



# OPEN Groundwater potential zones demarcation in the hard rock province of South India: insights from remote sensing, GIS and AHP techniques

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The research aims to assess the groundwater potential zones (GWPZs) in the Chinnalapatti firka hard rock region to aid in sustainable groundwater management. The GWPZs were determined with the aid of Analytic Hierarchy Process (AHP) along with remote sensing (RS) and geographical information system (GIS) technologies. These Remote sensing and GIS greatly enhance groundwater potential mapping and assessment, as well as monitoring and conservation efforts. To evaluate groundwater potential (GWP) in the area of interest, remote sensing (RS) and conventional data sources were used to construct eight thematic maps. These maps included lineament density, drainage density, rainfall, geomorphology, geology, land use/land cover, soil and slope. Using AHP, each thematic layer, along with its subclasses, was assigned weights based on their influence on groundwater occurrence. Following this, the GWPZ map of Chinnalapatti firka was prepared by integrating the thematic layers with weighted overlay analysis in ArcGIS 10.7. The resulting map classified the study area into five groundwater potential groups: very good (19.97%), good (31.78%), moderate (30.61%), poor (17.63%), and very poor (0.01%). Utilizing the ArcSDM tool within ArcGIS software, the receiver operating characteristic (ROC) curve analysis showed that the area under the curve AUC = 0.80, which means that the GWPZ has good model performance. Planning and implementing artificial groundwater recharge projects, especially in semi-arid and hard rock terrains, is greatly aided by the spatial database created in this study. To improve groundwater sustainability, appropriate locations for recharge activities must be found. These results provide important information for sustainable groundwater management and long-term planning of water resources in the Chinnalapatti Firka region.

**Keywords** Groundwater potential, Analytic hierarchy process, GIS, Hard rock area, Receiver operating characteristic (ROC), Area under the curve (AUC)

In order to define groundwater potential zones in a semi-arid and geologically complex area, the current study on groundwater potential in Chinnalapatti Firka takes a unique integrative strategy that integrates field validation, GIS-based analysis, and remote sensing. The utilization of high-resolution satellite imagery and thematic layers such as slope, land use/land cover, lineament density, drainage density, geology, soil, slope, and geomorphology, integrated through weighted overlay analysis to create an extensive groundwater potential map, is what makes this work distinctive. This study uses a GIS and AHP methodology, which offers a more accurate and spatially explicit evaluation than earlier research<sup>1,2</sup> that just used hydrogeological data. To facilitate sustainable water resource management, well-informed decision-making, and efficient planning for agriculture and rural development, the primary goal of this study is to evaluate and map the groundwater potential zones of Chinnalapatti Firka. It significantly contributes to meeting the needs of various industries, including residential use, agriculture, industry, and the drinking water supply, as well as other developmental endeavours<sup>3,4</sup>. About

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34% of the annual water supply comes from groundwater<sup>5</sup>, a rich and plentiful source of freshwater<sup>6–8</sup>. The GW is a changeable resource that is difficult to measure in space and time, is found in complex subterranean formations, and cannot be observed directly from the Earth's surface<sup>9</sup>. Due to the erratic availability of surface water throughout the year, residents in semiarid regions rely significantly on groundwater supplies for their livelihood. Groundwater is an essential resource for several purposes, including household, agricultural, and industrial<sup>10</sup>. Over time, the unsustainable and unscientific consumption of groundwater has been the primary cause of the persistent and alarmingly falling water table. This issue is most apparent in areas with access to fresh groundwater. Hence, to enhance groundwater recharge, we must establish and utilize effective management practices of surface water<sup>11</sup>.

Geographic Information Systems (GIS) and remote sensing have become effective tools for mapping groundwater potential zones because they provide sophisticated capabilities in spatial analysis, data integration, and acquisition<sup>12,13</sup>. Critical surface elements like geological structures, geomorphology, land cover, drainage patterns, and vegetation indices are revealed by satellite photography and aerial photographs. These features have an impact on the occurrence of groundwater. By combining these disparate statistics into a single geographic framework using thematic layers that describe important variables like geology, slope, soil type, and lineament density, GIS performs a crucial role<sup>14,15</sup>. By improving groundwater potential mapping precision and effectiveness, this integrative method makes resource management more sustainable and informed. Finding regions that are favourable for groundwater occurrence and recharge is made possible by merging and analysing these layers using sophisticated spatial analytic methods<sup>16</sup>.

The spatial occurrence of groundwater in India is affected by the country's varied geography, geology, and climate. For groundwater in hard rock areas, locations of interest are in the form of deeper fractures and joints in semi-confined settings and shallow unconfined aquifers in the weathered zone. Severe water scarcity can develop from the extensive impacts of growing water demand on surface and groundwater resources<sup>17</sup>. As a result, precise quantitative evaluations based on scientific principles and bolstered by contemporary methodologies are essential for the sustainable development and management of groundwater resources<sup>18</sup>. In regions with limited water resources, groundwater is a crucial natural resource that supports industrial growth, agricultural production, and human health. Groundwater has come to be a very important component of water resource management in light of competition for water on a worldwide scale and limits on surface water supply, particularly in semiarid and hard rock areas. However, because of its intrinsic variability due to a number of geological, topographic, and climatic reasons, there are considerable challenges to sustainable use. Urgent need for scientifically informed management techniques in India has highlighted concerns about extraordinary declines in water tables due to dependence and unscientific extraction of groundwater. The Analytic Hierarchy Process (AHP) and other decision-support tools, in conjunction with recent advances in GIS technologies, may provide credible techniques for assessing groundwater potential. AHP provides a credible approach to delineate groundwater potential zones by integrating thematic layers, namely geology, rainfall, slope, and land use<sup>19</sup>.

Traditionally, the process of identifying groundwater potential zones (GWPZ) was performed through lengthy, expensive geological, hydrogeological, geophysical and or photogeological methods<sup>20</sup>. In the last few years, academics from different parts of the world have been increasingly using geographic information systems (GIS) and remote sensing (RS) technology for that purpose<sup>21</sup>. These modern-day methods are less expensive, more reliable and effective, and satellite-based RS data provide most of the essential data requirements for the GIS applications<sup>3,22–26</sup>. Delineating groundwater zones has proven to be an effective use of geospatial tools such as Remote sensing data and GIS in conjunction with Multi-Criteria Decision-Making (MCDM) methodologies<sup>27</sup>. One of the most popular Multi-Criteria Decision-Making (MCDM) techniques in water resource planning is Saaty's Analytical Hierarchy Process (AHP)<sup>28,29</sup>. As it is effective, simple, reliable, and cost-saving, AHP can be ideally applied to be utilized in a Geographic Information System (GIS) and Remote Sensing (RS) environment. AHP gives appropriate weights to various thematic layers prior to their incorporation in a GIS environment via expert judgment and results of previous studies. AHP technique calculates geometric mean and normalized weights for an attribute by examining large data sets based on pairwise comparison matrices<sup>30</sup>. Numerous studies demonstrate how important it is to monitor, assess, conserve, and manage groundwater resources sustainably for future usage by combining the use of RS, GIS, and AHP<sup>19,31–33</sup>. There are no thorough studies of the groundwater resources in the study area, and limited research data is available for effective groundwater governance. Therefore, the study is significant for researchers, policymakers, and lawmakers who are interested in improving socioeconomic groundwater resource management. It was carried out in the Chinnalapatti Firka of Dindigul district, which is dominated by the Charnockite and Migmatite Gneiss Complexes governed by hard rocks. Being an interdisciplinary research with the applied geospatial approach using remote sensing (RS), geographical information systems (GIS), and the analytical hierarchy process (AHP), the research is new and innovative. Groundwater potential zones (GWPZs) were delineated, available data sets were consolidated, and new thematic layers were created through this procedure.

