Assessment of groundwater study using geophysical and geochemistry mapping in Thamirabarani sub-basin, Karunkulam area, Southern India

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Abstract
Groundwater exploration study has been carried out in Karunkulam area, Srivaikundam taluk, Thoothukudi district, Tamil Nadu, with the help of geophysical and geochemical characteristics. The study area was covered in the meta-sedimentary rock of quartzite, and the source rock of sandstone was delineated from the channel of the Thamirabarani River. Resistivity sounding square array, 2D electrical resistivity imaging technique and magneto-telluric method were used to identify the aquifer thickness and bedrock in quartzite terrain of the study area. An attempt has been made to use GIS spatial distribution map for irrigation suitability and livestock drinking purposes. The hydro-geochemical facies were used to analyze the cations and anions exchange process. It was also observed that the Ca2+-HCO3− was dominant in the low alkalinity in nature and the quality of groundwater represents the geochemical nature in aquifer media. The type of rock–water interaction with Mg2+-Na+-Ca2+-Cl−-HCO3−, Na+-Ca2+-Mg2+-Cl− and Na+-Mg2+-Ca2+-Cl− indicates the rock water interaction between the quartzite, gneissic and some granitic intrusion in the part of the area. Based on geophysical 2D imaging and magneto-telluric resistivity, inferred fracture quartzite zones were water-bearing formation in the study area. This primarily supports the hypothesis assumed at the beginning of the research in the study area.

Keywords Aquifer · Quartzite · Azimuthal square array · Magneto-telluric method · Aquachem · GIS

Introduction
Water is a major play role in drinking and agriculture in and around the world. Worldwide groundwater has been widely used for drinking and agricultural purposes (Yousef et al. 2018). Water scarcity is one of the important problems in India. Hydrogeologists and research scientists have been studied the water need for scientific methods in Southern India (Adimalla 2019). In many parts of the world, high-quality groundwater available for drinking and agriculture over exploitation of groundwater turns into an inexorably rare commodity in various arid and semi-arid areas (Bouderbala et al. 2016). The quality of groundwater has a significant impact on the soil and development, rocks and man-made activities (Singaraja 2017). An aquifer mapping study using geophysical and geochemical method is used for drinking and agriculture development (Song et al. 2020). The Quartzite ridge and associated gneissic rock are having good groundwater potential in the fractured zone of their formation (Ravindran et al. 2018). Aquifer mapping and groundwater quality for drinking and agriculture purposes have been studied by the researchers (Stanly et al. 2021; Duraisamy et al. 2019). The geophysical method is an indirect method to explore groundwater in a quartzite ridge (Kumar et al. 2020). The azimuthal square array method is used to identify the fractured zone of quartzite rock for aquifer mapping; the study was carried out by Basheer and Alezabawy (2020). The 2D electrical resistivity imaging technique is covered both vertical and horizontal structural features of folding and fracturing zone of aquifer flow have been studied by Gao et al. (2018), Ravindran et al. (2015) and Ravindran (2013). The magneto-telluric method is used to map the subsurface features for folded mountain.
of quartzite ridge, and aquifer thickness is studied in this area. The chemistry of groundwater is an important factor to determine its use for domestic needs, irrigation and industrial purposes (Verma et al. 2020). The main objective of the study is (1) to evaluate the aquifer mapping in fractured quartzite terrain using geophysical methods and (2) hydrogeochemical characteristic study in physicochemical properties of groundwater using WQI and GIS spatial maps. The suitability for drinking and agriculture purposes in Karunkulam area, Srivaikundam taluk, Thoothukudi district, Tamil Nadu, India, and the research completely shows the water is suitable for purification and irrigation purposes.

Study area

The study area was fully covered with red sandy soil and river alluvium in the Karunkulam village. This area is located between the 8°38′40.2″N of latitude, 77°51′11.6″E of longitude and 8°38′30.1″N of latitude and 77°51′12.1″E of longitude (Fig. 1). The study area was extended over 20 km in and around the Karunkulam area. The study area is generally made up of red sandy soil and a small elevated quartzite hill with granitic intrusion. This place is fully covered with highly vegetated and agricultural irrigation lands. The topography is generally made up of river alluvium and sandy sediments. This area is generally a quartzite rock and metamorphic rock intrusion of granitic rock. The average temperature around 31.6 °C during the summer season in May is the hottest month of every year. After another month of January is average temperature around 26.5 °C the section of every year. Then, average rainfall to this area for October to December varies from about 570 mm to 740 mm. The northeast monsoon climate is contributing to rainfall in the study area. During the period from October to January, the climate remains relatively cooler.

