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Groundwater Potential Zone Delineation Using Multi-criteria Decision-making Approach: A Case Study

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ABSTRACT

Over-exploitation of groundwater from coastal aquifers causes seawater intrusion and depletion of freshwater resources. As 40 percent of the world's population live within 100 km of the coast. This will increase the demand for potable water in coastal aquifers. Hence, it is essential to evaluate the sources of fresh-groundwater potential and productivity in coastal aquifers. Nowadays, integrated studies based on geographic-information systems play a major role in groundwater-exploration studies. Thus, the current study was carried out with the objective to delineate groundwater potential in the Nambiyar river basin in Tamil Nadu's southeast coastal area, where groundwater is in a critical condition. In order to improve groundwater recharge, it is very important to identify possible recharge areas. A novel work of the integration of remote sensing, geographic information system (GIS) and multi-criteria decision-making approaches of analytical hierarchical-process methodologies (AHP) was used in the present study. A total of 11 thematic layers, such as slope, curvature, soil, roughness, topographic-wetness index, drainage density, land use/land cover, geology, geomorphology, lineament density and rainfall, were generated for delineating groundwater potential zones. All the thematic maps are weighted using AHP based on the attributes of the classes and the potential capacity of their water supply. The demarked region of groundwater potential was validated by comparing pre-monsoon and post-monsoon groundwater levels. The groundwater potential zone map was classified into five categories: very high, high, moderate, low and very low. Areas with very high and very low potentials are delineated only in very limited areas. 64% of the regions are covered under the moderate-potential zones. The low-and high-groundwater potential zones are delineated at 22% and 14%, respectively.

KEYWORDS: GIS, Recharge areas, Groundwater potential, Nambiyar river basin, AHP.

INTRODUCTION

India contains 18% of the world's population; yet just 4% of the world's renewable water resources (India-WRIS Wiki, 2015). Water is necessary for human development, socio-economic development and ecosystem diversity (Omar et al., 2021). Water is required to support the domestic, irrigation and industrial demands of more than 1.2 billion people globally. The total quantity of water used is influenced by urbanization and industrial growth. As a result, the gap between supply and demand for water has been steadily growing. To meet a rapidly rising demand for freshwater, India needs to carefully utilize both its surface and groundwater resources. About 58 percent of India's annual groundwater recharge is largely dependent on monsoon rains. Around 32% of water recharge occurs from seepage from canals, tanks, ponds and other water structures, as well as from irrigation (Central Groundwater Board, 2014). The occurrence of groundwater is affected by climatic, geological, hydrological, biological and physiographic elements, as well as by their interconnections (Arkoprovo et al., 2012).

It is critical to establish the prospective zone of groundwater where artificial recharge methods can be used to boost the quantity of recharge. The management

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and conservation of groundwater have become difficult problems in the current situation because of groundwater depletion (Omar et al., 2020a). The standard approach for finding, defining and mapping groundwater potential zones depends on costly and time-consuming ground surveys integrating geophysical, geological and hydrogeological methods (Israil et al., 2006). A detailed review of literature depicts that several researchers have utilized a variety of methodologies to locate and describe groundwater potential regions. For example, some researchers have applied probabilistic models; namely, frequency ratio (Ozdemir, 2011), multi-criteria decision analysis (Chowdhury et al., 2009), weights-of-evidence (Corsini et al., 2009; Pourghasemi and Beheshtirad, 2015), logistic regression (Pourtaghi and Pourghasemi, 2014), evidential belief function (Nampak et al., 2014), certainty factor (Razandi et al., 2015), decision tree (Chenini et al., 2010), artificial neural network model (Lee et al., 2012), Shannon's entropy (Naghibi et al., 2015) and machine-learning techniques (Rahmati et al., 2016) like the random forest. It is possible to determine the groundwater potential zone using the statistical method, expert evaluation or deterministic method (Gupta et al., 2018). Omar et al. (2020b) used the integration of GIS and the groundwater-flow model to evaluate groundwater potential zones and applied various possible scenarios to improve groundwater management.

Groundwater potential zones have been mapped using remote sensing and geographic information system (GIS) methods in a number of earlier studies across the globe (Arulbalaji et al., 2019; Dar et al., 2020; Jahan et al., 2018; Owolabi et al., 2020). Slope, curvature, soil, roughness, topographic wetness index, drainage density, land use/land cover, geology, geomorphology, lineament density and rainfall are the primary factors involved in the process of potential zone identification. The occurrence of groundwater is based on geological formation and hydrological properties. Knowledge-based ranking was used to assign weights and ranks to the parameters (Sitender, 2010), multi-criteria decision-making analysis (Bagyaraj et al., 2013) and parameter favourability (Savita et al., 2018). Among all, the multi-criteria AHP technique is reliable and cost-effective in deciphering groundwater potential zones. Thus, this technique was applied in the present study.

The groundwater potential zones were identified using an integrated strategy that included Analytical Hierarchy Processes (AHPs), remote sensing and Geographic Information System (GIS). The AHP is an effective decision-making tool for dealing with complicated groundwater issues. It was developed by Thomas Saaty to simplify complicated problems by breaking them down into pairwise comparisons and then merging the outcomes. The study area has 31 large-scale and 11043 small-scale industries, where the groundwater condition is critical. Hence, the augmentation of groundwater is very essential to prevent seawater intrusion. Previous studies have been conducted to characterize the sub-surface geology of this area. However, no attempts have been made to map the groundwater potential zones for the entire study area using multiple variables. Thus, the objective of this study was to prepare a precise groundwater potential map by utilizing a systematic and scientific GIS-based AHP method. The results of the current study can be useful to determine the groundwater potential zones in similar drought-prone regions.

Study Area

The current study was conducted in the Nambiyar river basin, a small sub-tropical river basin. The Nambiyar basin is 45 km^2 in area. Groundwater resources in this region are overexploited based on the study conducted by the Central Groundwater Board (CGWB). The Nambiyar river basin falls under the white category of groundwater development, which implies that the degree of groundwater development is around 40% and there are no constraints on future groundwater development. The climate in this region is sub-tropical and the months of May and June are frequently hot and dry. The relative humidity is between 79 and 84 percent on average. The average daily temperature is 22.9°C, with a maximum of 33.5°C. Rainfall in the region is as a result of the influence of the southwest and northeast monsoons. The annual rainfall averages 879 mm. Figure 1 shows the location of the study area.