Additionally, Receiver Operating Characteristic (ROC) curve analysis and well yield data were used to confirm the defined GWPZs. This study's main goal is to identify Groundwater Potential Zones (GWPZs) within the research region in order to support efficient and sustainable groundwater resource management. To aid in upcoming groundwater exploration initiatives, the study also intends to create a projected guide map. Since a sizable section of the region is used for agriculture, the research also aims to increase agricultural production and upgrade irrigation systems. Different groundwater potential zones, from extremely poor to very good, will be used to categorize the study region. Future groundwater investigation, artificial recharge projects, and the creation of sustainable use plans in this water-stressed hard rock terrain would all benefit greatly from this classification.

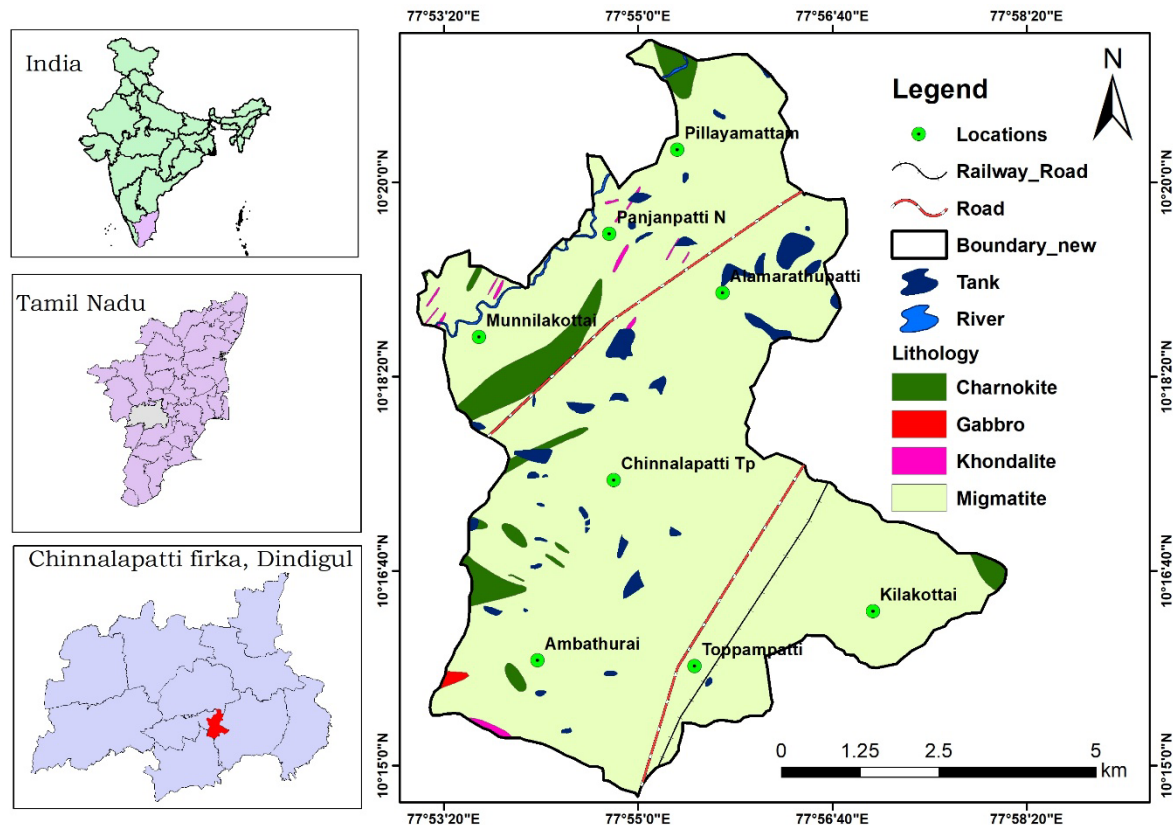
## Study area

Chinnalapatti firka consists of nine villages in the Athoor taluk, and the study area is 13 kms from Dindigul town. The latitude and longitude extensions are 10°15'00"–10°20'00"N and 77°53'20"–77°58'20"E, covering an area of 54.21 km<sup>2</sup>. The economy relies on textiles and agriculture, with agricultural activities more prevalent in northern Chinnalapatti. The study area map is shown in Fig. 1.

The area sees comparatively high mean temperatures from 27 to 39 °C throughout the summer months (April to June). Mean annual potential evapotranspiration is 1470 mm<sup>34</sup>, exceeding rainfall, indicating a negative water balance. As a result, the total amount of water available at this time may be significantly reduced<sup>35</sup>. On the other hand, November through January are typically nice months with mild temperatures between 22 and 31 °C. According to the<sup>34</sup> climatic classification, the Chinnalapatti Firka lies in a semi-arid sub-region (mean annual rainfall ≈ 810 mm). Charnokite and migmatite gneiss complexes are found in the research region. Charnokite and other high-grade metamorphic rocks are typically composed of large quantities of feldspar, quartz, and pyroxene minerals. It experiences profound crustal processes and is known for being hard and weather-resistant. The migmatites, on the other hand, are mixed rocks that were partially melted, a sign of high-temperature metamorphic processes. The study area's geomorphology includes a pediment-plain complex, many water bodies, and sharply divided structural hills and valleys. The pediment-pediplain combination is becoming more and more noticeable in geomorphology. This pediplain represents the last stage of the erosion and development process.

## Geology and hydrogeology

The entire firka is underlain by crystalline rocks, which consist of Charnokites, Hornblende–Biotite gneiss, and Epidote-Hornblende gneiss. The geological unit boundary was derived from GSI 1:50,000 geological map (Sheet 58F/12) and field verification (April 2023). Groundwater is found in phreatic conditions in weathered and fractured gneiss. The weathering processes in the rocks are highly erratic, and the depth of the abstraction structures associated with groundwater is dependent on the weathering and fracturing norms. The dug wells with large diameters are the more common groundwater abstraction structures in this area. The dug well is a circular structure of diameter 5–10 m, and its depth is expected to be between 10 and 18 m. Dug wells can yield 30–100cu.m. The yield data correspond to a 6-h pumping duration, equivalent to 1.4–4.6 L s<sup>-1</sup>, from<sup>36</sup>, volume in summer, and a few wells came to be dry during this period<sup>36</sup>. Dug well yield is sufficient to irrigate one or two crops during the monsoon period, but ineffective during summer, as the groundwater storage level decreases by the subsequent abstraction<sup>5</sup>.



**Fig. 1.** Geology Map of the Study area (This figure was prepared using ArcGIS Desktop 10.7 Esri; <https://www.esri.com>, and the geology map was prepared by GSI <https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx>).