Petrological study

The study area has high-grade metamorphic terrain of granulite facies and forms a part of the Achankovil shear zone. The area is essentially comprised of different litho-types i.e., quartzite, calc-silicate, gneissic rock, granite vein and charnockite rock. The texture and mineral content of the rocks was studied to establish using microscopy and megascopy (Fig. 2B & 2C).

The petrological study shows the quartzite was composed of quartz, feldspar and biotite. Coarse-grained sedimentary quartzite was formed at the top of meta-sedimentary rocks (Ollé et al. 2016). Mountain activity in the southern granitic region of Vallanadu and the connected quartzite ridge was formed in the study area.

Materials and methods

Geophysics method was identifying the subsurface geology and rocks. The electrical resistivity of azimuthal square array is used to identify fracture quartzite, gneissic and charnockite (Bayewu et al. 2016). Azimuthal square array has greater penetration depth than the Wenner and Schlumberger arrays. The resistivity meter of CRM-500 (Auto-C) equipment is used in the field for square array data collection. 2D ERI is a suitable method for underground exploration of quartzite rock (Ravindran et al.)

![Fig. 1 Location map and water sample collection in the study area](image-url)
The magneto-telluric method was used to identify the structure of the folded and disturbed zone in the study area.

In the field of hydrological research, a total of 15 water samples were collected randomly in the pre- and post-monsoon seasons for hydrochemical processes. The analysis of surface water data is presented in (Table 1). The basic cations and anions $\text{Na}^+$, $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, $\text{K}^+$ and $\text{HCO}_3^-$, $\text{Cl}^-$, $\text{SO}_4^{2-}$ are analyzed and plotted in Aquachem software. GIS-based spatial analysis was used to generate distribution pattern maps in the Karunkulam area. The inverse distance weighted interpolation (IDW) was used to generate an interpolation map for pH, TDS and conductivity (EC) in the pre- and post-monsoon periods of the study area (Fig. 10 A, B and C).

**Result and discussion**

**Square Array Method**

The azimuthal square array is a useful technique for groundwater surveys that have been studied by Ravindran (2013) and Şener et al. (2021). It is used to identify the fractured aquifers of quartzite, gneiss and granite. Compared with the Wenner and Schlumberger sub-structures below the underground geological details of groundwater, this method has a greater penetration depth, 360° rotating resistivity technology. It is used to identify the aquifer mapping fracture direction of quartzite, gneiss, and granite rocks.

The five profiles show the resistivity range of 110–120 $\Omega$.m that indicates the freshwater aquifer zone in the study area. Under three different aquifer conditions, the water-bearing zone is located at depths of 25 m, 45 m and 65 m. The apparent resistivity of 150–200 $\Omega$.m represents the granite and gneiss in the study area (Fig. 3).

**2D Electrical Resistivity Tomography**

2D electrical resistivity imaging tomography was used to study the characteristics of underground structures, and 40 electrodes were used. The resistivity measurement is carried out with the help of CRM 500 Auto-C equipment with a multi-electrode system.
Profile 1

The 2D ERI techniques are used to recognize the quartzite and associated granitic rock. The apparent resistivity of 10.9 -14.4 Ω.m shows the freshwater or aquifer zone at the depth of 13.7 m. The quartzite is intended in the top layer having apparent resistivity of 85 Ω.m. The weathered gneissic and granitic rocks are identified with apparent resistivity of 36.4 Ω.m. The water-bearing zone occurred in the fractured rock of quartzite with pegmatite veins having resistivity of 120 Ω.m.

Profile 2

Profile 2 has four different types of rock formation, such as red soil, quartzite, gneissic rock with granitic intrusion and charnockite rock. The resistivity value of 5-61Ω.m is to focus on the shallow freshwater discharge in the northeast corner of the profile. The southeast corner of the area covered with hard foliated quartzite was exposed in the upper formation of terrain. The weathered gneiss rock has an apparent resistivity of 25–41.1 Ω.m at the depth of 13 m.

