According to the sample distribution, the center of the research region has the highest concentration of bicarbonate. Fluoride content is a significant factor in health difficulties, especially in the majority of Tamil Nadu (BIS 2012; Mayakannan, A & Sivalingam et al. 2019). High F^- content causes fluorosis, whereas low F^- content causes dental caries (WHO 2004). Therefore, it is essential to have a safe fluoride limit of no more than 1 mg/L in drinking water. Eleven samples have high fluoride concentrations that, on average, range from BDL to 2.9 mg/L, exceeding the amount considered not safe for human consumption. Due to geologic processes, the area's groundwater is largely fluoridated (Patolia and Sinha 2017; Kumar et al. 2022). According to the anions' chemistry, Cl^- and SO_4^{2-} are the two most common anions, followed by HCO_3^- and NO_3^- (Table 1).

Table 1 Statistical values of analytical results with BIS (2012) and WHO (2013) guideline value for groundwater parameters.

S.No.	Elements	Min.	Max.	Avg.	Stand. Dev.	BIS (2012)				
						R. Limit	P. Limit	< R. limit	> R.Limit	> P. Limit
2	TDS (mg/L)	117	8553	1872	1719	500	2000	6	22	16
4	pH	6.0	8.7	7.8	0.5	6.5-8.5	-	1	41	2
6	Ca^{2+} (mg/L)	9	490	138	107	75	200	17	15	12
7	Mg^{2+} (mg/L)	10	328	108	83	30	100	6	33	5

8	Na^+ (mg/L)	12	1558	329	369	200 (WHO 2013)		-	22	22
9	K^+ (mg/L)	1	579	29	88	20	-	33	11	-
10	Cl^- (mg/L)	10	3301	658	827	250	1000	20	16	7
11	SO_4^{2-} (mg/L)	10	2036	282	341	200	400	22	12	10
12	NO_3^- (mg/L)	2	187	33	35	45	-	31	13	-
13	HCO_3^- (mg/L)	37	793	298	138	No limits recommended				
14	F^- (mg/L)	BDL	2.9	1.1	0.7	1	1.5	19	14	11

Drinking water quality index (DWQI)

The DWQI was employed to obtain a comprehensive picture of groundwater quality overall. According to Ramachandran et al. 2020, Bawoke and Anteneh 2020, the definition of DWQI is a score that indicates the cumulative impact of different water quality measurements on the overall quality of water. The DWQI was calculated using the Indian standard for drinking water (BIS 2012). The DWQI was determined using three steps. The first step was to give each of the parameters (Ca^{2+}, Mg^{2+}, Na^+, F^-, Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, pH, and TDS) a weight (Wi) based on how relevant it is in comparison to other parameters, such as those that have a substantial impact on health (Karung Phaisonreng Kom et al. 2023; Acharyaz and Sharma 2018; Boufekane and Saighi 2019). Due to their important significance in determining water quality, TDS, pH, and F^- were given the highest weights (5), whereas SO_4^{2-}, Na^+, and Mg^{2+} were given the lowest weights (2), reflecting their minimal significance. Other variables, such as Ca^{2+}, K^+, Cl^-, and NO_3^-, were given weights between 1 and 5 according to how important they were to the assessment of the water quality (Table 2). Second, the following equation was used to calculate the chemical parameter's relative weight (Wi):

$$W_i = w_i / \sum_{i=1}^{n} wi \quad (1)$$

Where,

W_i = relative weight,

w_i = weight of each parameter and

n = number of parameters.

Then, a quality rating (qi) is for each parameter is assigned by dividing its concentration in each water sample by its permissible limits values given by the BIS (2012) and the result being multiplied by 100:

$$q_{i}=(C_i/S_i)*100 \tag{2}$$

where,

q_i = the quality rating,

C_i = concentration of each chemical parameter in each water sample in mg/l, and

S_i = Indian drinking water standard for each chemical parameter in mg/l (BIS 2012).

For computing WQI, the sub index (SI) is first determined for each chemical parameter, as given below:

$$SI=W_i*q_i \tag{3}$$

$$WQI=\sum SI_{i-n} \tag{4}$$

where,

SI_i = sub index of ith parameter;

W_i = relative weight of ith parameter;

q_i = rating based on concentration of ith parameter, and

n = number of chemical parameters.

According to Teikeu et al. (2016), the computed water quality index values are divided into five categories. During the season, 25% of samples were in "excellent" condition, while 45% of samples were in "good," 23% of samples were in "poor," 5% of samples were in "very poor," and 2% of samples were in "unsuitable" condition (Table 3). The DWQI value ranges from 20 to 562, with an average of 103. The spatial diagram of the DWQI shows the middle part of the study area is unsafe for drinking, which indicates a greater influence of anthropogenic sources at certain sample locations (Fig. 6). The majority of fluoride in groundwater comes from geologic sources, with minor amounts coming from anthropogenic sources such as waste discharges from the steel and metal industries, phosphorus fertilizer, glass production, and china sintering. The remaining factors are also regarded as key factors because of their impact on quality and the weight they have in the study area (Sarfo and Shankar 2020; Sener et al. 2017).

Table 2 Weights assigned for DWQI parameters based on BIS (2012) and WHO (2013) standards.

Parameters	Weight	Relative weight	BIS/WHO standard
Ca^{2+}	3	0.09	200
Mg^{2+}	2	0.06	100
Na^{+}	2	0.06	200
K^{+}	3	0.09	20
Cl^{-}	3	0.09	1000
NO_3^{-}	4	0.12	45
SO_4^{-}	2	0.06	400
pH	5	0.15	8.5
TDS	5	0.15	2000
F^{-}	5	0.15	1.5
	$\sum wa=34$	$\sum Wa=1$	

Table 3 DWQI classification of groundwater

Category	**No. of samples**	**Percentage of samples**
Excellent	2	5
Good	23	52
Poor	19	43
Very Poor	0	0
Unsuitable	0	0

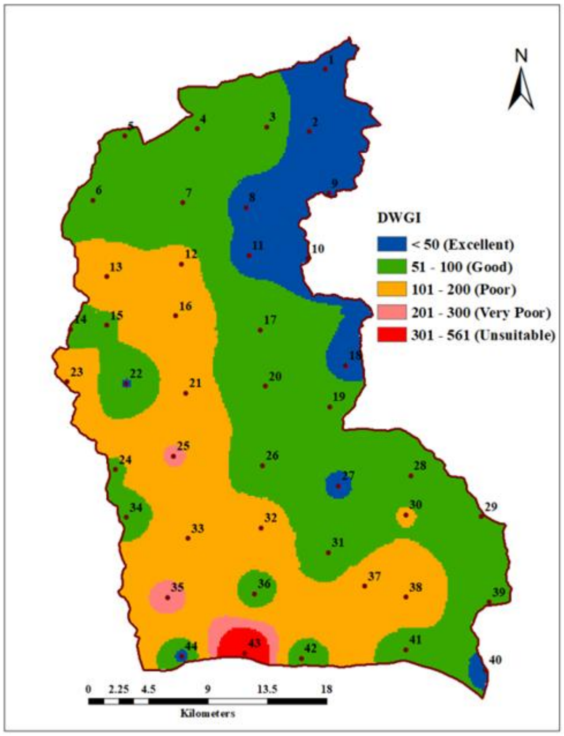

Fig.6 Spatial distribution of Drinking Water Quality Index (DWQI).