S.No	Thematic maps	Data sources	Resolutions	Criterion
1	Rainfall	Public Works Department (From 2009 to 2022)		Rainfall distribution map
2	DEM/Slope	SRTM (30 m)/USGS	33 m	Slope percentage
3	Drainage density	NRSC – Bhuvan	1:50000	Drainage network
4	Lithology	Bhukosh, Geological Survey of India	1:50000	Rock formations types
5	Geomorphology	Bhukosh, Geological Survey of India	1:250000	Landform types
6	LULC	ESRI Sentinel-2/ USGS	10 m	Different landscape Use
7	Soil type	National Bureau of Soil Survey (ICAR) and Department of Agriculture, Tamil Nadu	1:250000	Soil groups, depth, texture, and permeability
8	Lineament density	NRSC-Bhuvan Thematic Services	1:50000	Underground faults and fractures

**Table 1.** The information on the data sources used to create the theme layers.

Intensity of importance	Definition	Expression
1	Equally importance	Two activities equally contributed to the objective
3	Moderate importance of one over another	Experience and judgment strongly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

**Table 2.** Fundamental scales of AHP<sup>30</sup>.

## Methodology

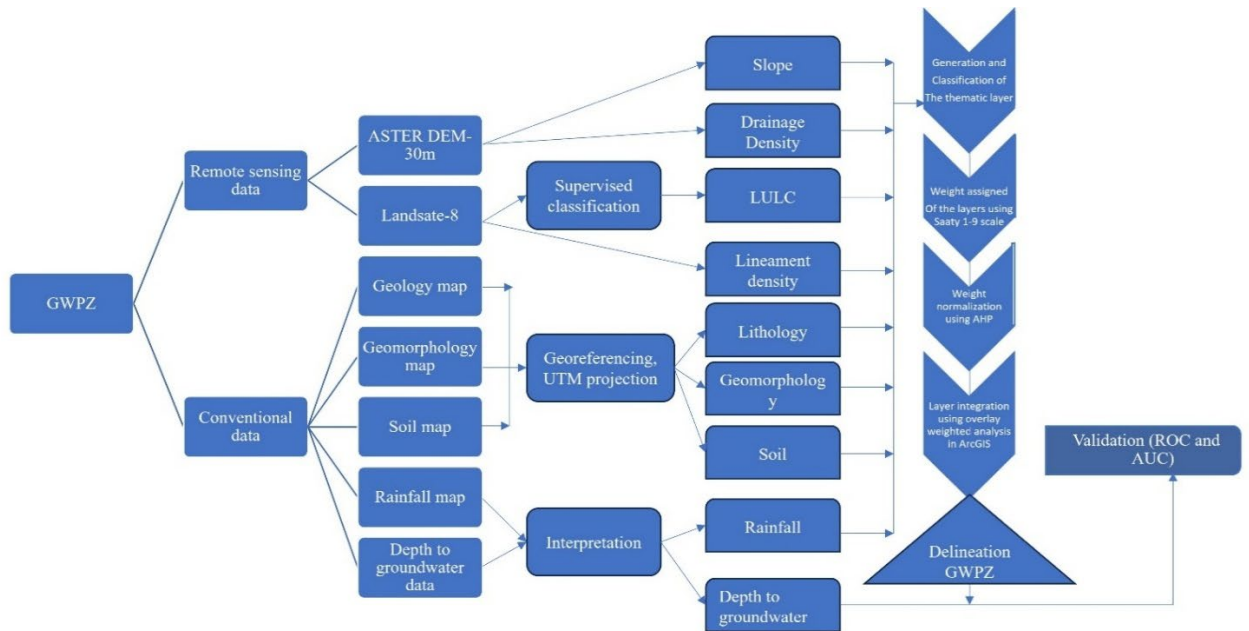
In this study, groundwater potential zones (GWPZ) were delineated by integrating both conventional datasets and remote sensing, together with GIS-based multi-criteria decision analysis. Key thematic layers like lineament density, slope, drainage density and land use/land cover (LULC) were extracted using remote sensing data, which comprised ASTER DEM (30 m resolution) and Landsat-8 imagery. To determine appropriate zones with varied groundwater potentiality, thematic layers have been prepared with a range of geographical, conventional, and meteorological data collected from numerous organisations and websites Table 1. To create precise LULC maps, supervised classification methods were used on Landsat-8 data. Concurrently, traditional data sources were gathered and converted to digital format, including soil, rainfall maps, geology, geomorphology, and groundwater depth data. All raster layers were resampled to 30 m using bilinear interpolation in UTM Zone 43 N (WGS 84). To ensure uniformity in geographical analysis, all spatial datasets were georeferenced to a standard UTM projection system. As part of the Analytic Hierarchy Process (AHP), the resulting thematic layers slope, drainage density, LULC, lineament density, lithology, geomorphology, soil, rainfall, and groundwater depth were each given relative priority weights based on the Saaty 1–9 scale in Table 2. To keep the weights consistent and to analyze their effects on groundwater occurrence, these weights were further recalculated. Vulnerable groundwater areas were subsequently mapped by overlaying all the thematic layers via weighted overlay analysis using ArcGIS 10.7 (Esri; <https://www.esri.com>). Area Under Curve (AUC) statistics and Receiver Operating Characteristic (ROC) curve analysis were subsequently utilized to validate the accuracy and reliability of the GWPZ map. The flow chart of the methodology is presented in Fig. 2.

### AHP method for GWP zoning

This research employs the Analytic Hierarchy Process (AHP), a Multi-Criteria Decision-Making (MCDM) technique developed by Saaty in 1980, to evaluate the influence of thematic layers and their parameters on groundwater occurrence. The method is suited for pairwise comparisons to derive ratio scales. AHP approximates the relative importance of each factor according to the decision maker's rating of a list of criteria<sup>37</sup>. Based on the relative importance of every factor, a score of 1 to 9 was assigned. Considering multiple criteria and alternatives, the relative magnitude of the various factors was determined based on expert judgment and literature survey-based evidence from previous studies. The criteria were evaluated in depth and compared using the Analytic Hierarchy Process (AHP) matrix<sup>38</sup>. Consistent and reliable results are the main issue in resolving multi-criteria decision-making (MCDM) problems. This is offered by the Analytical Hierarchy Process (AHP), which includes pairwise comparison to determine the relative weights of various criteria. AHP uses mathematical computation to offer a systematic matrix showing the relative importance of some attributes to others. Saaty formulated AHP, where a common scale and systematic method of measuring the opinion of an expert exists and determining the optimal solution in multi-criteria scenarios. A shortened version of Saaty's initial scale was utilized in the AHP analysis of this research to obtain the relative weights of the parameters through a series of computational steps. The calculation is described below.

First, add values in each column of PCM by employing Eq. (1):

$$L_j = \sum_{ij=1}^n C_{ij} \quad (1)$$



**Fig. 2.** Methodology flow chart present study.

N	1	2	3	4	5	6	7	8
Scale of Importance	Equal	Weakly	Moderate	Moderate plus	Strong	Strong plus	Very strong	Very, very strong
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

**Table 3.** RI and Saaty’s relative importance scale<sup>39</sup>.

Here,  $L_j$  = “total values in each column of a pairwise matrix and  $C_{ij}$  number assigned to each factor at  $i^{\text{th}}$  row and  $j^{\text{th}}$  column.

