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DELINEATION OF GROUNDWATER POTENTIAL ZONES USING FUZZY ANALYTIC HIERARCHY PROCESS IN CHEYYAR WATERSHED, TAMIL NADU

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Abstract

The present study is conducted in the Cheyyar watershed part of the Palar basin, where 45% of the groundwater resources were overexploited. Three broad factors have been selected to carry out the study: topographic factors (slope, roughness, curvature, drainage density, Topographic Wetness Index (TWI) and Topographic Position Index (TPI)), geological factors (geology, geomorphology, soil type and lineament density), land use and climatic factors (land use/land cover, rainfall, temperature and Normalised Difference Moisture Index (NDMI)). All the thematic layers are reclassified with fuzzy triangular membership function and integrated with the global weightage for mapping groundwater potential zones. The ROC curve is used to estimate the accuracy, which is 86.15%. This study showed that 37% (~805 sq. km) of the study area has high to very high groundwater potential. The potential zones identified in the study would be helpful to the policymakers in implementing the recharge structures to manage and conserve groundwater resources in this overexploited region.

Key Words: Fuzzy Analytic Hierarchy Process, Groundwater potential zones, Cheyyar watershed, GIS.

Introduction

Water plays an influential role in human life on the planet. The development of the human race primarily depends on water resources. About 70% of the earth's surface is covered by water. Oceans and seas cover 97% of the global water as saline water; only 3% is freshwater. Glaciers and ice sheets contain about 70% of the total freshwater; the rest is primarily in the subsurface as groundwater. Hence, groundwater in confined and unconfined aquifers is one of the most precious resources in the earth's sub-surface for all water needs of humankind (Naghibi, 2015).

All over the globe, there is significant pressure on freshwater resources, notably in developing and overpopulated countries. Over the past decade, the need for freshwater has been increasing continuously all over the globe due to population and industrial growth (Masilamani et al., 2023; Killivalavan et al., 2022). Most of the earth's population depends on groundwater resources for various purposes, and groundwater extraction is an easy and cost-effective method. Therefore, regular assessment of the quality and quantity of groundwater resources is essential for sustainable development. In general, the groundwater table recovers itself by infiltration of rainwater, but the infiltration rate cannot meet the exploitation rate if it is over-exploited. If the recharge process is insufficient compared to the extraction rate, drying unconfined aquifers and subsequent drought-like situations are common in most parts of the country (Biswajit et al., 2019).

Groundwater potential zone identification is the most significant step in optimising and preserving the water resource (Balasubramani et al., 2020). There are many techniques have been used to demarcate the groundwater potential zones; those techniques are mainly based on field surveys that are usually time-consuming and not cost-effective (Arulbalaji et al., 2019). There are enormous cost and time-effective methods and models are used such as multicriteria decision-making techniques (Chowdhury et al., 2008), logit regression (Pourghasemi and Beheshtirad, 2015), frequency ratio (Razandi et al., 2015), decision tree (Chenini and Ben Mammou, 2010), Artificial neural network (ANN) (Lee et al., 2012), Shannon's entropy (Naghibi et al., 2015), Machine learning techniques (Rahmati et al., 2016) and Certainty factor (Razandi et al., 2015) in the recent past. Remote sensing (RS) and Geographical Information System (GIS) techniques play a significant role in these techniques as they provide valuable tools for mapping water resources. Many researchers have used RS and GIS techniques to demarcate the groundwater potential zones, especially in hard rock terrains. Since many physical-climatic-environmental factors control groundwater, the application of the Analytical Hierarchical Process (AHP), multicriteria decision-making (MCDM) technique is extensively considered for mapping and managing water resources (Rahaman et al., 2015). In recent years, AHP has been combined with fuzzy logic that can set up an outline to get reliable outcomes using fuzzy triangular membership functions. The Fuzzy Analytical Hierarchical Process (FAHP) has a flexible membership function that makes the way to increase the accuracy and reliability of the results. The Receiver Operating Characteristic (ROC) curve is used to examine the overall validity of the groundwater potential zones with the help of the locations of the existing groundwater wells.

The study examines potential groundwater zones by integrating RS, GIS and FAHP techniques in the Cheyyar watershed in Tamil Nadu with the help of topographic, geological and land use and climatic factors. The study used characteristics of groundwater wells to validate the results and suggested remedial measures to attain sustainability in groundwater management.

Study Area

Cheyyar watershed is a region drained by river Cheyyar which originates in Jawadhu hills in Tiruvannamalai and Tirupattur districts. It fully drains in Tiruvannamalai district, mainly in the Taluks of Cheyyar, Chengam, Vandavasi and Polur, before it opens in River Palar (Fig. 1). It is one of the essential seasonal rivers flow in Northern Tamil Nadu.