GROUNDWATER QUALITY FOR IRRIGATION

Wilcox diagram

The sodium in irrigation water is usually estimated as percent sodium and can be determined by the following formula (Wilcox, 1955);

$$Na\,\% = \{(Na^{+} + K^{+}) / (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}) *100$$

All ions are in milliequivalents per mL (meq). The classification of groundwater samples in the study area based on their sodium and EC percentages is shown in Fig. 7. 14% of samples fall into the "very good to good" category, while 30% of samples are in the "good to permissible" range. The majority of groundwater samples from the study area show good condition, but in a relatively few places they are not good for irrigation purposes (Table 4).

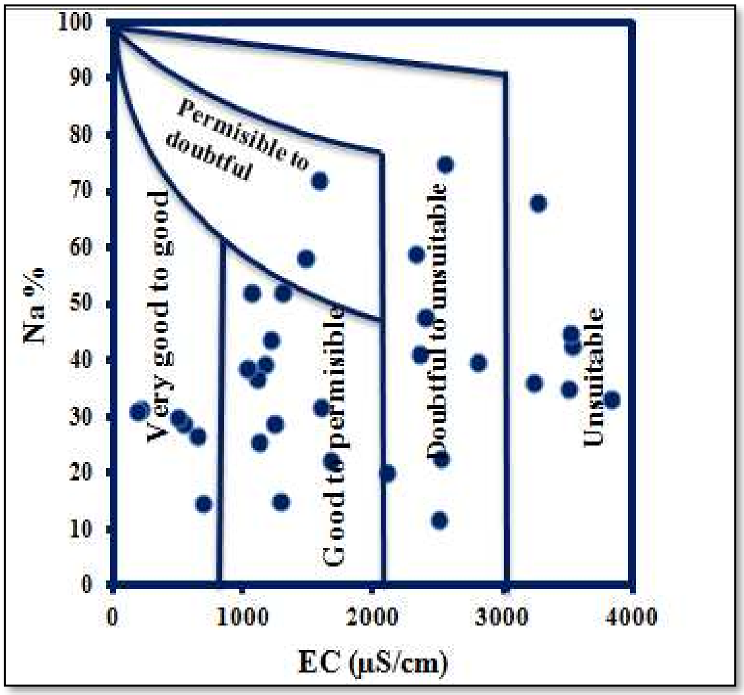

Fig. 7 Wilcox diagram for classification of groundwater for irrigation purpose

U. S. Salinity Diagram

An illustration of water provided by the USSL was used to categories and understand the groundwater data for irrigation (1955) is employed. The salinity hazard, salt (alkali) hazard, boron hazard, and bicarbonate hazard have all been used to describe the diagram (U.S. Salinity Laboratory, 1954; Wilcox, 1955 more realistic illustration of the sodium hazard for irrigation is provided by the Sodium Adsorption Ratio (SAR), which is utilized to indicate reactions with the soil. The SAR is computed as

$$\mathrm{SAR} = (\mathrm{Na}^{+}) / \{(\sqrt{}\ (\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}+)/2\}$$

The results are shown in Table 5, where all ionic concentrations are represented in milliequivalents per liter (meq). When SAR and the water's particular conductance are known, the USSL diagram can be used to graphically classify groundwater for irrigation. Fig. 8 shows the USSL. diagram plots of the research area's groundwater chemistry. The majority of samples in the study area fall into the C3 S1 category at 39 %, indicating that the groundwater is too salinized to be used on soil with limited drainage. However, crops that are sensitive to sodium, like avocados and stone fruit trees, may suffer damage from excessive sodium levels (Fei Liu et al. 2021). The next major group, C4S2, accounts for 25% of the total and indicates that extremely high salinity groundwater is not generally suitable for irrigation but may be used in exceptional circumstances. However, the soil needs to be able to tolerate salt well, and it is best to choose crops that can withstand salt well and irrigation water that has been applied in excess. Because of this, the majority of the C3S1 category suggests that the groundwater quality in the study area is suitable for irrigation.

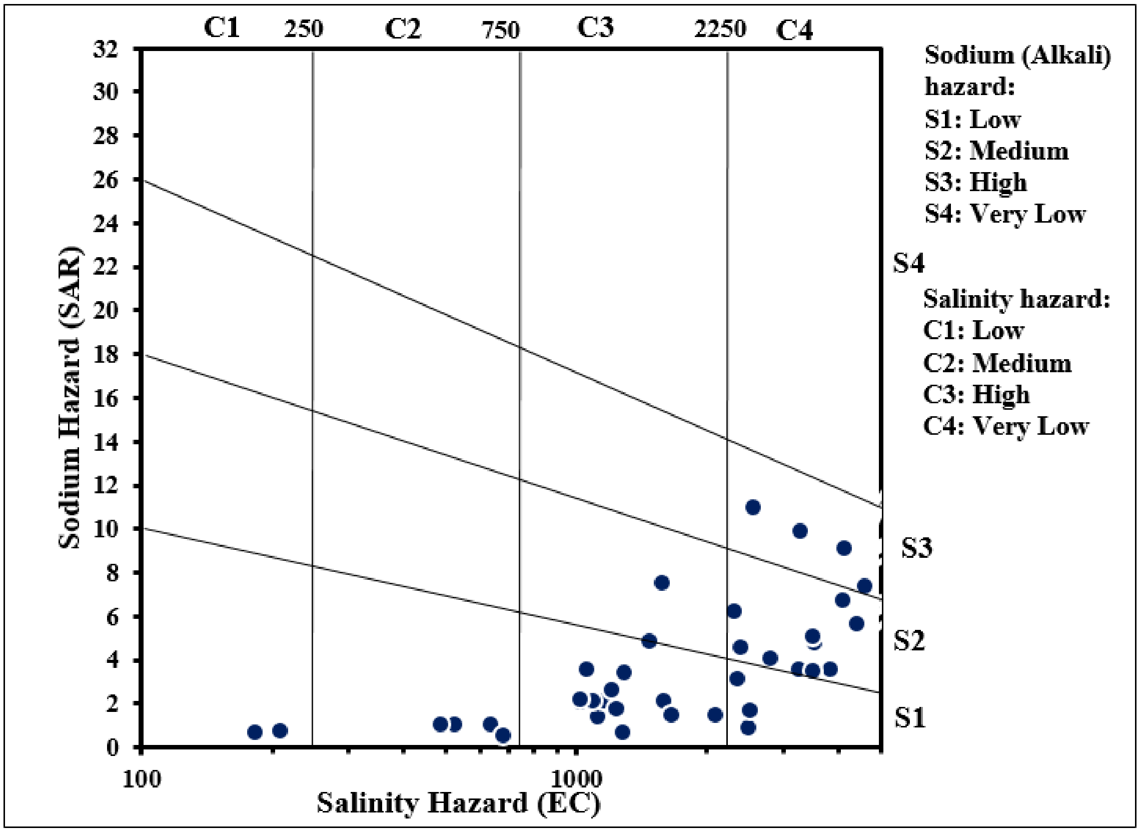

Fig. 8 USSL diagram for classification of groundwater for irrigation purpose.

