

P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating (2025): 4.5
IJGGE 2025; 7(12): 64-74
www.geojournal.net
Received: 20-10-2025
Accepted: 25-11-2025

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Delineation of groundwater potential zones in Vadipatti Taluk, Madurai district, Tamil Nadu using geospatial technology and analytical hierarchy process

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DOI: <https://www.doi.org/10.22271/27067483.2025.v7.i12a.462>

Abstract

Groundwater resource management in hard rock terrains presents significant challenges due to complex hydrogeological conditions and water scarcity. This study presents an integrated geospatial approach to delineate groundwater potential zones (GWPZs) in Vadipatti Taluk, Madurai District, Tamil Nadu, India. Seven thematic layers Geology, Geomorphology, Slope, Soil texture, Lineament density, Land use/Land cover (LULC) and Tank buffer, were derived from remote sensing data, topographic maps and secondary sources. The analytical hierarchy process (AHP) was employed to assign weights to each parameter based on hydrogeological significance. Weighted overlay analysis in ArcGIS 10 produced a groundwater potential map classified into five categories: Very High (42 km²), High (153 km²), Moderate (169 km²), Low (80 km²) and Very Low (17 km²). Results indicate that fluvial geomorphic units and areas proximal to water bodies exhibit the highest groundwater potential, while structural hills and elevated terrain show limited potential due to high surface runoff. These findings provide critical information for optimizing groundwater exploration, developing water harvesting structures, and planning sustainable water resource management in the region.

Keywords: Geospatial technology, groundwater potential, analytical hierarchy process, hard rock aquifers, water resource management

1. Introduction

Groundwater is a crucial natural resource that supports public health, economic development, and ecological sustainability, particularly in arid and semi-arid regions (Foster & Chilton, 2003). Hard rock terrains in these climatic zones often face severe water scarcity due to diverse physiographic conditions and limited groundwater occurrence (CGWB, 2019; Todd & Mays, 2005). The pronounced heterogeneity of hard rock aquifers complicates groundwater exploration, and the high costs associated with drilling necessitate the application of scientific and cost-effective methods for identifying groundwater potential zones (Singh & Prakash, 2002; Jha *et al.*, 2007).

The convenient availability of groundwater at or near the point of consumption, along with its minimal requirement for treatment, makes it one of the most important sources of water supply, particularly in arid and semi-arid regions (Todd & Mays, 2005). In a tropical country such as India, water scarcity has become increasingly critical due to rising demands driven by population growth, agricultural irrigation, industrial expansion, and tourism activities (Sishodia *et al.*, 2016; Etikala *et al.*, 2019; Kumar *et al.*, 2021; Mahanuradha & Pragatheeswaran, 2023; Libina *et al.*, 2023). In addition, anthropogenic factors such as changes in land-use patterns and excessive groundwater extraction for domestic, agricultural, and industrial purposes have significantly influenced subsurface water levels (Nayak *et al.*, 2015; Kumari *et al.*, 2022). Groundwater systems are inherently dynamic, continuously responding to variations in climatic conditions, extraction pressures, and land-use changes over both short- and long-term time scales.

Conventional groundwater exploration methods are labor-intensive and expensive. Modern geospatial technologies remote sensing and Geographic Information System (GIS) provide efficient, accurate alternatives for demarcating groundwater potential zones in both accessible and inaccessible areas^[4]. These techniques enable integration of multiple

hydrogeological parameters to generate spatially distributed groundwater potential assessments. The analytical hierarchy process (AHP), a multi-criteria decision-making technique, facilitates systematic weightage assignment to hydrogeological parameters based on their relative importance^[5].

Vadipatti Taluk in Madurai District exemplifies hard rock terrain facing severe groundwater depletion and recurring water scarcity during dry seasons. This study was motivated by the critical need to identify suitable zones for groundwater extraction, recharge structure placement, and sustainable water resource management. The integration of remote sensing, GIS and AHP methodologies provides a systematic framework for groundwater potential zone delineation.

2. Study Area

2.1 Geographic representation

Vadipatti Taluk (Longitude: 77°57' 39.6576 E Latitude: 10°5'3.5448 N) is located in Madurai District, Tamil Nadu, South India, approximately 29 km north of the district headquarters. The taluk covers an area of 463 km² and comprises a population of approximately 21,833 inhabitants. It is bounded by Nilakottai Block to the west, Alanganallur Block to the east, Chellampatti Block to the south, and Vattalkundu Block to the northwest, lying at the border between Madurai and Dindigul districts.