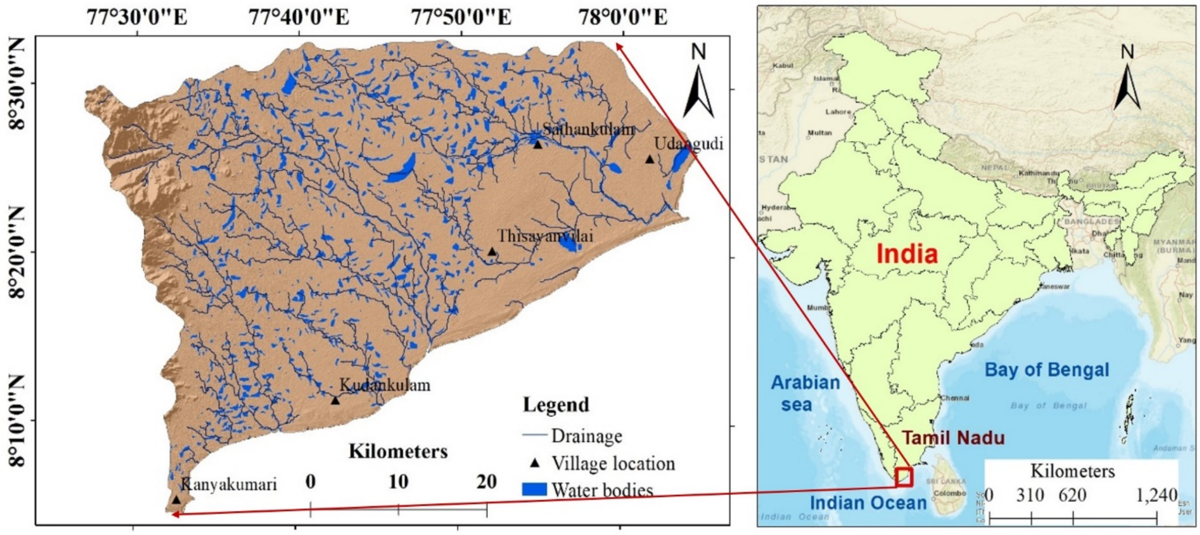

Figure (1): Location map of the Nambiyar river basin

MATERIALS AND METHODS

The groundwater potential zones of the Nambiyar river basin were identified using knowledge-based factor analysis, which included slopes, curvature, soil, roughness, topographic wetness index, drainage density, land use/land cover, geology, geomorphology, lineament density and rainfall. The data acquired from the Bhuvan website was pre-processed and analyzed using the image processing program ERDAS Imagine 9.2. Thematic maps were created using ArcGIS 10.2 based on geographic-information techniques. Digital elevation model taken from Shuttle Radar Topographic Mission (SRTM-30 m resolution) data was used to delineate the river basin using the hydrology tool in ArcGIS software. Geo-coded false-color composite satellite data derived from IRS LISS-III (24 m spatial resolution) was used for the preparation of LU/LC, geology and geomorphology.

The geological survey of India's published geology map and the National Bureau of Soil Survey's published soil atlas was collected and digitized for thematic-layer preparation. The slope, curvature and roughness was calculated using SRTM data retrieved from Earth Explorer. To learn about the characteristics of the ground surface, DEM data from the SRTM was used. DEM data was projected to the World Geodetic System 1984 (WGS, 1984) of the global reference system and the Universal Transverse Mercator (UTM) Zone-44N coordinate system (Omar et al., 2019). The Indian Meteorological Department provided rainfall statistics. The spatial distribution of rainfall was mapped using ArcGIS's kriging interpolation method. The drainage lines are extracted automatically from the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a 30-m spatial resolution.

The lineament map was derived from an Indian Remote Sensing Satellite P6 (Resourcesat-1) Linear Imaging Self-scanning Sensor III (IRS P6 LISS III) image with a 24- m spatial resolution. The spatial analyst tool in GIS software is used to create drainage and lineament density maps from the drainage and lineament data. The prepared thematic layers were cross-checked with the data collected during the fieldwork for ground-truth verification. The flow chart of the approach used in this study is depicted in Figure 2.

AHP-based Multi-criteria Decision-making

The most typical method for identifying groundwater potential zones is to adopt an integrated strategy that includes remote sensing, geographic information system (GIS) and multi-criteria analysis. Various thematic maps are generated using remote-sensing images, weightage is assigned based on multiple criteria using AHP and the maps are then stored, analyzed and integrated using GIS. A total of 11 different thematic layers, such as slope, curvature, soil, roughness, topographic wetness index, drainage density, land use/land cover, geology, geomorphology, lineament density and rainfall are considered for this study. Considering the occurrence of groundwater, the valuable literature and expert opinions, these influence maps are weighted accordingly. The thematic map with a high impact on groundwater storage is given a high weight, while the thematic map with a low impact is given a low weight. Weights are assigned to thematic maps depending on their significance and capacity to store water. The relative relevance values of each map were assigned weights using Saaty's scale (1-9). Furthermore, the weights were calculated by a review of past studies as well as field experience. According to Saaty's relative-importance scale, a value of 9 indicates very extreme importance, 8 indicates extreme importance, 7 specifies very strong importance, 6 specifies strong plus, 5 shows strong importance, 4 shows moderate plus, 3 shows moderate importance, 2 shows weak importance and 1 shows equal importance (Arulbalaji et al., 2019). Each thematic map's sub-classes were re-classified on the GIS platform using the natural-break classification technique before being awarded weights. A grade of 0-9 was assigned for each sub-class of each thematic map according to its relative impact on groundwater development. As a consequence, all theme layers were compared to one another in a pair-wise-comparison matrix (Table 1). Table 1 shows the pairwise comparison of each layer with another layer. It is calculated by the assigned weight of each thematic layer with another thematic layer in the table.

