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Delineation of groundwater potential zones using remote sensing and Geographic Information Systems (GIS) in Kadaladi region, Southern India

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Abstract: The primary objective of this research is to delineate potential groundwater recharge zones in the Kadaladi taluk of Ramanathapuram, Tamil Nadu, India, using a combination of remote sensing and Geographic Information Systems (GIS) with the Analytical Hierarchical Process (AHP). Various factors such as geology, geomorphology, soil, drainage, density, lineament density, slope, rainfall were analyzed at a specific scale. Thematic layers were evaluated for quality and relevance using Saaty's scale, and then integrated using the weighted linear combination technique. The weights assigned to each layer and features were standardized using AHP and the Eigen vector technique, resulting in the final groundwater potential zone map. The AHP method was used to normalize the scores following the assignment of weights to each criterion or factor based on Saaty's 9-point scale. Pair-wise matrix analysis was utilized to calculate the geometric mean and normalized weight for various parameters. The groundwater recharge potential zone map was created by mathematically overlaying the normalized weighted layers. Thematic layers indicating major elements influencing groundwater occurrence and recharge were derived from satellite images. Results indicate that approximately 21.8 km^2 of the total area exhibits high potential for groundwater recharge. Groundwater recharge is viable in areas with moderate slopes, particularly in the central and southeastern regions.

Keywords: Groundwater; Satellite image; Remote sensing; GIS techniques; Analytical Hierarchy Process (AHP)

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Introduction

Water is essential for human survival, playing a crucial role in both rural and urban areas. The growing demand for water is influenced by factors such as high infiltration rates, deforestation, reduced precipitation, and urban growth, as studied by Abishek and Ravindran (2023). Groundwater depletion is driven by escalating urbanization, agricultural activities, and population growth, emphasizing the urgent need for effective resource management and the implementation of artificial recharge structures to mitigate the water crisis prevalent in the region (Fu et al. 2023). Groundwater, accounting for approximately 34% of the global fresh water supply, holds paramount importance in India, meeting about 90% of rural and 50% of urban water demands, and around 70% of agricultural needs. However, the escalating demand for water, driven by population growth, economic development, and climate change, has led to severe water scarcity worldwide, with India facing significant challenge in groundwater management due to excessive usage and declining water levels, as highlighted by Murmu et al. (2019) and Chenini and Msaddek (2020). To address these challenges, effective groundwater management strategies, including the utilization of artificial recharging structures are imperative. An in-depth exploration of the local hydrogeological context is essential, considering the intricate link between groundwater in coastal regions, geological formations, land use patterns, and human activities. Incorporating rele-

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vant background information could involve conducting a detailed analysis of the geological characteristics of the Quaternary sediments, examining the impact of sea level variations on groundwater dynamics, and investigating anthropogenic influences on the coastal aquifer system, as discussed by Muduli et al. (2023). Groundwater serves a vital water supply for drinking and farming, especially in areas with arid to semiarid climates. Many non-perennial river basin ecosystems around the world, particularly those in southern India, heavily rely on groundwater for drinking and irrigation purposes. To address the complexities of water-related challenges, geospatial technology has been used to create various thematic layers, as highlighted by (Rajasekhar et al. 2018). Recent advances in geospatial technologies, particularly when integrated with Geographic Information Systems (GIS) and remote sensing, have significantly enhanced the capability to detect groundwater zones, producing remarkably accurate results. These technologies aid in the identification of high-potential artificial recharge sites in both accessible and inaccessible areas. The latest GIS and remote sensing advances enable precise monitoring of groundwater quality and levels across a wide range of spatial distributions. Integrating thematic layers into GIS and extracting surface features from satellite remote sensing data have simplified the identification of suitable locations for artificial recharge beds, particularly in challenging terrains. Geostatistical modeling, applied to geospatial layers, has yielded promising results in identifying suitable locations for artificial groundwater recharge. Utilizing remote sensing and GIS analysis to assess various geoenvironmental properties, including site-specific geo-hydrological processes, provides a reliable mapping methodology for groundwater potential zones, as demonstrated by Sathiyamoorthy et al. (2023). Remote sensing data, encompassing spectral, temporal, and sensor readings, provides critical information about the Earth's surface, facilitating the identification of potential groundwater recharge zones using RS and GIS approaches. This is especially evident when using satellite imagery to create layers for geology, soil, land use, slope, lineament, and drainage. Numerous published studies outline methodologies for defining groundwater recharge zones using GIS and the Analytical Hierarchical Process (AHP). AHP systematically evaluates multiple datasets using pairwise comparison matrices, simplifying the calculation of geometric means and normalized weights for various variables. Incorporating spatial parameters such as geological structure, geomorphic features, and hydrological characteristics is essential for accurately identifying groundwater recharge zones, often associated with surface runoff dynamics. Saaty (1980, 2001) initially employed AHP to address socioeconomic decision-making issues between 1980 and 2001. Downscaling studies, utilizing empirical algorithms and GIS methods, efficiently combine multiple characteristics, resulting in intricate maps depicting groundwater potential zones when combined with statistical techniques for predicting reservoir inflows. The significance of downscaling analysis, statistical approaches in water resource management, and the critical role of GIS technologies in integrating criteria to accurately identify groundwater potential zones are extensively discussed in Alharbi et al. (2023).

Groundwater serves as a crucial resource for agriculture and domestic purposes, particularly in regions with arid to semiarid climates like the Kadaladi region in southern India. Recent advances in geospatial technology, particularly remote sensing and Geographic Information Systems (GIS), have created new opportunities for studying and managing groundwater resources. These technologies enable the analysis and integration of various spatial and non-spatial data layers, resulting in a more comprehensive understanding of the factors influencing groundwater occurrence. Sustainable management of groundwater resources is critical for ensuring their long-term availability and preventing adverse environmental impacts. Identifying the potential zones for groundwater recharge is essential for sustainable water resource management. This research aims to enhance the detection, assessment, and management of groundwater resources by utilizing cutting-edge geospatial technologies, such as remote sensing and GIS. The objective is to utilize these technologies to identify potential artificial recharge zones in arid to semi-arid climates, with a special focus on the study area.

