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Integration of GIS and AHP techniques for the sustainability of groundwater potential zones in the coastal environs

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Coastal aquifers are facing significant threats from overexploitation, seawater intrusion, and reduced recharge. Effective groundwater management necessitates a precise spatial evaluation of groundwater potential. This research aims to identify Groundwater Potential Zones (GWPZ) of Tarangambadi Taluk in Mayiladuthurai district, Tamil Nadu, using integrated GIS, Remote sensing, and the Analytical Hierarchy Process (AHP) methods. The study included fourteen thematic layers selected based on hydrogeological relevance. Each layer's weight was calculated utilizing the AHP methods, facilitated through analysis of weighted overlay in GIS to produce the spatial distribution of the GWPZ. The study zone was classified into five potential categories. Analysis indicates that 52% of the area is classified within high to very high potential zones, predominantly located in the central and western taluk, characterized by favorable geological conditions. Conversely, approximately 19% of the area, primarily along the eastern coastline, is categorized as low to very-low potential zones due to factors such as impervious surfaces and saline intrusion risks. The resulting GWPZ map aligns well with borewell data, affirming its precision and utility. The outcomes serve as a valuable resource for sustainable planning and aquifer management in coastal areas.

KEYWORDS

groundwater potential zones, remote sensing, AHP, geographic information systems, coastal aquifers, seawater intrusion

1 Introduction

Water is a basic resource required for life, and groundwater has become a significant natural resource in providing the freshwater needs of various sectors in the world. Groundwater is integral to India's drinking water security and agriculture, accounting for approximately 62% of irrigation, 85% of rural water supply, and 50% of urban supply (Central Groundwater Board, 2024). Climate action and anthropogenic factors have a significant impact on groundwater resources. Increased population and urbanization have led to overutilization of groundwater resources, resulting in challenges related to water scarcity (Patidar et al., 2021). The excessive withdrawal of groundwater for agricultural and urban purposes generally lowers water levels, thereby increasing the susceptibility of aquifer saltwater intrusion, which compromises the quality of freshwater resources for potable and irrigation uses (Ramasubramanian et al., 2025). Because of extensive use and improper management, groundwater levels have decreased over the decades (Ostovari et al., 2015). Consequently, the investigation and sustainable management of groundwater resources crucially rely on the capacity of underlying aquifers, which requires

the implementation of pioneering decision-making methodologies and sophisticated data amalgamation techniques to identify areas with significant groundwater potential accurately (Arabameri et al., 2019).

Groundwater potential advances Sustainable Development Goal 6 (SDG 6) by facilitating sustainable water access. It also fosters SDG 13 by bolstering resilience against climate-induced groundwater challenges. Furthermore, it aligns with SDG 15 by supporting terrestrial ecosystems and land productivity (Dange et al., 2025). Sustainable utilization of water resources requires groundwater management. Topographical, hydrological, geological, and climatic factors influence the availability and management of groundwater (Golkarian et al., 2018). Delineating the groundwater potential zones is crucial for effective planning, management, and sustainable development of any region because groundwater is an imperceptible natural resource (Dist and Mondal, 2017).

Hydrogeological, geological, and geophysical surveys are expensive and time-consuming in traditional groundwater mapping methods (Pandey et al., 2022). On the other hand, an alternative, quick, and less costly option is provided by geospatial technology such as GIS and RS (Arulbalaji et al., 2019). By combining more thematic layers, enabling quick and economic data collection, giving synoptic coverage, and leveraging the requirement for substantial fieldwork and specialized labor, remote sensing and GIS facilitate successful groundwater management (Narendra et al., 2013; Raj et al., 2024). Leveraging these benefits, various factual methods have been developed to integrate multiple parameters using the GIS technique, facilitating the effective and economically viable production of a comprehensive groundwater potential map (Selvam et al., 2016; Muthu and Sudalaimuthu, 2021). Many researchers have successfully identified groundwater potential areas for sustainable sources of planning and management in recent decades by using Remote sensing and GIS approaches (Kanagaraj et al., 2019; Abijith et al., 2020; Thirunavukkarasu and Ambujam, 2020).

Generally, expert judgment systems and machine learning algorithms are the two approaches for creating a groundwater potential map (Díaz-Alcaide and Martínez-Santos, 2019). GIS approaches have been integrated into expert judgment systems such as logistic regression (LR) (Zhang et al., 2018), certainty factor (CF), probability frequency ratio (FR), weighted evidence (WE), evidentiary belief function (EBF), Analytic hierarchy process (AHP), Fuzzy AHP, and Multi-influence factor techniques are based on human judgment (Boughariou et al., 2021; Kumar et al., 2021; Gandhi et al., 2024). On the other hand, machine learning

models have become prominent for their efficacy in elucidating intricate linkages and forecasting groundwater resources, resulting in several investigations into the identification of groundwater potential zones (GWPZ) (Vafadar et al., 2023). There are numerous machine learning techniques are Artificial Neural Network (ANN), Logistic Regression (LR), Support Vector Machine (SVM), Random Forest (RF), Decision Trees (DT), K-Nearest Neighbor (KNN), Gradient Boosting, Predictive Neural Network (PNN), and Classification regression tree (CRT) used in many regions across the world (Berhanu and Hatiye, 2020; Prasad et al., 2020; Saha et al., 2021; Talukdar et al., 2022; Shandu and Atif, 2023; Khan et al., 2024).

Various methods used for groundwater potential studies require extensive data and resources, this is often limited in coastal regions. As a result, Previous studies sometimes overlooked expert-based thematic layer weighting, which can lead to biased outcomes (Berhanu and Hatiye, 2020). Moreover, the lack of systematic evaluation in GIS groundwater has led to an underestimate of the importance of key influencing factors (Doke et al., 2021). The Analytic Hierarchy Process (AHP) functions as a robust Multi-Criteria Decision-Making (MCDM) methodology, quantifying expert assessments and systematically integrating criteria (Elubid et al., 2020). Intensive agriculture and urbanization in the coastal deltas have caused groundwater over-exploitation, leading to seawater intrusion and groundwater quality degradation (Sridhar et al., 2014).

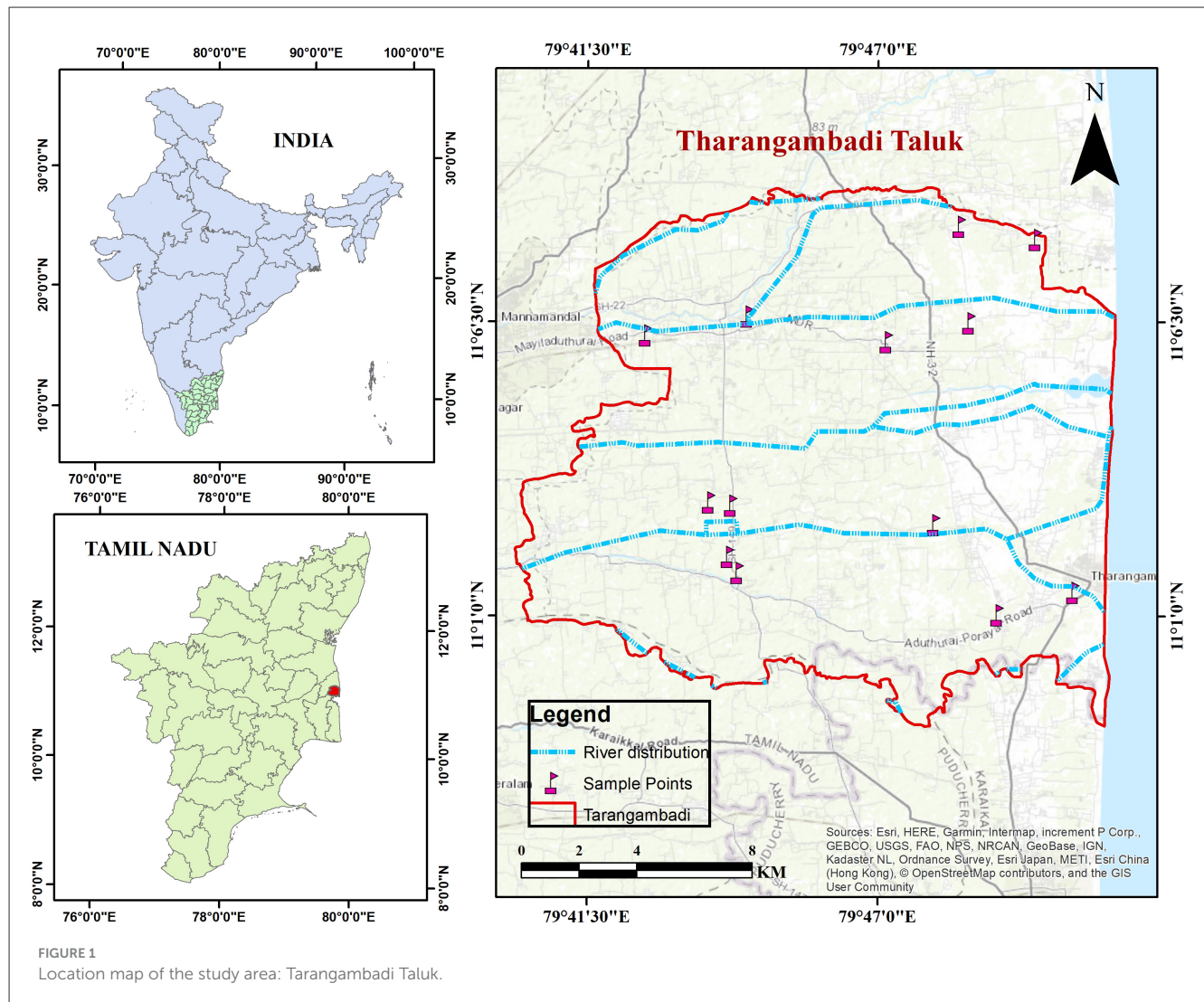
Tarangambadi taluk is a coastal agricultural region in Tamil Nadu. There is no previous research that has been conducted to identify the groundwater potential zone in this area. Determining the GWPZ is crucial for the area's sustainable management. The main objective of the research work is to delineate the groundwater potential zone for Tarangambadi taluk through the integration of remote sensing, GIS, and AHP techniques with locally calibrated thematic weights based on recent hydrogeological and remote sensing datasets for the sustainable management of groundwater resources. In a novel approach to GWPZ, the Proximity to sea is a thematic layer to directly examine the spatial influence of seawater intrusion, an essential factor in managing coastal aquifers. This study's innovation is a coastal focus, requiring dual planning for Tarangambadi: recharge enhancement and seawater intrusion prevention.