Permeability Index (PI)

Using the Permeability Index (PI), the classification of groundwater for irrigation has been studied. Doneen (1964) altered a standard for figuring out if groundwater is appropriate for irrigation based on PI.

$$\text{Permeability Index (PI)} = [\{Na^{+} \sqrt{(HCO_3)}\} / (Ca^{2+} + Mg^{2+} + Na^{+})] \times 100$$

where all concentrations are listed as milliequivalents per litre (meq). Permeability index is calculated by taking into account the overall salt concentration, sodium content, and carbonate content, all of which affect soil permeability. The groundwater can be classified as Class I (Excellent), Class II (Good), or Class III (Unsuitable) for irrigation based on the PI values (Table 6). The values in the class I category for the research area are 50%, 39%, and 11%, respectively, according to the PI values (Fig. 9). The majority of samples fall into the class I group, which denotes that they are typically "good" for irrigation purposes, based on the observation of PI values over all seasons.

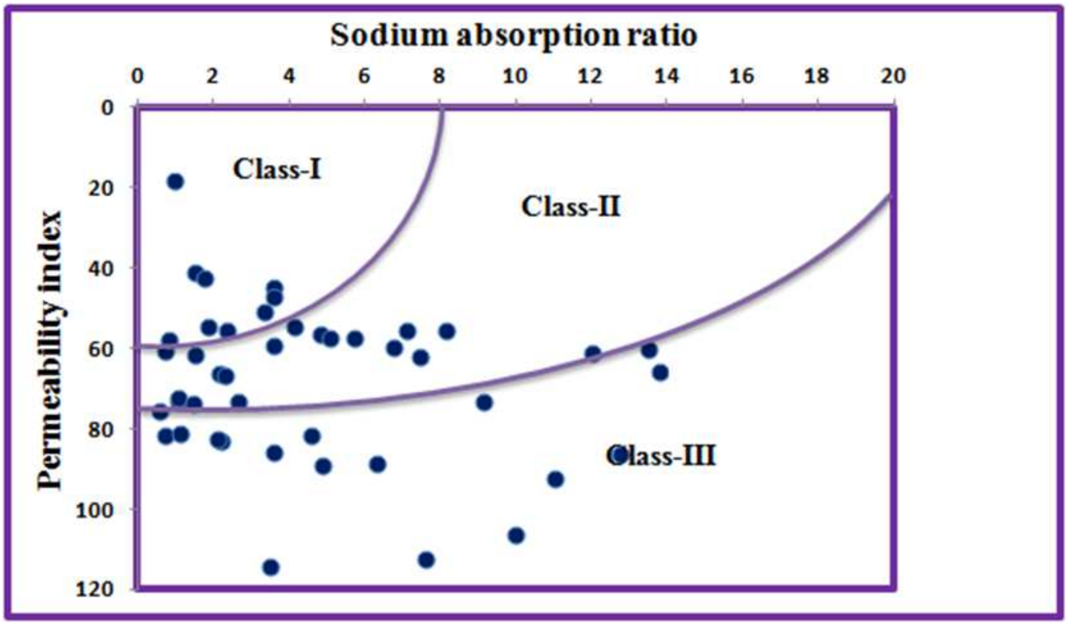

Fig. 9 Permeability Index for classification of groundwater for irrigation purpose.

Sodium Absorption Ratio (SAR)

Irrigation waters are categorized using SAR based on how exchangeable sodium affects the physical state of the soil. The salinity laboratory of the U.S. Department of Agriculture has given a suggestion for using water for irrigation practice (Todd and Mays 2013; Nagaraju et al. 2014). It suggests that sodium adsorption by soil particles will result in a rise in soluble sodium, which could create an alkali hazard in the soil and obstruct the successful development of crops (Mistry and Lienhard 2013). Where groundwater has significant concentrations of calcium and magnesium ions, the threat from sodium is reduced. A higher SAR value will impact the soil's permeability (Singh et al. 2015). The following formula gives the definition of SAR:

$$SAR = Na^{+} / \sqrt{((Ca^{2+} + Mg^{2+})/2)}$$

where the milliequivalents per litre unit of measurement is used to express all concentrations (meq). When water has a high salt concentration, it flocculates (Singh et al. 2015). The groundwater is divided into five groups based on the sodium adsorption ratio (SAR), including excellent (10), good (10 to 18), doubtful (18 to 26), and unsuitable (>26). (Singh et al. 2015). According to SAR observations in the study area, 89% of the samples are in "good" condition (Table 7). Therefore, it suggests that most of the areas in the study basin are suitable for irrigation.

WATER QUALITY FOR DOMESTIC AND INDUSTRIAL PURPOSE

Nearly every industrial unit has its own specifications, and the quality essential for industrial water supply vary greatly. There are three types of industrial water process, boiler, and cooling waters Industries frequently encounter corrosion and scaling, which are caused by chemical reactions in poor-quality water. Corrosion is a chemical process that occurs on metals and causes the metal to be eaten away. The deposition of undesirable components results in material corrosion. The following water quality metrics were used in the current study to determine the scaling and corrosive properties of waters (Rao et al. 2005).

Total Hardness

Total hardness, measured as $CaCO_3$, is mostly determined by the amount of calcium and magnesium in the water, with minor contributions from other elements like aluminum, manganese, iron, and zinc (Prasanth et al. 2012). Table 8 displays findings and classification. Eighty percent of the groundwater samples from the study area were deemed to be "very hard," with the central portion of the study area hosting the majority of these samples. Only 16 percent of the samples were classified as "hard". Only 4% of the samples were found to be in a "soft" state for industrial usage, and these samples were found in the NE regions of the research area (Fig 10).