Cheyyar is the main source of water in Tiruvannamalai district. The watershed covers an area of around 2,072 sq. km in Tiruvannamalai and Tirupattur District and it extends 12^{0}14'5" N to 12^{0}38'49" N latitude and 78^{0}39'46" E to 79^{0}24'12" E longitude. The study area covers the hilly regions of Tirupattur district and eleven blocks in Tiruvannamalai district, namely, Chengam, Peranamallur, Thurinjapuram, Tiruvannamalai, Chetpet, Vandavasi, Polur, Cheyyar, Jawadi, Kalasapakkam and Pudupalayam. The entire watershed covers 296 villages (1,317 sq. km) and 23 Reserve forests, which cover 755 sq. km. The pediment pediplain complex is the predominant geomorphological feature, occupying 1,244 sq. km of the study area. Charnockite is the major dominating geological structure found in the study area. The largest towns in the study area are Polur, Chengam, Cheyyar, Chetpet and Vandavasi, and the rest are agricultural villages. Agriculture is the backbone of the Cheyyar watershed. Paddy and Groundnut are the most prevalent crops in the region. Irrigation is mainly done through tube wells, canals and open wells. Since groundwater is a significant source of fresh water for various purposes, identifying groundwater potential zones is essential research to be done in the study area.

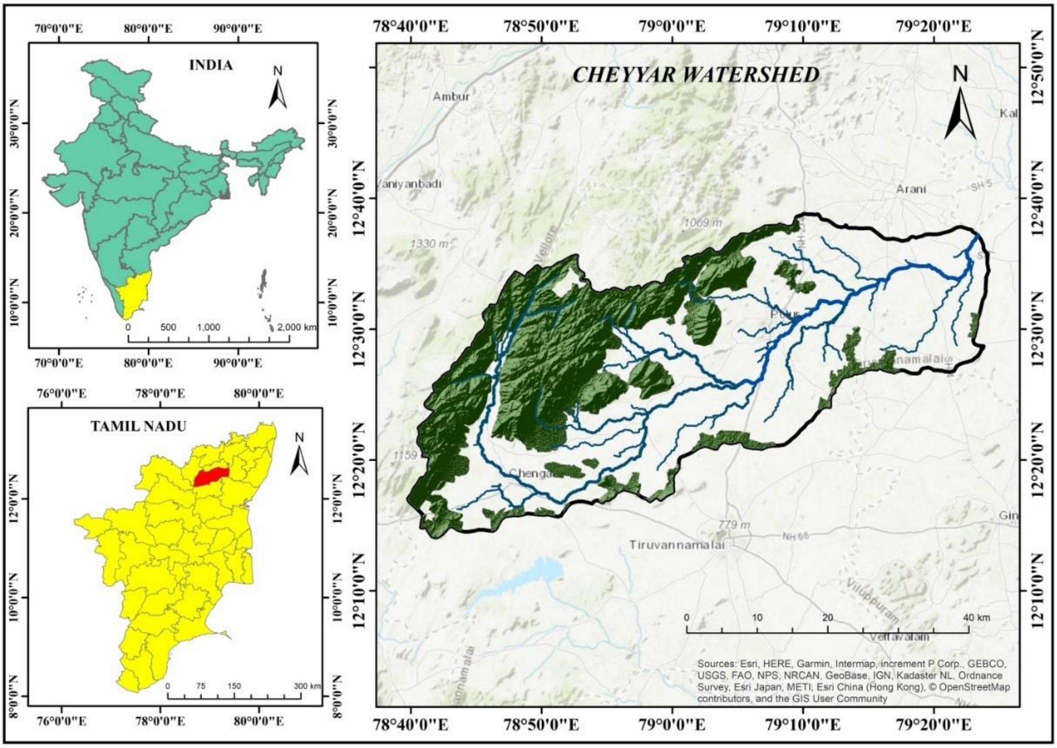

Figure 1: Location of the Study area

Data and Methods

Data

The mapping of the groundwater potential zone for the Cheyyar watershed is attempted through multiple remote sensing data products. All the topographical factors like slope, roughness, curvature, drainage density, Topographic Wetness Index (TWI) and Topographic Position Index (TPI) are computed from high-resolution ALOS PALSAR DEM data which has 12.5 m spatial resolution. The Geological Survey of India (GSI) provides region-wise geology maps from which the geological feature of the watershed is mapped, and the general soil types are mapped from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Tamil Nadu Soil Map (Table 1). Then factors like geomorphology and lineament density are extracted (e.g., clipped) according to the study area from the Bhuvan web portal and mapped. The daily recorded rainfall data for 1991 - 2021 is collected from the Statistical Department of Tamil Nadu. Further, the Landsat 8 OLI data is utilised to map the land use/land cover through the visual interpretation, land surface temperature (temperature) extracted through the split window algorithm and NDMI extracted with a per-defined algorithm (Ravichandran et al., 2022).