The consistency ratio (CR) is calculated using the following steps (Saaty, 1977): (1) the eigen-vector approach was used to get the principal eigen-value (λ) and (2) the Consistency Index (CI) was derived using Equation (2). The average value (λ_{avg}) of the principal eigen-values was calculated from Table 2. The total value of λ for the eleven thematic maps is 121.50; then, the average was taken as in Eqn. (1).

$$\lambda_{avg} = \frac{121.50}{11} = 11.05 \qquad \text{Eqn. (1)}$$

$$\mathrm{CI} = \frac{\lambda_{avg} - n}{n-1} \qquad \text{Eqn. (2)}$$

where n denotes the number of factors included in the analysis.

$$\mathrm{CI} = \frac{11.05-11}{11-1} = 0.005\,. \qquad \text{Eqn. (3)}$$

Consistency Ratio is defined as CR = CI/RCI, where RCI = Random Consistency Index value, the value of which was attained from the Saaty’s standard (Saaty, 1980).

$$\mathrm{CR} = \frac{0.005}{1.51} = 0.003. \qquad \text{Eqn. (4)}$$

The GIS platform was used to build a groundwater potential zone map of the Nambiyar river basin by combining all eleven thematic layers using the weighted overlay analysis approach (Rose and Krishnan, 2009).

$$GWPZ = \sum_{i}^{n} (W_A \,\mathrm{X}\, R_B) \qquad \text{Eqn. (5)}$$

where GWPZ = groundwater potential zone, W characterizes the weight of the thematic layers and characterizes the rank of the sub-class. A term (A = 1, 2, 3, ……, x) indicates the thematic map and B term (B = 1, 2, 3, ……, y) indicates the thematic map classes. The result of consistency is given in Table 2. In Table 2, values are derived from the pairwise comparison with the normalized weight. Then, the principal eigen-value is calculated by dividing of weighted sum value by the thematic weight. The assigned ranks and weights of thematic levels are shown in Table 3. In Table 3, the rank was assigned by referencing various literature on similar geological formations.

The produced pairwise matrix consistency index and consistency ratio value were used to generate normalized weights for each layer. If the CR value of the resulting matrix is less than 0.1, it is termed consistent. After the weights were assigned, the layers were subjected to weighted overlay analysis. Based on the index value produced using Eqn. 5, the groundwater potential zone was classified into five categories. The groundwater potential zone map was divided into five groups: very low, low, moderate, high and very high. Data from pre-monsoon and post-monsoon well yields, as well as groundwater variability, were utilized to cross-check the results.

Table 1. Normalized pair-wise comparison matrix and AHP weight factors for groundwater-potential mapping

Thematic layers	Assigned Weight	Geomorphology	LU/LC	Geology	Lineament Density	Soil	Drainage Density	Slope	Rainfall	TWI	Roughness	Curvature	Normalized Weight
Geomorphology	8	1.00	1.14	1.33	1.14	1.60	1.60	2.00	1.60	2.00	2.67	2.67	0.14
LU/LC	7	0.88	1.00	1.17	1.17	1.40	1.40	1.75	1.40	2.33	2.33	2.33	0.13
Geology	6	0.75	0.86	1.00	0.86	1.20	1.20	1.50	1.20	1.50	2.00	2.00	0.10
Lineament Density	7	0.88	1.00	1.17	1.00	1.40	1.40	1.75	1.40	1.75	2.33	2.33	0.12
Soil	5	0.63	0.71	0.83	0.71	1.00	1.00	1.25	1.00	1.25	1.67	1.67	0.09
Drainage Density	5	0.63	0.71	0.83	0.71	1.00	1.00	1.25	1.00	1.25	1.67	1.67	0.09
Slope	4	0.50	0.57	0.67	0.57	0.80	0.80	1.00	0.80	1.00	1.33	1.33	0.07
Rainfall	5	0.63	0.71	0.83	0.71	1.00	1.00	1.25	1.00	1.25	1.67	1.67	0.09
TWI	4	0.50	0.57	0.67	0.57	0.80	0.80	1.00	0.80	1.00	1.33	1.33	0.07
Roughness	3	0.38	0.43	0.50	0.43	0.60	0.60	0.75	0.60	0.75	1.00	1.00	0.05
Curvature	3	0.38	0.43	0.50	0.43	0.60	0.60	0.75	0.60	0.75	1.00	1.00	0.05

Table 2. Results of consistency ratio

Thematic layers	Geomorphology	LU/LC	Geology	Lineament Density	Soil	Drainage Density	Slope	Rainfall	TWI	Roughness	Curvature	Weighted Sum Value	Thematic Weight	l
Geomorphology	0.14	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	1.54	0.14	11.04
LU/LC	0.12	0.13	0.12	0.14	0.12	0.12	0.12	0.12	0.16	0.12	0.12	1.41	0.13	11.06
Geology	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.16	0.10	11.04
Lineament Density	0.12	0.13	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.35	0.12	11.04
Soil	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.96	0.09	11.04
Drainage Density	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.96	0.09	11.04
Slope	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.77	0.07	11.04
Rainfall	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.96	0.09	11.04
TWI	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.77	0.07	11.04
Roughness	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.58	0.05	11.04
Curvature	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.58	0.05	11.04