2.2 Hydro-geomorphologic Characteristics

Vadipatti is traversed by the Vaigai River (also known as the MullaiPeriyar Irrigation Channel), which originates in

the Varushanadu Hills of Theni District at an elevation of 1,524 m and flows in a northwest-southeast direction. The region features diverse landforms including structural and denudational hills, residual wells, linear ridges, pediplains, and younger alluvial plains along the Vaigai River valley.

2.3 Climate and Hydrology

The region experiences a tropical monsoon climate with precipitation distributed across all seasons. The northeast monsoon contributes the maximum annual rainfall (665.5 mm), with average annual precipitation of 247.8 mm. Mean maximum and minimum temperatures during 2017-2018 were 39.6°C and 22.9°C, respectively. Peak temperatures occur during April-May, with significant evaporation losses. The region is heavily dependent on monsoon precipitation for groundwater recharge through infiltration processes.

2.4 Geological Framework

Vadipatti is underlain by Archean crystalline basement rocks comprising hornblende-biotite gneisses, charnockites, granites, and anorthosites. Charnockites dominate the northern portions (259 km²), while hornblende-biotite gneiss covers the southern regions (165 km²). A thin veneer of fluvial deposits (alluvium) occurs along the Vaigai River valley. Weathered zones (20-25 m depth below ground level) and interconnected fractures serve as the primary groundwater reservoirs. Groundwater occurs under phreatic conditions in weathered residuum and fracture zones, transitioning to semi-confined conditions in deeper fractures.