Table 1. Variables of the study and their data sources

Factors	Data Source
Slope Roughness Curvature Drainage Density Topographic Wetness Index (TWI) Topographic Position Index (TPI)	ALOS PALSAR DEM
Geology	Geological survey of India (GSI) Map
Soil	National Bureau of Soil Survey of India
Geomorphology Lineament Density	Bhuvan web portal
Rainfall	Statistical Department of Tamil Nadu
Land Use/Land Cover Land Surface Temperature Normalised Difference Moisture Index (NDMI)	Landsat 8 OLI

Analysing Method

Around 14 significant factors are adopted and grouped into three sections namely, Topographic factors (slope, roughness, curvature, drainage density, Topographic Wetness Index (TWI) and Topographic Position Index (TPI)), Geological factors (Geology, Geomorphology, general soil type and Lineament density), Land use and climatic factors (land use/land cover, rainfall, temperature and Normalised Difference Moisture Index (NDMI)). The weightage of the 14 factors is calculated by utilising the Fuzzy Analytical Hierarchical Process (FAHP) and these factors are integrated into three main factors to construct a groundwater potential zone. Table 2 represents the pairwise comparison matrix constructed using FAHP techniques and its weight is assigned for each factor (Fig. 2). Finally, the ROC curve has been made by using existing groundwater well locations collected from the field to validate the results.

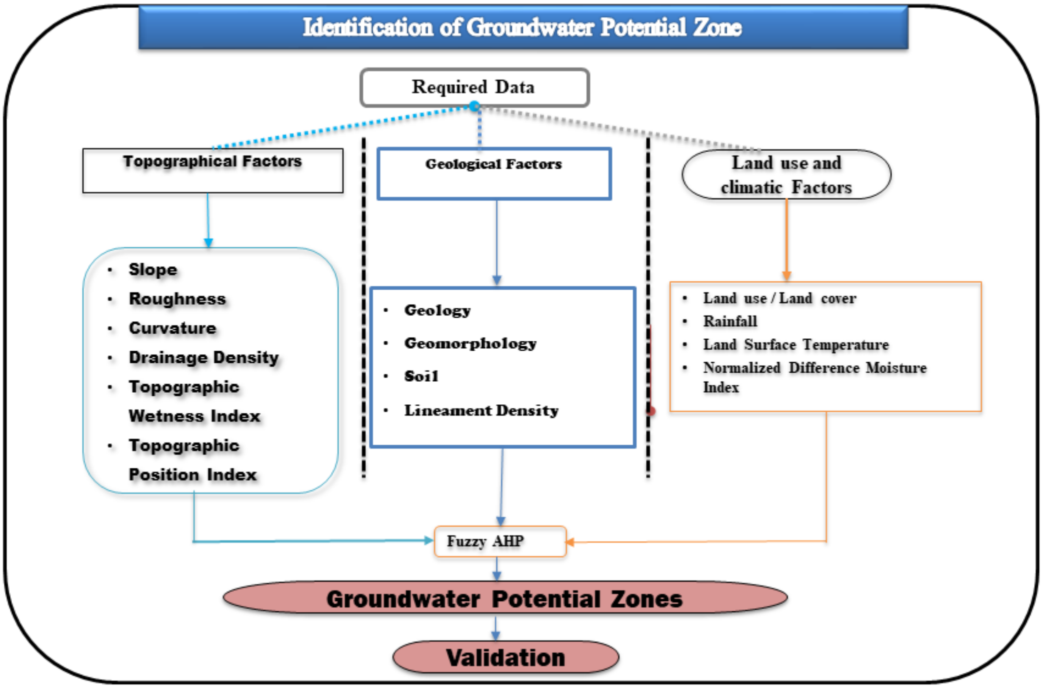

Figure 2: Methodological Flow chart of the Study

Fuzzy Analytical Hierarchical Process (FAHP)

The FAHP is one of the best techniques in the multicriteria decision-making process (Saaty, 1980; Rahaman et al., 2015). Thus, the study utilised the efficiency of FAHP to assign criterion weights and rank for the factors of groundwater potential zone. The procedure and steps mentioned below have achieved it. Initially, the pairwise comparison matrix for each factor is computed with the fuzzy triangular elements (Eq. 1). Based on the relative scale of importance, the decision maker assigns the value ranges from 1 to 9, reflecting the relationship between each criterion.