1 Study area

The study area encompasses the Kadaladi region of Tamil Nadu State, situated in the Ramanathapuram district, between latitudes 90°6′N to 90°21′N and longitudes 78°18′E to 78°45′E (Fig. 1). It is delineated based on Survey of India toposheets 58K/7, 58K/8, 58K/11, and 58K/12, covering an approximate area of 612 square kilometres. The primary water resource in the region is the Guntar River, flowing through Kadaladi Taluk and draining into the Bay of Bengal. Ramanathapuram experiences average

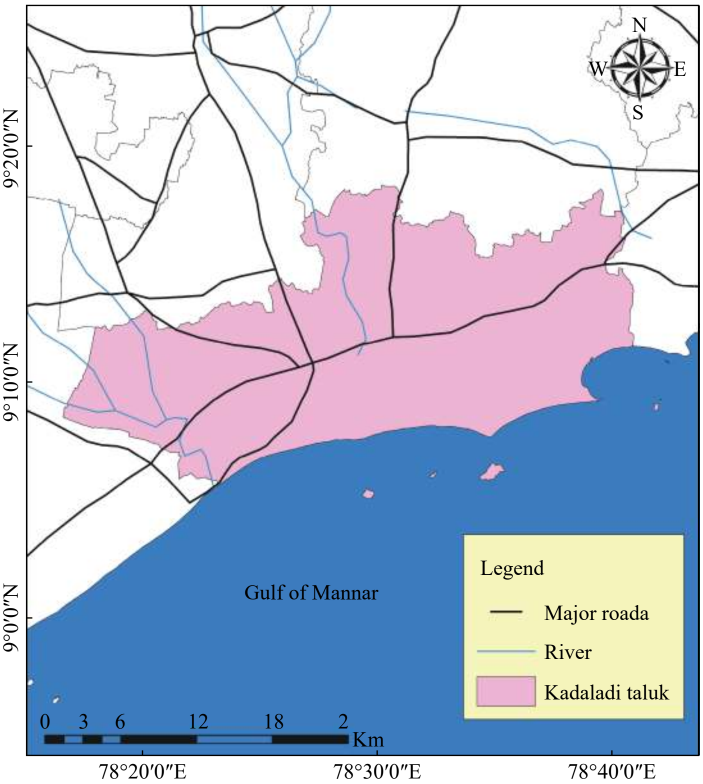

Fig. 1 Location map of the study area

temperature is 28.70 degrees Celsius, with the hottest months being May, June, July, August, and September, and the wettest months being October, November, and December, marked by significant amount of rainfall during the Northeast Monsoon. The weather remains mild from January to April Kadaladi Taluk has a population of 144,386 people, according to the 2011 census.

The Kadaladi block is primarily composed of sedimentary formations, with Quaternary-age deposits such as fluvial, fluvial-marine, aeolian, and marine sediments prevailing in the area (Balasubramanian et al. 2015). Fluvial deposits consist of a mixture of sand, silt, and clay. The western part of the study area exhibits exposure to Archaean rocks, including garnetiferous biotite gneiss, quartzite, and charnockites. The alluvium comprises alternating layers of clay and sand, ranging from 15 m to 25 m in thickness, with freshwater lenses confined to depths of 6–7 m below ground level. These lenses can pump for up to 2 hours, producing approximately 2–5 L/s. Dug wells (3–6 m depth) are preferred over bore wells (30–50 m) for extracting high-quality groundwater, which floats on saline water. The narrow land strip between red sand dunes, running parallel to the coast for approximately 10 km, and the coastline itself, exhibit relatively good-quality water.

2 Data sources and data processing

The term "groundwater recharge" refers to the process of water entering the saturated zone from the unsaturated zone beneath the water table, along with the corresponding outflow from the saturated zone. Various approaches, including geological, hydrogeological, and Remote Sensing (RS), can be employed to determine groundwater recharge potential zone of a region. In the present study, groundwater potential was determined by integrating data from diverse sources for each criterion to develop a thematic database for individual parameters. The litho units exposed in the area were extracted from a resource map created by the Geological Survey of India (2002) and subsequently analyzed for lithological investigation during the study. Additionally, the slope map of the area was created by extensive topographic processing of digital elevation data obtained from the Shuttle Radar Topography Mission (SRTM). Rainfall data sourced from the IMD website were utilized to create the area's slope map, alongside the comprehensive topographic processing of the Shuttle Radar Topography Mission's (SRTM), Digital Elevation Map (DEM) acquired from the USGS Earth Explorer.

$$\text{Consistency Index}\,(CI) = \frac{\text{Max principal Eigen value}\,(\lambda) - \text{Number of factors}\,(n)}{\text{Number of factors}\,(n) - 1} \tag{1}$$

$$\text{Consistency Ratio}\,(CR) = \frac{\text{Consistency Index}\,(CI)}{\text{Random consistency Index}\,(RI)} \tag{2}$$

So:

$$\text{Consistency Index}\,(CI) = \frac{6.5 - 5.7}{8 - 1} = \frac{0.8}{7}$$

$$\text{Consistency Index}\,(CI) = 0.11$$

$$\text{Consistency Ratio}\,(CR) = \frac{0.11}{1.41} = 0.07$$

To determine the percentage influence of these prepared layers, the AHP pairwise comparison decision-making technique is utilized, following the methodology outlined by Saaty (2001, 2008). The concept of hierarchy is employed in this study to assess groundwater potential, as described by Saranya et al. (2020). The groundwater potential zone is structured into eight thematic layers, each comprising various feature classifications. Tables 1 and 2 present the results of the comparison matrix's evaluation depicting the relationships between each layer. In Tables 3 and 4, the primary Eigenvalue of this matrix is considered to determine the percentage influence of thematic layers. Finally, the consistency ration, consistency ratio and consistency index are calculated using the following formulas to ensure the stability of the analysis is 0.078, indicating that the pairwise comparison has a reasonable level of consistency. Accordingly, weights of 0.19, 0.16, 0.15, 0.13, 0.13, 0.1, 0.08, and 0.06 (i.e. 5%, 22%, 10%, 15%, 12%, 20%, and 14%, respectively) are assigned to geomorphology, geology, Land Use and Land Cover (LULC), lineaments density, drainage density, Digital Elevation Models (DEM), slope, and rainfall, as shown in Table 4 for the various themes.

3 Results and discussion

Table 1 The fundamental scale of AHP (Saaty, 1980)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential of strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring 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 Saaty's ratio index for different values of N

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

Table 3 The resulting weights are based on the principal Eigen vector of the decision matrix

Thematic layers	Geomorphology	Lithology	LULC	Lineament density	Drainage density	Slope	Rainfall	DEM
Geomorphology	1	2	3	6	5	4	3	5
Lithology	0.5	1	2	6	5	4	3	2
LULC	0.33	0.5	1	2	2	4	3	2
Lineament density	0.17	0.17	0.5	1	1	2	3	2
Drainage density	0.2	0.2	0.5	1	1	4	3	2
Slope	0.25	0.25	0.25	0.5	0.25	1	3	2
DEM	0.33	0.33	0.33	0.33	0.33	0.33	1	1
Rainfall	0.2	0.5	0.5	0.5	0.5	0.5	1	1

Table 4 These are the resulting weights for the criteria based on your pairwise comparisons

Categories		Priority	Rank
1	Geomorphology	30.90%	1
2	Lithology	23.30%	2
3	LULC	13.20%	3
4	Lineament density	7.70%	5
5	Drainage density	9.30%	4
6	Slope	6.00%	6
7	DEM	4.50%	8
8	Rainfall	5.20%	7

3.1 Geomorphology

Geomorphology is the study of the Earth's surface characteristics and their relationship with geological formations (Fig. 2). In the Ramanathapuram District, the geomorphology encompasses a 260-kilometers-long coastline. The coastal regions are characterized by a beach ridge complex, consisting of sand dunes, swales, marshes, and backwaters. Another notable coastal feature is the sand flat, composed of clays and silts, often covered with salt and submerged in seawater. Except for a few remaining hills in the western part, the district is predominantly a gentle sloping plain towards the sea, comprising gneiss laterite, clay, silt, and sand formations. Along the western border of the study area, a small piece of Archaean rock, primarily composed of gneisses and charnockite, is exposed. Satellite imagery is utilized to map hydro geologically significant palaeo-channels along the Gundar River. The red sands of the Aeolian deposits represent ancient dunes stretching over 3.2 km wide and 8 km long parallel to the coast. There deposits consist of black clay and marshy deposits, with a calcareous hardpan underlying the sand. The geomorphology of the study area has been classified based on its percentage composition. This classification includes Other Water Bodies (11%), Pediment Pediplain Complex (8.2%), Flood Plain (2.1%), River Water Bodies (0.9%), Salt Pan (0.7%), Aeolian Sand Dune (0.5%), Aeolian interlunar depression (0.5%), and Palaya (0.09%).