Profile 3

In Profile 3, the apparent resistivity of 10.5 Ω.m was obtained to indicate a freshwater zone in fractured quartzite rock. The apparent resistivity of 15.5 -22.7 Ω.m has demarcated the gneiss rock in the profile. The plotted picture of apparent resistivity of 71.4–105 Ω.m has pointed out charnockite rock associated with quartzite rock.

Profile 4

Profile 4 is a massive quartzite with water-bearing zone identified at 21.5 m depth of 8.57–12.5 Ω.m. The gneissic rock was distinguished from the apparent resistivity of 17.8–25.7 Ω.m. The apparent resistivity of 76.9–111 Ω.m was obtained from the charnockite rock.

Profile 5

Profile 5 covered a length of 200 m in the range of resistivity, and this indicates 10.2 Ω.m delineated water potential zone in quartzite ridge. The obtained apparent resistivity of 20–39 Ω.m points out the gneissic rock in the study area (Figs. 4, 5, 6, 7, and 8).

Magneto-Telluric Method

The magneto-telluric method is the latest technology to identify the subsurface feature and aquifer mapping in quartzite gneiss, schist and granitic rock. The data were collected using ADMT-300S equipment. The earth subsurface material and the natural electromagnetic field strength relied on the changes of resistivity values to convert into a subsurface geological formation. The pair of copper electrodes M and N is used for the transmission and receiver to identify the subsurface lithology.

Profile 1

Profile 1 has a resistivity of 0.05–0.09 Ω.m which represents the shallow underground aquifer in the downward movement of the quartzite at the northeast angle. The resistivity is 0.11

Table 1 Water sample location

| Sample ID | Location     | Latitude     | Longitude    | Water Type                                      |
|-----------|--------------|--------------|--------------|------------------------------------------------|
| K1        | Well         | 8.645668     | 77.853946    | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
| K2        | Well         | 8.6455       | 77.853495    | Na⁺-Ca²⁺-Mg²⁺-Cl⁺                           |
| K3        | temple dug well | 8.64417     | 77.853657    | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
| K4        | dug well     | 8.641252     | 77.850205    | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
| K5        | dug well     | 8.641048     | 77.848841    | Na⁺-Ca²⁺-Mg²⁺-Cl⁺                           |
| K6        | Well         | 8.637195     | 77.844918    | Na⁺- Mg²⁺-Ca²⁺-Cl⁻-HCO₃⁻                     |
| K7        | dug well     | 8.634617     | 77.842479    | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
| K8        | dug well     | 8.639001     | 77.849602    | Na⁺-Ca²⁺-Mg²⁺-Cl⁺                           |
| K9        | dug well     | 8.640738     | 77.852772    | Na⁺-Ca²⁺-Mg²⁺-Cl⁺                           |
| K10       | Bore         | 8.641902     | 77.850287    | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
| K11       | dug well     | 8.638462     | 77.866585    | Na⁺-Ca²⁺-Mg²⁺-Cl⁺                           |
| K12       | Bore         | 8.646479     | 77.855788    | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
| K13       | Bore         | 8.64854      | 77.853125    | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
| K14       | dug well     | 8.645545     | 77.85892     | Na⁺-Ca²⁺-Mg²⁺-Cl⁺                           |
| K15       | dug well     | 8.640842     | 77.86551     | Mg²⁺-Na⁺-Ca²⁺-Cl⁻-HCO₃⁻                      |
-0.19 \, \Omega \cdot m. The quartzite did not fracture. The resistivity of 0.19 -0.22 \, \Omega \cdot m is specified in the granite intrusions in the study area.

**Profile 2**

Profile 2 covers a distance of 90 m and the depth of 130 m. The minimum resistivity of 0.04 -0.08 \, \Omega \cdot m is to show the...
freshwater area. The resistivity range of 0.10–0.16 Ω.m shows the folded quartzite with massive granite. The range of resistivity is 0.26–0.29 Ω.m indicating the intrusive granite from the lower layer to the upper layer.

Profile 3

Profile 3 has low resistivity of 0.30–0.05 Ω.m. The depth of groundwater was occurred in the quartzite fracture zone. The range of resistivity is 0.05–0.09 Ω.m that represents granite.

The resistivity value of 0.11–0.21 Ω.m is massive intrusive charnockite rock.