Second, divide each element in the matrix by its column total to generate a normalised pairwise matrix” by employing Eq. (2):

$$X_{ij} = \frac{C_{ij}}{L_j} \tag{2}$$

Here,  $X_{ij}$  = “value at  $i^{\text{th}}$  row and  $j^{\text{th}}$  column in the normalised pairwise matrix”.

“Finally, divide the sum of the normalised row of the matrix by several factors used (8 for the current study) to generate standard weights by employing Eq. (3):

$$w_i = \frac{\sum X_{ij}}{N} \tag{3}$$

where  $W_i$  is the Standard weight and  $N$  is the number of factors.

“Consistency ratio (CR)” has been calculated to find any discrepancies and to determine the best weights after the PCM has been finished and the weights of its components have been determined. Only when the CR was 0.1 or less did the AHP analysis move forward. However, inconsistencies in the review process could result in erroneous results if  $CR > 0.1$ . CR was established for the matrix by comparing the “consistency index (CI)” and “random index (RI)” to evaluate the reliability of relative weights. CI was determined utilising Eq. (4). RI in the present investigation is 1.12 for strong, as indicated in Tables 2 and 3<sup>30,39</sup>.

$$CI = \frac{\lambda - n}{n - 1} \tag{4}$$

“Where  $\lambda$  = consistency vector.  $n$  = number of factors used.

The consistency ratio was measured by employing Eq. 5

$$CR = CI/RI \tag{5}$$

Here, “CI and CR” mean consistency index and consistency ratio, respectively.

Factors	Rainfall	Geology	Slope	Drainage density	LULC	Lineament density	Soil	Geomorphology	Normalised principal Eigenvector
Rainfall	1	5	3	3	5	5	5	3	34.89%
Geology	1/5	1	3	3	5	5	5	5	22.50%
Slope	1/3	1/3	1	1	3	3	5	3	12.33%
Drainage density	1/3	1/3	1	1	1	2	3	5	10.66%
LULC	1/5	1/5	1/3	1	1	1	3	1	6.02%
Lineament density	1/5	1/5	1/3	1/2	1	1	3	1	5.41%
Soil	1/5	1/5	1/5	1/3	1/3	1/3	1	1	3.38%
Geomorphology	1/3	1/5	1/3	1/5	1	1	1	1	4.81%

**Table 4.** Pairwise comparison matrix with normalised relative weights.

Matrix	Rainfall	Geology	Slope	Drainage density	LULC	Lineament density	Soil	Geomorphology
Rainfall	1.0000	5.0000	3.0000	3.0000	5.0000	5.0000	5.0000	3.0000
Geology	0.2000	1.0000	3.0000	3.0000	5.0000	5.0000	5.0000	5.0000
Slope	0.3333	0.3333	1.0000	1.0000	3.0000	3.0000	5.0000	3.0000
Drainage density	0.3333	0.3333	1.0000	1.0000	1.0000	2.0000	3.0000	5.0000
LULC	0.2000	0.2000	0.3333	1.0000	1.0000	1.0000	3.0000	1.0000
Lineament density	0.2000	0.2000	0.3333	0.5000	1.0000	1.0000	3.0000	1.0000
Soil	0.2000	0.2000	0.2000	0.3333	0.3333	0.3333	1.0000	1.0000
Geomorphology	0.3333	0.2000	0.3333	0.2000	1.0000	1.0000	1.0000	1.0000

**Table 5.** Pairwise comparison matrix and AHP consistency calculations.

This Random Consistency Index (RCI) was computed using Saaty's standard 1–9 scale table. To obtain accurate results, the Consistency Ratio (CR) of an AHP analysis should be below 10%<sup>39</sup>. A review of the judgments is required to identify and solve any inconsistency in case of a value of CR higher than the value<sup>40</sup> The CR value of this research is 0.001, which indicates an excellent consistency level and confirms that parameters under consideration are appropriate for weight analysis and groundwater potential zone (GPZ) demarcation.

### AHP-based weighting and normalisation analysis

The weights assigned to thematic layers employed to delineate Groundwater Potential Zones (GWPZ) appear in Table 2. From the effect each stratum contributes to groundwater occurrence, and based on the research that has been conducted in areas of equivalent characteristics as found in Chinnalapatti firka, the weights were obtained. Prior studies by<sup>6,28,41–45</sup> included approaches that were followed in the weighing procedure.

In this study, rainfall has been assigned the largest weight and indicates that it may have a far bigger impact on groundwater, while geomorphology has been assigned a lower weight because of its less significant impact<sup>3</sup>. A pairwise comparison matrix is produced once each element has been given a relative weight (Table 3). Every theme was compared to every other theme in order to create a pairwise comparison matrix<sup>46,47</sup>. The normalised weights of the eight themes and the subgroups were obtained using Saaty's AHP technique<sup>41,48</sup>. Table 3 shows the normalisation of the provided relative weights to eight theme maps using a pairwise comparison matrix.

Pairwise comparison table employed in the Analytic Hierarchy Process<sup>49</sup>. (Table 4) was evaluated on whether it is logically consistent. The largest eigenvalue was  $\lambda_{\max} = 8.736$  which gave a Consistency Index of  $CI = 0.1052$ . The Consistency Ratio Table 5 was determined using the Saaty random Index, with eight criteria ( $RI = 1.41$ ) and had the value of  $CR = 0.0746$ , which is far below the acceptable ratio of 0.10. In this way, results can be said to be consistent and reliable, and the obtained criterion weights (34.9–3.4%) can be used to conduct further analysis of groundwater potential.

### Sensitivity analysis

Another experiment to test the strength of the groundwater potential zone (GWPZ) model was the perturbation of AHP-derived criterion weights (0.05) by + –10%. In both cases individual weights were multiplied and divided 10 percent keeping the normalized sum equal to 1. All the perturbation cases were re-run on the model and the class areas of GWPZ were compared with the base map. The highest difference between the maximum variation of all the classes was not more than 5, which means that the model output is relatively stable and not that sensitive to small differences in criteria weights. The specific output of the perturbation tests is available in Supplementary Table 6.

### Identification of groundwater potential zones

The maps used in the study were converted from vector to raster format using the provided ranks and weights. In ArcGIS 10.7, these maps were then combined using weighted overlay analysis. The purpose of this analysis was to determine the GWPZs. The GWP map was computed using the following formula<sup>50,51</sup> as shown in Eq. (6):

$$GWPI = \sum_{w=1}^m \sum_{j=1}^n W_j \times X_i \quad (6)$$

where N—total classes of thematic layers;  $X_i$ —rank associated with classes of the  $i^{\text{th}}$  thematic layer; M—Number of total thematic layers used;  $W_j$ —normalised weight of the  $j^{\text{th}}$  thematic layer.

The main thematic layers that contribute to GW were superimposed to create the “GWPM. The Groundwater Potential Index (GWPI), which was computed by combining all of the thematic layers that affect GW, was used to evaluate GW prospect zones.