3.2 Lithology

The lithological composition of Kadaladi Taluk encompasses various sediment types. The predominant lithology is black silty clay, covering 55.7% of the area. Another significant component is the brown silty clay of the Palaeo Tidal Flat, accounting for 12.7% of the land. The Palaeo beach ridge

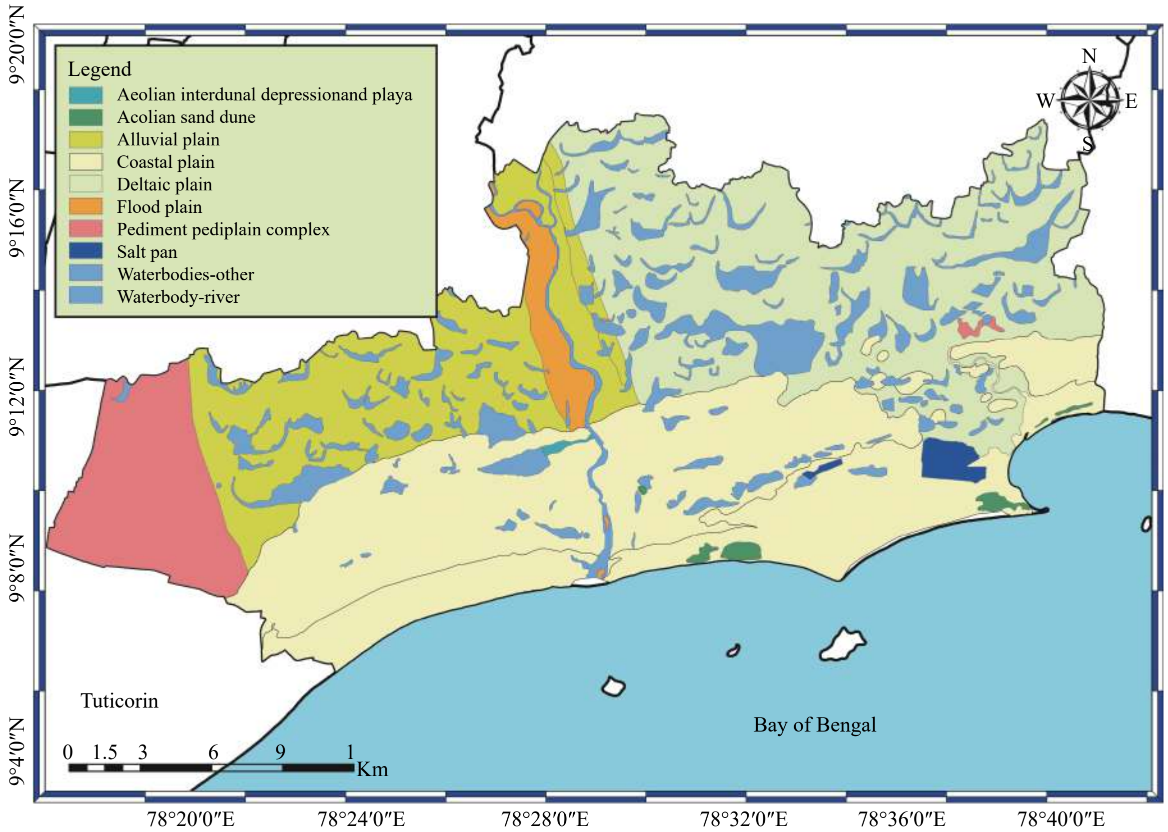

Fig. 2 Geomorphology map of the study area

consists of brown, fine sands along the Taluk coastline edge, accounting for 6.3% of the total area. The southwestern and southeastern parts of the taluk contain distinct patches of reddish sand (16.5%), coral sand (0.1%), and black clay (6.8%). The Guntar River, flowing through the taluk, deposits coarse sand and rock fragments covering 0.7% of the region. Additionally, intermittent deposits of channel and point bar formations contain 0.2% sand. Tidal Channel Bar, which contains less than 0.02% gray fine sand and 0.3% hornblende biotite gneiss, is another notable feature in the area. This comprehensive understanding of lithological distribution sheds light on the diverse geological formations of the Kadaladi Taluk, providing a solid foundation for future geological and hydrological studies in the region (Fig. 3).

3.3 Land use and land cover

Land Use and Land Cover (LULC) maps were created using LANDSAT-8 satellite images from the ESRI website and GIS tools. These maps show the distribution and natural characteristics of land resulting from human activities. Data analysis reveals significant changes in land cover attributes driven by the local economic downturn, particularly the rapid conversion of agricultural fields into development areas. The study area exhibits distinct LULC patterns, including highland regions with evergreen forests and scrublands, midland areas featuring agriculture and fallow areas, and lowland zones comprising built-up areas (Arulbalaji et al. 2019). Various land use types such as terrains, water bodies, mud land, flora, villages, barren ground, and shrub covers are identified within the research area. Each type of land use is assigned a weight based on its coverage area, infiltration rate, and capacity to hold surface water. Agricultural lands and water bodies receive significant weight due to their high-water retention capabilities, whereas barren land settlements are assigned lower weights. The classification of land use and cover ranges from extremely low to extremely high, with water covering 4%, crops covering 61.1%, rangeland covering 25.9%, built-up areas covering 4.8%, vegetation covering 2.5%, and barren terrain covering 4.8% (Fig. 4).