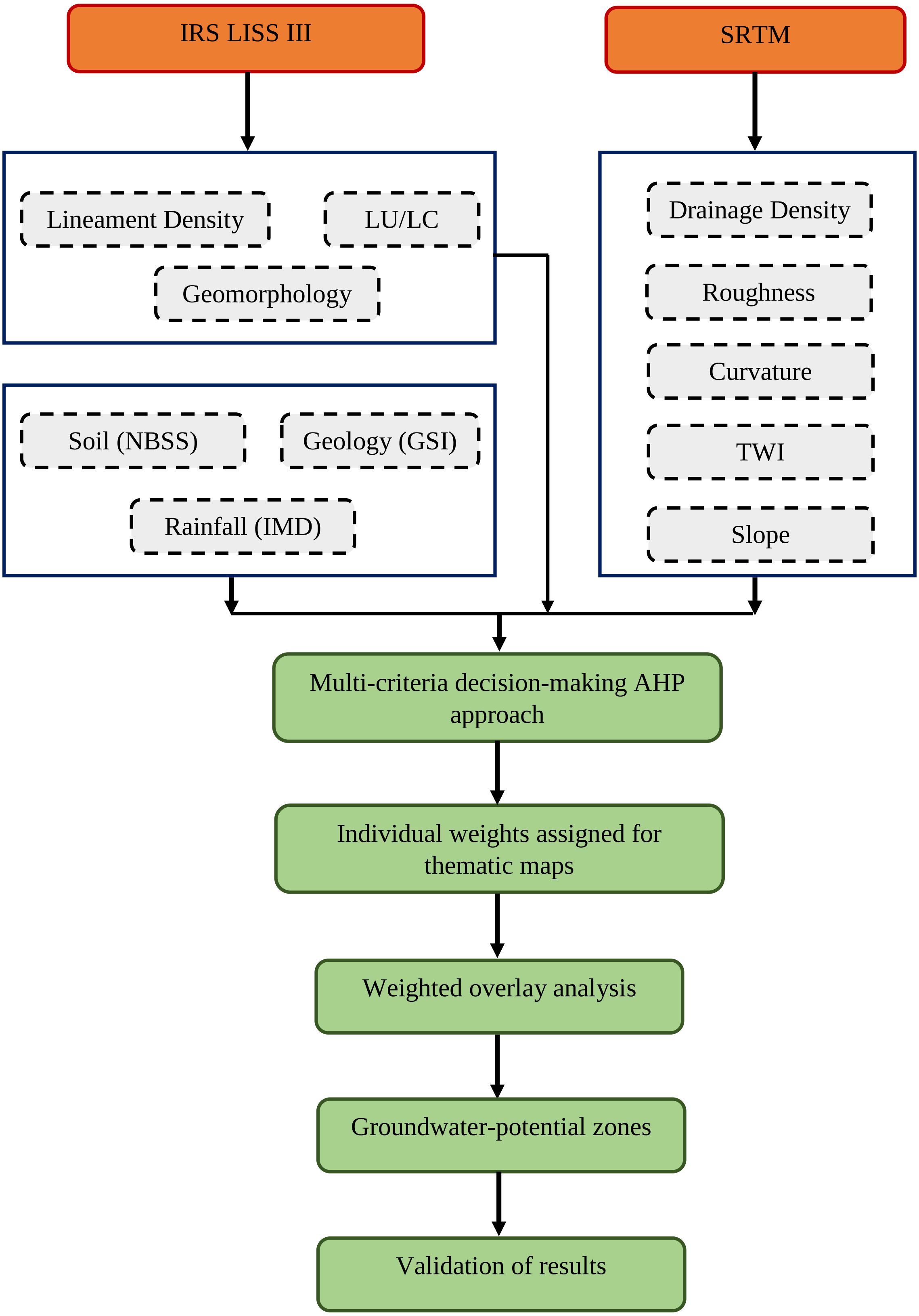

Figure (2): Flowchart of the methodology used for groundwater potential zone mapping

Table 3. AHP weight and rank for calculating groundwater potential

Parameter	Domain of effect	Rank	AHP weight
Geology	Sand / silt and clay	5	0.1
	Charnockite	2	
	Gneiss	2	
	Sand and silt	8	
	Coastal / alluvial sands	8	
	Shaly sandstone	7	
Geomorphology	Bajada	5	0.14
	Pediment	2	
	Denudational hills	2	
	Deflection slope	3	
	Eolian plain	5	
	Coastal plain	7	
	Alluvial plain	8	
	Flood plain	7	
	Plateaus	5	
	Valleys	9	
	Structural hills	2	
	Sedimentary plain	7	
	Hills and Plateaus	4	
	Sedimentary high ground	2	
LU/LC	Agricultural land	5	0.13
	Buit-up land	2	
	Forest	5	
	Saltpan	3	
	Waste land	3	
	Water body	8	
Lineament Density (km/km^2)	Very low (0 - 0.16)	2	0.12
	Low (0.17 -0.38)	4	
	Moderate (0.39 - 0.55)	6	
	High (0.56 - 0.75)	7	
	Very high (0.76 - 1.2)	8	
Soil	Alfisols	4	0.09
	Entisols	9	
	Hill soil	3	
	Inceptisols	8	
	Reserve forest	2	
	Vertisols	6	
Drainage Density	Very low (0 - 0.20)	8	0.09

Parameter	Domain of effect	Rank	AHP weight
(km/km^2)	Low (0.20 - 0.47)	6	
	Moderate (0.47 - .73)	4	
	High (0.73 - 1.02)	3	
	Very High (1.03 - 1.67)	2	
Slope (degree)	Flat (0 - 1.1)	8	0.07
	Gentle (1.2 - 4.4)	6	
	Moderate (4.5 - 9.4)	4	
	Steep (9.5 - 25)	3	
	Very steep (26 - 47)	2	
Rainfall (mm)	Very low (510 - 630)	2	0.09
	Low (640 - 740)	3	
	Moderate (750 - 870)	4	
	High (880 - 1000)	5	
	Very high (1100 - 1200)	6	
TWI	3.4 - 7.4	2	0.07
	7.5 - 8.8	3	
	8.9 - 10	4	
	11 -12	5	
	13 -18	6	
Roughness	0.01 - 0.34	6	0.05
	0.35 - 0.45	5	
	0.46 - 0.55	4	
	0.56 - 0.66	3	
	0.67 - 0.99	2	
Curvature	-16 - -4.2	2	0.05
	-4.1 - -0.1	3	
	-0.09 - 2.5	4	
	2.6 - 6.8	5	
	6.9 - 15	6	

RESULTS AND DISCUSSION

Geology

Geological formations with water-bearing properties influence groundwater occurrence and movement (Arkoprovo et al., 2012). The geology map was digitized from the published Geological Survey of India (GSI, 1995) map. A majority of the basin is composed of rock from the archaean Khondalite and Charnockite groups. In the lowlands, Archaean migmatite gneiss can also be found. The coastal plains contain rocks from the Misocene, Quaternary and Recent epochs. Recent kankar and tuffaceous limestone may be observed along the nallahs of the Karamaniyar, Nambiyar and its tributaries. It is generally hard, massive and shows a modular structure. The geological map of the study area is visualized in Fig. 3 (a). Geologically, this region comprises sand/silt, clay, charnockite, gneiss, coastal/alluvial sand and shaly sandstone. A number of variables, including rock types, origins, occurrences, weathering, as well as other factors, are taken into account when calculating the rank and weight. The majority of the study area is made up of gneiss formations which have a low weight. Sand, silt and coastal/alluvial sand contents are given a high weight based on the rock properties. Clay content is given a moderate weight. Charnokite is given a low weight.