Aquachem software analysis

Aquachem software was designed specifically for the management, analysis and tracking of water quality data. It has a fully customizable database of physical and chemical parameters and provides a complete set of analysis, calculation and graphing tools for interpreting water quality data. The cations and anions of water samples of Na+, Ca2+, Mg2+, K+ and HCO−3, Cl−, SO2−4 are analyzed and expressed in the Aquachem software (Logeshkumaran et al. 2015). The geochemical results are plotted in Box and Whisker plot, Piper plot and Wilcox plot to represent the water quality study.

The Water Quality Index (WQI) assesses the impact of natural and anthropogenic activities. It is based on several key parameters of the chemical composition of groundwater. The physical and chemical parameters are having relative importance in overall water quality for drinking water. The average values of pH and TDS concentration in this area are 7.77–7.18 and 494–1005 mg/l, respectively. For groundwater sources, World Health Organization (2017) standards (pH: 6.5–8.5) and (TDS: 1000 mg/l) are acceptable. Physicochemical parameters’ groundwater analysis results were compared with standard guideline values recommended by WHO (Table 2).
The mean values of pre- and post-monsoon samples are easily classified by changes in the composition of the groundwater in monsoon variation. The Box and Whisker plots show $\text{Na}^+$, $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, $\text{HCO}_3^-$, $\text{Cl}^-$ and $\text{SO}_4^{2-}$ for the distribution of variation in pre- and post-monsoon (Fig. 9) samples 2019 in the study area.

In the Piper chart, a shape is made up of three well-defined fields. The general properties of groundwater are represented by a central diamond-shaped field representing the position of the site in the triangular field. The plot shows that alkaline soil ($\text{Ca}^{2+} + \text{Mg}^{2+}$) is in excess following the $\text{HCO}_3^-$ and $\text{SO}_4^{2-}$ types. It can be seen that the groundwater

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**Fig. 6** Magneto-telluric profiles in this study area

**Fig. 7** 3D groundwater flow and aquifer thickness model using magneto-telluric method
after the monsoon tends to change from HCO⁻₃–Cl⁻ type to Na⁺–Mg²⁺ type. Such a change in the chemical phase can be due to the dissolution of salts deposited by evapotranspiration of irrigation water followed by mixing with groundwater. Na⁺ is provided by the interaction of groundwater with silicate minerals and the return of evaporated sediments and irrigation (Fig. 9B).

The Wilcox diagram is commonly used to determine water quality. The samples pre- and post-monsoon rainy season measure low to medium concentration levels of sodium hazard in this plot of S1-low, S2-medium. After that, C1-low, C2-medium, C3-high and C4 sodium will change before and after the 2019 monsoon, and the contents of agricultural water quality and household classification will be medium to high (Fig. 9C). This clearly shows that post-monsoon irrigation has better groundwater quality than pre-monsoon periods.

**GIS-based analyses**

The GIS software was used to map the water quality indicators of the given study area. The method of inverse distance weighting (IDW) classification of spatial map interpolation was generating the pH, TDS and Ec parameters for the study area (Panneerselvam et al. 2020). The IDW method relies on techniques such as accurate local deterministic interpolation. In IDW, points closer to the predicted position have a greater effect on the predicted value than points far from the predicted position (Chabuk et al. 2020; Selvam et al. 2013). This procedure was applied in this study and generated an interpolation between selected points or locations using the IDW method within the low, medium and high values of each parameter.

The water pH exhibits acidic or basic properties and is an important parameter for drinking and irrigation water. It has a serious impact on water quality, affecting metal solubility, alkalinity and water hardness (Jesuraja et al. 2021). Groundwater pH values varied from the minimum and maximum values in the pre-monsoon and post-monsoon studies of 7.5–7.96 and 6.79–7.91 (Fig. 10A). These results indicate that the water sample is alkaline. The TDS concentrations in the given study area are 175–1150 and 764–1150 mg / l values for the minimum and maximum level ratios (Fig. 10B). The EC values for post-monsoon period are 153–1292 and 496–1541 μS / cm. The maximum EC value was determined when the electrical conductivity (EC) of water appears to be directly related to the concentration of dissolved solids in water (Fig. 10C). In addition, pollutants can cause high EC values in surface waters. In general, the content of major ions changed in response to the interaction of water