3.4 Lineament density

Lineament structures play a crucial role in channeling surface water runoff to underground aquifers. These structures, which represent linear or curved geological features beneath the Earth's surface,

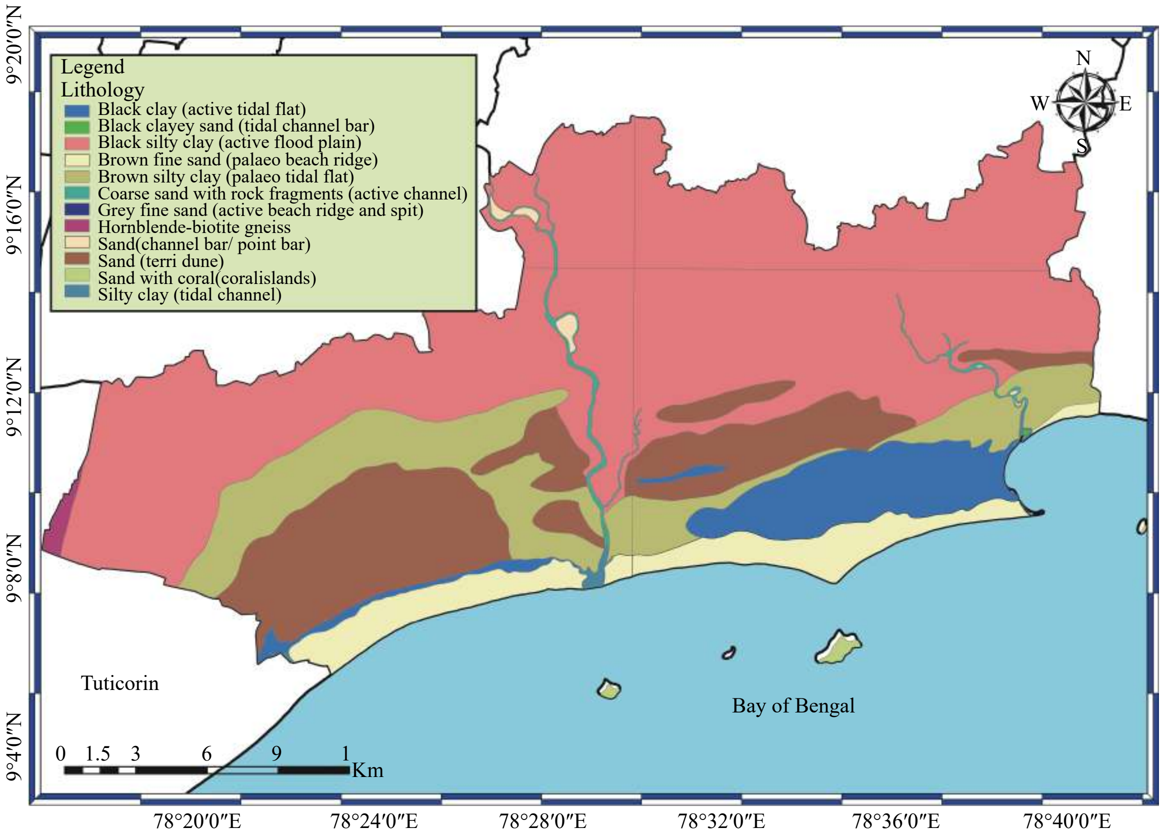

Fig. 3 Lithology map of the study area

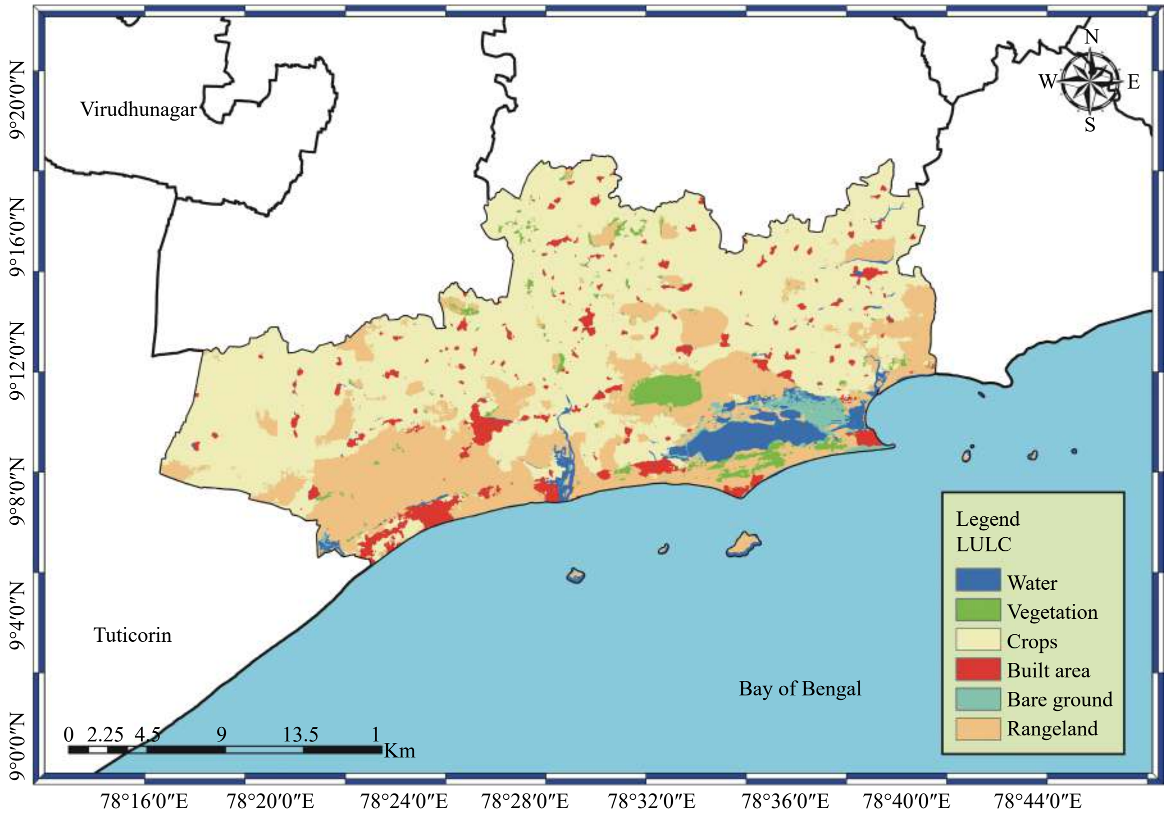

Fig. 4 Land use and land cover map of the study area

appear as folds, fractures, or faults at the Earth's surface. Lineaments often exhibits linear and curved alignments when analyzed using satellite data for soil texture, vegetation, drainage, soil tonalities, and relief. Mapping these lineaments with satellite imagery is valuable for investigating groundwater potential, as they may indicate geological features such as joints, bedding planes, faults, fractures, or geological connections. Lineaments have key characteristics such as high porosity and hydraulic conductivity, which influence groundwater potential. Lineament density is categorized into five levels, ranging from extremely low to extremely high. The distribution across these categories includes low (12%), medium (7.1%), high (0.7%), very high (0.7%), and very low (79.3%). This classification highlights the prevalence and significance of lineaments in the study area, with higher density categories indicating areas with greater groundwater potential (Fig. 5).