### Cross-validation

The GWPZ map of Chinnalapatti firka was validated in this study using the “Ground Water Prospect Study” map, which provides spatial information on well yield and is accessible on the Bhujal-Bhuvan portal (<https://bhuvan-app1.nrsc.gov.in/gwis/gwis.php>). The groundwater monitoring well (depth to the water table) was given by the Central Groundwater Board (CGWB). The Area under the Curve (AUC) and Receiver Operating Characteristic (ROC), which were plotted using the ArcSDM tool in ArcGIS software, were also used to validate the results. The ROC curve analysis was used for quantitative validation by comparing the generated recharge groundwater potential map with the real bore well data. One popular method for evaluating the dependability of diagnostic tests is the ROC curve analysis. For ROC, false positive values are plotted along the x-axis, while true positive values are shown along the y-axis. The ROC curve describes a balance between the two values. According to the ROC approach, the area under the curve runs from 0.5 to 1, which can be divided into the following ranges: “0.5–0.6 (poor). 0.6–0.7 (average); 0.7–0.8 (good); 0.8–0.9 (very good); and 0.9–1 (outstanding)”.

## Results and discussion

### Thematic maps

To create the Groundwater Potential Zonation (GWPZ) map of the research area, eight hydrogeological elements were incorporated into thematic layers: Rainfall, geology, slope, drainage density, land use/land cover, lineament density, soil, and geomorphology.

### Rainfall

The most significant factor in GWPZ mapping is thought to be precipitation. According to (Magesh et al. 2012c), surface flow, recharge, and infiltration are all greatly impacted by the duration and amount of precipitation. The region’s main supply of surface and groundwater is rainfall, which has a major impact on the basin’s recharge volume because of its quantity and spatial distribution<sup>29,52</sup>. The rainfall data from 2009 to 2022 annual average was taken from the CHIRPS dataset for this investigation. For additional study, the precipitation map that was produced was then divided into three different classifications: low, moderate, and high (Fig. 3a).

### Geology

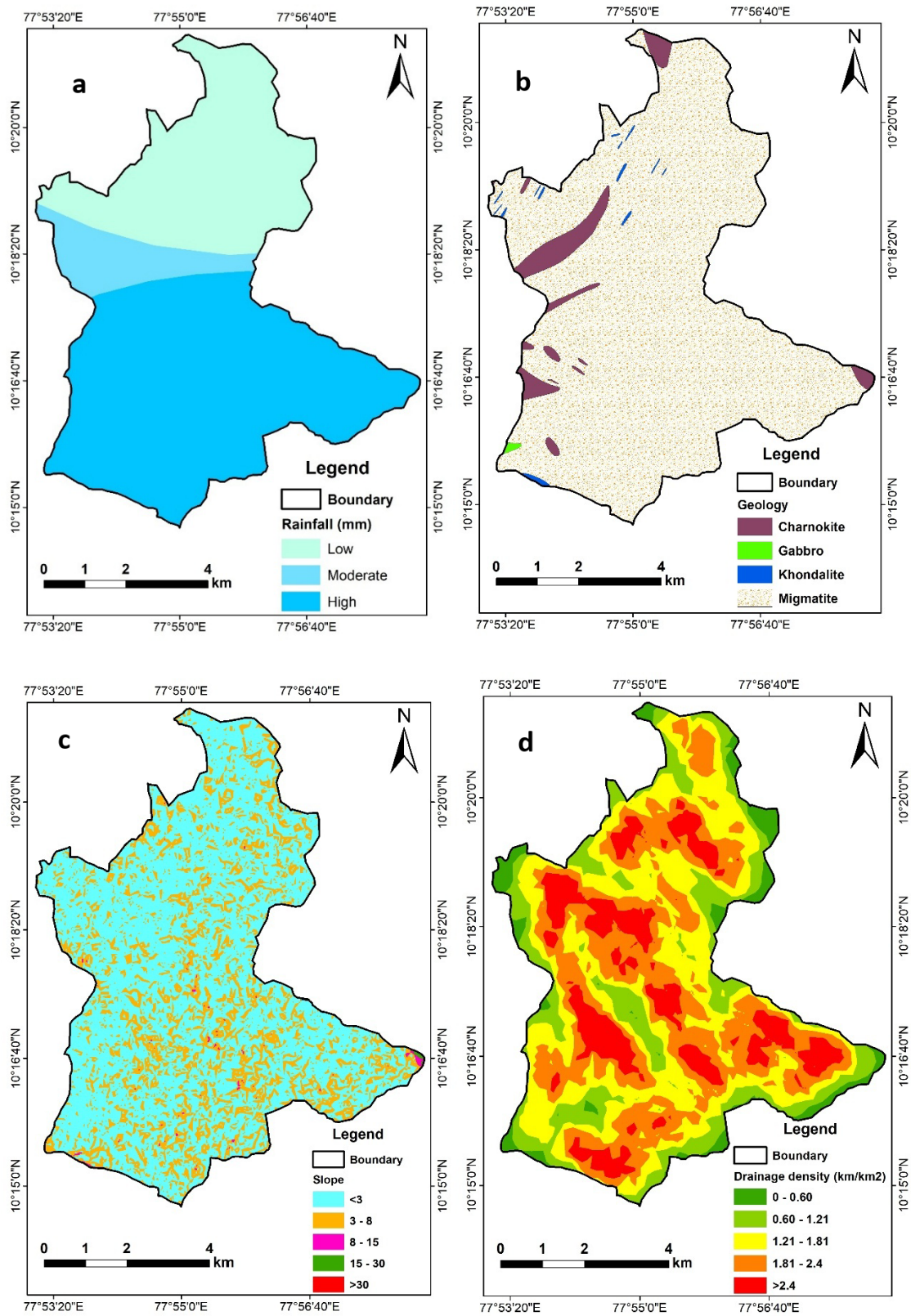
The distribution and properties of groundwater occurrences are greatly influenced by geology<sup>38</sup>. Geology includes the permeability and porosity of aquifer rocks. The type of rock present at the surface significantly influences groundwater recharge<sup>53</sup>. The research area has been found to have a variety of lithological units, such as charnockite, gabbro, khondalite, and migmatite (Fig. 3b). A weight was given to each of these units based on how much of an impact they had on groundwater potential. The migmatite was given a higher order priority rating of 4 because it contains more fractured and foliated units than other lithological units, which increases its influence on groundwater occurrence. The favourable groundwater occurrence in a location determines the high value that is assigned.

### Slope

According to<sup>54</sup>, slope has a direct impact on both surface runoff and infiltration rates, making it a significant factor in determining groundwater potential. Steeply sloping regions typically have higher runoff and less infiltration, which lowers groundwater recharge. Gentle sloped areas, on the other hand, allow for longer infiltration time and less surface runoff, which increases groundwater recharge. Data from the Digital Elevation Model (DEM) was used to create a slope map for the current investigation (Fig. 3c). The slope percentage of the area is between 0 and 30%. Based on the degree of slope, the study area was separated into five slope classes: “(a) less than 3%, (b) 3–8%, (c) 8–15%, (d) 15%–30%, and (e) >30%.” The area that shows a 3% slope is regarded as “very good” because of the almost level topography and very high infiltration rate. A highly steep location was categorised as a lower inland area with a higher runoff rate, and it was assigned a lower score, whereas a flat terrain with a high water-holding capacity was classified with a higher rank (Table 6).