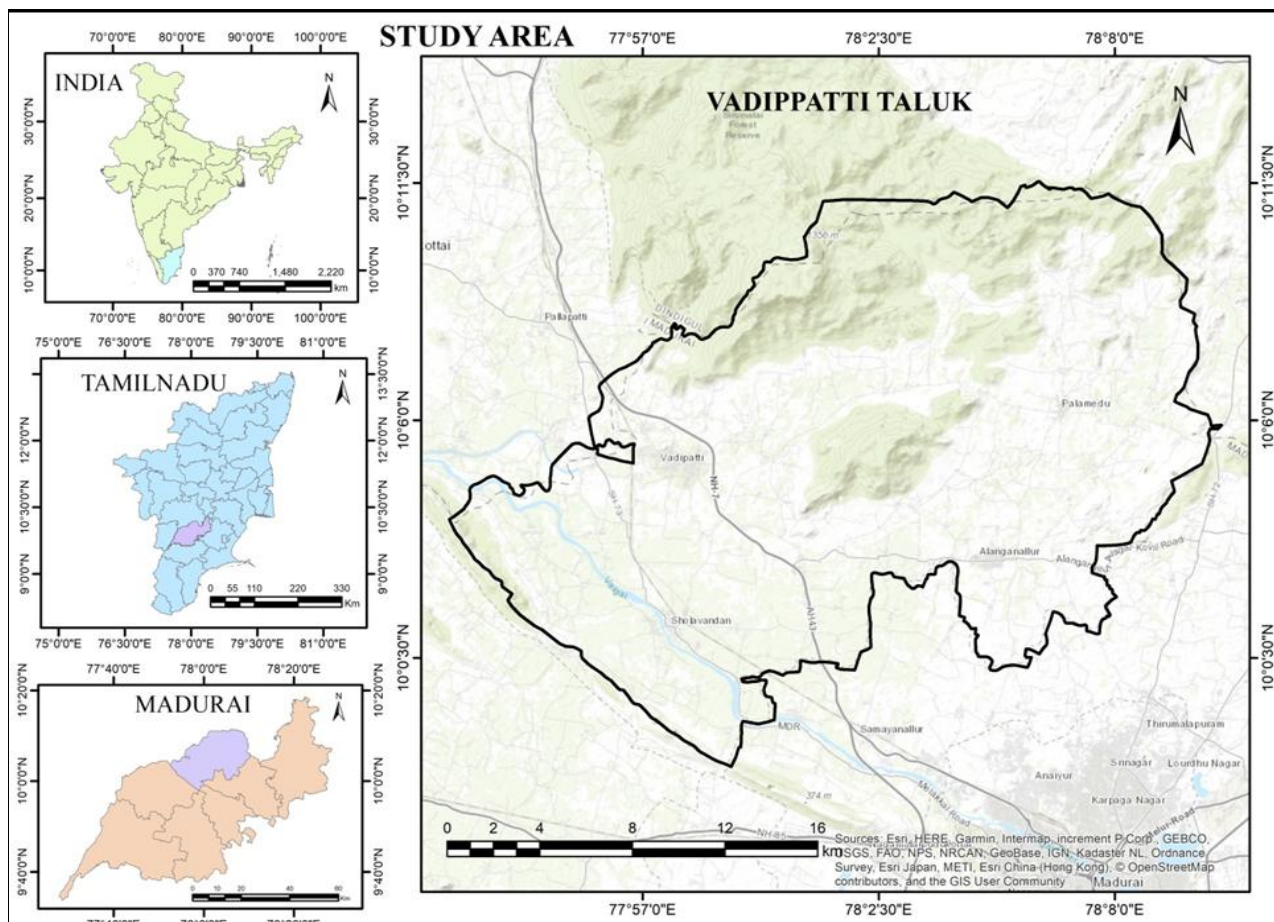


Fig 1: Study Area Map

3. Materials and Methods

3.1 Data Sources and Materials

Geospatial data were compiled from multiple authoritative sources:

Table 1: Data sources and materials utilized for groundwater potential zone mapping

Data Layer	Source
Topographic basemap (1:50,000 scale)	Survey of India, Dehradun
Slope	ALOS PALSAR DEM
Geology and geomorphology	Bhuvan Thematic Services; Geological Survey of India
Lineament delineation	Bhuvan portal analysis
Land use/land cover	Landsat 8 multispectral imagery (2021)
Soil texture classification	Tamil Nadu Agricultural University, Coimbatore
Water bodies	Survey of India topographic sheets
Software: ArcGIS 10, ENVI	ESRI, Exelis Visual Analytics

3.2 Thematic Layer Preparation

- **Geology:** Lithological maps derived from the Geological Survey of India delineated six major rock types. Individual geological units were coded and digitized into vector format, then converted to raster data (30 m resolution).
- **Geomorphology:** Geomorphic units were extracted from Bhuvan services and field observations, classified into seven categories representing denudational, structural, and fluvial landforms. Each unit was digitized and rasterized.
- **Slope:** Digital Elevation Model (DEM) from ALOS PALSAR (30 m resolution) was processed in ArcGIS Spatial Analyst to generate slope raster in degrees. Slope values were reclassified into five categories: Very Low (0-4.65°), Low (4.65-11.63°), Moderate (11.63-20.94°), High (20.94-30.54°), and Very High (>30.54°).
- **Soil Texture:** Soil type data from Tamil Nadu Agricultural University were digitized, classified into 12 categories reflecting soil depth, drainage characteristics, and texture. Raster layers (30 m cell size) were generated based on soil hydraulic properties and water-holding capacity
- **Lineament Density:** Lineaments (fractures, faults, joints) were manually delineated from satellite imagery and DEM-derived topographic analysis. Line density analysis tool in ArcGIS calculated lineament density (km/km²) in 500 m × 500 m moving windows, classified into five classes: Very Low (0-89.71), Low (89.71-179.42), Moderate (179.42-269.14), High (269.14-358.85), and Very High (358.85-448.56 km/km²).
- **Land Use/Land Cover (LULC):** Landsat 8 multispectral data (30 m resolution) from 2021 were processed using supervised classification with Maximum Likelihood algorithm in ENVI software. Four LULC classes were identified: Built-up (55 km²), Agricultural land (73 km²), Fallow land (150 km²), Vegetation (176 km²), and Water bodies (10 km²).
- **Tank Buffer Analysis:** Multi-ring buffer zones (1, 2, 5, and 10 km) were generated around mapped water bodies (tanks, ponds, reservoirs) to quantify proximity influence on groundwater recharge potential.