Geomorphology

The geomorphological features of different landforms are formed by changes in temperature, geochemical reactions, water movement, freezing and thawing and many other processes (Kumar et al., 2016; Rajaveni et al., 2017). Groundwater recharge is greatly influenced by geomorphology (Karanth, 1987). groundwater potential is good to very good in geomorphologic units, such as valley fill and flood plain (Figure 3 (b)), plateaus, sediments, coastal and alluvial plains. By drilling a well in these geomorphological features, farmers can have a long-term source of water for pumping. Denudational hills are generated through erosion and weathering, but they are weak at absorbing surface water (Ramaiah et al., 2012). The pediment is the gently sloping surface that forms the transition between the hill and the plain. It has a huge land area and a low groundwater potential. groundwater potential is good in geomorphic units, such as coastal sand and coastal ridges, while groundwater potential is moderate in Bajada and the eolian plain.

Land Use / Land Cover (LU/LC)

Land use denotes human activities, such as agriculture, habitation and industry, whereas land cover refers to land characteristics, such as lakes, mountains, plateaus and rocks. Land use/land cover (LU/LC) patterns influence the rate and amount of groundwater recharge. The LU/LC classes in the region are delineated from LISS-III satellite data using supervised classification (Omar et al., 2020b) in ArcGIS. In ArcGIS, the maximum-likelihood classification tool was used to classify landus. The algorithm used by the Maximum Likelihood Classification tool is based on two principles: (1) The cells in each class sample in the multi-dimensional space are normally distributed; (2) Bayes' theorem of decision-making. Figure 3 (c) depicts the pattern of land use, which includes agricultural land (cropland, fallow land and plantation), built-up land, woodland, saltpan, wasteland (land with or without brush, stony waste) and water bodies.

Lineament Density

The GSI (1995) geology map, satellite data and field trips are used to create the lineament map. It may be identified using the linear alignments in satellite images. Lineaments are extracted from LISS-III satellite data using the automated lineament extraction method (Nampak et al., 2014; Arulbalaji and Gurugnanam, 2016). Figure 3 (d) illustrates the lineament density generated in ArcGIS using the line-density tool. The distance between lineaments is used to rank lineament density. The lineament density was classified into five lineament density zones, such as 0-0.16 km/km^2 (very low), 0.17-0.38 km/km^2 (low), 0.39-0.55 km/km^2 (moderate), 0.56-0.75 km/km^2 (high) and 0.76-1.2 km/km^2 (very high). The groundwater potential is very good in high lineament density zones which have high infiltration capacity and it gradually reduced towards the low density zone. As a result, a high rank was given to high density zones and a low rank to low density zones.

Drainage Density

The topography, slope and sub-surface conditions all have an impact on an area's drainage. The drainage density is derived by dividing the total length of all streams and rivers in a drainage basin by the entire area of the drainage basin (Rajaveni et al., 2017). Drainage density is inversely related to permeability. The greater the drainage density, the greater the run-off and the lower the rate of water percolation into the subsurface. As a result, groundwater potential is extremely low in high-drainage density zones. At low-drainage density, infiltration is greater, implying that the groundwater potential is greater. The drainage pattern is primarily parallel to sub-parallel in nature (Fig. 1). Figure 3 (e) illustrates the drainage density estimated using the Kernel density approach to understand the ability of the watershed to favour groundwater potential. The drainage density of this region is classified into five drainage density zones, such as very low (0-0.20 km/km^2), low (0.21-0.47 km/km^2), moderate (0.48-0.73 km/km^2), high (0.74-1.02 km/km^2) and very high (1.03-1.67 km/km^2). A high rank was provided to extremely low and low drainage density zones for the purpose of identifying groundwater potential zones, while a low rank was assigned to high-and very high drainage density zones (Rashid et al., 2012).

Slope

The slope is an important groundwater recharge-controlling parameter, particularly in mountainous watersheds. Because of the steep slopes, there will be a quick runoff, increased soil erosion and a lack of groundwater recharge (Singh et al., 2013). The slope of the region is calculated using SRTM DEM data. The slope is a major topography feature that represents the ground surface's steepness. The groundwater potential is high on the flat terrain which allows more water to infiltrate into the sub-surface system. Figure 3 (f) illustrates the slope map. The slope values in degrees were grouped into five categories: flat (0-1.1), gentle (1.2-4.4), medium (4.5-9.4), steep (9.5-25) and very steep (26-47). Flat and gentle slopes are given a high rank. A low rating is given for steep and very steep hills.