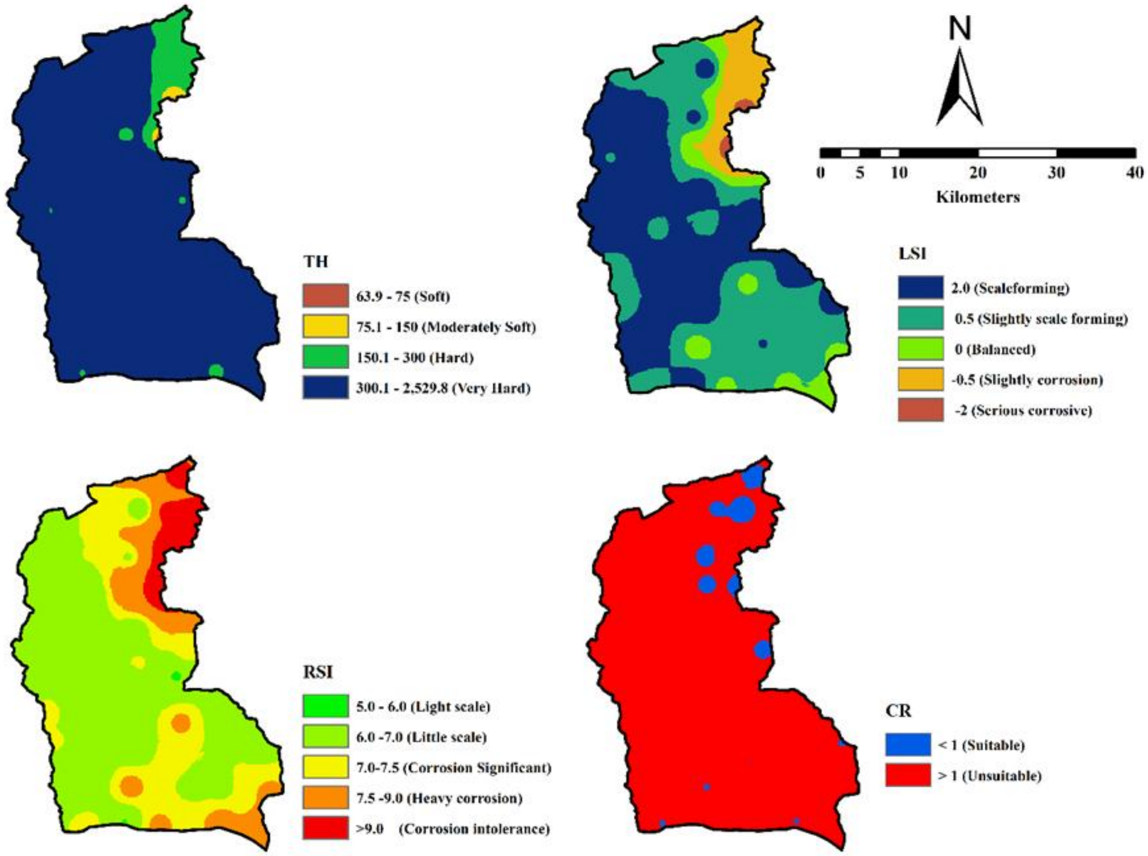

Fig. 10 Spatial distribution of Industrial quality parameters

Langelier Saturation Index (LSI) and Ryznar stability index (RSI)

For industrial applications, the Langelier Saturation Index (LSI) and Ryznar Stability Index (RSI) are the two primary indices used to assess the water chemistry. These indices primarily evaluate the pH of water, which calcium carbonate regulates and which is controlled by the presence of free CO_2 in the water (Sajil Kumar 2019). In order to forecast the tendency of water to precipitate or dissolve calcium carbonate, Langelier W.F. created the Langelier Saturation Index (LSI) in 1936 (Langelier 1936). The pH value, temperature, total dissolved solids (TDS), bicarbonate and carbonate alkalinity, and calcium hardness of the given water are all taken into account by LSI in order to calculate the pH value (pHs) when calcium carbonate is saturated. This calculation is done in accordance with theoretical principles. The actual pH, less the pHs, is equal to the LSI number (Hwang et al. 2017). Table 9 provides the category in the Langelier Saturation Index (Mirzabeygi et al. 2016). This is useful in determining whether the groundwater has a tendency to scale or corrode. If it is negative, the water sample is corrosive and will dissolve calcium carbonate in water. If it is positive, scaling is present and calcium carbonate precipitates in the water sample (Gupta et al. 2011). The following equation can be used to calculate the value of pHs:

$$\text{pHs} = (9.3 + A + B) - (C + D)$$

Where:

$A = (\log(\text{TDS in ppm}) - 1)/10$

$B = (-13.12 \log(\text{temp. } ^{o}\text{C} + 273)) + 34.55$

$C = (\log(\text{calcium hardness as } CaCO_3 \text{ in ppm})) - 0.4$

$D = \log(\text{M alkalinity as } CaCO_3 \text{ in ppm})$

The value of the LSI ranges from -3.19 to 1.21, and 50% of the groundwater samples have scale-forming conditions. These conditions are largely concentrated in the area's center, while the least corrosive groundwater conditions (5%) are found around the Kollimalai hills.

There are several instances of good groundwater quality along the study's southern limit, which is where the Cauvery River's flood plain is located. Ryznar's Stability Index (RSI), which is a modified version of the Langelier Saturation Index (LSI) (Ryznar 1944), provides a better understanding of groundwater with corrosive or scaling properties for industrial usage (Egbueri 2020). The formula for calculating RSI is as follows: RSI = 2pHs - pH (Ryznar 1944), where pH is the actual pH and pHs are the calculated pHs.The RSI's category ranges from 5.89 to 12.38, and it shows that the majority of the samples (50 percent) are of a slight scale and are located in the middle of the study region (Table 10). For industrial usage, the water is too corrosive in some areas along the Kollimali Hills (Fig 10). The distribution of the same groundwater features is shown by both index.

Corrosivity Ratio (CR)

Transport of groundwater taken from the research area for diverse uses involves using standard techniques like tankers and steel pipes. The decrease in a pipe's hydraulic capacity is a result of corrosion. The amount of water that is corrosive determines how long these traditional procedures last. The corrosive ratio proposed by Ryzner in 1944, and Hwang et al. in 2017 could be used to emphasize this fact. The following formula determines the corrosivity ratio:

$$\text{Corrosivity Ratio (CR)} = \{(C1^{-}/35.5) + 2(SO_4^{2-}/96)\}/\, 2\,(HCO_3^{-} + CO_3^{-})\,/100$$

where the milliequivalents per liter unit of measurement is used to express all concentrations (meq). It measures the groundwater's susceptibility to corrosion and is expressed as the ratio of alkaline earths to saline salts. The results show that 77% of the samples have a higher corrosivity ratio value. The majority of the groundwater in the research area is considered "unsafe” (Table 11). Since the CR value is greater than 1, it is advised to convey the water using polyvinyl chloride pipes and EPI-coated tankers. With respect to LSI and RSI values, the spatial distribution of CR exhibits the same distribution trend (Fig 10).

Table 4 Groundwater classification for irrigation purpose based on Wilcox diagram (Wilcox 1955)

Category	No. of samples	Percentage of samples
Very good to good	6	14
Good to Permissible	13	30
Permissible to Doubtful	2	5

Doubtful to Unsuitable	6	14
Unsuitable	17	39

Table 5 Groundwater classification for irrigation purpose based on U. S. Salinity Diagram (USSL 1954).

Category	No. of samples	Percentage of samples
C1S1	2	5
C2S1	5	11
C3S1	17	39
C4S1	3	7
C3S2	2	5
C4S2	11	25
C4S3	4	9
C4S4	0	0

Table 6 Groundwater classification for irrigation purpose based on Permeability Index (PI) (Doneen 1964)

Category	No. of samples	Percentage of samples
Class-I	22	50
Class- II	17	39
Class-III	5	11

Table 7 Groundwater classification for irrigation purpose based on Sodium Absorption Ratio (SAR) (Todd 1959; Richards 1954).

Range	Category	Percentage of samples
<10	Excellent	89
10-18	Good	11
18-26	Doubtful	0
>26	Unsuitable	0

Table 8 Classification of groundwater based on hardness (Sawyer and McCarty 1967).

TH (ppm)	Classification	No. of Sample	Percentage of Sample
<75	Soft	2	5
75-150	Moderately hard	0	0
150-300	Hard	7	16
>300	very hard	35	80

Table 9 Groundwater classification based on the Langelier Saturation Index (Carrier 1965).

LSI value	Identification	No. of Sample	Percentage of sample
2	Scale forming but non corrosive	22	50
0.5	Slightly scale forming and corrosive	11	25
0	Balanced but pitting corrosion possible	6	14
-0.5	Slightly corrosive but non scale forming	3	7
-2	Serious corrosion	2	5

Table 10 Groundwater classification based on the Ryznar Stability Index (Carrier 1965).