3.3 Methodology Work Flow Chart

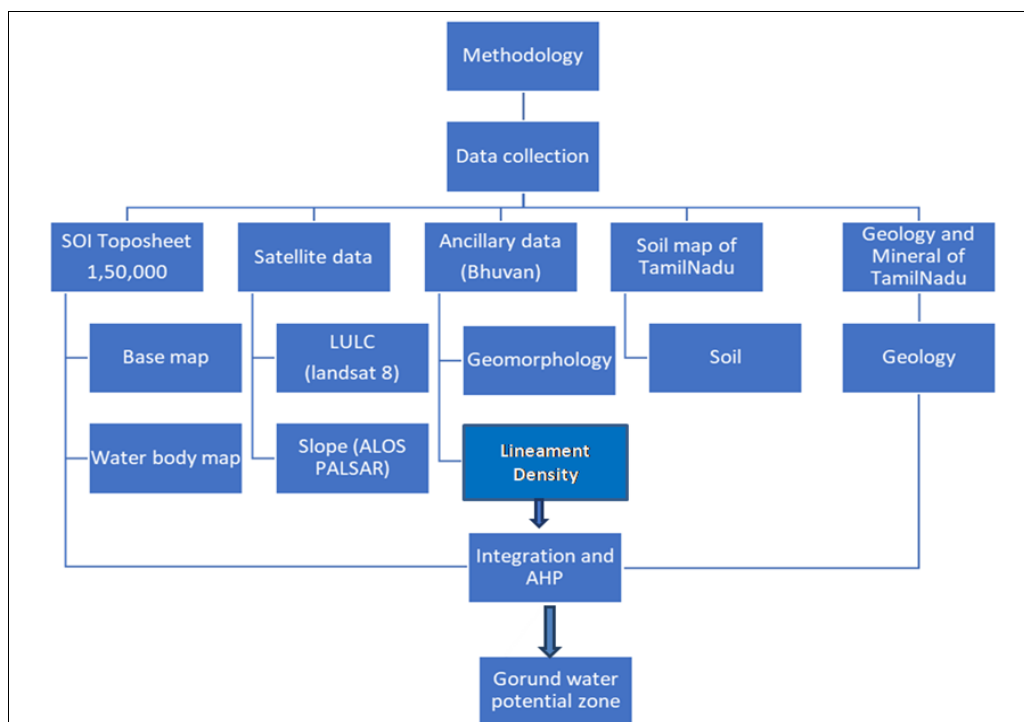


Fig 2: Work Flow Chart

3.4. Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process, developed by Saaty^[6], is a multi-criteria decision-making technique that structures complex problems hierarchically and assigns weights based on pairwise comparisons. This methodology was selected because it accommodates both quantitative data and expert judgments regarding hydrogeological importance of groundwater-controlling parameters.

In this study, AHP involved the following steps:

1. **Hierarchy development:** Seven thematic parameters and their constituent classes were organized in a decision hierarchy with groundwater potential as the ultimate goal.
2. **Pairwise comparison:** Parameters were compared systematically using a 1-9 intensity scale reflecting relative hydrogeological importance (e.g., geology vs. slope in controlling groundwater occurrence).
3. **Weight calculation:** Normalized weights were derived from the pairwise comparison matrix using the eigenvector method. Consistency ratios were calculated to verify judgment reliability.
4. **Local and global weights:** Local weights were assigned to individual classes within each parameter, then multiplied by global parameter weights to obtain final combined weights.
5. **Weighted integration:** Raster layers were multiplied by their respective weights and summed in raster calculator to produce the groundwater potential index.

3.5 Weight Assignment and Normalization

Global parameter weights (Table 1) were established through expert elicitation and literature review of groundwater occurrence factors in similar hard rock settings:

Table 2: Global parameter weights assigned using AHP

Parameter	Global Weight
Slope	0.24
Land Use/Land Cover	0.27
Geology	0.15
Geomorphology	0.14
Lineament Density	0.12
Soil Texture	0.05
Tank Buffer	0.03
Total	1.00

Local weights for individual classes within each parameter reflected their hydrogeological significance. For example, within LULC, water bodies (weight: 0.32) received the highest weight due to direct recharge potential, followed by vegetation (0.27) and agricultural land (0.21). Similarly, within slope categories, very low slopes (<4.65°) received maximum weight (0.32) due to optimal infiltration conditions, while steep slopes (>30.54°) received minimum weight (0.06) due to high runoff losses.