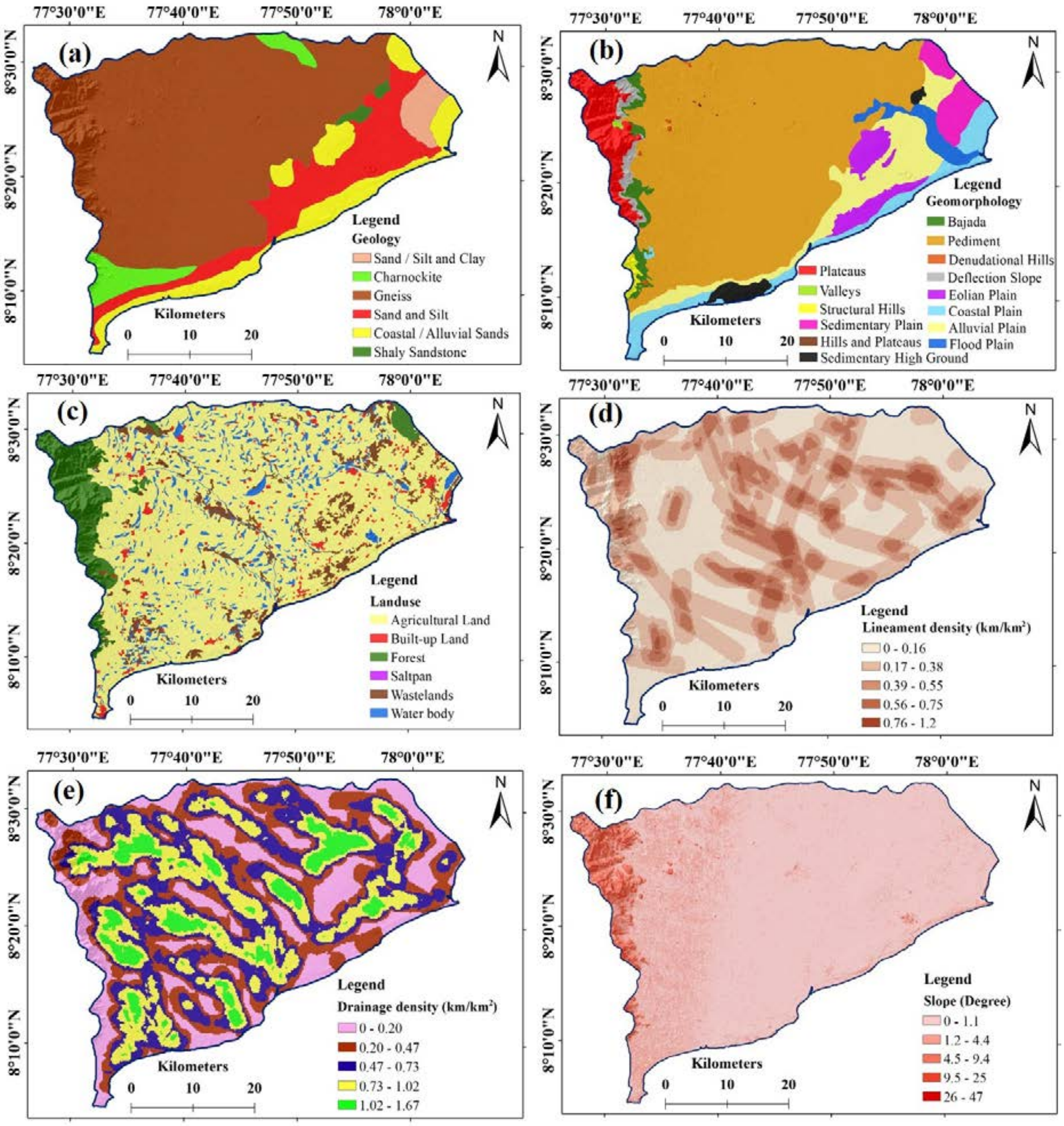

Figure (3): (a) Geology; (b) Geomorphology; (c) Land use/land cover map; (d) Lineament density (e) Drainage density; (f) Slope map of the study area

Soil

Figure 4 (a) represents the soil classification based on the National Bureau of Soil Survey (NBSS). Alfisols, entisols, hill soil, inceptisols, reserve forest and vertisols are the different types of soil found in this area. Most of the study area is covered by entisols and inceptisols. Entisols and inceptisols were given a higher rank than alfisols and vertisols, because these two groupings include considerable amounts of sand, which is more conducive to groundwater recharge. Vertisols and alfisols are assigned a moderate ranking, since they include a large amount of clay and expansive clay. Hill soils and reserve-forest soils are given a low rank, indicating that they receive less groundwater recharge than other soils.

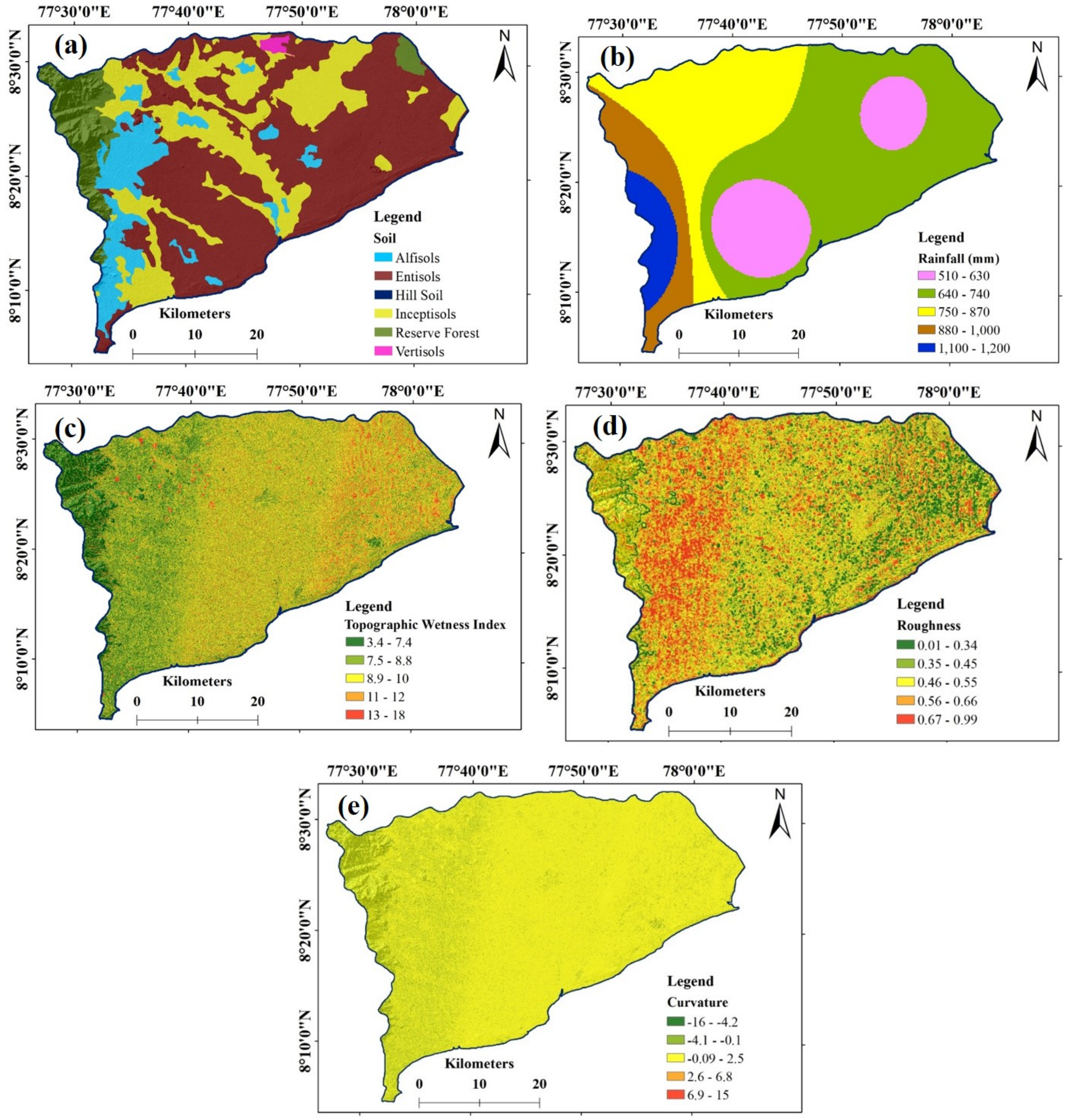

Figure (4): (a) Soil map; (b) Rainfall map; (c) Topographic wetness index; (d) Roughness; (e) Curvature map of the study area