RSI value	Identification	No. of Sample	Percentage of sample
4.0-5.0	Heavy scale	0	0
5.0-6.0	Light scale	3	7
6.0-7.0	Little scale or corrosion	22	50
7.0-7.5	Corrosion significant	8	18

7.5-9.0	Heavy corrosion	7	16
>9.0	Corrosion intolerable	4	9

Table 11 Groundwater classification for industrial and domestic purpose based on Corrosivity Ratio (CR)

Limit	Category	No. of Sample	Percentage of samples
<1	Suitable	14	32
>1	Unsuitable	30	68

STATISTICAL ANALYSIS

A useful method for estimating and understanding the geographical and temporal fluctuations in groundwater quality indicators is principal component analysis (PCA) (Garreta et al. 2018; Ramachandran 2020; Ali et al. 2024). It helps in the analysis of relationship variables from the complexity data for straightforward interpretation. The complex groundwater geochemical data can be reduced to an easily interpretable form using factor analysis (Davis 2002). Jayaprakash et al. (2007) used it to understand factors affecting groundwater chemistry in Neyveli, Tamil Nadu. Srinivasamoorthy et al. (2012) employed factor analysis to assess groundwater quality and fluoride contamination in Mettur, Tamil Nadu. Leventeli and Yalcin (2021) used factor analysis method to examine heavy metal concentrations and their sources in Akcay River water as it enters the Mediterranean Sea near the Finike coast in Turkey. Meanwhile, Adithya et al. (2016) used factor analysis to investigate the sources and factors contributing to higher Uranium levels in Central Tamil Nadu's groundwater.

In this work, Factors with Eigenvalues of 1.0 were chosen (Davis 1986) and the Rotated Component Matrix method was then employed to maximize each factor's explanatory power. In the context of factor loadings, values greater than 0.75 were classified as high loadings, while loadings between 0.40 and 0.75 were considered moderate (Srinivasamoorthy et al. 2012; Tavakol, Wetzel 2020). Three controlling factors for groundwater quality were identified in this investigation, collectively explaining 58.6 percent of the observed variance (Tables 12. Factor 1 encompasses the loadings of electrical conductivity (EC), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), sulfate (SO_4^{2-}), and total hardness (TH), accounting for a total variance of 36.5 percent. Spatial distribution analysis (Fig. 11a) highlights the prevalence of this component in the central regions of the study area, with the highest concentration observed in the southwestern zone. This observation elucidates the influence of groundwater in the research area on the dissolution of salts from the surrounding soil (Valdes et al. in 2007). Factor 2, with a variance of 11.2 percent, exhibits loadings for bicarbonate (HCO_3^-), pH, and oxidation-reduction potential (ORP). Spatial distribution patterns, as represented in Fig. 11b, indicate an uneven distribution of this factor. Considering the loadings, this factor may be influenced by the mixing of fresh water with water characterized by prolonged residence times. Factor 3, with a total variance of 10.9 percent, is characterized by loadings of ORP and nitrate (NO_3^-). Spatial variation, as shown in the diagram (Fig. 11c), suggests that the southern part of the study area, where the Cauvery River flows adjacent to the boundary, indicates the potential influence of atmospheric interactions between surface water in agricultural land and the reentry of nitrate fertilizers into the groundwater. Spatial distribution of three factors are shown in the Fig.11d.

Table 12 Factor analysis

Parameters	**Component**		
	1	**2**	**3**
EC	**0.977**	0.160	0.007
Cl^-	**0.957**	0.125	-0.075
Ca^{2+}	**0.939**	0.094	0.111
TH	**0.939**	0.173	0.063
SO_4^{2-}	**0.913**	-0.049	0.188
Na^+	**0.909**	0.205	-0.096
Mg^{2+}	**0.901**	0.229	0.022
K^+	**0.687**	-0.199	0.277
HCO_3^+	-0.025	**0.733**	-0.112
pH	0.125	**0.682**	-0.093
ORP	0.224	**0.614**	**0.473**
F^-	0.281	0.282	-0.714
NO_3^-	0.349	0.059	**0.560**
Variance %	**36.5**	**11.2**	**10.9**