### Drainage density

The relationship between drainage density and permeability is inverse. More surface runoff and less infiltration mean less groundwater recharge, while low drainage density indicates more precipitation penetration and adds more to groundwater potential<sup>38</sup>. Five drainage density classes very low (0.0–0.60 km/km<sup>2</sup>), low (0.60–1.21 km/km<sup>2</sup>), moderate (1.21–1.81 km/km<sup>2</sup>), high (1.81–2.4 km/km<sup>2</sup>), and very high (>2.4 km/km<sup>2</sup>) are distinguished within the research area (Fig. 3d). Higher infiltration potential is linked to lower drainage density in groundwater assessment. As a result, larger drainage density locations were given lower ranks, while lower drainage density areas were given higher ranks. The ranking matrix’s consistency was assessed using the Analytic Hierarchy Process (AHP), and the final weights were determined based on good consistency results (Table 7).



**Fig. 3.** Groundwater potential zones prepared using the following thematic layers: (a) Rainfall, (b) Geology, (c) Slope, (d) Drainage Density, (e) LULC, (f) Lineament Density, (g) Soil and (h) Geomorphology. (This figure was prepared using ArcGIS Desktop 10.7 Esri; <https://www.esri.com>, and <https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx>).

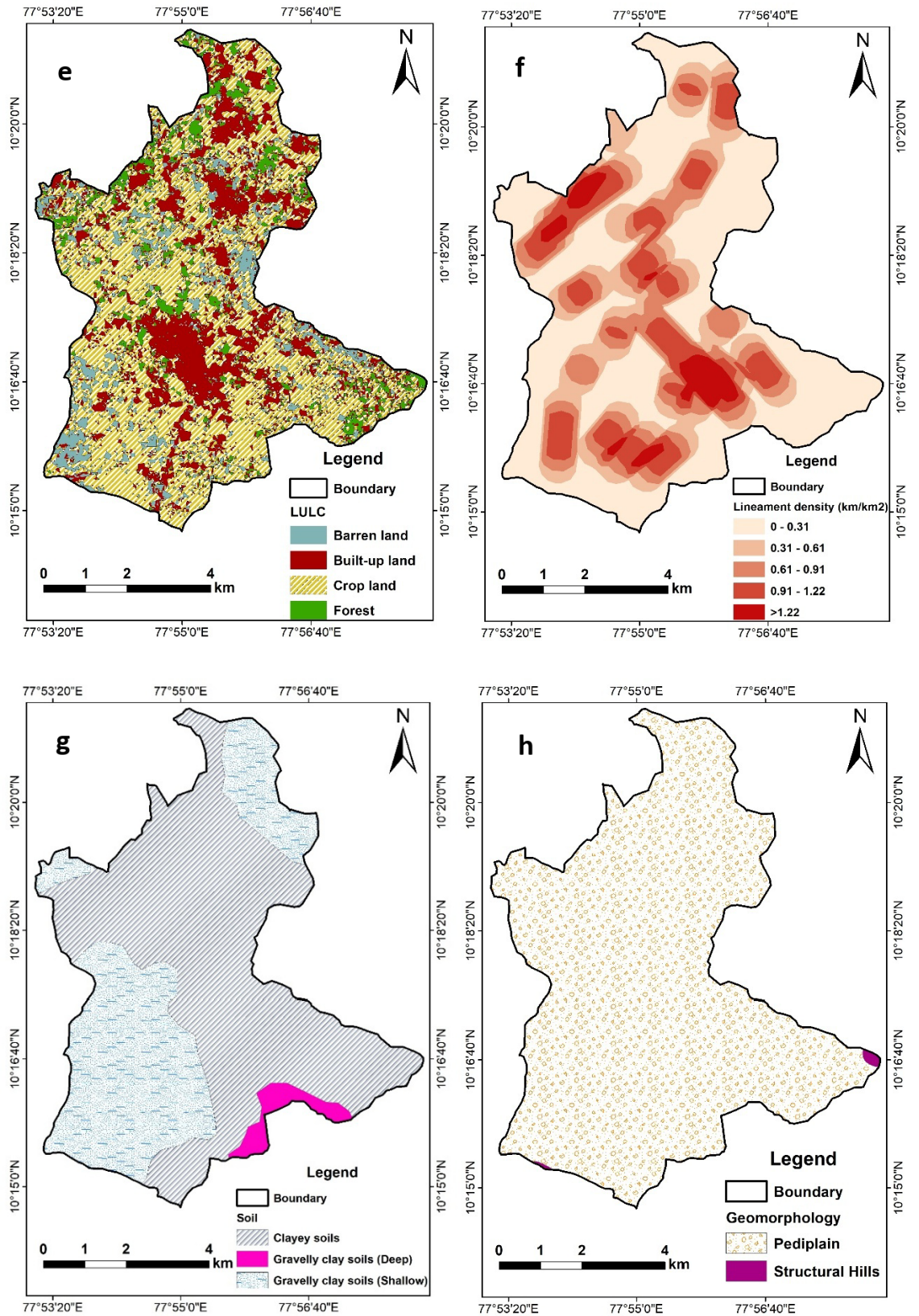


Fig. 3. (continued)

**Land use and land cover**

The analysis was conducted using Level 3 classes and the land use/land cover map that was retrieved from the

Criterion perturbed ( $\pm 10\%$ )	Very High (%)	High (%)	Moderate (%)	Low (%)	Very Low (%)	Maximum change (%)
Rainfall	+1.8 / -1.3	+2.1 / -1.7	+1.2 / -1.0	+0.9 / -0.7	+0.6 / -0.4	2.1
Geology	+1.5 / -1.2	+1.9 / -1.6	+1.1 / -0.8	+0.8 / -0.6	+0.5 / -0.3	1.9
Slope	+1.2 / -1.0	+1.6 / -1.3	+0.9 / -0.7	+0.7 / -0.5	+0.4 / -0.3	1.6
Drainage Density	+1.1 / -0.9	+1.5 / -1.2	+0.8 / -0.6	+0.6 / -0.4	+0.3 / -0.2	1.5
LULC	+0.8 / -0.7	+1.1 / -0.9	+0.6 / -0.5	+0.5 / -0.4	+0.2 / -0.2	1.1
Lineament Density	+0.7 / -0.6	+1.0 / -0.8	+0.6 / -0.4	+0.4 / -0.3	+0.2 / -0.1	1
Soil	+0.6 / -0.5	+0.9 / -0.7	+0.5 / -0.4	+0.3 / -0.3	+0.2 / -0.1	0.9
Geomorphology	+0.7 / -0.6	+1.0 / -0.9	+0.6 / -0.5	+0.4 / -0.3	+0.2 / -0.2	1

**Table 6.** Percentage change in GWPZ classes under  $\pm 10\%$  weight perturbation.

Parameters	Classes	Weight	Normalised Wi	Influence%	Rank
Rainfall	Low	0.35	0.110	35	1
	Moderate		0.309		2
	High		0.581		3
	CI - 0.002	CR - 0.004	RI - 0.58		
Geology	Charnockite	0.23	0.099	23	2
	Gabbro		0.099		1
	Khondalite		0.284		3
	Migmatite		0.518		4
	CI - 0.002	CR - 0.002	RI - 0.9		
Slope	< 3	0.12	0.445	12	5
	3-8		0.297		4
	8-15		0.147		3
	15-30		0.073		2
	> 30		0.037		1
	CI - 0.068	CR - 0.060	RI - 1.12		
Drainage density	Very low (0-0.60)	0.11	0.445	11	5
	Low (0.60-1.21)		0.297		4
	Moderate (1.21-1.81)		0.147		3
	High (1.81-2.4)		0.073		2
	Very high (> 2.4)		0.037		1
	CI - 0.068	CR - 0.060	RI - 1.12		
Land use/ land cover	Barren land	0.6	0.122	6	2
	Built-up land		0.057		1
	Cropland		0.263		4
	Forest		0.558		3
	CI - 0.058	CR - 0.065	RI - 0.9		
Lineament density	Very low (0-0.31)	0.5	0.045	5	1
	Low (0.31-0.61)		0.077		2
	Moderate (0.61-0.91)		0.154		3
	High (0.91-1.22)		0.274		4
	Very high (> 1.22)		0.450		5
	CI - 0.012	CR - 0.010	RI - 1.12		
Soil	Clayey soils	0.3	0.110	3	1
	Gravelly clay soils deep		0.309		2
	Gravelly clay soils shallow		0.581		3
	CI - 0.002	CR - 0.004	RI - 0.058		
Geomorphology	Structural hill	0.5	0.091	5	1
	Pediplain		0.445		2
	CI - 0.00	CR - 0.00	RI - 0.058		