2 Study area

Tarangambadi, formerly Tranquebar, is a panchayat town in the Mayiladuthurai District of the Indian state of Tamil Nadu. It lies 15 km north of Karaikal, near the mouth of a distributary of the Cauvery River. Tarangambadi is the headquarters of Tarangambadi Taluk. The coordinates of the Tarangambadi taluk lie between 10°58'56.53"N to 11°09'1.86"N latitude and 79°40'7.60"E to 79°51'29.41"E longitude. It covers an area of 280.96 km². The regional hydrogeological boundaries are delineated in Figure 1.

Elevations vary from −1 to 13 m above sea level, and slope angles range from 0° to 12°. During the month of summer, March to May, the maximum temperature reaches, and the average annual minimum and maximum temperatures are 24°C and 37°C, respectively. The average yearly rainfall ranges from 886.6 mm to 1,398 mm. The maximum rain falls during the northeast monsoon

Abbreviations: AHP, Analytical Hierarchy Process; CI, Consistency Ratio; CR, Consistency Index; DEM, Digital Elevation Model; GIS, Geographic Information Systems; GSI, Geological Survey of India; GWPI, Groundwater Potential Index; GWPZ, Groundwater Potential Zone; LULC, Land Use Land Cover; MCDA, Multi-Criteria Decision-Making; NBSS & LUP, National Bureau of Soil Survey and Land Use Planning; NDVI, Normalized Difference Vegetation Index; NDWI, Normalized Difference Water Index; NPCM, Normalized Pairwise Comparison Matrix; RI, Random Consistency Index; RS, Remote Sensing; SDG, Sustainable Development Goal; SRTM, Shuttle Radar Topography Mission; TPI, Topographic Position Index; TWI, Topographic Wetness Index; WOA, Weighted Overlay Analysis.



from October to December. Its topography exhibits a diverse landscape comprising lowlands, alluvial plains, river deltas, and coastal plains. Geology formation majorly consists of active alluvial deposits, active marine deposits, and paleo marine and alluvial deposits. In terms of land cover and land use classification, it predominantly consists of agricultural land, built-up areas, water bodies, and coastal areas. Agriculture is the primary source of income for the rural population. Paddy is the major crop (97 % during the monsoon season), and 47 % of the area is covered under winter crops. Rainfall and groundwater are the main sources of irrigation. Due to the erratic behavior of the southwest monsoon, supplementary irrigation is also required during the Kharif (monsoon) season.

3 Materials and methods

3.1 Groundwater influencing factors

The accuracy of groundwater potential assessment depended on the selection of influencing factors. The groundwater

influencing factors are selected based on the nature of the study area, considering those with the most significant impact on groundwater recharge. In this process, several elements influencing the presence of groundwater are represented by thematic layers, which are geomorphology, Land use land cover (LULC), geology, soil, rainfall, drainage density, lineament density, proximity to stream, proximity to sea, topographic wetness index (TWI), topographic position index (TPI), slope, normalized difference vegetation index (NDVI), and normalized difference water index (NDWI).

The Geological Survey of India (GSI) contributed geomorphological and geological data. The National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) offered Soil data. Specifically, geology, Geomorphology, and soil maps were used at a 1:50,000 scale. In the present investigation, the Land Use/Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Water Index (NDWI) were extracted from Sentinel-2B-2A imagery. Specifically, we utilized a dataset acquired on 16 September 2024 (late southwest monsoon/early northeast monsoon), chosen for minimal cloud cover and representative hydrological conditions was computed

TABLE 1 Detailing sources, processing techniques, and seasonality of thematic layers.

S. No.	Thematic layer(s)	Data source	Spatial resolution/Scale	Processing technique	Website
1	Geomorphology, Geology	Geological Survey of India (GSI)	1:50,000	Visual interpretation of GSI maps, supported with satellite imagery	https://bhukosh.gsi.gov.in/Bhukosh/Public
2	Soil	National Bureau of Soil Survey & Land Use Planning (NBSS & LUP)	1:50,000	Direct use of NBSS&LUP maps	https://icar-nbsslup.org.in/
3	LULC, NDVI, NDWI	Sentinel-2B Level 2A	10 m	Band combinations & indices; supervised maximum likelihood classification	https://browser.dataspace.copernicus.eu
4	Rainfall, Groundwater Level	State Ground & Surface Water Resources Data Centre (PWD)	Point data	Data interpolation IDW techniques for rainfall and observation wells for water level	https://www.groundwatertnpwd.org.in/indexnew.htm
5	Lineament Density, Drainage Density, Slope, TWI, TPI, Proximity to Stream and Sea	SRTM DEM (USGS)	30 m	DEM derivatives: slope & terrain indices (GIS), hydrological analysis for drainage; lineament extraction via edge detection & directional filtering	https://earthexplorer.usgs.gov/

from Band 8 (NIR) and Band 4 (Red), while NDWI was derived from Band 8 (NIR) and Band 3 (Green), all of which have a 10 m spatial resolution. LULC mapping was performed using Supervised maximum likelihood algorithms, and accuracy assessment was conducted with reference samples (Google Earth and field verification). Rainfall and groundwater level data were sourced from the State Ground and Surface Water Resources Data Center, Tamil Nadu. Topographic and hydrological parameters, including lineament density, Drainage density, Slope, TWI, TPI, Proximity to stream, and Proximity to sea, were extracted from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at a 30-meter resolution. All the data are collected from various sources (Table 1) and processed in ArcGIS 10.8 software. Interpolation techniques were adopted to formulate continuous spatial surfaces from distinct point measurements, thus supporting the accurate estimation of parameter values in sites that had not been sampled. Among the various methods evaluated, Inverse Distance Weighted was chosen due to its exceptional statistical efficacy with the lowest RMSE and an excellent R^2 accuracy. Figure 2 illustrates the comprehensive methodological framework utilized for calculating the Groundwater Potential Index (GWPI).

3.2 Analytical hierarchy process

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty (1980), is a decision-making framework that helps to solve complex problems in a clear hierarchical model. It applies pairwise comparison to quantify the relative importance of criteria using a standard scale. AHP also calculates consistency ratios to ensure the expert judgments remain logically sound and reliable (Saaty, 1987). AHP offers advantages such as transparency and simplicity, effectively integrating quantitative and qualitative criteria in water resources management (Cabrera et al., 2011). The Analytic Hierarchy Process (AHP) provides a versatile framework that facilitates the modification of expert assessment, affording individuals the most challenging and intricate issues (Galo, 2017).