Rainfall

Rainfall is the most significant source of water in the hydrological cycle, as well as the most influential factor on groundwater levels in the study area. The rainfall data in this study is based on a five-year average. Rainfall in the study region is influenced by both the southwest and northeast monsoons. The northeast monsoon, which is brought in by low-pressure troughs that form in the south Bay of Bengal between October and December, is chiefly responsible for the rainfall in this area. Annual precipitation ranges from 510 to 1200 mm. In ArcGIS, a rainfall-distribution map was created by using the kriging interpolation method (Figure 4 (b)). The interpolated rainfall was classified into five different zones, such as very low (510-630 mm), low (640-740 mm), moderate (750-870 mm), high (880-1000 mm) and very high (1100-1200 mm). The amount of rain and how long it falls have an impact on infiltration. Rainfall with a high intensity and a short duration results in more surface runoff and less infiltration, whereas rain with a low intensity and a long duration results in more infiltration and less surface runoff (Abuzied et al., 2015). Due to the lack of availability of rainfall duration and frequency, the average rainfall is considered to detect groundwater potential. A high rank was assigned to the zones with very high to high rainfall and a low rank was assigned to low-to very low-rainfall zones.

Topographic Wetness Index (TWI)

The Topographic Wetness Index (TWI) assesses the potential for groundwater penetration as a result of topographic characteristics (Mokarram et al., 2015). It is frequently used to evaluate the topographic influence on hydrological processes. TWI was mapped using ArcGIS 10.2 using a slope map created from a DEM. This was accomplished by using Eqns. (6) and (7) to calculate the rate of change of an aspect of a cell grid within its neighborhood (Hojati and Mokarram, 2016). To integrate the impacts of slope, elevation and landform on groundwater development, the TWI map was used (Pourali et al., 2016). It computed the effect of topographic roughness, hillslope and foothill on lateral groundwater flow. TWI-rich areas allow for the determination of locations with high soil-moisture accumulation and infiltration potential, which are unique to foothills (Arulbalaji et al., 2019). The study area's TWI ranged from 3.4 to 18, as shown in Fig. 4 (c). The results were classified into five zones based on the natural breaks (Jenks) method. Jenks natural breaks classification method is a data-clustering method designed to determine the best arrangement of values into different classes. This is done by seeking to minimize each class's average deviation from the class mean while maximizing each class's deviation from the means of the other classes. Five zones of TWI are very low (3.4-7.4), low (7.5-8.8), moderate (8.9-10), high (11-12) and very high (13-18). A high rank was assigned to zones with high to very high TWI values and a low rank was assigned to low-to very low-TWI value zones.

$$TWI = \ln\left[\frac{a}{tan(\beta)}\right] \quad \text{Eqn. (6)}$$

$$a = \frac{A}{L} \quad \text{Eqn. (7)}$$

where tan(β) represents the slope, 'a' represents the specific catchment area which can be calculated as an 'A' area above the contour line and L represents the length of the contour line.

Roughness

The amount of elevation variation between consecutive cells is expressed by the roughness index of a digital elevation model (DEM) (Riley, 1999). The topography's undulation is often expressed by the roughness index. More undulated terrains have high roughness values. In the long term, weathering and erosion processes turn a craggy landscape into a smooth and flat surface, resulting in undulated topography in a mountainous area. The roughness map was generated from the slope map in ArcGIS using spatial analysis and the raster calculator tool. The first slope map was reclassified using the spatial analyst tool. Then, the reclassified map is considered as input to calculate focal statistics using the raster calculator tool. The output generated in focal statistics is a roughness map as illustrated in Figure 4(d) with values ranging from 0.01 to 0.99. The roughness values were divided into five zones: very low (0.01-0.34), low (0.35-0.45), moderate (0.46-0.55), high (0.56-0.66) and very high (0.67-0.99). Low to very low roughness values are given high ranks, while high to very high roughness zones are provided low ranks.

Curvature

Curvature is a numerical expression of a surface profile's nature, which might be concave or convex upward (Nair et al., 2017). In the convex and concave profiles, the water slows down and collects (Arulbalaji et al., 2019). Grounds with gentle slopes usually have a concave upward profile, which helps recharge a good amount of water. The steep slope has a convex profile which reduces water recharge. The study area's curvature ranged from -16 to 15, as shown in Fig. 4 (e). The curvature values are classified into five zones: extremely low (-16 to -4.2), low (-4.1 to -0.1), moderate (-0.09 to 2.5), high (2.6 to 6.8) and very high (6.9 to 15). For estimating groundwater potential, high curvature zones were given a high rank, whereas low curvature zones were given a low rank.

Groundwater Potential Zone (GWPZ)

Groundwater occurrence in this basin is mostly governed by weathered zones, jointed and crack parts. The weight of each thematic map is determined by AHP. Using ArcGIS 10.2, the eleven thematic maps were converted into raster format with a cell size of 30.91 m * 30.91 m and multiplied with determined weights and ranks. By integrating all layers in the ArcGIS raster calculator, a weighted overlay analysis was performed to calculate groundwater potential. The weighted overlay tool applies one of the most used approaches for overlay analysis to solve multi-criteria problems. A weighted overlay is an overlay approach that reclassifies the values of a series of input rasters to a specified scale and weights the importance of each layer. The weighted overlay result was divided into five categories based on the natural breaks of Jenks optimization approaches. Jenks classification method can be advantageous, because if there are clusters in the data values, it will identify them. The final groundwater potential map was created using Equation (5), which includes very low, low, moderate, high and very high groups, with spatial distributions of 0.5 km^2, 10 km^2, 28 km^2, 6 km^2 and 0.5 km^2, correspondingly (Fig. 5 (a)).