Weighted index values for each pixel were calculated as:

$$WI = \sum_{i=1}^7 (G_i \times L_i)$$

where WI is the weighted index, G_i is the global weight of parameter i , and L_i is the local weight of the corresponding class.

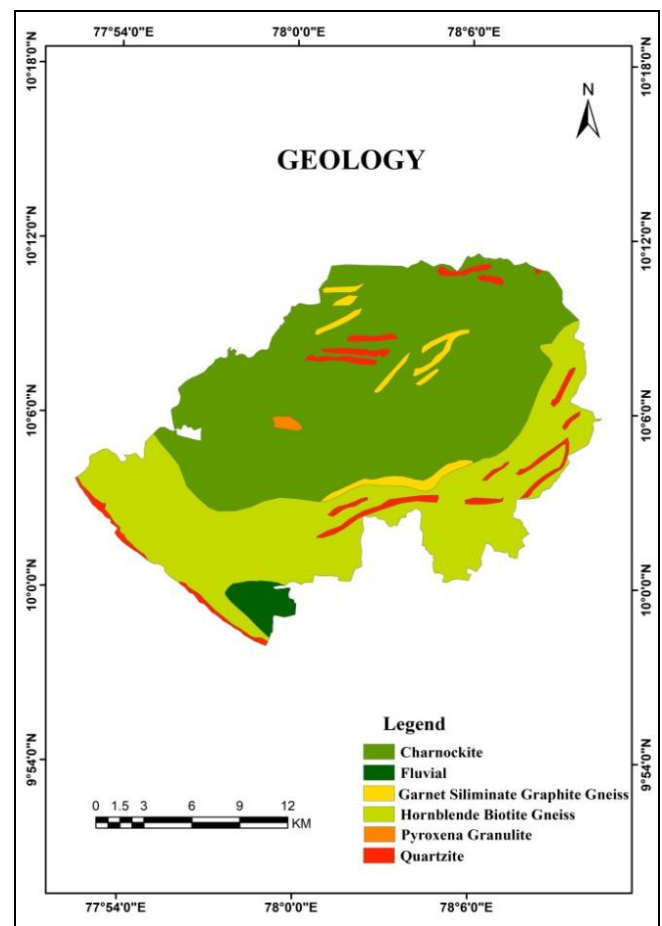
3.6 Overlay Analysis and GWPZ Classification

All weighted thematic raster layers were integrated using raster overlay analysis (weighted sum method) in ArcGIS Spatial Analyst. The resulting groundwater potential index raster was reclassified into five qualitative categories representing groundwater potential zones: Very High, High, Moderate, Low, and Very Low.

4. Results

4.1 Thematic Parameter Analysis

Geology: Six lithological units were identified. Charnockite (259 km²) and hornblende-biotite gneiss (165 km²) dominate, comprising 91.6% of the taluk. Fluvial alluvium (9 km²) occurs along the Vaigai River. Quartzite, garnet-sillimanite graphite gneiss, and pyroxene granulite comprise <2.6% of the area. Hard rock lithologies with limited weathering (charnockite, quartzite) received lower local weights (0.06-0.11) compared to weathered gneisses (0.27) and alluvium (0.32), which provide favorable pore space for groundwater storage.