$$\tilde{A}_{ij} = (\tilde{a}_{ij})n \times n = \begin{pmatrix} (1,1,1) & (l_{12}, m_{12}, n_{12}) & (l_{1n}, m_{1n}, n_{1n}) \\ (l_{12}, m_{12}, n_{12})^{-1} & (1,1,1) & (l_{in}, m_{in}, n_{in}) \\ (l_{1n}, m_{1n}, n_{1n})^{-1} & (l_{in}, m_{in}, n_{in})^{-1} & (1,1,1) \end{pmatrix} \qquad (1)$$

The initial value is transformed into a fuzzy value through the eq (2)

$$\tilde{a}_{ij} = (l_{ij}, m_{ij}, n_{ij})_{=} \; \tilde{a}_{ij}^{-1} = \left(\frac{1}{n_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}} \right) \text{ where i, j=1, 2,…n and i} \neq \text{j} \qquad (2)$$

Through equation 3, the fuzzy geometric mean value for every criterion (a_{ij}) is calculated

$$\tilde{r}_i = \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n} \quad \text{Where, i= 1, 2,…..n} \tag{3}$$

Each criterion (a_{ij}) fuzzy weightage ($\tilde{w}_i$) are assessed through eq (4)

$$\tilde{w}_i = \tilde{r}_i \times \left(\tilde{r}_1 + \tilde{r}_2 + ...\tilde{r}_n \right)^{-1} \tag{4}$$

De-fuzzification of fuzzified value into a numerical value (w_i) through eq (5)

$$w_i = \left(\frac{l\tilde{w}_i + m\tilde{w}_i + n\tilde{w}_i}{3} \right) \tag{5}$$

Finally, numerical value (w_i) is normalised through eq (6)

$$N_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{6}$$

Results

Topographic Factors

The slope is divided into four classes based on the slope in degrees that are flat (less than 2), gentle (2–7), moderate (7–12), and steep (more than 12) (Showmitra et al., 2022). The maximum portion of the study area is flat terrain and highly steep slopes in the upper part (Fig. 3). Roughness is classified by four as less than 0.3, 0.3–0.5, 0.5–0.7 and more than 0.7 (Showmitra et al., 2022). Moderate roughness values (0.3 – 0.5) dominated the study area about 900 sq. km fell under this category. Curvature values are classified as very low (less than -0.3), low (-0.3–0.1), moderate (0.1–0.7) and high (more than 0.7). The low curvature is the dominant distribution and all the other classes are found only in trace amounts.

The drainage density is characterised by five classes: very low (sparse), low, moderate, high and very high (dense). The centre portion, along with the main river channel in the study area, is the high drainage density area with a high potential of water infiltration and less dense areas with less groundwater potential. The TWI has been categorised into four classes: less than 8, 8–11, 11–15 and more than 15.