**Table 7.** The normalised weights of features for the eight thematic maps.

GSI portal. The pairwise comparison method was used to assess the LU/LC characteristics. According to<sup>55</sup>, infiltration, surface runoff, evapotranspiration, and groundwater recharge are all significantly impacted by land use/land cover (LULC). The geospatial technologies are essential for precisely evaluating and mapping LULC across various geographies<sup>56</sup>. Studies have indicated that forest regions encourage higher infiltration rates than cropland. According to<sup>57</sup>, barren land and built-up areas typically have lower infiltration rates, which lowers the possibility of groundwater recharge. The cropland and forest land are given a higher rank than other classes in Table 7 and the spatial distribution map, Fig. 3e.

### Lineament density

A lineament is a linear feature found in a landscape that may be recognised by satellite photography and indicates the presence of an underlying geological structure, such as a fault. Fractures, cleavages, faults, and other discontinuity surfaces are represented by aligned rectilinear or slightly curved line features<sup>58</sup>. Lineaments indicate the presence of faulting and fracturing zones, resulting in increased secondary porosity and permeability<sup>59</sup>. In this work, groundwater potential zones were analysed using the GSI lineament map. The ArcGIS platform was used to create the lineament density map. Five classifications were then distinguished based on their density: very high (> 1.22), high (0.91–1.22), moderate (0.61–0.91), low (0.31–0.61), and very low (0–0.31). The likelihood of groundwater occurrence increases with density. As a result, the extremely low ranges were given the lowest weight, and the very high ranges the highest. The pairwise comparison matrix's consistency was examined using the AHP analysis, and it was determined to be satisfactory. The normalised and final weights were used to generate a weighted lineament density map (Fig. 3f), which is displayed in Table 7.

### Soil

Soil is one of the most important key determinants that influences an area's capacity for infiltration, as it depends on porosity, moisture content, and density of the soil's texture<sup>60,61</sup>. Compared to fine-textured soil, infiltration rates are higher in coarse-textured soil. As a result, soils are prioritised more highly (Ranked 3). Some soils have a lesser priority and are classified as ranked 1 because they do not permit water to seep in. Gravelly clay soils, deep soil, for example, well-drained and marginally erosion-capable soils, were prioritised. A lesser priority was assigned to clayey soil, which is shallow, gravelly clay soil with moderate to severe erosion. These variables were used to rank and analyse soils using the AHP approach in order to create the weighted soil map (Fig. 3g) and ascertain how they impact groundwater conditions (Table 7).

### Geomorphology

The examination of a region's topography and landforms is referred to as geomorphology, offering insights into the distribution of various geographical features, temperature variations, water movement, geochemical processes, and freeze–thaw cycles. The structural evolution of the underlying geological formations has a significant impact on it<sup>62,63</sup>. Study area has two major geomorphological classes, pediplain and structural (Fig. 3h). Weathered/fractured rocks that are suitable for groundwater recharge cover the gently sloping plains of the pediment landform<sup>64</sup>.

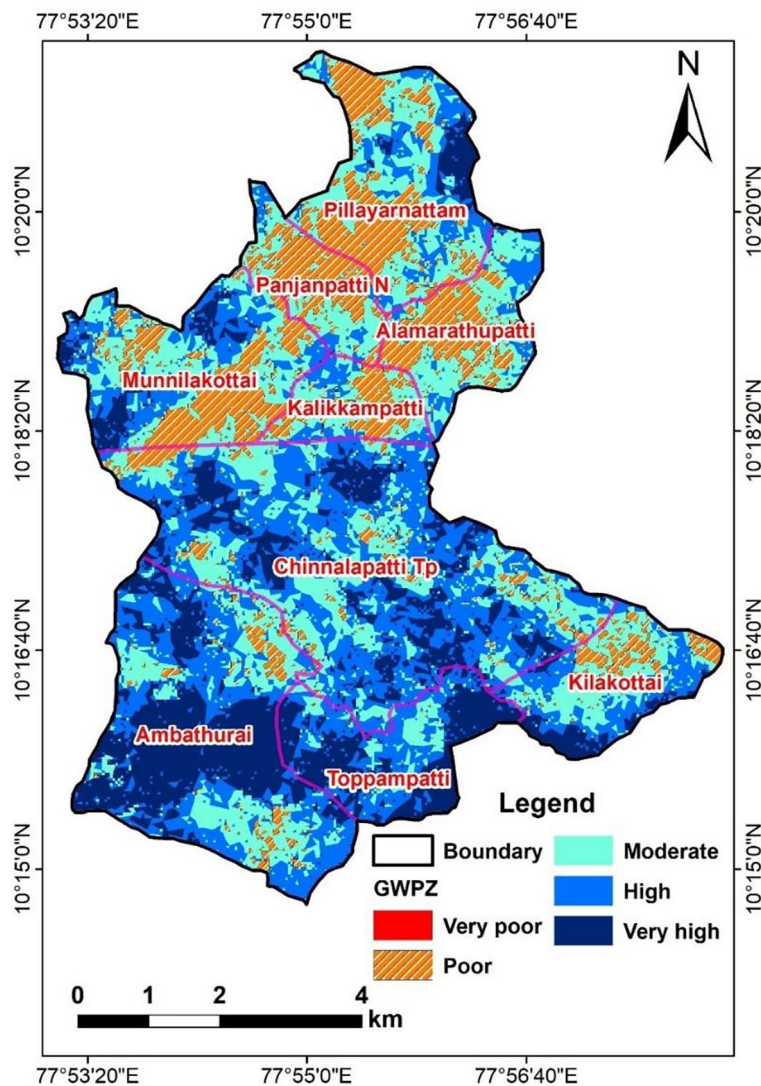
### Preparing the GWPZ map

No prior research has been conducted on GWPZ mapping in the study area. Research data on groundwater resources is lacking for management in the future. Consequently, this study is essential for scholars and policymakers who want to improve the socioeconomic management of groundwater resources. Utilising the weighted overlay method in ArcGIS's spatial analysis tool, the GWP map was created by allocating cumulative weights to the rainfall, geology, slope, and drainage density. Land use land cover, lineament density, soil and geomorphology of eight thematic layers. A Groundwater Potential Zonation (GWPZ) map offers important information on the groundwater status of a region, which can be used to plan for sustainable groundwater extraction. GWPZs were divided into five groups within the study area: “very poor”, “poor”, “moderate”, “good”, and “very good”. 54.21 km<sup>2</sup> are covered by these zones, which are as follows: “very good (19.97%), good (31.78%), moderate (30.61%), poor (17.63%), and extremely poor (0.01%)”. There are many locations on the southern margin of the study area with an extremely high GWPZ (10.82 km<sup>2</sup>). Different GWPZ classifications in the Chinnalapatti firka are depicted in Fig. 4. Table 8 displays the area and percentage dispersion of the five GWPZ classes.