3.3 Assignment of the weight by AHP

The Analytical Hierarchy Process (AHP) is a coherent approach utilized for the organization and scrutiny of complex decision-making environments, and it is broadly implemented in groundwater potential evaluation. The determination and ranking of parameters and sub-parameters in the AHP necessitate a coherent framework that incorporates expert evaluation, thematic layers, and geospatial analysis (Anteneh et al., 2022). The specification of parameters is commonly guided by specialist perspectives and extensive literature assessments, thereby affirming that the most relevant elements are acknowledged for the designated research area (Osinowo and Arowoogun, 2020). The AHP methodology utilizes Saaty's nine-point scale to allocate weights to each parameter according to its relative significance, as displayed in Table 2 (Hayer et al., 2023). This scale facilitates a pairwise comparison of parameters, thereby promoting a structured decision-making paradigm. Following the assignment of initial weights, the values undergo normalization to ensure that they collectively equal one (Ravindran et al., 2024). This procedure is instrumental in preserving consistency and comparability across various parameters. The weights are derived by averaging the normalized values corresponding to each row, yielding a priority vector that conveys the relative importance of each criterion (Jarrah et al., 2022). These weights equate to unity as they are extracted from a normalized matrix, thereby guaranteeing that cumulative importance is allocated across all criteria (Szabo et al., 2021). The final weights exemplify the relative importance of each criterion within the decision-making framework, thus enabling a clear prioritization of alternatives (Howari et al., 2023). Applied importance based on the Saaty scale in the pairwise matrix for the AHP is displayed in Table 3.

The Consistency Ratio (CR), a construction first articulated by Saaty in 1980, serves as a metric for evaluating the coherence in the allocation of weight attributed to various parameters. This ratio facilitates a quantitative evaluation of weights derived from the normalized pairwise comparison matrix (NPCM) delineated in Table 4. If the CR fall below 0.10 (10%), it signifies a substantial degree of precision; in contrast, if the CR surpasses 0.10, it may

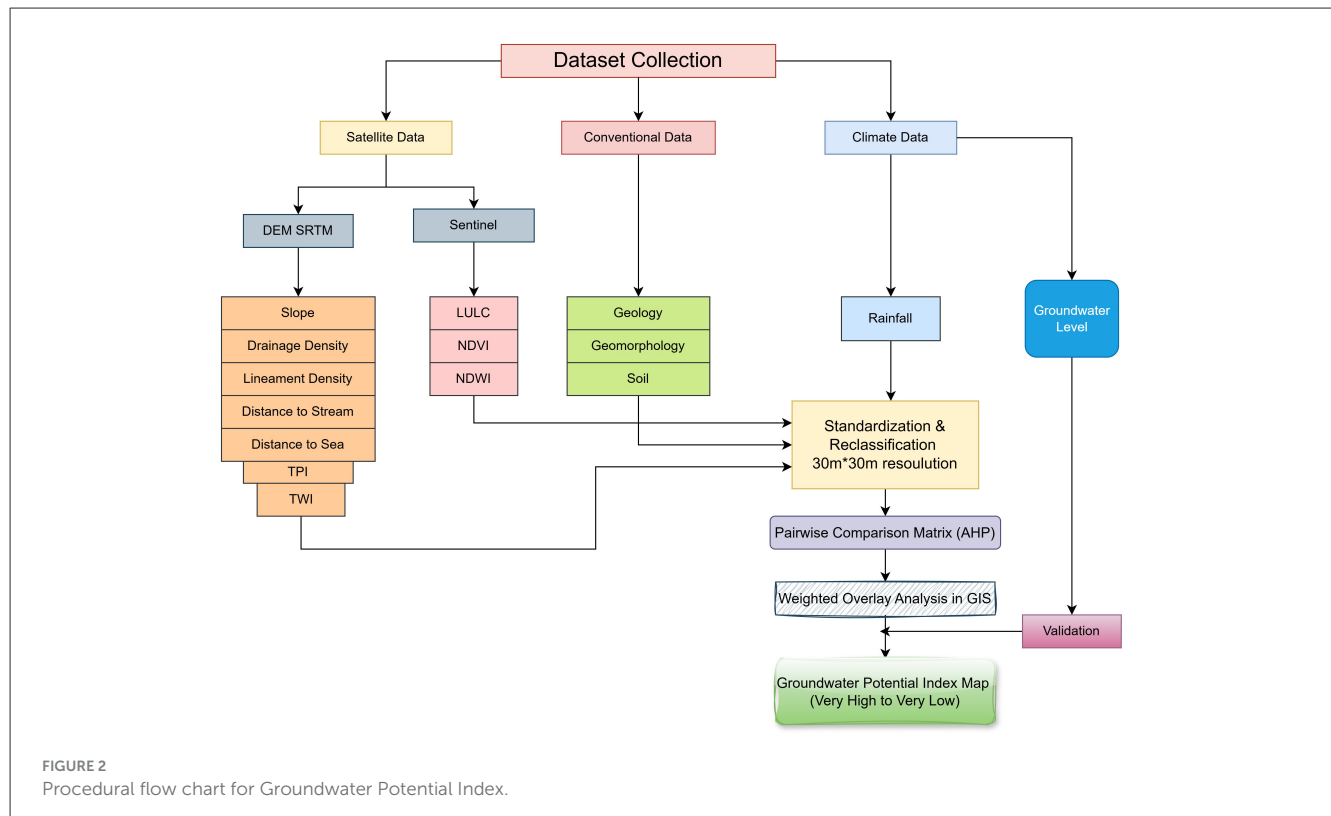


TABLE 2 The fundamental scale of AHP (Saaty, 1980).

Scale	Intensity of Importance
1	Equal importance
3	Moderate importance
5	Strong importance
7	Strong Plus importance
9	Very strong plus importance
2,4,6,8	Adjacent judgment of the intermediate value

necessitate a re-evaluation of the judgments to secure enhanced accuracy (Saaty, 1977).

$$CI = \frac{\lambda_{max} - N}{N - 1} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

Where CR = Consistency Ratio (CR)

CI = Consistency Index (CI), and RI = Random Consistency Index (RI)

λ_{max} = largest eigenvalue and N = Number of parameters.

3.4 Groundwater potential zone model

A commonly applied technique for identifying Groundwater Potential Zones (GWPZ) in the realm of Geographic Information

Systems (GIS) is the Weighted Overlay Analysis (WOA) (Thanh et al., 2022; Jebaraj and Rajagopal, 2024). WOA represents a multi-criteria decision-making (MCDM) approach that synthesizes diverse thematic layers, each assigned weights that accurately represent their respective impacts on groundwater potential (Berhanu and Hatiye, 2020). This methodology facilitates spatial decision-making by systematically and transparently amalgamating standardized raster inputs.

Weights are allocated to each variable following their comparative significance to the prevalence of groundwater occurrence (Kandakoglu et al., 2019). Those weights can be allocated through expert assessments, comprehensive literature evaluations, or applied through a systematic AHP technique (Aladejana et al., 2016). The weights for fourteen criteria and their sub-criteria were incorporated into thematic layers in ArcGIS. The groundwater potential map was produced through weighted overlay analysis in GIS. This process involved computing the weighted sum of thematic layers as per Equation 3.

$$GWPZ \text{ Index} = \sum_{i=1}^n (W_i \times X_i) \quad (3)$$

Where W_i is denoted as the weightage of each parameter, and X_i refers to the rank of each thematic layer. The raster output layer from the Weighted Overlay Analysis (WOA) is classified into five categories: very low, low, moderate, and very high. This classification is based on the identification of regions with varying groundwater potential yield in the research area.

TABLE 3 Matrix for pairwise comparison in the Analytical Hierarchy Process (AHP).

Thematic Maps	GM	LULC	GG	S	RF	DD	LD	PST	PSE	TWI	TPI	SLOPE	NDVI	NDWI
Geomorphology (GM)	1	2	2	2	2	3	4	4	4	6	6	7	7	7
LULC	1/2	1	3	3	3	2	3	3	5	5	6	6	6	7
Geology (GG)	1/2	1/3	1	2	2	2	2	3	4	4	6	5	5	7
Soil (S)	1/2	1/3	1/2	1	2	3	3	2	3	3	4	4	5	7
Rainfall (RF)	1/2	1/3	1/2	1/2	1	2	2	3	2	3	4	3	4	5
Drainage Density (DD)	1/3	1/2	1/2	1/3	1/2	1	3	2	3	3	3	3	4	4
Lineament Density (LD)	1/4	1/3	1/2	1/3	1/2	1/3	1	3	3	2	3	3	4	5
Proximity to Stream (PST)	1/4	1/3	1/3	1/2	1/3	1/2	1/3	1	2	3	3	4	4	5
Proximity to Sea (PSE)	1/4	1/5	1/4	1/3	1/2	1/3	1/3	1/2	1	3	2	3	4	4
TWI	1/6	1/5	1/4	1/3	1/3	1/3	1/2	1/3	1/3	1	3	3	5	5
TPI	1/6	1/6	1/6	1/4	1/4	1/3	1/3	1/3	1/2	1/3	1	3	5	5
SLOPE	1/7	1/6	1/5	1/4	1/3	1/3	1/3	1/4	1/3	1/3	1/3	1	3	3
NDVI	1/7	1/6	1/5	1/5	1/4	1/4	1/4	1/4	1/4	1/5	1/5	1/3	1	3
NDWI	1/7	1/7	1/7	1/7	1/5	1/4	1/5	1/5	1/4	1/5	1/5	1/3	1/3	1

TABLE 4 Normalized Pairwise Comparison Matrix (NPCM).