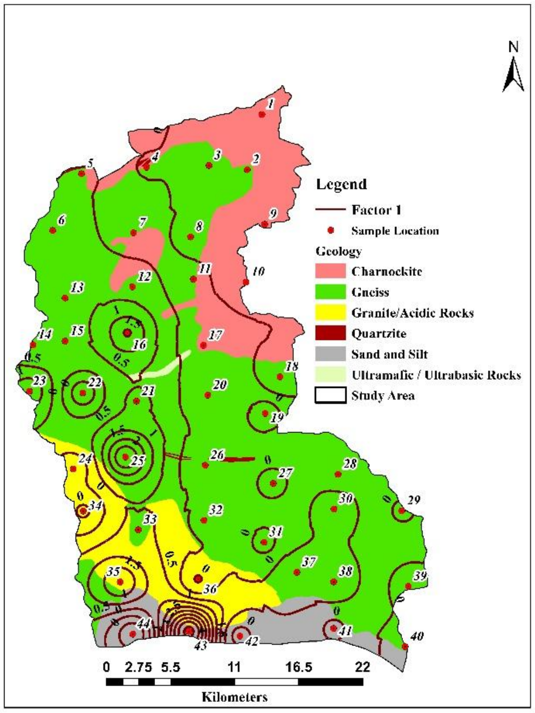

Fig. 11a Spatial distribution of factor-1

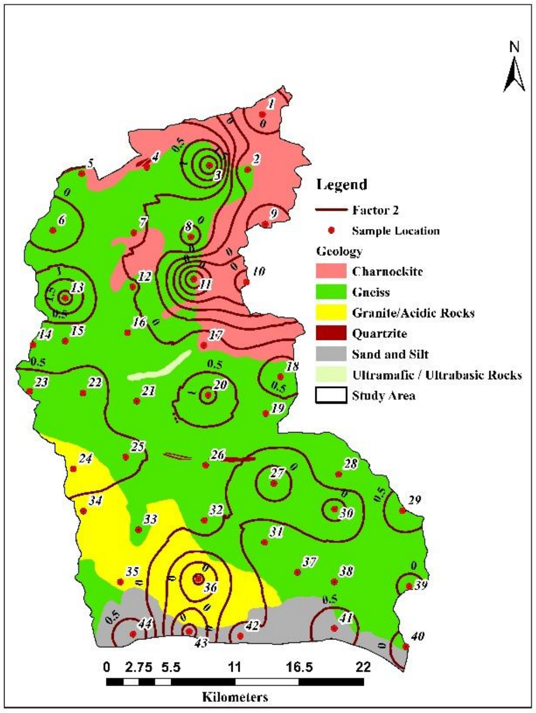

Fig. 11b Spatial distribution of factor-2

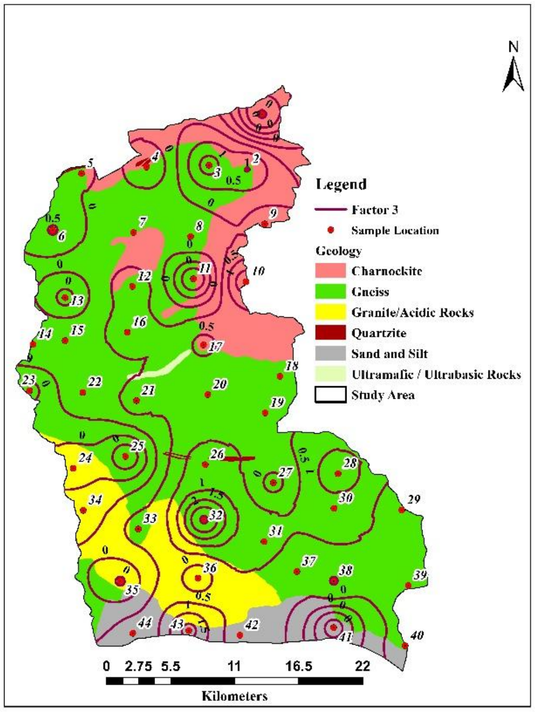

Fig. 11c Spatial distribution of factor-3

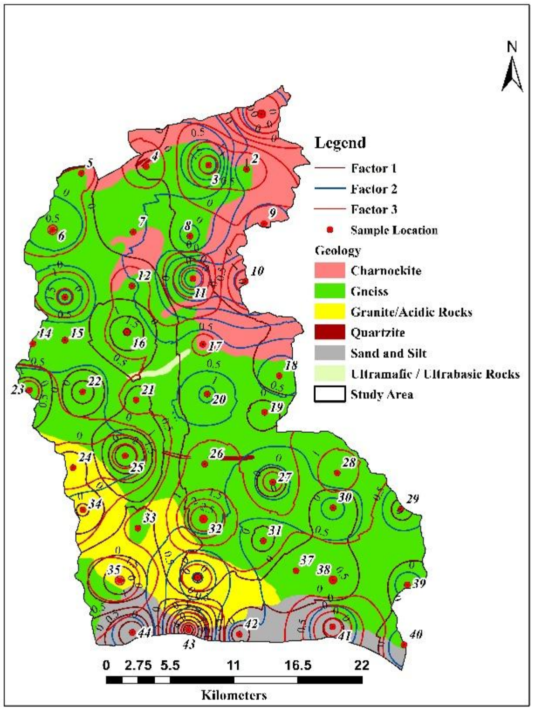

Fig. 11d Spatial distribution of factor-1,2&3

CONCLUSION

With the exception of nitrate, the majority of samples exhibit significant concentrations along the center of the basin based on the quality and distribution of individual ions. It suggested that significant groundwater extraction may have taken place nearby, causing ions to dissolve into the groundwater. The central region of the area was not safe for drinking, according to the DWQI results, which cause a variety of illnesses depending on the types of elements exceeded. For agricultural use, the majority of the groundwater is in acceptable condition, but, in some areas, the plant that needs to be watered must be able to tolerate salt. The majority of the samples, with the exception of the NE section, were found to be unsuitable for industrial use by TH, LSI, RSI, and CR due to the high hardness in the sense of the groundwater's tendency to develop scale. According to Gibbs and Piper's trilinear diagrams, most samples were influenced by rock-water interaction and evaporation due to long residence times and low rainfall. Principal component analysis indicates the main sources of groundwater chemistry in the rock-water interaction, with greater solubility of minerals and some anthropogenic influences such as industrial discharges and agrochemical input. Due to extensive human activity, the groundwater in the area's central region is not suitable for all purposes. Therefore, it is necessary to build more surface water recharge structures in a variety of ways in the designated area as well as in any other suitable location.

Acknowledgement

The author gratefully acknowledge the financial support provided by the University of Madras under the University Research Fellow (URF) scheme (Ref. no. 226/URF/APP.GEO/2015). Additionally, the author expresses their gratitude to the Head of the Department of Applied Geology, University of Madras, for the facilities provided and his constant encouragement.

REFERENCES

Adesiji, A. R., Jimoh, O. D., Adeoye, P. A., Odofin, A. J., Asogwa, O. E., Mangey, J. A., & Odekunle, O. M. (2023). Effect of chemical fertilizers on groundwater quality in an unconfined aquifer. *Arid Zone Journal of Engineering, Technology & Environment (AZOJETE)*, 19(1), 113–120.

Aghazadeh, N., Chitsazan, M., & Golestan, Y. (2017). Hydrochemistry and quality assessment of groundwater in the Ardabil area, Iran. *Applied Water Science, 7*(7), 3599–3616. https://doi.org/10.1007/s13201-017-0530-1

Ali, S., Verma, S., Agarwal, M. B., et al. (2024). Groundwater quality assessment using water quality index and principal component analysis in the Achnera block, Agra district, Uttar Pradesh, Northern India. *Scientific Reports, 14,* 5381. https://doi.org/10.1038/s41598-024-56056-8

Alsabti, B., Sabarathinam, C., & Svv, D. R. (2023). Identification of high nitrate concentration in shallow groundwater of an arid region: A case study of South Kuwait's Bay. *Environmental Monitoring and Assessment, 195*(1), 143. https://doi.org/10.1007/s10661-022-10553-0

American Public Health Association (APHA). (1998). *Standard methods for the examination of water and wastewater* (20th ed.). American Public Health Association.

Asare-Donkor, N. K., & Adimado, A. A. (2020). Groundwater quality assessment in the northern and upper east regions of Ghana. *Environmental Earth Sciences, 79,* 205. https://doi.org/10.1007/s12665-020-08956-x

Ayuba, R., Tijani, M. N., & Omonona, O. V. (2017). Hydrochemical characteristics and quality assessment of groundwater from shallow wells in Gboloko area, central Nigeria. *Global Journal of Geological Sciences, 15,* 65–76.

Biazar, S. M., Dinpashoh, Y., & Singh, V. P. (2019). Sensitivity analysis of the reference crop evapotranspiration in a humid region. *Environmental Science and Pollution Research, 26*(31), 32517–32544. https://doi.org/10.1007/s11356-019-06464-w

Bureau of Indian Standards (BIS). (2012). *Indian standard drinking water specification (2nd rev.) IS 10500.* BIS.

Canadian Council of Ministers of the Environment (CCME). (2001). *Canadian water quality guidelines for the protection of aquatic life: CCME water quality index 1.0 user's manual.* Canadian Environmental Quality Guidelines.

Central Ground Water Board (CGWB). (2008). *District groundwater brochure: Namakkal district, Tamil Nadu.* Ministry of Water Resources, Government of India.

Chen, F., Yao, L., Mei, G., Shang, Y., Xiong, F., & Ding, Z. (2021). Groundwater quality and potential human health risk assessment for drinking and irrigation purposes: A case study in the semiarid region of North China. *Water, 13,* 783. https://doi.org/10.3390/w13060783

Chidambaram, S., Panda, B., Keesari, T., Prasanna, M. V., Singh, D. K., & Ramanathan, A. L. (2022). Isotopic signatures to address the groundwater recharge in coastal aquifers. *Marine Pollution Bulletin, 174,* 113273. https://doi.org/10.1016/j.marpolbul.2021.113273

Chidambaram, S., Ramanathan, A. L., Prasanna, M. V., Anandhan, P., Srinivasamoorthy, K., & Vasudevan, S. (2008). Identification of hydrogeochemically active regimes in groundwaters of Erode district, Tamil Nadu: A statistical approach. *Asian Journal of Water, Environment and Pollution, 5*(3), 93–102.