### Groundwater potential zone (GWPZ) validation

The Chinnalapatti firka GWPZ map was created by combining eight different thematic maps, including rainfall, geology, slope, drainage density, land use land cover, lineament density, soil and geomorphology using AHP, a popular MCDM approach. The “Ground Water Prospect Study” map, created by CGWB and NRSC, Hyderabad, was used to validate the GWPZ map, and well yield data was used to confirm the GWPZs. The findings of this validation approach demonstrated that all groundwater potential zones in the research region had a correct classification of the number and percentage of points, which correspond to particular yield ranges. This affirms that the used strategy produced authentic and notable results, warranting its use in the present study. Policymakers can apply the information to assist in the development of effective plans for groundwater management<sup>49</sup>.

Agree, agree-less, and agree-excess agreement statuses were used as 1 to construct the ROC curve, and disagree was used as a value of 0. The ROC curve graph between GWPZ agreement and well yield data was constructed using the ArcSDM tool of ArcGIS software (version 10.7). The area under the curve (AUC) calculated is shown in Fig. 5 and was 80%. In accordance with<sup>65</sup>, the area under the curve (AUC) was within the acceptable range<sup>66,67</sup>.



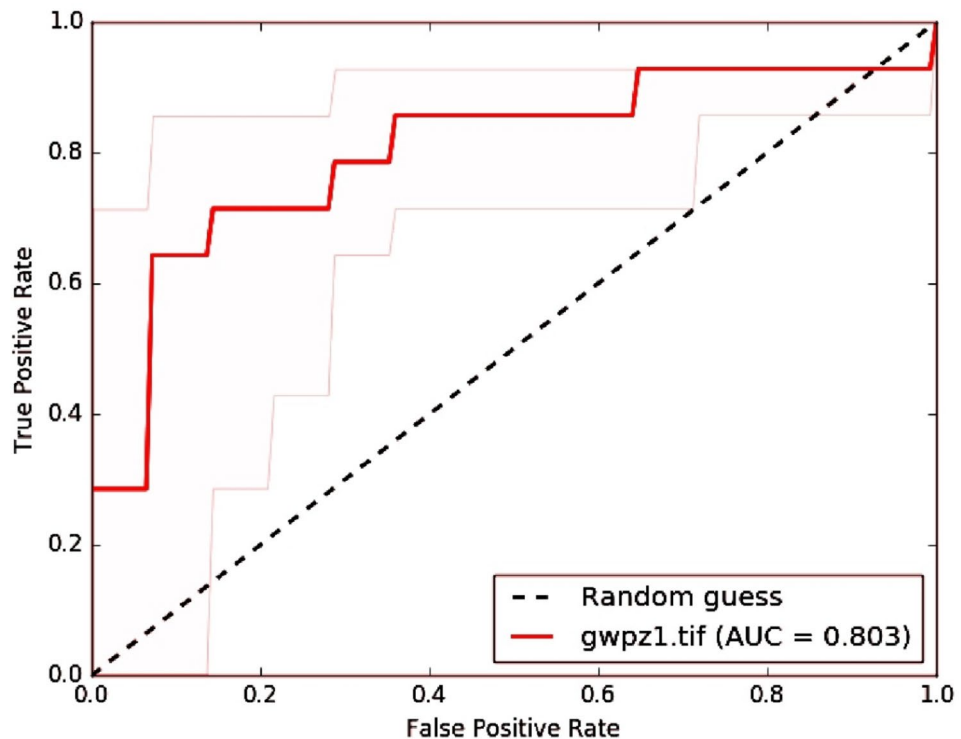
**Fig. 4.** Groundwater Potential Zone (GWPZ) map of the study area (This figure was prepared using ArcGIS Desktop 10.7 Esri; <https://www.esri.com>,

Sl.no	Class	Area (km <sup>2</sup> )	Area%
1	Very poor	0.01	0.01
2	Poor	9.56	17.63
3	Moderate	16.59	30.61
4	Good	17.23	31.78
5	Very good	10.82	19.97
		54.21	100.00

**Table 8.** The area and percentage dispersion of the five GWPZ classes.

### Conclusions

The study suggested a Groundwater Potential Index (GWPI) map to demarcate groundwater potential areas of Chinnalapatti firka, Athoor Taluk, Dindigul district. The current study is an integrated and innovative approach that harmonizes remote sensing (RS), geographic information systems (GIS), and the analytical hierarchy process (AHP). The proposed combined methodology helps in making speedy and effective decisions for sustainable water resource management. Eight key parameters were selected prior to overlay analysis since they had the highest contribution to groundwater potential. Groundwater Potential Zones (GWPZs) of the study area were categorized into five classes on the basis of them: very poor, poor, moderate, good, and very good. The corresponding areas covered by these zones are 54.21 km<sup>2</sup>, very good (19.97%), 10.82 km<sup>2</sup>, good (31.78%), 17.23



**Fig. 5.** The ROC curve for accuracy assessment and AUC.

km<sup>2</sup>, moderate (30.61%), 16.59 km<sup>2</sup>, poor (17.63%), 9.56 km<sup>2</sup>, and very poor (0.01%). Low zone refers to a low groundwater potential zone. Very high zone, on the other hand, refers to the most favourable location for GWP. The accuracy of the GWPZ map is validated using well yield data by an agreement scheme on the basis of the groundwater prospects map and ROC curve analysis. The outcome reveals that the GWPZ map prediction was satisfactory at 80%, respectively. This simple but methodical technique has been applied to assess Groundwater Potential (GWP) sites effectively. Its methodical character is also as efficient and of general application, especially for groundwater studies and demarcation of potential areas for artificial recharge in arid and hard rock hydrogeology. Hence, it is a valuable technique for long-term sustainable groundwater development and aquifer management. Follow-up investigations of the model should include field work such as water quality sampling and pumping tests to improve the model's precision and relevance further. Providing a degree of credibility to the model's reliability, the field tests would also help establish whether decisions made based on the application of model outputs were scientifically and operationally justifiable.

### Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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## Author contributions

K. Pragadeeshwaran—wrote the main manuscript text and prepared figures and tables All authors reviewed the manuscript. B. Gurugnanam (gurugis4u@gmail.com)-wrote the main manuscript text and prepared tables. All authors reviewed the manuscript. M. Bagyaraj (geobagya25@gmail.com)-wrote the main manuscript text and prepared figures All authors reviewed the manuscript. S. Bairavi (bairuguru98@gmail.com)-wrote the main manuscript text and prepared tables All authors reviewed the manuscript. D. Karunanidhi (karunasamygis@gmail.com)-wrote the main manuscript text and prepared figures and tables. All authors reviewed the manuscript. Berihu Abadi Berhe -Read and reviewed the final manuscript and made ready for submission.

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## Declarations

## Competing interests

The authors declare that they have no competing interests.

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