Thematic maps	GM	LULC	GG	S	RF	DD	LD	PST	PSE	TWI	TPI	SLOPE	NDVI	NDWI
Geomorphology (GM)	0.21	0.32	0.21	0.18	0.15	0.19	0.20	0.17	0.14	0.18	0.14	0.15	0.12	0.10
LULC	0.10	0.16	0.31	0.27	0.23	0.13	0.15	0.13	0.17	0.15	0.14	0.13	0.10	0.10
Geology (GG)	0.10	0.05	0.10	0.18	0.15	0.13	0.10	0.13	0.14	0.12	0.14	0.11	0.09	0.10
Soil (S)	0.10	0.05	0.05	0.09	0.15	0.19	0.15	0.09	0.10	0.09	0.10	0.09	0.09	0.10
Rainfall (RF)	0.10	0.05	0.05	0.04	0.08	0.13	0.10	0.13	0.07	0.09	0.10	0.07	0.07	0.07
Drainage Density (DD)	0.07	0.08	0.05	0.03	0.04	0.06	0.15	0.09	0.10	0.09	0.07	0.07	0.07	0.06
Lineament Density (LD)	0.05	0.05	0.05	0.03	0.04	0.02	0.05	0.13	0.10	0.06	0.07	0.07	0.07	0.07
Proximity to Stream (PST)	0.05	0.05	0.03	0.04	0.03	0.03	0.02	0.04	0.07	0.09	0.07	0.09	0.07	0.07
Proximity to Sea (PSE)	0.05	0.03	0.03	0.03	0.04	0.02	0.02	0.02	0.03	0.09	0.05	0.07	0.07	0.06
TWI	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.01	0.03	0.07	0.07	0.09	0.07
TPI	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.07	0.09	0.07
SLOPE	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.05	0.04
NDVI	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.02	0.04
NDWI	0.03	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01

4 Results and discussion

This study employed fourteen thematic maps to evaluate groundwater potential. The maps comprised Geomorphology, LULC, Geology, Soil, Rainfall, Drainage Density, Lineament Density, Proximity to Stream, Proximity to Sea, TWI, TPI, Slope, NDVI, and NDWI, all recognized for their impact on groundwater. The assessment of each thematic layer's weight was performed using the Analytic Hierarchy Process (AHP) (Twaha et al., 2024), which entails systematic pairwise comparisons based on the relative significance of each parameter (geomorphology, LULC, soil, Rainfall, etc.) concerning groundwater occurrence and recharge. The relative significance of those variables was ascertained through

a comprehensive examination of extant peer-reviewed literature on groundwater potential mapping within analogous hydrogeological contexts, in conjunction with distinctive characteristics of the study area, encompassing hydrogeological conditions and field observations. In the lack of direct consultation with subject matter experts, we utilized the established weight range documented in credible academic research (Arulbalaji et al., 2019; Senthilkumar et al., 2019) and modified it by the regional characteristics identified in Tarangambadi Taluk. The resultant pairwise matrix attained a consistency ratio (CR) of less than 0.1, signifying a robust and dependable weighting framework. The study reported a consistency index (CI) of 0.155 and a consistency ratio (CR) of 0.094323, indicating satisfactory consistency. The thematic map category

rankings were derived from previous studies and field expertise. Variables significantly affecting groundwater were assigned higher weights, while those with minimal influence received lower weights (Kadiri et al., 2023). The pairwise comparison matrix and normalized weights for parameters according to the AHP model are illustrated in Tables 3, 4. Table 5 displays the weightage assigned to the fourteen thematic maps and their respective subclasses.

4.1 Geomorphology

Assessment of geomorphology elucidates the genesis, distribution, and dynamics of groundwater (Letz et al., 2021). In geomorphological formations, the presence of groundwater is predominantly shaped by lithological characteristics, gradient, drainage configuration, infiltration capacity, and hydrological runoff (Arulbalaji et al., 2019; Pandey and Purohit, 2022). Based on the geomorphological attributes of the research area (Figure 3a) includes a deltaic plain, floodplains, a coastal plain, a salt pan, and water bodies. The deltaic plain, which constitutes the predominant portion of the region (77.66%), displays elevated groundwater potential. This phenomenon can be attributed to its fine-textured alluvial deposits and level topography that facilitate both infiltration and groundwater retention (Nazir et al., 2024). Floodplains, despite occupying a lesser area (6.10%), also manifest extremely high groundwater potential. The coastal plain comprises 14.17% of the area and is characterized by moderate groundwater potential. Salt pans represent only 0.53% of the area and demonstrate minimal groundwater potential due to saline soil and poor infiltration capacity. Conversely, water bodies, although they represent only 1.54% of the total area, are classified as exhibiting very high groundwater potential.

4.2 LULC

Evaluating land use and land cover (LULC) is essential for understanding groundwater resources and sustainable management (Ramasubramanian et al., 2025). Land use and cover alterations significantly affect groundwater potential through their effect on recharge, groundwater levels, and water quality (Siddik et al., 2022; Salem et al., 2023). The LULC maps originate from Sentinel-2 Level-1C satellite imagery from 2023. The study area is characterized by cropland area (77.47%), built-up area (17.86%), water (2.27%), trees (0.64%), flooded vegetation (0.04%), Bare land (0.06%), and Range land (1.65%), as shown in Figure 3b. Cropland, water, trees, and flooded vegetation are optimal for recharge due to their facilitation of rainwater and irrigation water percolation, thus receiving greater weightage (Saravanan et al., 2020). In built-up areas, minimal weightage is observed due to increased runoff and reduced recharge (Kumar et al., 2024).

4.3 Geology

Geological factors critically influence groundwater potential by affecting its storage, flow, and replenishment (Pandey and Purohit, 2022). In the Tarangambadi Taluk study area, four prominent

geological formations were delineated: palaeo marine deposits, palaeo fluvial deposits, active marine deposits, and active fluvial deposits, each possessing unique lithological and stratigraphic characteristics that influence groundwater behavior (Figure 3c). Palaeo marine deposits, comprising 27.58% of the region, consist of ancient sediments primarily formed from compacted clays and silts, exhibiting limited groundwater potential due to their fine-grained composition and low permeability (Faria et al., 2022). Conversely, Palaeo Fluvial deposits, which are 18.97%, are characterized by well-sorted sands and gravels that enhance porosity and permeability, thus facilitating significant groundwater recharge and functioning as crucial aquifer units (Sahoo et al., 2024). Active marine deposits, representing 46.69% of the area, consist of silty sands with moderate permeability, leading to a low to moderate groundwater potential, while active fluvial deposits, despite their smaller coverage of 6.76%, demonstrate exceptional groundwater resource potential due to their high recharge capacity from unconsolidated materials (Sud et al., 2023). Figure 3c presents the geological map of the research area.

4.4 Soil

Soil properties are critical for evaluating groundwater potential, as they affect infiltration and recharge rates (Arunbose et al., 2021). The interrelationship between soil and groundwater potential is governed by soil texture, structure, and hydraulic properties that affect groundwater infiltration and recharge (Muniraj et al., 2020; Vellaikannu et al., 2021). The soil group is classified into four categories: Entisols, Inceptisols, Vertisols, and Pondicherry soils, each uniquely influencing groundwater processes, as displayed in Figure 3d. Entisols, constituting approximately 37.60% of the study area, are relatively immature soil exhibiting minimal profile development, predominantly sandy to loamy in texture, which allows for moderate infiltration and drainage (Sathiyamoorthy et al., 2023). Inceptisols, representing 17.56%, are more developed than entisols, typically situated on alluvial plains, possessing superior structure and porosity that enhance vertical percolation and groundwater recharge (Loganathan and Sathiyamoorthy, 2024). Vertisols, the predominant soil type at 44.71%, are distinguished by their high clay content and shrink-swell characteristics (Raj et al., 2024; Loganathan and Sathiyamoorthy, 2024). Finally, a negligible 0.13% of the area consists of Pondicherry soil, which is coastal and often saline.

4.5 Rainfall

Precipitation significantly influences the assessment of groundwater potential, serving as the principal contributor to aquifer recharge (Thirunavukkarasu and Ambujam, 2020; Raj et al., 2024). The replenishment of groundwater through rainfall is contingent upon precipitation levels, soil moisture deficits, interception losses, and potential evaporation rates (Siddi Raju et al., 2019). The magnitude and temporal extent of precipitation significantly influence infiltration capacity and recharge potential (Muniraj et al., 2020). Prolonged low-intensity rainfall enhances

TABLE 5 Weightage and rank of subclasses of groundwater influencing factor.