3.5 Drainage density

The drainage pattern of a terrain provides information about both surface features and underlying geological structures. Drainage density plays a crucial role in delineating Ground Water Potential Zone (GWPZ) due to its inverse relationship with permeability. Permeability, influenced by lithology, governs how quickly water can infiltrate the soil, making it an important indicator for understanding drainage characteristics and water movement within the terrain. In the Kadaladi region, drainage density was calculated using DEM data and a Geographic Information System (GIS) application. Various factors influence the overall drainage pattern, including slope, variations in rock strength, structural controls, recent land deformation, and morphological changes. Areas with low drainage density indicate a higher infiltration rate, implying significant groundwater potential. In terms of groundwater potential, regions with low drainage density are prioritized as they exhibit a greater potential for groundwater recharge, whereas zones with high drainage density are assigned less weightage. The coverage percentages for drainage density categories are as follows: 23% (very low), 28.5% (low), 25.2% (middle), 17.7% (high), and 5.3% (very high). These percentages provide a quantitative assessment of the drainage density distribution in the study area, allowing for the identification of zones with varying groundwater potentials (Fig. 6).

3.6 Slope

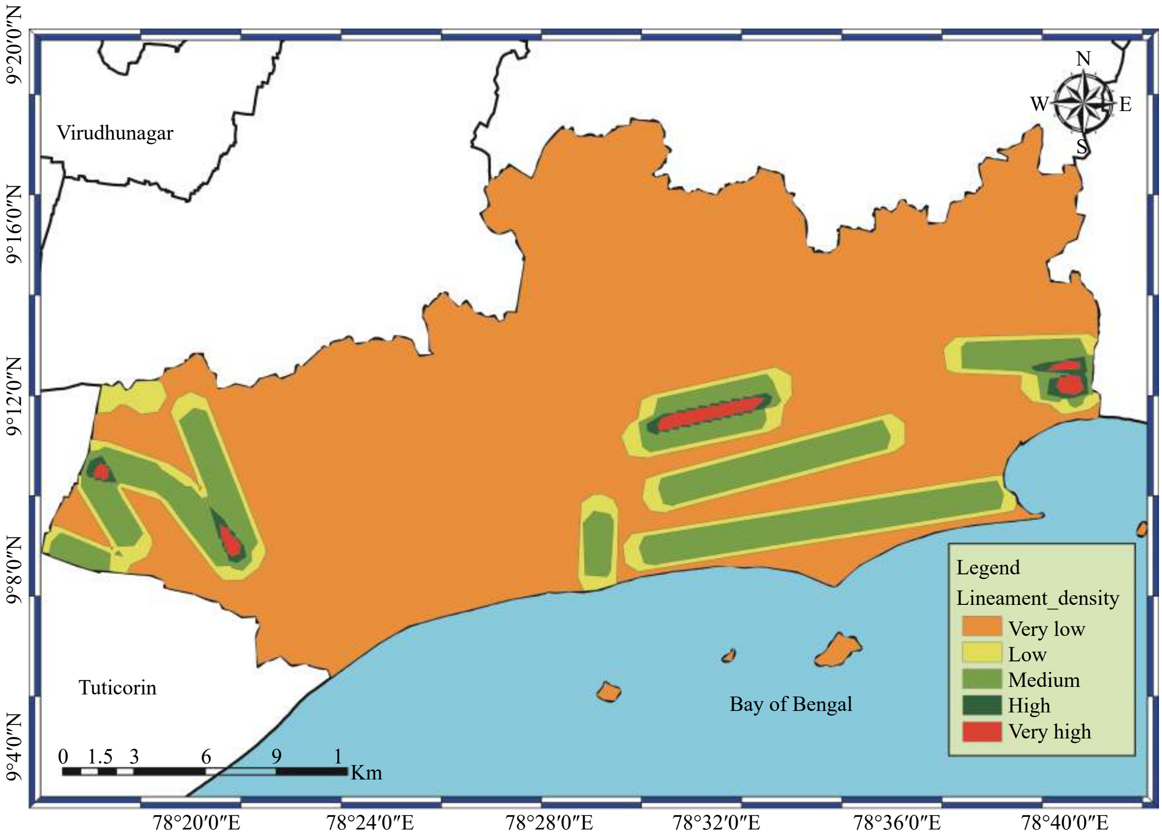

Fig. 5 Lineament map of the study area

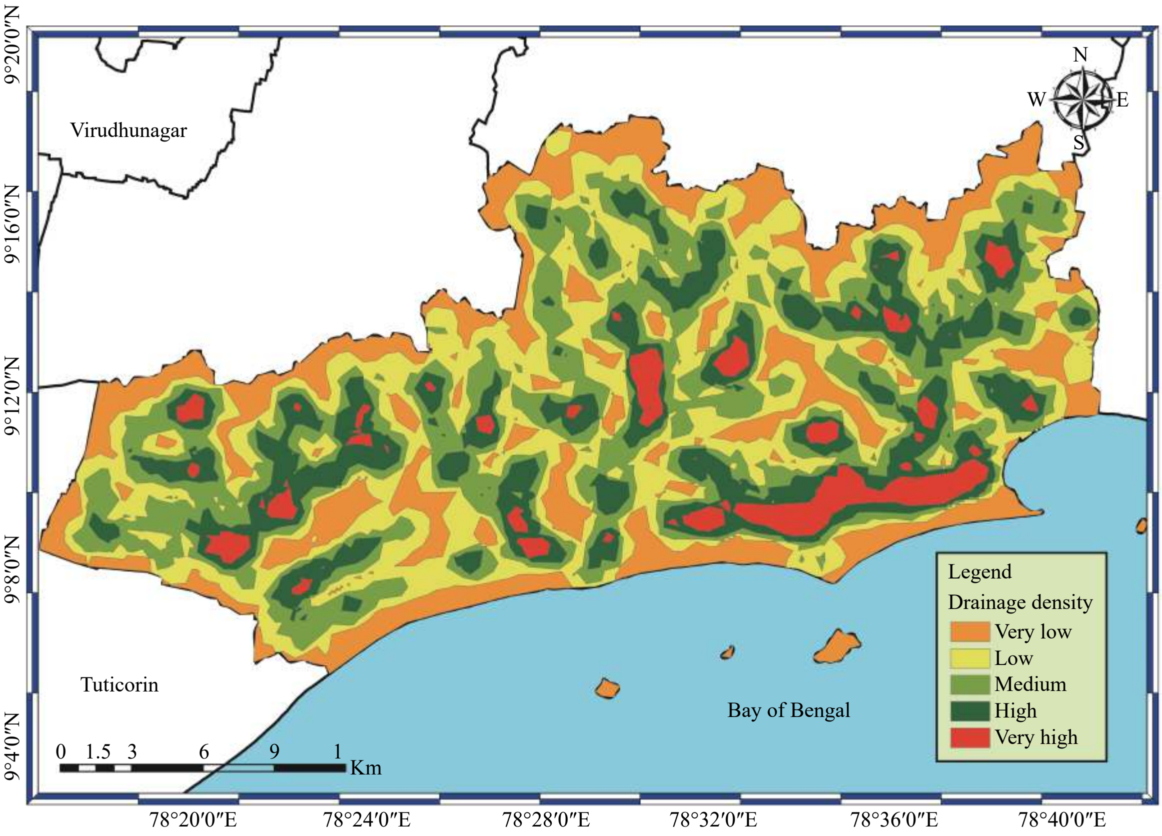

Fig. 6 Drainage map of the study area

The gradient of the terrain significantly influences the amount of infiltration and water retention. Moderate surface slopes tend to facilitate more percolation and less drainage compared to steeper. This phenomenon occurs because water tends to accumulate on the surface of moderate slopes. A slope map generated from SRTM data (Biswajit et al. 2018) provides insight into the elevation characteristics of the terrain. Terrain elevation plays a significant role in defining groundwater potential zones. Lower elevation areas typically retain water for longer periods of time, indicating higher permeability and suitability for recharge zones. Conversely, higher elevation areas experience shorter water retention periods, leading to increased runoff. The study area exhibits slopes ranging from 0 to 15 degrees, highlighting the importance of understanding how these moderate slopes influence water dynamics. Areas with lower slopes receive greater consideration in the assessment of groundwater potential due to their potential for extended water retention and higher permeability, making them ideal for recharge zones. This nuanced consideration of slope variations helps to provide a comprehensive understanding of groundwater dynamics in the study region (Fig. 7).

3.7 DEM

Radar interferometer or stereoscopic optical satellite imagery are useful in satellite remote sensing for generating accurate Digital Elevation Models (DEMs). DEMs, when combined with Geographic Information System (GIS) technology, play an important role in identifying various features such as watersheds, stream networks, and their ordering. These DEMs serves as the foundation for creating contour lines, slope maps, and aspect maps, enabling the extraction of essential information about basins and sub-basins, including their characteristics, dimensions, length, and the drainage network slope. Digital elevation models are reliable and efficient tools for conducting such analyses (Fig. 8). Furthermore, DEMs facilitate the retrieval of key parameters such as area, slope, direction, flow length, and surface flow lengths, which are vital for understanding the terrain's hydrological characteristics. By employing distributed hydrological models, the study reveals the spatial variability of basin physical parameters and enables a thorough assessment of hydrological factors. The primary goal of this study is to use DEMs to determine water flow directions, generate flow accumulation grids, and delineate drainage networks and sub-basin boundaries. The integration of GIS is critical