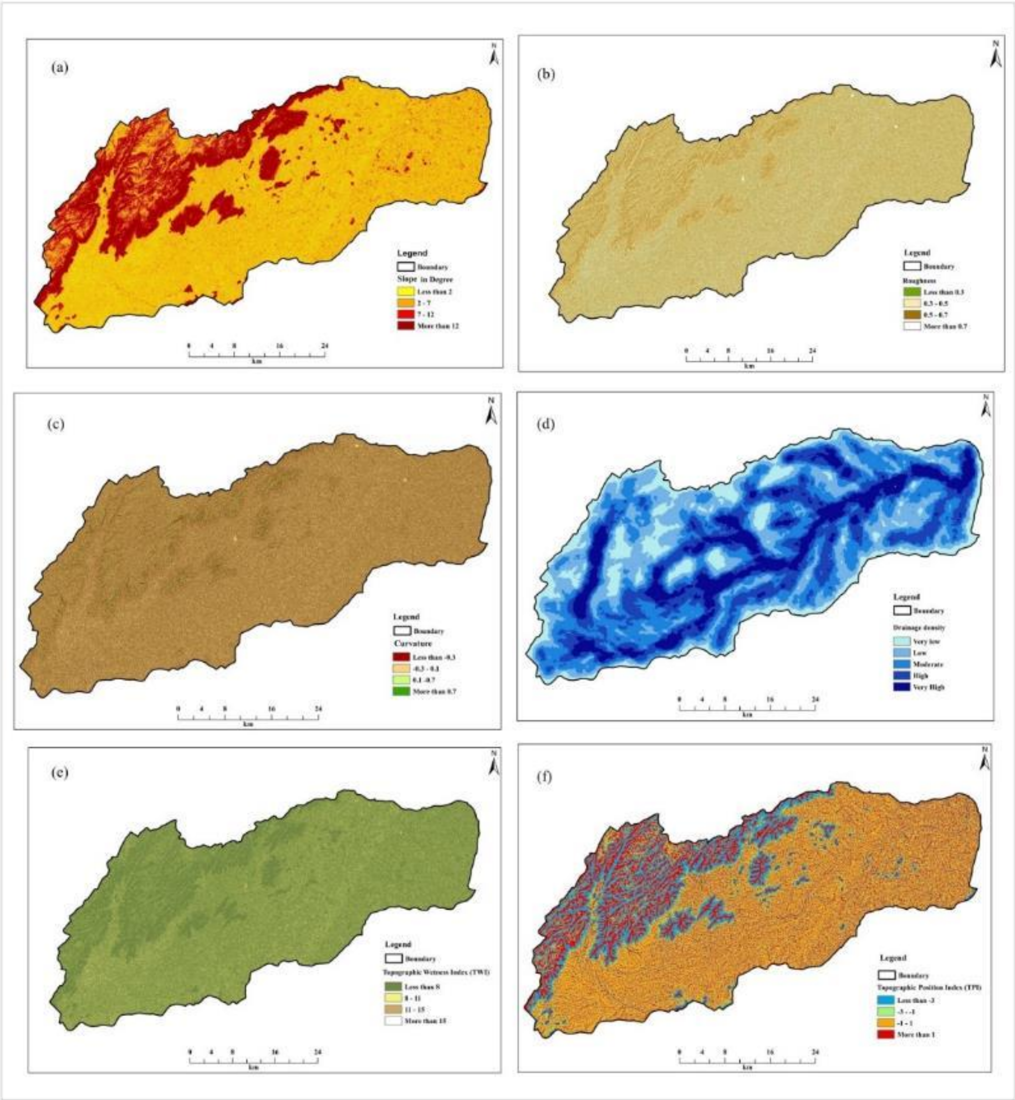

Figure 3: Spatial distribution of topographical factors (a) Slope, (b) Roughness, (c) Curvature, (d) Drainage Density, (e) TWI and (f) TPI.

Most of the study area is occupied by less than 8 and 8-11, representing low groundwater potential (52%), especially in the northwestern part (Jawadhu Hills). The infiltration is high in the foothills parts of the study area and sparse over the other parts of the study area. TPI less than -3 refers to a flat surface, and more than one refers to an elevated region. The northwestern part of the studyarea is highly elevated and sparsely in the central portion. Low elevation values highly influence the groundwater potential. Notably, the foothills of Jawadhu Hills have a high potential for groundwater recharge.

Geological Factors

Charnockite is the primary dominating geological structure in the Cheyyar watershed; it consists of metamorphic rocks with variable chemical composition. It occupies an area of 1526 sq. km (74%). Hornblende-biotite genesis covers 416 sq.km (20%). The other geological features are found in the study, such as Pyroxene Granulite, Pink Migmatite, Epidote, Granite, Ultramafic rocks and Magnetite quartzite, which covers 6% of the study area. High weightage is given to Magnetite Quartzite, and the lowest weightage is given to Pink Mignatite, which has less infiltration (Fig. 4). The geomorphological structure of the Cheyyar watershed shows well-matured Pediplain complex; it also has the Dissected Hills of Jawadhu Hills in which the mainstream of Cheyyar rises. The pediment pediplain complex occupies around 1244 sq. km (60%) of the study area. Dissected Hills and valleys are found mainly in the northwestern portion of the Cheyyar watershed region; it covers an area of 462 sq. km (22%).

The waterbody includes the main Cheyyar stream along with lakes and ponds covering an area of 153 sq. km (7%). The dissected upper plateau found in Jawadhu Hills covers an area of 96 sq. km (4.6%). Bajada is like an alluvial fan occupying 92 sq. km (4.4%) of the study area. The piedmont slope covers 17 sq. km. Active flood plain forms at the confluence of river Cheyyar with Palar in the Northeastern direction of the study area and covers 8 sq. km. Active floodplains, water bodies, and plain land are more effective in infiltration rate than hills and valleys.

Clayey type of soil is the most dominant in the Cheyyar watershed. Gravelly clay soil, cracking clay soil and clayey soil are subtypes that cover almost 90 per cent of the total study area; loamy soil covers 196 sq. km, and it has three subtypes: loamy soil, stratified loamy soil and gravelly loam soil. The combination of clay soil and rock outcrop has the lowest infiltration rate. Similarly, loam soil and fine soil are greatly benefitting groundwater rejuvenation. Lineament density has been divided into four classes such as < 0.4, 0.4 – 0.8, 0.8 – 1.2 and > 1.2. High weightage is given to high lineament density and contrariwise. Lineament density is low all over the study area except the hilly region.