S. No	Factors	Weightage	Sub classes	Rank	Assigned rank
1	Geomorphology	0.178	Flood plain	9	Very High
			Coastal plain	5	Moderate
			Salt pan	1	Very Low
			Deltanic plain	7	High
			Water body	9	Very High
2	LULC	0.163	Water	9	Very High
			Trees	7	High
			Flooded vegetation	6	Moderate
			Crops	7	High
			Built-Up	1	Very Low
			Bare land	3	Low
			Rangeland	5	Moderate
3	Geology	0.118	Palaeo marine deposit	1	Very Low
			Palaeo fluvial deposit	7	High
			Active marine deposit	4	Low
			Active fluvial deposit	9	Very high
4	Soil	0.103	Entisols	6	moderate
			Inceptisols	8	high
			Pondicherry	4	Low
			Vertisols	2	Low
5	Rainfall	0.082	886.6 to 976.9	3	Low
			977 to 1,089	3	Low
			1,090 to 1,199	5	Moderate
			1,200 to 1,300	7	High
			1,301 to 1398	9	Very High
6	Drainage Density	0.073	0 to 0.2798	9	Very High
			0.2799 to 0.7927	7	High
			0.7928 to 1.29	5	Moderate
			1.291 to 1.943	3	Low
			1.944 to 3.963	1	Very Low
7	Lineament Density	0.062	0 to 0.1363	1	Very Low
			0.1364 to 0.3969	3	Low
			0.397 to 0.6334	5	Moderate
			0.6335 to 0.8539	7	High
			0.854 to 1.022	9	Very High
8	Proximity to Stream	0.054	0 to 391.9	9	Very High
			392 to 832.9	7	High
			833 to 1,404	5	Moderate
			1,405 to 2,205	3	Low
			2,206 to 4,164	1	Very Low
9	Proximity to Sea	0.043	0 to 3,621	1	Very Low
			3,622 to 7,400	3	Low

(Continued)

TABLE 5 (Continued)

S. No	Factors	Weightage	Sub classes	Rank	Assigned rank
			7,401 to 11,100	5	Moderate
			11,110 to 14,880	7	High
			14,890 to 20,070	9	Very High
10	TWI	0.039	4.881 to 7.914	1	Very Low
			7.915 to 9.868	3	Low
			9.869 to 11.89	5	Moderate
			11.9 to 14.59	7	High
			14.6 to 22.07	9	Very High
11	TPI	0.032	−3.6 to −0.5209	9	Very High
			−0.5208 to −0.1403	7	High
			−0.1402 to 0.3095	5	Moderate
			0.3096 to 0.863	3	Low
			0.8631 to 5.222	1	Very Low
12	Slope	0.023	0 to 0.5531	9	Very High
			0.5532 to 1.408	7	High
			1.409 to 2.414	5	Moderate
			2.415 to 3.771	3	Low
			3.772 to 12.82	1	Very Low
13	NDVI	0.017	−0.1423 to 0.1015	1	Very Low
			0.1016 to 0.1857	3	Low
			0.1858 to 0.2728	5	Moderate
			0.2729 to 0.3686	7	High
			0.3687 to 0.5979	9	Very High
14	NDWI	0.013	−0.51271 to −0.31534	1	Very Low
			−0.31533 to −0.23859	3	Low
			−0.23858 to −0.16184	5	Moderate
			−0.16183 to 0.068635	7	High
			−0.068634 to 0.1863	9	Very High

infiltration and recharge, whereas short-duration, high-intensity precipitation leads to increased surface runoff and diminished recharge (Muniraj et al., 2020; Senapati and Das, 2022). In the study zone, average annual rainfall varying from 886.6 mm to 1398 mm is shown in Figure 4a. The rainfall map was classified into five categories: 886.6–976 mm (18.59%), 977–1,089 mm (16.03%), 1,090–1,199 mm (16.37%), 1,200–1,300 mm (20.42%), and 1,301–1,398 mm (28.59%).

4.6 Drainage density

The drainage density is crucial for evaluating groundwater potential, indicating surface runoff relative to infiltration (Francis et al., 2024). In the studied region, drainage density is classified into five categories, each representing a unique correlation

with groundwater recharge capability. Areas with high drainage density (1.994–3.963 km/km²) constitute 2.35% of the region. High drainage density suggests steep terrains and impermeable surfaces, which elevate surface runoff and diminish infiltration (Guduru and Jilo, 2022). Similarly, a zone with moderately high drainage density (1.292–1.943 km/km²) covers 8.65% and aligns with inadequate groundwater recharge due to increased runoff (Uc Castillo et al., 2022). Conversely, regions with very low drainage density (0–0.2798 km/km²), which comprise 54.05% of the area, are characterized by mild slopes and permeable materials that facilitate infiltration and aquifer recharge (Melese and Belay, 2022). Low drainage density zones (0.2799–0.7927 km/km²) cover 15.59% of the area, while moderate drainage density values (0.7928–1.29 km/km²) represent 19.36% of the study region. Figure 4b shows the spatial distribution of the drainage density map.

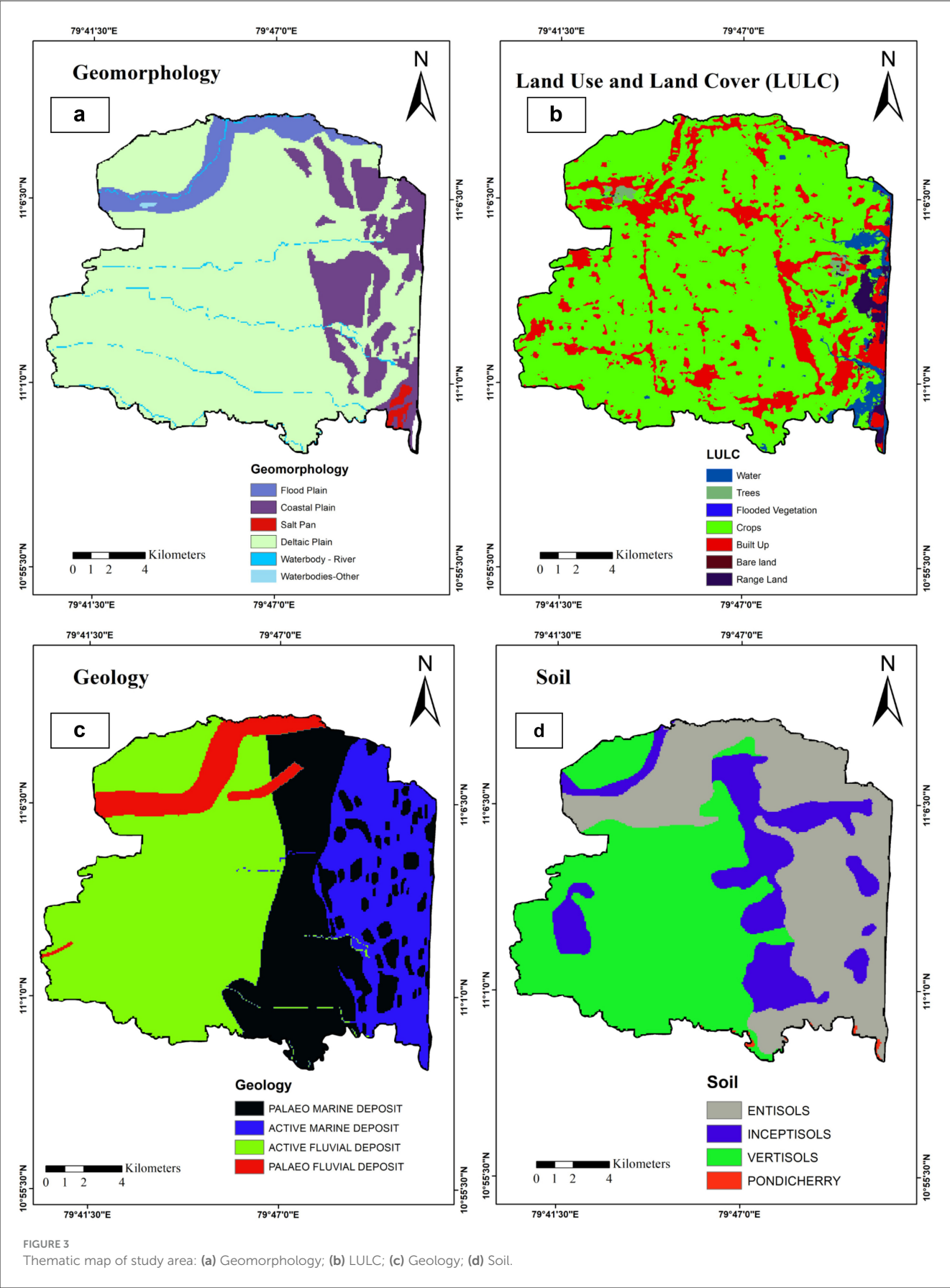
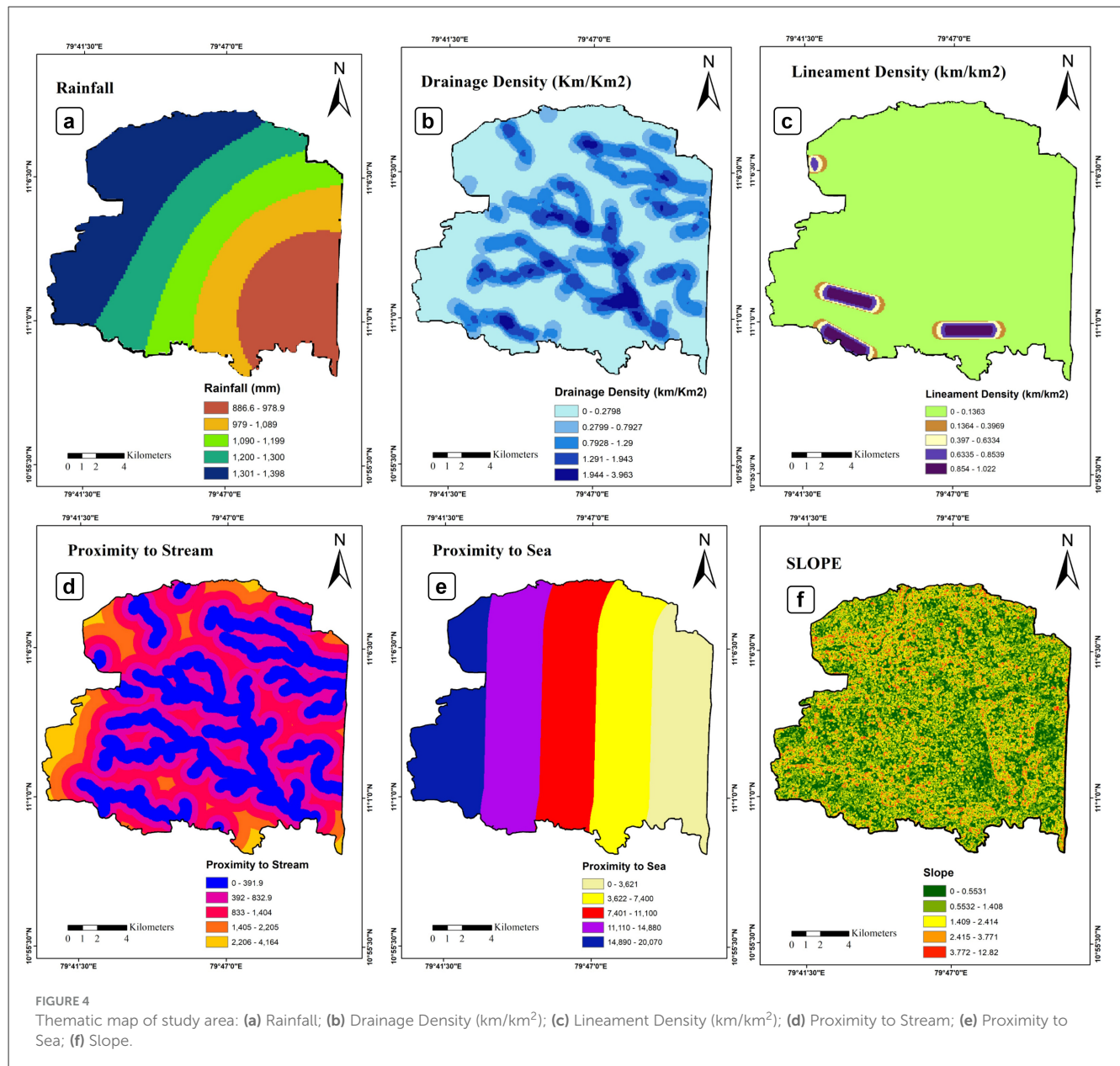