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**Table 2** Statistical summary of the groundwater chemistry analysis in the pre-monsoon and post-monsoon samples

| Parameter (mg/l) | Pre-monsoon 2019 | Post-monsoon 2020 | Acceptable Limit WHO 2017 |
|------------------|-------------------|-------------------|--------------------------|
|                  | Min | Max | Average | St. Dev | Min | Max | Average | St. Dev |
| Ca²⁺             | 14  | 200 | 67      | 61.0    | 11  | 145 | 65      | 49      | 75   |
| Mg²⁺             | 9   | 61  | 22.9    | 14.7    | 7   | 78  | 29      | 19      | 50   |
| Na⁺              | 7   | 31  | 16.5    | 6.5     | 2   | 37  | 17      | 11      | 200  |
| K⁺               | 4   | 12  | 5.7     | 3.3     | 2   | 25  | 13      | 7       | 12   |
| Cl⁻              | 27  | 172 | 66.1    | 35.5    | 42  | 172 | 110     | 40      | 250  |
| HCO⁻₃            | 37  | 324 | 118.1   | 78.8    | 31  | 324 | 165     | 91      | 250  |
| SO₂⁻₄            | 19  | 169 | 79.7    | 41.7    | 62  | 285 | 136     | 55      | 250  |
| Cond             | 153 | 1292| 633.6   | 332.0   | 496 | 1541| 1118    | 328     | -    |
| TDS              | 175 | 1150| 494.1   | 272.0   | 768 | 1350| 1006    | 143     | 1000 |
| TEMP°C           | 29  | 30  | 29.4    | 0.3     | 28.4| 32.9| 30      | 1       | -    |
| Ph               | 7.5 | 7.96| 7.8     | 8.3     | 6.79| 7.91| 7       | 7       | 6.5–8.5 |

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**Fig. 8** Water sample collections in open and bore well for Karunkulam area
Fig. 9  A. Box and Whisker plot for a. pre-monsoon 2019 and b. post-monsoon 2020 Karunkulam area. B. Piper plot for given a. pre-monsoon 2019 and b. post-monsoon 2020 Karunkulam area. C. Wilcox diagram for a. pre-monsoon 2019 and b. post-monsoon 2020 Karunkulam area
Fig. 10  A. Spatial distribution map of pH ratio a. pre-monsoon 2019 and b. post-monsoon 2020. B. Spatial distribution map of TDS ratio a. pre-monsoon 2019 and b. post-monsoon 2020. C. Spatial distribution map of electrical conductivity ratio in a. pre-monsoon 2019 and b. post-monsoon 2020.
and rock. However, anthropogenic pollutants predominate in some places. According to “WQI,” the assessment of water samples falls into the “low”, “medium” and “high” categories, indicating the quality of the water.

**Conclusion**

The study has demarcated the groundwater identification along with aquifer mapping in quartzite terrain for drinking and agricultural purposes in the study area. Azimuthal square array was carried out in the apparent resistivity range of 110–120 Ω.m; it is expressed as quartzite in freshwater; and the apparent resistivity range of 14–75 Ω.m (red soil with gravel), 25–100 Ω.m (weathered gneiss), 100–200 (quartzite) and 200–1000 Ω.m is large scale of gneiss rock. 2D electrical resistivity imaging technology is used to shallow aquifer mapping of weathered quartzite with an apparent resistivity of 10–12 Ω.m; it is another apparent resistivity calculated in meters as 17–25 Ω.m, and 54–179 Ω.m is used to distinguish gneiss and charnockite in the study area. The magneto-telluric resistivity method is used to survey deep subsurface aquifers. The average resistivity of 0.03–0.5 Ω.m represents the aquifer of fractured quartzite. The water-bearing zone is clearly shown in the magneto-telluric profile at a depth of 10 m.

Geochemical water quality analysis is to determine the interaction of rock with water and the presence of silica-rich quartzite freshwater. GIS-based spatial distribution map of the groundwater parameters in the area falls into the satisfactory category in both seasons. Groundwater in the pre-monsoon period was mainly influenced by the processes of mineral dissolution and ion exchange, and groundwater after rains also contributed to the regional groundwater with saline rainwater in the unsaturated zone. For farmers, developing new arable land and promoting agricultural development in areas with low rainfall is beneficial for agricultural development. The interaction between water-type rocks and water is primarily Mg$^{2+}$-Ca$^{2+}$-Na$^+$. Studies of rock–water interactions are used to distinguish between gneiss and quartzite groundwater sources for drinking and agriculture purposes.

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**Declarations**

**Conflict of interest** Conflict of interest is confirmed.

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