Land Use and Climatic Factors

The study area is ultimately covered with agricultural area and vegetation. The barren land is sparsely spread throughout the study region (Fig. 5). Water bodies and agricultural land have a high groundwater potential. Barren and rocky land has less potential since the infiltration is low. The rainfall Is classified into five classes: very low, low, moderate, high and very high. So, intense rainfall with stagnant surface water increases the groundwater potential. The high rainfall found in the central and eastern parts of the study area has a high possibility of water infiltration into the subsurface due to low runoff. Low rain in the northwestern part of the Cheyyar watershed has lead to a less infiltration. The highest temperature in the study area is 37^0 C found in the part of Chengam, and the lowest is 17^0 C in the higher altitude part of Jawadhu Hills. About half of the study area experienced more than 27^0 C temperature.

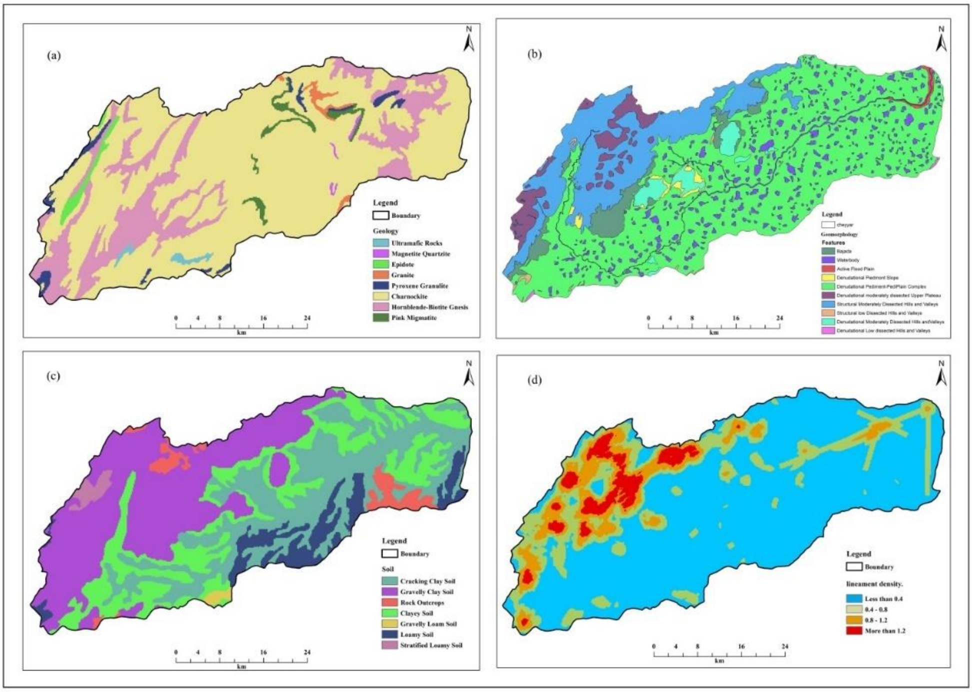

Figure 4: Spatial distribution of geological factors (a) Geology (b) Geomorphology (c) Soil and (d) Lineament Density.

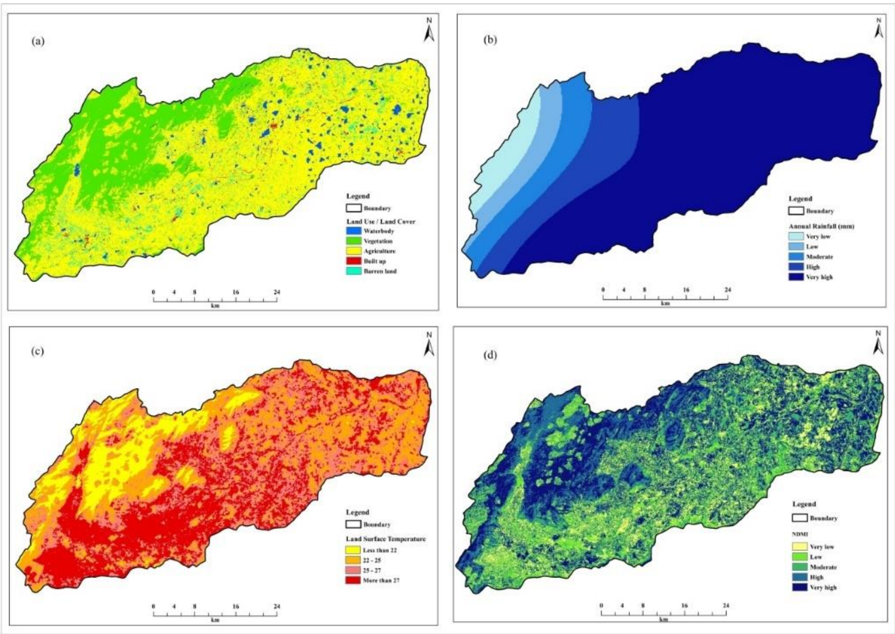

Figure 5: Spatial distribution of land use and climatic factors (a) Land use / Land cover (b) Rainfall, (c) LST and (d) NDMI.