FIGURE 3
Thematic map of study area: (a) Geomorphology; (b) LULC; (c) Geology; (d) Soil.



4.7 Lineament density

Various geological formations encompassing faults, fractures, joints, and dykes serve as fundamental elements for the quantification of lineaments (Kanagaraj et al., 2019). The geological configuration of the lithosphere profoundly affects hydrological flow in both surface and subsurface environments (Hussein et al., 2017). A distinct correlation exists between the lineament density and zones of groundwater potential, as the lineament density regulates the volume of surface water that infiltrates aquifers (Sathiyamoorthy et al., 2023). An area characterized by a heightened lineament length density signifies substantial groundwater potential, suggesting an augmentation in secondary porosity (Kumar et al., 2024). The majority (90%) of areas are viable locations associated with diminished lineament density values, as exemplified in Figure 4c.

4.8 Proximity to stream

Areas closer to the stream generally have higher recharge capacity because water infiltration is more extensive, and greater influence on groundwater levels (Popalzai et al., 2023). Flat terrain where the groundwater level is higher than in another region, especially if it's closer to a stream network (Faheem et al., 2023). Water near the stream spends less time traveling through the subsurface before reaching the water-bearing layers. In the research zone, the location near the stream, approximately 392 m away, is classified as a very high-potential area, accounting for 36%. The distance of 833 m is classified as high potential, with 32% of the area falling under this category. The remaining 21 and 8% of areas come under moderate and low potential, respectively. Figure 4d shows the proximity to stream of the study area.

4.9 Proximity to sea

The intrusion of the Sea can compromise the quality of groundwater and limit its availability in coastal zones (Prusty and Farooq, 2020). Due to the minimal inland topographical variation and the progressive rise in sea levels, low-lying coastal areas exhibit heightened susceptibility (Zamrsky et al., 2024). When evaluating groundwater potential, incorporating Proximity to Sea habitats as an essential factor significantly enhances the utility of GIS-oriented MCDA-AHP techniques (Alshehri et al., 2024). Distance to sea is a crucial factor for evaluating groundwater potential assessment in coastal areas (Bhawan Faridabad, 2014). The Distance from the Sea varies from 0 to 20,700 m, as shown in Figure 4e. It is classified into five categories: 0 to 3621 m is very close to the sea with the highest risk of seawater intrusion, followed by 3,622 m to 7,400 m, which has a moderate risk of seawater intrusion. Ranges that 41.45% of the area studied fall under the very high to high risk of seawater intrusion, which indirectly affects the potential areas.

4.10 Slope

The slope is one of the fundamental units of assessing groundwater potential because it directly affects the surface runoff and water level (Babu and Maury, 2025). A steep slope reduces water recharge, while a lower slope enhances recharge (Kumar et al., 2024). The slope has a positive correlation with surface runoff but a negative correlation with surface water infiltration and percolation (Ghosh, 2021). In areas that seep deeper into the earth, eventually raising groundwater levels. The slope ranges from 0 to 12.82 degrees, as shown in Figure 4f. In the study area, nearly 66% of the area contributes a high yield of groundwater potential, which is a more flat or plain surface. The remaining 21.52 and 12.48% have moderate and low yield capacity for groundwater potential, respectively.

4.11 TWI

The Topographic Wetness Index (TWI) is derived from the catchment area in conjunction with the terrain of slope, thereby yielding crucial insights into regions where water accumulation is probable (Hassaballa and Salih, 2024). TWI generally exhibits a gradient from minimal value in the areas characterized by adequate drainage (for instance, ridges and steep slopes) to elevated value in areas with inadequate drainage (such as valleys and flat plains) (Tripathi et al., 2025). The TWI values range from 4.881 to 22.07, as shown in Figure 5a, which is common in natural landscapes. The TWI values indicate that 65.9% of the area lies in a low potential area, and 16.39% of the area contributes to a high potential area. TWI is calculated using this Equation 4.

$$TWI = \ln\left[\frac{A_s}{\tan \beta}\right] \quad (4)$$

Where, A_s denoted as the area of boundary, and $\tan(\beta)$ represents a specific grid of local slope angle.

4.12 TPI

The gradation of landforms at topographical slope sites is conventionally quantified and automated through the application of the Topographic Position Index (TPI) methodology (Fatema et al., 2023). Elevated TPI values characterize elevated terrains such as hilltops and ridges, whereas valleys and depressions exhibit diminished TPI values; conversely, flat or mid-slope areas are associated with values that approximate zero (Arulbalaji et al., 2019). Given their capacity to capture surface runoff and facilitate infiltration, thereby enhancing groundwater recharge, regions with low TPI values, such as valleys and flat terrains, are generally associated with increased groundwater potential (Pillai et al., 2023). The TPI value ranges from -3.6 to 5.222 , shown in Figure 5b, with 35.82% of the area contributing high potential and 40% of the area being moderate, which has a near-zero value, representing a flat or plain terrain. Only 23.6% of the area has gentle ridges and peaks in the research area.