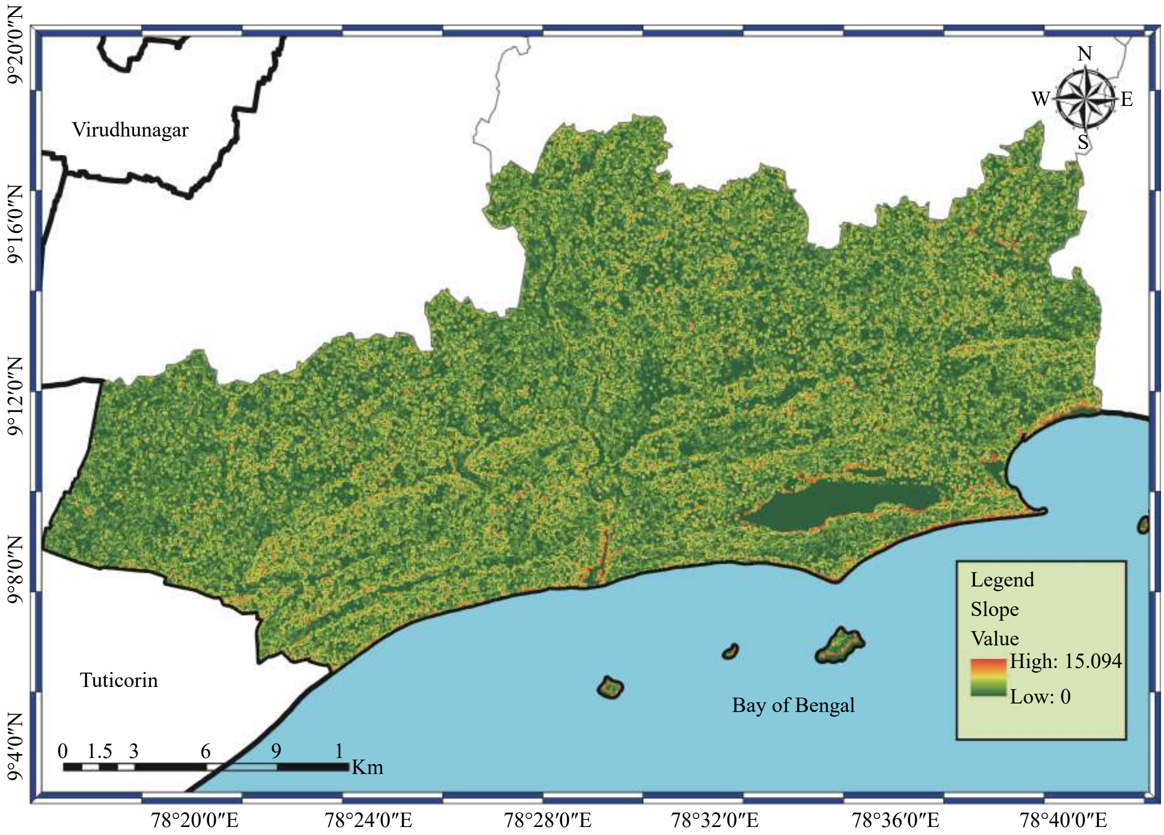

Fig. 7 Slope map of the study area

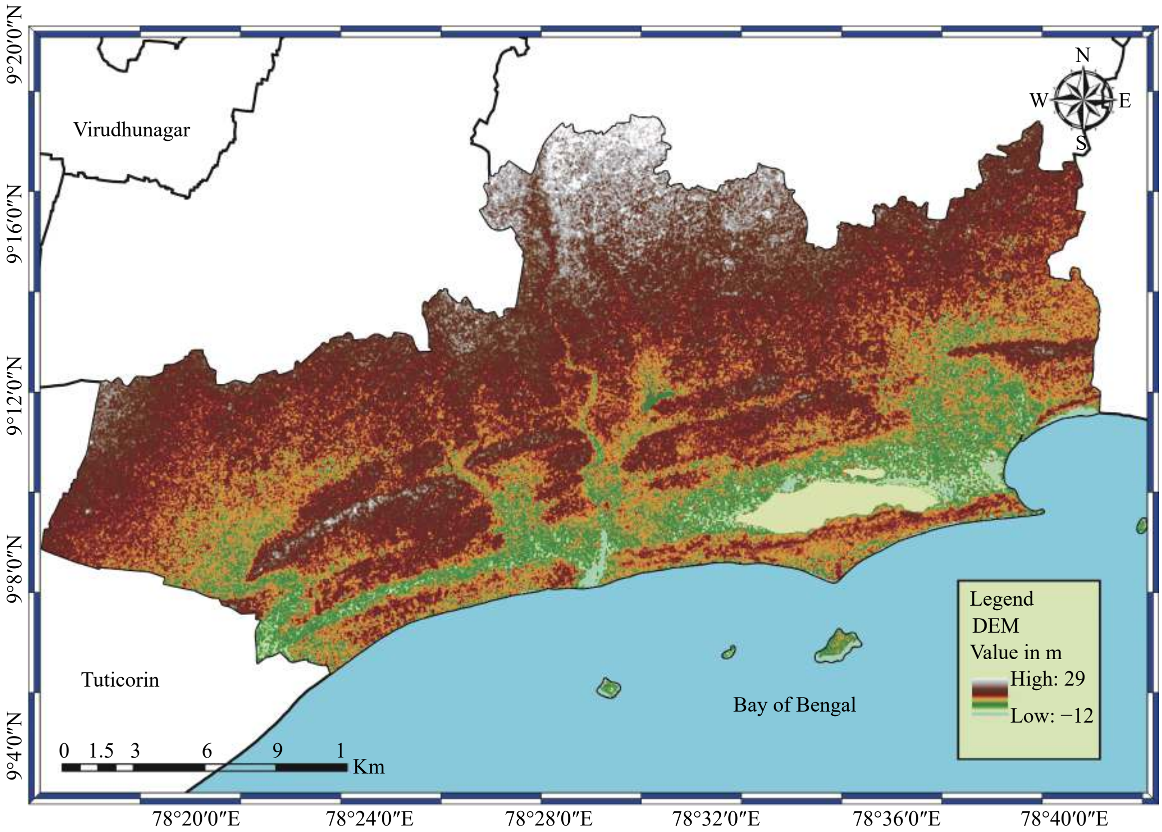

Fig. 8 DEM map of the study area

in assigning elevation information to each contour, thereby enabling the creation of three-dimensional models of the field. This approach not only provides a detailed understanding of the terrain's topography, but also facilitates the effective assessment and management of hydrological processes.

3.8 Rainfall

In the Kadaladi region, rainfall is the primary contributor to groundwater recharge. Flooding and surface runoff can occur when rain intensity exceeds the soil's infiltration capacity. The spatiotemporal distribution of rainfall intensities governs the groundwater recharge process, with higher-intensity rainfall events having a greater impact than lower-intensity ones. Rainfall in the Kadaladi region occurs primarily during the northeastern and southwest monsoon seasons. In semi-arid regions like this, recharge is irregular, with net recharge occurring mainly during periods of heavy rainfall. The rainfall map for the study area, sourced from the Indian Meteorological Department, was created using the IDW spatial interpolation method in the ArcGIS environment. To highlight the importance of the study area, the rainfall map was divided into five categories, each representing a different level of rainfall. The percentages assigned to each group are as follows. 