A high groundwater potential zone was found in the northeastern side of the study area where alluvial deposits, wasteland and flood plain were found predominantly. Despite receiving modest rainfall, the groundwater potential in this region is high due to increased lineament density, lowest drainage density and a high topographic wetness index; this region falls within the very high and high potential zones. Similarly, in the southwest, where rainfall intensity is strong, all of the water becomes run-off due to higher drainage density, high slope, reserved forests and high roughness, allowing very little water for recharge. As a result, such areas were discovered to have a very low potential zone. A very low potential zone was discovered in the region's north, where rock outcrops are present with little or no recharging. Because of improved geology, geomorphology favoring, moderate roughness and topographic wetness index, the highest 28 percent of the study area falls into the moderate potential zone in the centre half of the study area. The area covered with moderate drainage density has moderate groundwater potential zones. The majority of the high groundwater potential zone is located in the northeastern region, where sedimentary rocks are created. The current study is very valuable for water-resource management, because it shows potential development zones which help construct artificial recharge structures to improve groundwater recharge and can solve the critical zone of water development. More research may be done on the suitability of groundwater for various applications, as well as the amount of groundwater recharge and its relationship to rainfall.

The groundwater potential zone delineated by weighted overlay analysis was cross-checked with pre-monsoon and post-monsoon water-level data obtained from the Central Groundwater Board over the previous 5 years. About 13 observation wells were selected in and around the study region to check the extent of recharge. Figure 5 (b) shows that wells 3, 4, 5 and 11 have increased groundwater levels during pre-and post-monsoon in 2019 which were found to fall within the very high potential zone. Similarly, wells 6, 9 and 12 have a minimum or low recharge, as they lie in the low potential zone. The groundwater level is observed to be higher in the very high and high groundwater potential zones than in the low potential zone. As a result, the obtained results are more closely related to actual field data.

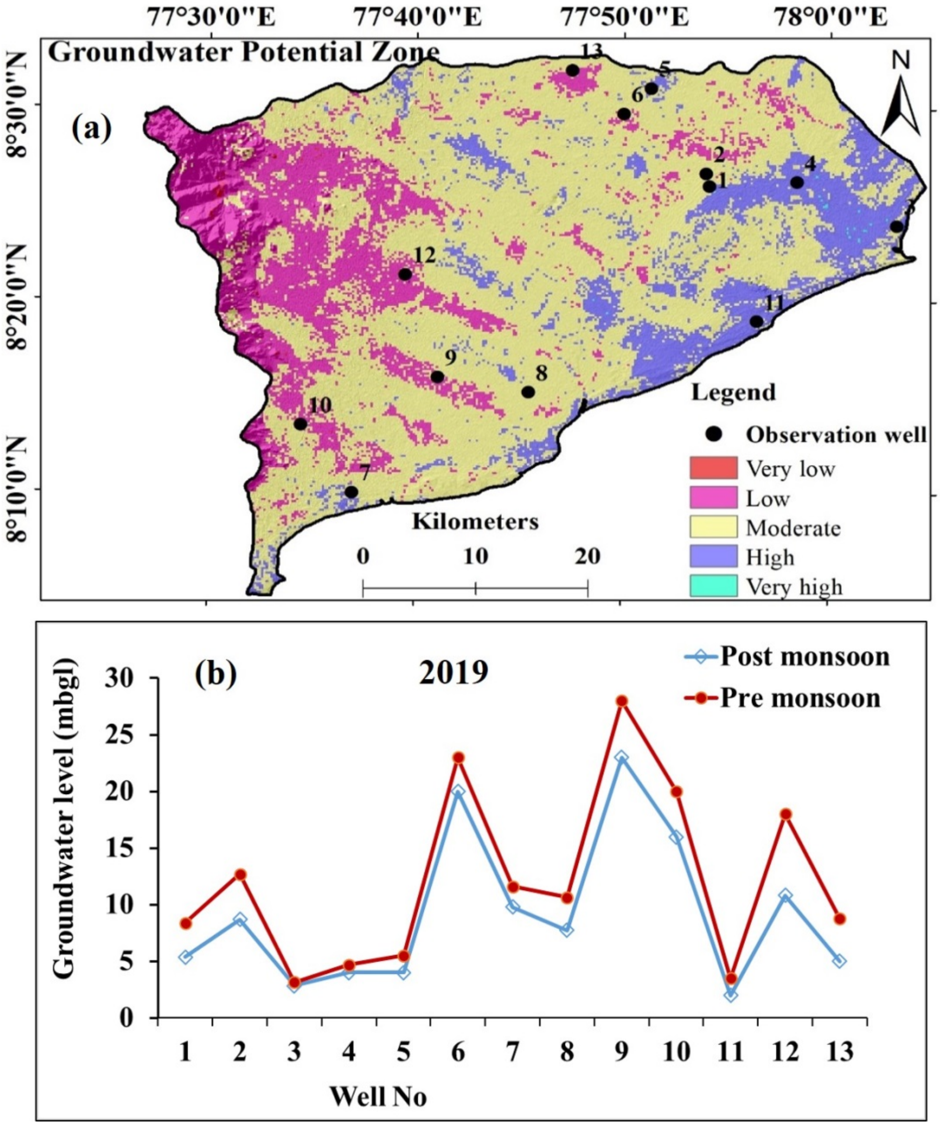

Figure (5): (a) groundwater potential zones of the study area; (b) Pre- and post-monsoon variations in groundwater level

CONCLUSION

The integrated approach of remote sensing, GIS and AHP represent the best way to identify GWPZs used in the Nambiyar river basin. All thematic maps used to designate groundwater potential zones are stored, analyzed and integrated using GIS. The research region may be divided into five separate groundwater potential zones based on the final output map, such as very high, high, moderate, low and very low. The high groundwater potential zone includes the water body, valleys, alluvial plain, low slope, sand, silt, high lineament density, entisols, low region of roughness and low drainage density regions. Wetland areas, medium slopes, plateaus and vertisol soils had medium groundwater-potential, whereas hills, valleys, wasteland, low curvature, low value of topographic wetness index and built-up regions had low groundwater potential. This region has 14% of its land in high 64% in the medium and 22% in the low groundwater potential zones. The low and medium groundwater potential zones changed more than the high groundwater potential zone, showing that the groundwater potential zones were verified using groundwater level data. This was caused by a low recharge rate in the low and medium groundwater potential zones and a high recharge rate in the high groundwater potential zone. The main advantage of this integrated approach is that GIS-based methods provide quite precise results and take less computation time for identifying the GWPZs compared to the traditional field methods. Hence, this study provides information to decision makers about how to improve and manage groundwater resources. This study also will help meet the water needs for domestic, agricultural, small-and large-scale industrial uses, since the estimation of groundwater resources for the Nambiyar basin has indicated that the basin is over-exploited and critical, requiring prompt attention. A major limitation of this AHP method includes the high computational requirements even for small problems, having a subjective nature.

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