4.13 NDVI

The normalized difference vegetation index (NDVI) yields vital insights into the moisture levels in the soil and the coverage of vegetation, both of which greatly influence the areas marked as having potential groundwater resources (Ravindran et al., 2024). Furthermore, beyond groundwater availability, different factors that could influence vegetation robustness, including soil moisture levels and modifications in land use, might also affect the NDVI (Babu and Maury, 2025). The NDVI ranges from -0.1432 to 0.5979 , as shown in Figure 5c. The NDVI classification shows that 46.7% of the areas contribute low potential yields, and 31.73% of the regions contribute high potential yields. NDVI was identified using Equation 5.

$$NDVI = \frac{RED - NIR}{RED + NIR} \quad (5)$$

4.14 NDWI

Determining groundwater potential is contingent upon the Normalized Difference Water Index (NDWI), a calculation obtained through remote sensing technology that measures how much water is contained in terrestrial soil and vegetation (Borah and Bora, 2025). This approach proves particularly helpful in regions where the recharge of groundwater may be significantly influenced by the extent of vegetation cover (Sulle et al., 2023). To enhance the accuracy of groundwater potential, these factors have supplementary environmental and geographic variables. The NDWI ranges from -0.51 to 0.18 (Figure 5d), closer to the 0.186 value, and contributes directly to groundwater recharge, which contains more moisture content and 8.6% of the area. NDWI was determined by using Equation 6.

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad (6)$$

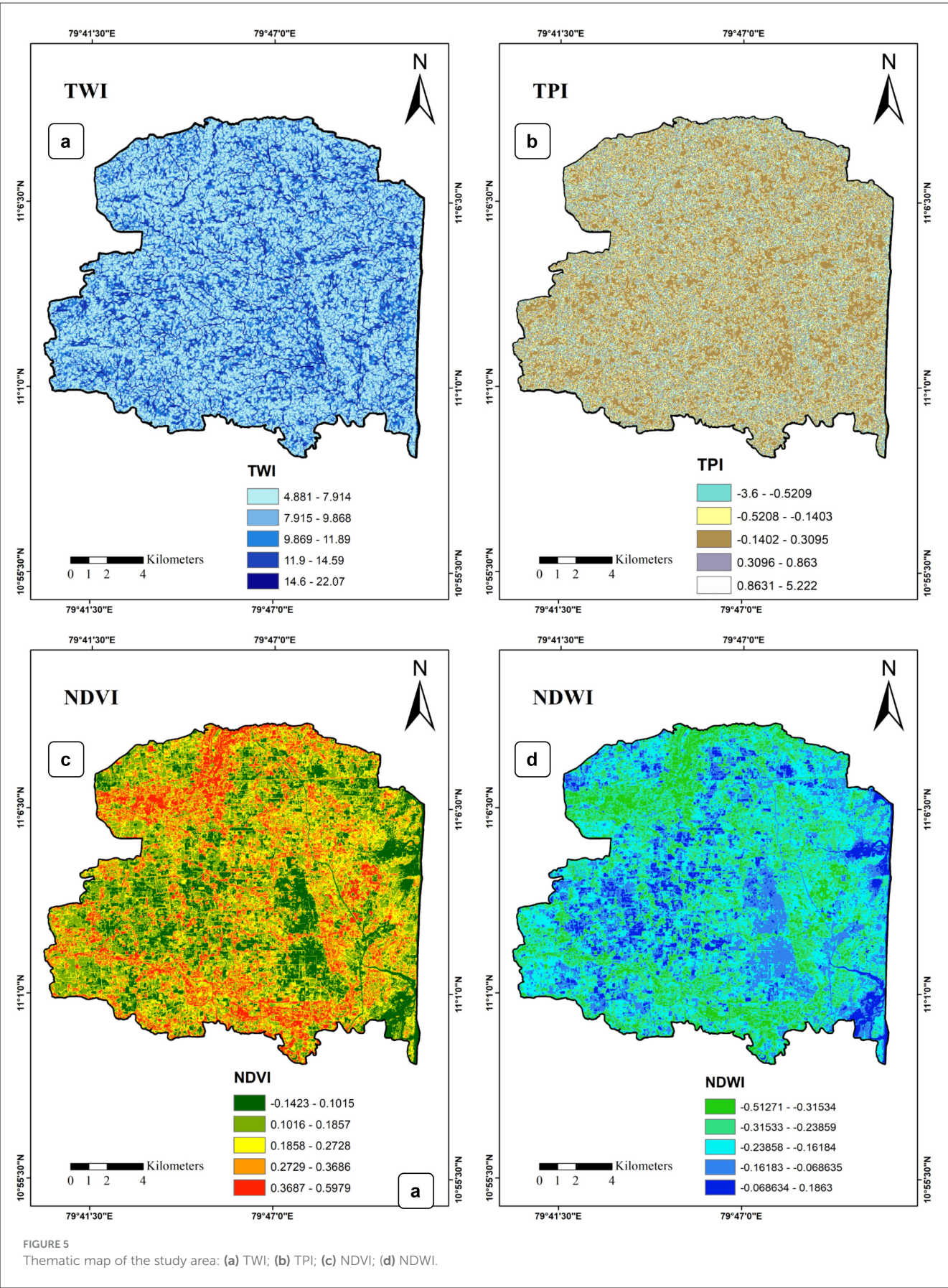
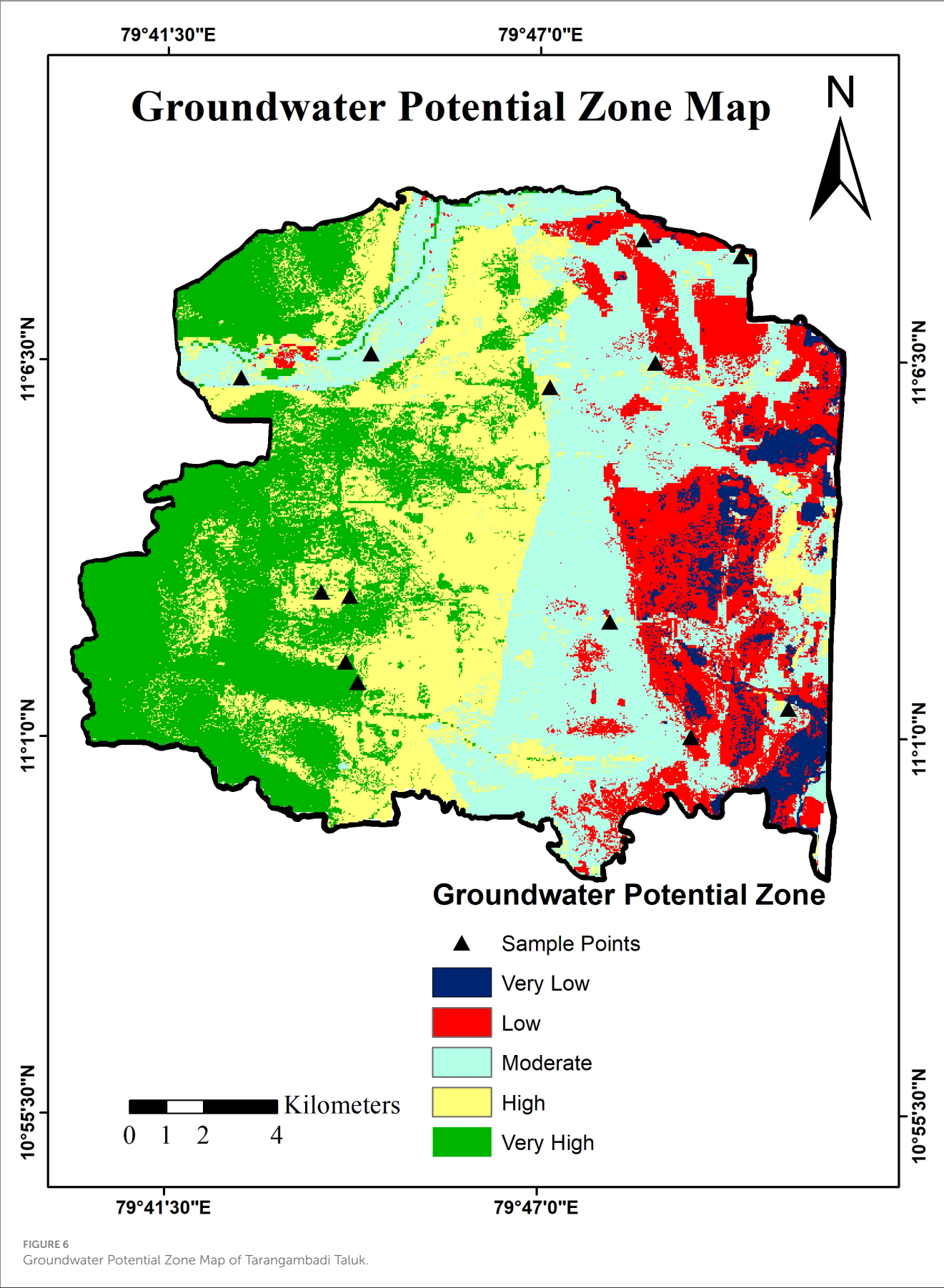


FIGURE 5
Thematic map of the study area: (a) TWI; (b) TPI; (c) NDVI; (d) NDWI.