35.9% classified as very low, 30.1% as low, 19.4% as medium, 11.0% as high, and 3.4% as extremely high (Fig. 9). These categories not only provide information about the varying levels of rainfall throughout the study area, but also help prioritize regions based on their potential impact on groundwater recharge. Analyzing rainfall patterns and intensities contributes to a comprehensive understanding of the region's hydrological dynamics.

4 Groundwater potential zone

The Groundwater Potential Index (GWPI) is calculated by considering thematic layers and features in an integrated layer:

$$\begin{aligned}\mathrm{GWPI} =& Gm_w Gm_r + Li_w Li_r + LCLU_w LCLU_r + \\ & LD_w LD_r + DD_w DD_r + S_w S_r + \\ & R_w R_r + D_w D_r \end{aligned} \tag{3}$$

To calculate the Groundwater Potential Index (*GWPI*), weights (*w*) are assigned to various contributing components and multiplied by their feature class ratings (*r*). These components include geology (*Gm*), lithology (*Li*), land cover and land use (*LCLU*), linear density (*LD*), drainage density

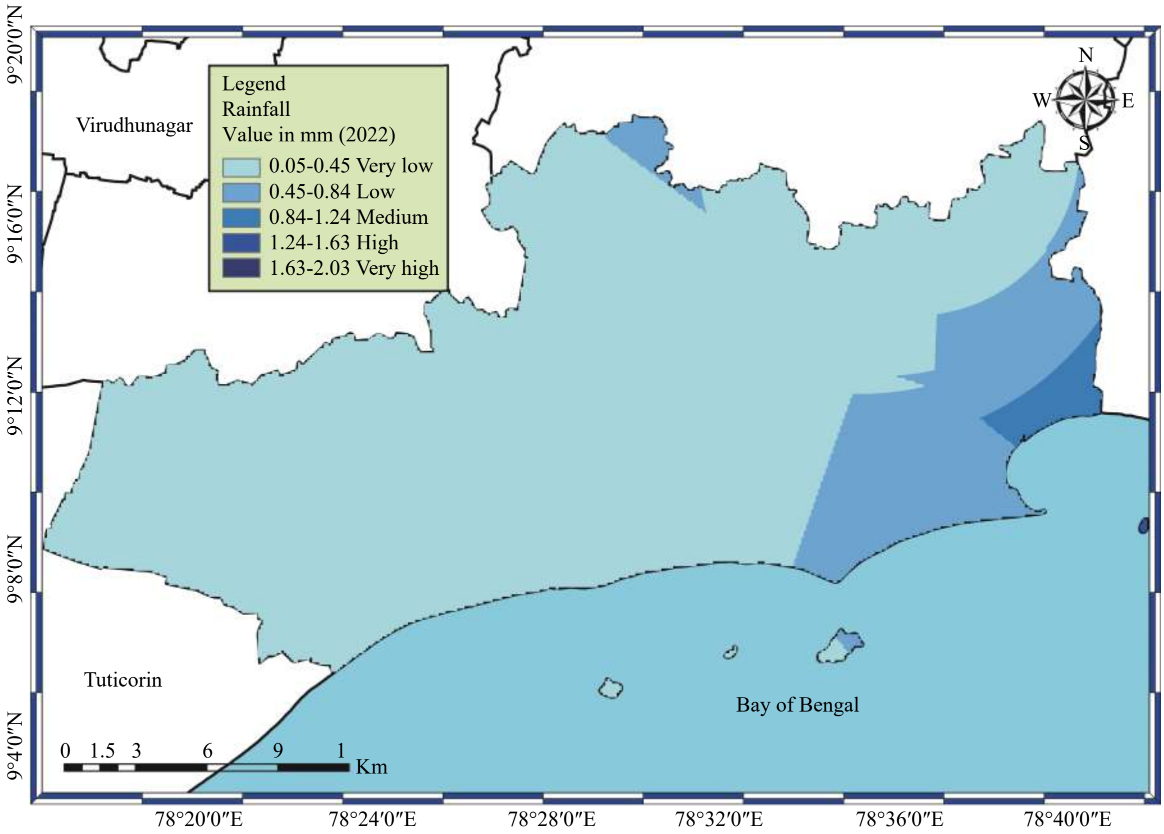

Fig. 9 Rainfall map of the study area

(*DD*), slope (*S*), DEM (*D*), and rainfall (*R*). To ensure a fair comparison, the weights assigned to each of the eight parameter feature classes are normalized. After computing the normalized weights for each feature class, ArcGIS gradually overlays the thematic layers for geology, lithology, land cover and land use, linear density, drainage density, slope, DEM, and rainfall (Table 5).