In the plain region, the infiltration rate is very high, and the potential is higher on flat surfaces. NDMI describes the water stress level of the area, and the moisture value is between -1 to 1. The northern portion of the study area is highly moist. The high and very high moisture levels are dominant in the study area.

Groundwater Potential Zones and Validation

The groundwater potential zones have been examined by using FAHP and proper weightage given to each sub-factor and class (Table 2). After executing the FAHP with proper weightage of factors, sub-factors and each class, the groundwater potential zones can be mapped by using the final weightage values. Low to high potential for groundwater dominantly prevails over the study area (Table 3.). However, the study area was dominated (63%) by moderate and high groundwater potential zones. Figure 7. shows the ROC curve of the study area. The Area Under Curve (AUC) in the ROC was about 86.15%, which denotes a reasonable accuracy.

Table 2. Representing the weight of each factor and sub-factor

Factors	Criteria Weight	Sub Factors	Sub - Criteria Weight
Topography Factors	0.41	Slope	0.1
		Roughness	0.05
		Curvature	0.04
		Drainage density	0.09
		TWI	0.07
		TPI	0.06
Geological Factors	0.32	Geology	0.06
		Geomorphology	0.14
		General soil type	0.09
		Lineament density	0.03
Land use and Climatic Factors	0.27	Land use/Land cover	0.08
		Rainfall	0.13
		LST	0.04
		NDMI	0.02

Discussion

The groundwater potential depends on many factors. Amongst, the slope is the most crucial topographic feature that determines the infiltration of precipitation (Yeh et al., 2009; Singh et al., 2013; Arulbalaji et al., 2019). The plain surface tends to have a high infiltration rate, and the high slope indicates steep terrain with a significantly lower infiltration ratio. Areas with steep slope with faster-flowing water do not get enough groundwater recharge, notably in the short seasonal (monsoonal) rainfall regions (Yeh et al., 2009). The roughness indicates the degree of undulation on the surface.

The area with a flat surface, i.e. low roughness and value has the potential for a high infiltration rate and vice versa for highly undulating surfaces. The slope curvature also constrains the erosion and runoff process (Rejith et al., 2019): the convex and concave helps to accumulate the groundwater. Therefore, roughness and curvature significantly impact groundwater potential. These parameters can also be understood indirectly by analysing the drainage patterns of the region (Singh et al., 2013). The higher the density, higher the infiltration; low the density, the lower the accumulation (Yeh et al., 2006). The higher density of streams was found in the central part of the study area, where the groundwater potential is high. In addition, TWI can be used to strengthen the analyses as infiltration is also affected by the hydrological process (Mokarram et al., 2015; Arulbalaji et al., 2019). The greater value represents the more significant the groundwater potential. Higher wetness is found in the parts of Jawahu Hills; however, there is less infiltration due to its topographical setup. An area's soil profile also substantially determines the infiltration and percolation rates of water entering aquifers, and it is essential for agriculture.

Table 3. Representing groundwater potential zone categories and their respective area and percentage of area.

Sl.No	Groundwater Potential Categories	Area in Sq.km	Percentage
1.	Very low	142.06	6.85
2.	Low	389.21	18.78
3.	Moderate	735.69	35.50
4.	High	565.96	27.32
5.	Very high	239.36	11.55

The geological structure of a watershed is the most important for analysing the morphology of the study area. The Magnetite Quartzite has the highest infiltration rate as reflected in the final potential map (Fig. 6). Combined with geomorphology, geological structures provide essential information about the infiltration process, groundwater variation, surface runoff and geochemical changes. (Raja Veni et al., 2017). Faulting and fracturing zones represented by lineaments are responsible for secondary porosity and permeability of the ground surface (Yeh et al., 2006). The high density of lineaments has a high potential for groundwater and vice versa. Still, in the case of the Cheyyar watershed, the plain region has less lineament density, which does not favour secondary porosity and permeability. The land use /land cover pattern in the study area gives an idea about the utilisation of groundwater. The increase in the build-up area with increased agriculture practices leads to decreased water quality and groundwater recharge (Elmahdy et al., 2020). Notably, in Chengam, there is minimal infiltration because it has highly dense built-ups. Rainfall also significantly affects groundwater recharge and water availability (Showmitra et al., 2022). Exceptionally, high rain with low runoff and high infiltration rates leads to high groundwater potential. The final result reveals that rainfall, land use and drainage density are the highly influencing factors in delineating the groundwater potential zones in the study area.