4.15 Coastal dynamics on groundwater potential

The incorporation of coastal dynamics provides a critical insight into the groundwater system of Tarangambadi Taluk. Regions situated in close proximity to sea environments and low-lying coastal geomorphic features were recognized as areas more susceptible to seawater intrusion and diminished recharge capacity. In contrast, inland coastal alluvial deposits and beach ridge formations demonstrate comparatively superior groundwater potential owing to conductive infiltration conditions. Through the integration of proximity to sea and coastal characteristics, the analysis underscores the extent to which the sea significantly influences and modifies the groundwater potential in coastal aquifers. This innovative focus on coastal dynamics serves to differentiate the current study from other inland groundwater potential studies and thereby augments the rigor of the identified zones.

4.16 Groundwater potential zones area

AHP methods assigned weights and ranks to fourteen thematic layers for the detection of the Groundwater Potential Zone (GWPZ). The layers were rasterised at a 30 * 30 m cell size and combined with weights and ranks using ArcGIS 10.8 (Abijith et al., 2020). The weighted overlay analysis's final output was generated by integrating all layers in the ArcGIS raster calculator, categorizing results into five very low, low, moderate, high, and very high) to create the GWPZ map. The delineated Groundwater Potential Zone (GWPZ) Map, displayed in Figure 6, offers a visual representation of the spatial heterogeneity concerning groundwater resources throughout the study region (Dar et al., 2021). Table 6 delineates the categorization of the research area according to groundwater potential and the associated spatial extent of each classification. Very high potential zones constitute 26.52% of the total area (74.51 km²), primarily dominating the western and southwestern regions of the study area, which exhibit advantageous hydrogeological conditions such as floodplains, active fluvial deposits, and low-gradient agricultural terrains. These regions are characterized by elevated infiltration rates and permeable soils, which are conducive to groundwater recharge. High potential zones encompass 25.30% (71.09 km²). This is particularly evident within the central corridor areas, which demonstrate moderate to high recharge potential. These zones may overlap with agricultural lands or geomorphological features such as coastal plains that possess sufficient permeability.

Moderate Potential zones represent the most significant proportion, spanning 29.49% (82.86 km²). These zones constitute the central spine and portions of the northern area, typifying transitional regions with a blend of moderate infiltration capacities and drainage characteristics. These areas may include diverse geomorphic units such as coastal plains and soils with moderate drainage. Low and Very Low zones collectively account for 18.69% of the study area (52.52 km²), primarily concentrated in the eastern and southeastern regions, particularly in Proximity to the coastline. These zones are predominantly characterized by impervious

formations, urbanized surfaces, or salt-affected soils (e.g., paleo-marine deposits), which hinder infiltration. Furthermore, the Proximity to Sea may pose a risk of saline intrusion, rendering these zones vulnerable and less appropriate for groundwater extraction without the implementation of desalination or recharge facilities.

This distribution indicates that over 50% of the study area demonstrates high to very high groundwater potential, presenting opportunities for sustainable groundwater development. However, areas with low and very low potential necessitate careful management for extraction, warranting the implementation of recharge strategies to enhance their viability.

4.17 Accuracy assessment of the model

Validation ascertains the GWPZ map's accurate representation of groundwater potential, which is imperative for sustainable resource management (Mihret and Wuletaw, 2025). A rigorously validated GWPZ map facilitates informed decision-making by supplying reliable data for conservation and utilization strategies (Duguma and Duguma, 2022). The validation datasets were procured from the State Ground and Surface Water Resources Data Centre, Tamil Nadu, covering the period from January 1991 to December 2024, with monthly records for each well. For validation purposes, we used the 34-year average annual water level for each well. This approach integrates both seasonal (pre-monsoon and post-monsoon) and interannual variability into a single representative value. By utilizing long-term averages, the validation outcomes are rendered less susceptible to the effects of anomalous wet or dry years, consequently providing a more robust foundation for comparison with the anticipated groundwater potential zones. To ensure GWPZ accuracy, data from 13 dug wells and Tube wells were cross-validated. Actual water levels from study area wells were compared to predicted groundwater potential index values for consistency (Loganathan and Sathiyamoorthy, 2024). To evaluate groundwater availability, long-term average water levels from the validated observation wells in Tarangambadi Taluk were categorized into High, Medium, and Low Potential. This classification utilized the equal interval method, based on water levels ranging from 2.36 to 14.21 mbgl (measured in meters below groundwater level, mbgl). High Groundwater Potential zones are categorized by shallow water levels (2.36–6.31 mbgl), signifying favorable groundwater access and enhanced recharge capacity. Medium Groundwater Potential areas range from 6.32–10.26 mbgl, indicating intermediate water table depths. Low Groundwater Potential zones, with depths of 10.27–14.21 mbgl,

TABLE 6 Groundwater potential area.

Value	% of area	Class	Area (km ²)
1	3.86	Very low	10.8432
2	14.83	Low	41.679
3	29.49	Moderate	82.8567
4	25.30	High	71.0928
5	26.52	Very high	74.5083

TABLE 7 Assessment of groundwater potential validation.

S.No	Location	Actual groundwater GWPZ	Predicted GWPZ	Agreement
1	Sembanarkoil	Medium	Moderate to high	Agree
2	Aaru Pathi	Medium	Moderate to high	Agree
3	Echchangudi	Low	High	Disagree
4	Narasinganatham	Low	High	Disagree
5	Aakur Pandaravadai	High	Moderate to high	Agree
6	Poraiyar	High	High	Agree
7	Thiruvilaiyattam	High	High	Agree
8	Keezha Perumpallam	High	High	Agree
9	Melaperumpallam	High	Moderate to high	Agree
10	Mamakudi	High	Moderate to high	Agree
11	Thillaiyadi	High	Low	Agree
12	Kattucheri	High	Low	Disagree
13	Thiruvilaiyattam	High	High	Agree

denote deeper water tables and possible limitations in recharge or risks of over-extraction. Most wells (10 out of 13) exhibited High Potential, reflecting prevalent shallow water levels and robust recharge conditions. The validation of the groundwater potential map accuracy was conducted through observed groundwater level data, with the findings encapsulated in Table 7. A strong correlation was observed in 10 out of 13 wells between actual groundwater conditions and predicted potential classes, with three wells showing discrepancies.

Total Wells count = 13

actual groundwater level data and predicted, same agreement, wells count = 10

actual groundwater level data and predicted, varying agreement, wells count = 3

groundwater potential accuracy = $(10/13) * 100 = 76.9\%$.

The accuracy of the GWPZ map was determined to be 76.92%. The findings point out the effectiveness of integrating the Analytical Hierarchy Process (AHP), Remote Sensing (RS), and Geographic Information System (GIS) for accurately assessing groundwater prospects in coastal agricultural sectors, including Tarangambadi Taluk.

5 Conclusion

The delineation of Groundwater Potential Zones (GWPZ) in Tarangambadi Taluk using GIS, remote sensing, and AHP techniques has effectively assessed groundwater resources. The evaluation of hydrogeological and terrain parameters facilitated the creation of a reliable groundwater potential map through pairwise comparison and overlays. Using weighted overlay analysis, the GWPZ map classified the region into five zones, which are very low, low, moderate, high, and very high. The regions that are in the very low and low potential zones represent 3.86% and 14.83% of the area, respectively. The percentage of the total areas that are in the moderate, high, and very high potential zones are 29.49%,

25.30%, and 26.52%, respectively. About 51.82% (145.59 km²) of the land is categorized as having high to very high potential, particularly in regions with favorable conditions for aquifer storage. These zones are ideal for planning irrigation and groundwater supply systems. Conversely, 18.69% (62.52 km²) of the area is identified as low to very low potential zones, primarily along coastal areas facing geological and urbanization challenges. The map of groundwater potential has a significant correlation with actual groundwater level, which shows that 76.92% accuracy of the model. To mitigate these issues, implementing artificial recharge structures is not only essential for improving groundwater recharge in these regions and site-specific interventions like tank rejuvenation and efficient irrigation methods can strengthen groundwater sustainability. This study's innovative aspect is its focus on coastal dynamics, necessitating a dual approach to enhance recharge and prevent seawater intrusion. The inclusion of Proximity to the sea as a criterion enhances the map's reliability, validated by field groundwater level data. The research outputs inform sustainable groundwater extraction and conservation, aiding hydrological modeling and climate resilience planning. Future research could integrate remote sensing trends, climate data, and machine learning to develop a dynamic groundwater risk and opportunity model.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RM: Conceptualization, Data curation, Methodology, Software, Visualization, Writing – original draft. MS: Investigation, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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