Using the ArcGIS weighted overlay analysis tool, these thematic layers are superimposed to generate the final groundwater potential zone map. The Groundwater Potential Index (GWPI), as calculated and presented in Table 6, categorizes regions based on their groundwater potential, ranging from very low to very high. Table 6 categorizes the specific zones by groundwater potential. This classification provides specific delineation, distinguishing areas with very low, low, medium, high, and extremely high potential. The high-to-medium concentration area encompasses a significant portion of the study region, ranging from 176.6 km^2 to 21.7 km^2. Overall, the study area exhibits a medium to high concentration of groundwater potential. This detailed analysis and classification provide a comprehensive understanding of the spatial distribution and intensity of groundwater potential across the study area (Fig. 10).

5 Conclusion

To identify and delineate geological features, hydro-morphological and geomorphological conditions, as well as lineament features, the study utilized satellite image data from IRS ID and Landsat 8. These characteristics, whether direct or indirect indicators of groundwater presence, were evaluated to determine groundwater potential. The use of GIS enabled more efficient management and manipulation of geographic data. The study identified groundwater quality zones crucial for residential applications by integrating and analyzing various thematic maps. Specific sections of the research area (southeastern, southwestern, northeastern, and central) with moderate to very high groundwater potential is experiencing contamination from improperly treated industrial effluents and municipal sewage. As a result, these areas are gradually transitioning from unfit to marginally suitable for domestic water use. To address this issue, the study recommends conducting groundwater quality monitoring studies. Such monitoring would enable tracking of new developments and addressing the removal of specific contaminants affecting accessible groundwater resources. This proactive approach is vital for ensuring the sustainable and

Table 5 List of parameters and APH ratings and weights

Thematic Layer	Factors	Rank	Weight	Overall
Geomorphology	Aeolian Interdunal Depression and Palaya	3	21	43
	Aeolian sand dune	3		43
	Alluvial Plain	4		44
	Coastal Plain	4		44
	Deltaic Plain	5		105
	Flood Plain	1		21
	Pediment Pediplain Complex	2		42
	Salt Pan	2		42
	Water Bodies - Other	1		21
	Water Body – River	4		48
Lithology	Black Clay	3	19	57
	Black Clayey Sand	5		95
	Black Silty Clay	4		76
	Brown Fine Sand	4		76
	Brown silty clay	3		57
	Coarse sand with rock fragments	3		57
	Grey fine sand	3		57
	Hornblende biotite gneiss	2		38
	Channel bar / Point bar	2		38
	Terri dune sand	3		38
	Sand with coarals	2		38
	Silty clay	2		38
LULC	Waters	5	16	80
	Vegetation	4		64
	Crops	3		48
	Built area	3		48
	Bare ground	2		32
	Range land	2		32
Lineament density	Very low	1	14	14
	Low	2		28
	Medium	3		42
	High	4		56
	Very high	5		70
Drainage density	Very low	1	14	14
	Low	2		28
	Medium	3		42
	High	4		56
	Very high	5		70
Rainfall	Very low	1	2	7
	Low	2		14
	Moderate	3		21
	High	4		28
	Very high	5		35

Table 5 (continued)

Thematic Layer	Factors	Rank	Weight	Overall
Slope	Very low	1	8	12
	Low	2		24
	Moderate	3		36
	High	4		48
	Very high	5		60
DEM	Very low	1	6	9
	Low	2		18
	Moderate	3		27
	High	4		36
	Very high	5		45

Table 6 Classification of groundwater potential zone

Classification	Total area covered /km^2	Area percentage/%
Very low	74.158614	12.769079
Low	136.132953	23.440195
Medium	160.855328	27.697043
High	176.653441	30.417257
Very High	21.761407	3.747011

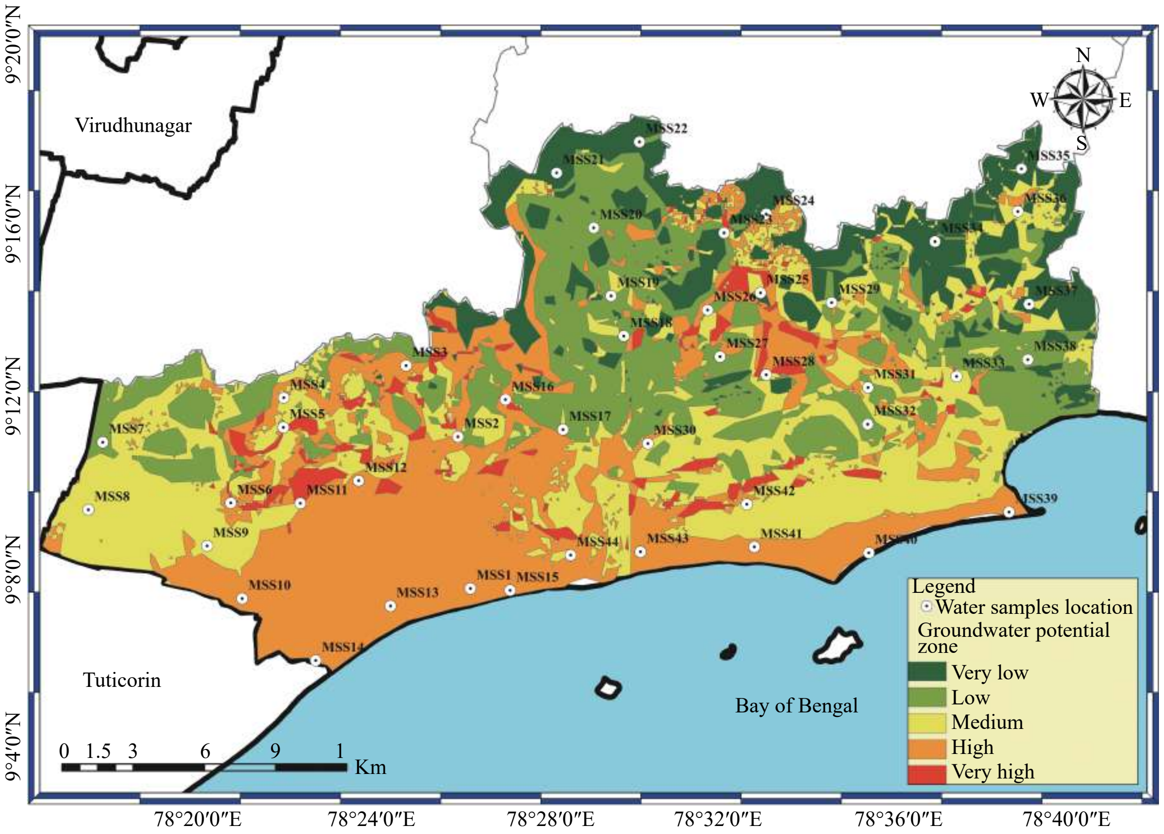

Fig. 10 Groundwater potential zone map of the study area

safe utilization of groundwater, particularly in areas where contamination poses a threat to water supply quality.

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