Chotpantarat, S., & Thamrongsrisakul, J. (2021). Natural and anthropogenic factors influencing hydrochemical characteristics and heavy metals in groundwater surrounding a gold mine, Thailand. *Journal of Asian Earth Sciences, 211,* 104692. https://doi.org/10.1016/j.jseaes.2021.104692

Das, N., & Mukhopadhyay, S. (2020). Application of multi-criteria decision-making technique for the assessment of groundwater potential zones: A study on Birbhum district, West Bengal, India. *Environment, Development and Sustainability, 22*(2), 931–955. https://doi.org/10.1007/s10668-018-0225-2

Davraz, A., & Batur, B. (2021). Hydrogeochemistry characteristics of groundwater and health risk assessment in Yalvaç–Gelendost basin (Turkey). *Applied Water Science, 11,* 14. https://doi.org/10.1007/s13201-021-01401-9

Deutsch, W. J., & Siegel, R. (1997). *Groundwater geochemistry: Fundamentals and applications to contamination.* Lewis Publishers.

Dewandel, B., Perrin, J., Ahmed, S., Aulong, S., Hrkal, Z., Lachassagne, P., & Massuel, S. (2010). Development of a tool for managing groundwater resources in semi-arid hard rock regions: Application to a rural watershed in South India. *Hydrological Processes, 24*(19), 2784–2797. https://doi.org/10.1002/hyp.7676

Dinpashoh, Y., Singh, V. P., Biazar, S. M., & Kavehkar, S. (2019). Impact of climate change on streamflow timing (case study: Guilan Province). *Theoretical and Applied Climatology, 138*(1), 65–76. https://doi.org/10.1007/s00704-019-02802-7

Domenico, P. A., & Schwartz, F. W. (1998). *Physical and chemical hydrogeology* (2nd ed.). Wiley.

El Osta, M., Masoud, M., Alqarawy, A., Elsayed, S., & Gad, M. (2022). Groundwater suitability for drinking and irrigation using water quality indices and multivariate modeling in Makkah Al-Mukarramah province, Saudi Arabia. *Water, 14*(3), 483. https://doi.org/10.3390/w14030483

Elango, L., Ramachandran, S., & Chowdary, Y. S. N. (1992). Groundwater quality in coastal regions of south Madras (Chennai). *Indian Journal of Environmental Health.*

Garcia, R. J. L., da Silva Júnior, J. B., Abreu, I. M., Soares, S. A. R., Araujo, R. G. O., de Souza, E. S., & de Souza Queiroz, A. F. (2020). Application of PCA and HCA in geochemical parameters to distinguish depositional paleoenvironments from source rocks. *Journal of South American Earth Sciences, 103,* 102734. https://doi.org/10.1016/j.jsames.2020.102734

Gibbs, R. J. (1970). Mechanisms controlling world water chemistry. *Science, 170*(3962), 1088–1090. https://doi.org/10.1126/science.170.3962.1088

Glynn, P. D., Plummer, L. N., Weissmann, G. S., & Stute, M. (2009). Geochemistry and the understanding of groundwater systems. *AGU Fall Meeting Abstracts.*

Gupta, T., & Kumari, R. (2023). Source apportionment of groundwater quality in agriculture-dominated semiarid region, India—Using an integrated approach of hydrochemistry, stable isotopes and land use/land cover change. *Environment, Development and Sustainability, 26,* 26579–26605. https://doi.org/10.1007/s10668-023-03744-6

Hem, J. D. (1985). *Study and interpretation of the chemical characteristics of natural water* (3rd ed., USGS Water-Supply Paper 2254). U.S. Geological Survey.

Ibrahim, E. S., Chiroma, J. T., Abubakar, M. A., et al. (2024). Spatial modelling of present and future groundwater potentials in Nigeria: Towards a sustainable water demand and supply. *Sustainable Water Resources Management, 10,* 137. https://doi.org/10.1007/s40899-024-01107-1

Jain, S. K., Agarwal, P. K., & Singh, V. P. (2007). Groundwater. In *Hydrology and water resources of India* (pp. 523–564). Springer. https://doi.org/10.1007/1-4020-5180-8_6

James, N. (2024). Urbanization and its impact on environmental sustainability. *Journal of Applied Geographical Studies, 3,* 54–66. https://doi.org/10.47941/jags.1624

Jenefer, S., Sridhar, S. G. D., Sangunathan, U., Balasubramanian, M., & Sakthivel, A. M. (2016). Trace metals in groundwater/drinking water, Pungar sub-basin, Karur district, Tamil Nadu, India. *EnviroGeoChimica Acta.*

Jiang, C., Cheng, L., Li, C., & Zheng, L. (2022). A hydrochemical and multi-isotopic study of groundwater sulfate origin and contribution in the coal mining area. *Ecotoxicology and Environmental Safety, 248,* 114286. https://doi.org/10.1016/j.ecoenv.2022.114286

Kanagaraj, G., Sridhar, S. G. D., Gopal, V., Shanmugasundharam, A., & Sangunathan, U. (2014). Geochemical characteristics of groundwater in parts of Kancheepuram District, Tamil Nadu, India. *EnviroGeoChimica Acta, 1*(2), 131–139.

Kannan, P., Balasubramaniyan, G., Karuppannan, S., & others. (2025). Groundwater quality beyond potability: Decoding the hydrogeochemical signatures using spatial and statistical methods in regions of Dindigul District, Tamil Nadu. *Discover Sustainability, 6*, 784. https://doi.org/10.1007/s43621-025-01344-0

Karanth, K. P. (1991). Impacts of human activities on hydrogeological environments. *Journal of the Geological Society of India, 38,* 195–206.

Kom, K. P., Gurugnanam, B., Bairavi, S., & Chidambaram, S. (2023). Sources and geochemistry of high fluoride groundwater in hard rock aquifer of the semi-arid region: A special focus on human health risk assessment. *Total Environment Research Themes, 5,* 100026. https://doi.org/10.1016/j.totert.2023.100026

Kumar, R., Kumar, K. V. V., Dharani, S. V., Kalaivani, S., & Sekhar, V. (2022). Prevalence of dental fluorosis among 12–15-year-old schoolchildren in Cheyyur Taluk, Chengalpattu District:

A cross-sectional survey. *Journal of Indian Association of Public Health Dentistry, 20*(3), 277–280. https://doi.org/10.4103/jiaphd.jiaphd_149_21

Li, D., Zhai, Y., Lei, Y., Li, J., Teng, Y., Lu, H., ... & Yang, J. (2021). Spatiotemporal evolution of groundwater nitrate nitrogen levels and potential human health risks in the Songnen Plain, Northeast China. *Ecotoxicology and Environmental Safety, 208,* 111524. https://doi.org/10.1016/j.ecoenv.2020.111524

Mackie, C., Lackey, R., Levison, J., & Rodrigues, L. (2022). Groundwater as a source and pathway for road salt contamination of surface water in the Lake Ontario Basin: A review. *Journal of Great Lakes Research, 48*(1), 24–36. https://doi.org/10.1016/j.jglr.2021.11.015

Malakootian, M., Mohammadi, A., & Faraji, M. (2020). Investigation of physicochemical parameters in drinking water resources and health risk assessment: A case study in NW Iran. *Environmental Earth Sciences, 79*(9), 1–11. https://doi.org/10.1007/s12665-020-09053-9