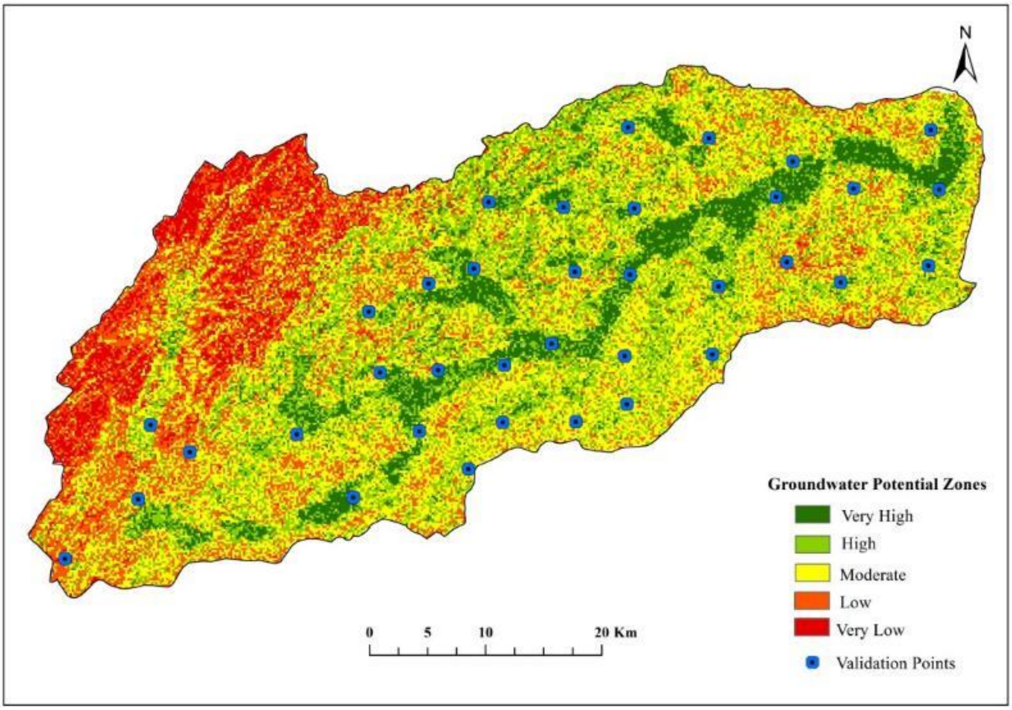

Figure 6: Spatial distribution of groundwater potential zone by integrating RS, GIS techniques and FAHP

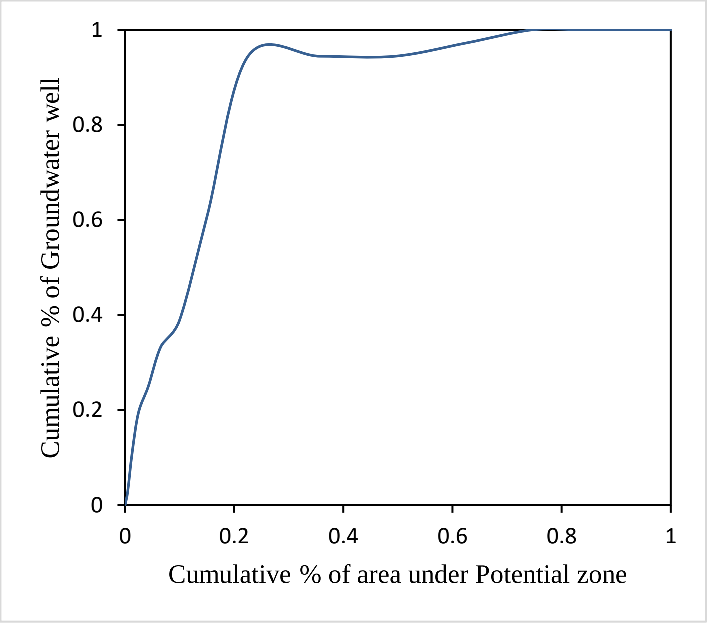

Figure 7: ROC curve for validation of groundwater potential

Conclusion

The study used three major factors and 14 sub-factors to assess the groundwater potential zones by integrating RS, GIS and FAHP. Based on the FAHP values, the study area has been divided into five classes: very low, low, moderate, high and high potential zones. However, about 37% (~ 805 sq. km) of the study area has high to very high groundwater potential, especially along the river banks and the foothills of Jawadhu hills, indicating that the construction of small check dams can subsequently increase the groundwater level. The accuracy of the study has been quantified using the ROC curve, and it was found that the accuracy of the final result is 86.15%, which is reasonable. Notably, most agricultural areas have moderate to high groundwater potential; therefore, implementing percolation ponds is recommended to increase the infiltration in these areas. The study results could help policymakers implement strategies for managing the groundwater resources, especially for irrigation and drinking purposes of the study area, and to attain a sustainable future.

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