Manimaran, D., Abishek, S. R., Pitchaimani, V. S., & others. (2025). Spatial variation and hydrogeochemical characterization of groundwater in Vallanadu region: Insights from water quality index and statistical analysis. *Discover Sustainability, 6*, 524. https://doi.org/10.1007/s43621-025-01381-9

Mark, I. A., Leddy, M. B., Bold, R. M., & Graves, A. K. (2012). Bacterial community composition in low-flowing river water with different sources of pollutants. *FEMS Microbiology Ecology, 79*(1), 155–166. https://doi.org/10.1111/j.1574-6941.2011.01206.x

Mathew, K., Newman, P. W. G., & Ho, G. E. (1982). Groundwater recharge with secondary sewage effluent. *Water Research, 16*(4), 517–522. https://doi.org/10.1016/0043-1354(82)90195-0

Mayakannan, A., & Sivalingam, V. (2019). Impact of fluoride on human health: A case study in Dharmapuri District, Tamil Nadu. *International Journal of Research and Analytical Reviews, 11*(2), 1–6.

Mohan, R., Singh, A. K., Tripathi, J. K., & Chowdhary, G. C. (2000). Hydrochemistry and quality assessment of groundwater in Naini Industrial Area, Allahabad District, Uttar Pradesh. *Journal of the Geological Society of India, 55*(1), 77–89.

Mondal, N. C., & Singh, V. P. (2012). Chloride migration in groundwater for a tannery belt in Southern India. *Environmental Monitoring and Assessment, 184*(5), 2857–2879. https://doi.org/10.1007/s10661-011-2156-x

Morsi, M., Farrag, A., Elewa, A., & El Sayed, E. (2015). Quantitative analyses of surface water and groundwater resources around the River Nile, Assiut Governorate, Upper Egypt: Water quality in relation to anthropogenic activities. *Journal of Hydrogeology and Hydrologic Engineering, 4*(3). https://doi.org/10.4172/2325-9647.1000129

Panda, D. K., Tiwari, V. M., & Rodell, M. (2022). Groundwater variability across India under contrasting human and natural conditions. *Earth's Future, 10*(1), e2021EF002513. https://doi.org/10.1029/2021EF002513

Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water analyses. *Eos, Transactions American Geophysical Union, 25*(6), 914–928. https://doi.org/10.1029/TR025i006p00914

Prasanna, M. V., Chidambaram, S., & Srinivasamoorthy, K. (2010). Statistical analysis of the hydrogeochemical evolution of groundwater in hard and sedimentary aquifer systems of Gadilam river basin, South India. *Journal of King Saud University-Science, 22*(3), 133–145. https://doi.org/10.1016/j.jksus.2009.12.001

Rajendiran, T., Sabarathinam, C., Panda, B., & Elumalai, V. (2023). Influence of dissolved oxygen, water level and temperature on dissolved organic carbon in coastal groundwater. *Hydrology, 10*(4), 85. https://doi.org/10.3390/hydrology10040085

Rajesh, R., Elango, L., & Brindha, K. (2019). Methods for assessing the groundwater quality. In *GIS and geostatistical techniques for groundwater science* (pp. 57–78). Elsevier. https://doi.org/10.1016/B978-0-12-815413-7.00006-7

Ramachandran, A., Abishek, S. R., Pitchaimani, V. S., Gandhi, M. S., & Prakash, V. (2025). Hydrochemical assessment of groundwater for drinking and irrigation suitability in Vaniyambadi region, Tamil Nadu, Southern India: A sustainable approach. *Cleaner Water, 4*, 100102. https://doi.org/10.1016/j.clwat.2025.100102

Ramachandran, A., Sivakumar, K., Shanmugasundharam, A., Sangunathan, U., & Krishnamurthy, R. R. (2021). Evaluation of potable groundwater zones identification based on WQI and GIS techniques in Adyar River Basin, Chennai, Tamil Nadu, India. *Acta Ecologica Sinica, 41*(4), 285–295. https://doi.org/10.1016/j.chnaes.2020.06.004

Razowska-Jaworek, L. (2014). *Calcium and magnesium in groundwater: Occurrence and significance for human health.* CRC Press.

Thivya, C., Chidambaram, S., Singaraja, C., Thilagavathi, R., Prasanna, M. V., Anandhan, P., & Jainab, I. (2013). A study on the significance of lithology in groundwater quality of Madurai district, Tamil Nadu (India). *Environment, Development and Sustainability.* https://doi.org/10.1007/s10668-013-9439-z

Yang, J., Ye, M., Tang, Z., Jiao, T., Song, X., Pei, Y., & Liu, H. (2020). Using cluster analysis for understanding spatial and temporal patterns and controlling factors of groundwater geochemistry in a regional aquifer. *Journal of Hydrology, 583,* 124594. https://doi.org/10.1016/j.jhydrol.2020.124594

DECLARATIONS

Ethics approval and consent to participate: Not Applicable

Consent for publication

Date: 23 October 2025

To
The Editor-in-Chief
Discover Geoscience
Springer Nature

Subject: Consent for Publication

Dear Editor,

I, **Dr. C. Thivya**, Assistant Professor, **Department of Geology**, **National College (Autonomous)**, Tiruchirappalli, Tamil Nadu, India, hereby give my full consent for the publication as corresponding author of our manuscript titled:

"GEOCHEMICAL EVALUATION AND POTABILITY OF GROUNDWATER IN A HARD ROCK TERRAIN: A CASE STUDY FROM THE KARAIPOTTANAR SUB-BASIN, SOUTHERN INDIA"

I confirm that:

1. The submitted manuscript is an original work and has not been published or submitted elsewhere in any form, either in part or in full.
2. All authors involved in the work have reviewed the final version of the manuscript and approved its submission to *Discover Geoscience*.
3. There are no conflicts of interest related to this study, and all ethical guidelines have been followed.
4. Upon acceptance, I grant the publisher the rights to publish, reproduce, and distribute the article in all forms and media, subject to the journal's policies.

I kindly request you to consider the manuscript for publication in your esteemed journal.

Thank you for your consideration.

Sincerely,
Dr. C. Thivya
Assistant Professor
Department of Geology
National College (Autonomous)
Tiruchirappalli – 620001, Tamil Nadu, India
✉ **Email:** thivya@nct.ac.in

Availability of data and material: Availability of data on request

Competing interests: Not Applicable

Funding: The author gratefully acknowledge the financial support provided by the University of Madras under the University Research Fellow (URF) scheme (Ref. no. 226/URF/APP.GEO/2015).

Author contributions Sangunathan Ulaganathan: Conceptualization, Investigation, Methodology, Data Curation and Original draught writing. **Sithu Govindasamy Dinakaran Sridhar, Chidambaram Sabarathinam :** Original draught, review and editing. **Hema Achyuthan**: Validation sampling, software and analysis. **Venkatesan Selvaraj:** Methodology, Interpretation, Conceptualization and Visualization. **Manikandan Nagarathinam:** Data Curation and software analysis. **Maniyarasan Subramaniyan, Shanmugasundaram Arumugam:** Interpretation, review and editing. **Thivya Chandrasekar:** Validation sampling and Data Curation.