Source: Geology and Mineral map

Fig 3: Geology Map

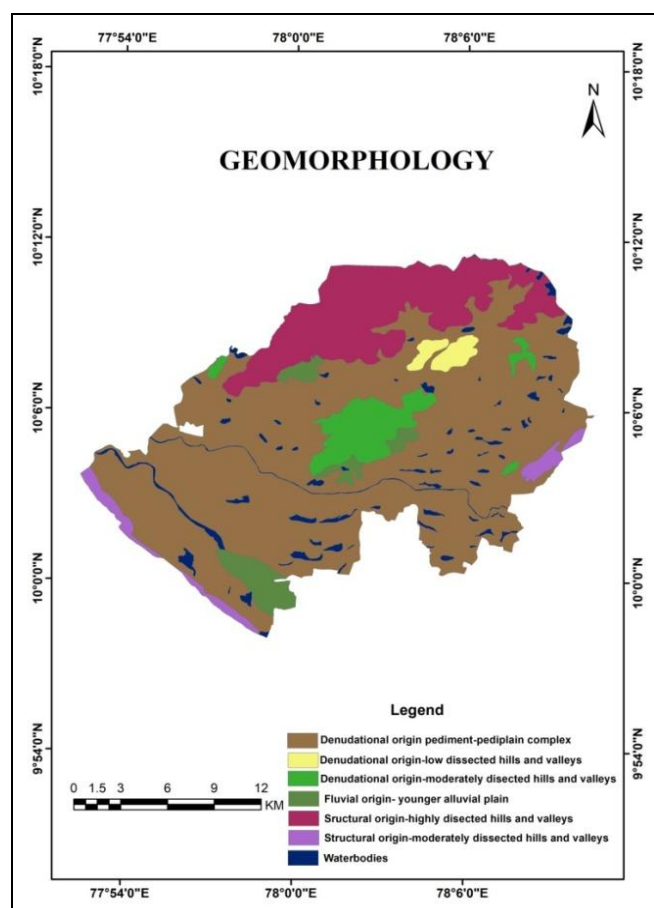
Table 3: Geology areas of Vadipatti Taluk

Types of Geology	Area (in sq.km)
Charnockite	259
Fluvial	9
Garnet Sillimanite Graphite Gneiss	11
Hornblende Biotite Gneiss	165
Pyroxene Granulite	1
Quartzite	9

The Geology of Vadipatti taluk is classified into 6 major types Charnockite, Fluvial, Garnet Siliminate Graphite Gneiss, Hornblende Biotite Gneiss, Pyroxena Granulite, and Quartzite.

Major parts are covered by Charnockite it covers 259 Sq.Km in the North and Hornblende biotite Gneiss covers 165 sqkm on the South. In the North West small portion is covered by Garnet Siliminate. Graphite Gneiss covers 11sqkm in Vadipatti Taluk. Fluvial type of Geology covers 9 sqkm which is found in the South west of the river deposits. In the central part we have Pyroxene Granulite which covers 1 sqkm. Quartzite covers 9 sqkm which is present in North East and Central part.

Geomorphology: Seven distinct geomorphic units were identified. Denudational origin pediments and pediplains (310 km², 66.9%) represent the dominant landform, characterized by gently sloping erosional surfaces favorable for infiltration. Structural origin hills covering 88 km² (19.0%) are characterized by high relief and steep slopes, promoting runoff. Fluvial origin younger alluvial plains (17 km², 3.7%) adjacent to the Vaigai River represent the most favorable groundwater recharge zones. Water bodies (16 km², 3.5%) include natural tanks and constructed reservoirs.



Source: Bhuvan portal

Fig 4: Geomorphology Map

The Geomorphology of Vadippatti Taluk is classified into 7 major types. Structural hills are also found in the central regions of South western parts of the study area near chellampati area and North region that is full of dense forest area near to sirumalai hills. Central region is full of Denutational origin that covers Vadipatti and its adjoining

areas. Southern region has fluvial origin due to Vaigai river deposits which is formed by alluvial plain. That comprises of boulders, pebbles, gravels and clay deposits that are found in Lower topographic locations. The major water body are present in the South side of the Vadipatti.

Table 4: Geomorphology area of Vadipatti Taluk

Types of Geomorphology	Area (in sq.km)
Denudational origin pediment Padi plain complex	310
Fluvial origin younger Alluvial plain	17
Denudational origin low dissected hills and valleys	7
Water body	16
Denudational origin moderately dissected hills and valleys	25
Structural origin moderately dissected hills and valleys	11
Structural origin highly dissected hills and valleys	77

Slope: The majority of Vadipatti (289 km², 62.4%) exhibits very low slopes (<4.65°), favorable for infiltration and groundwater recharge. Moderate (8.4%) and high (8.0%) slope zones are concentrated in the northwestern upland regions. Very high slopes (>30.54°) cover only 3.0% of the area, primarily in structurally controlled uplands. The high elevated mountains all are structurally formed hill. It is found in North western part of Vadipatti. The Green colour shows the plain region. In central part of the study area it shows some elevated mountains and low elevated mountains which are formed by moderately dissected hills. The major part of Mountains is covered in North western parts of the study area.

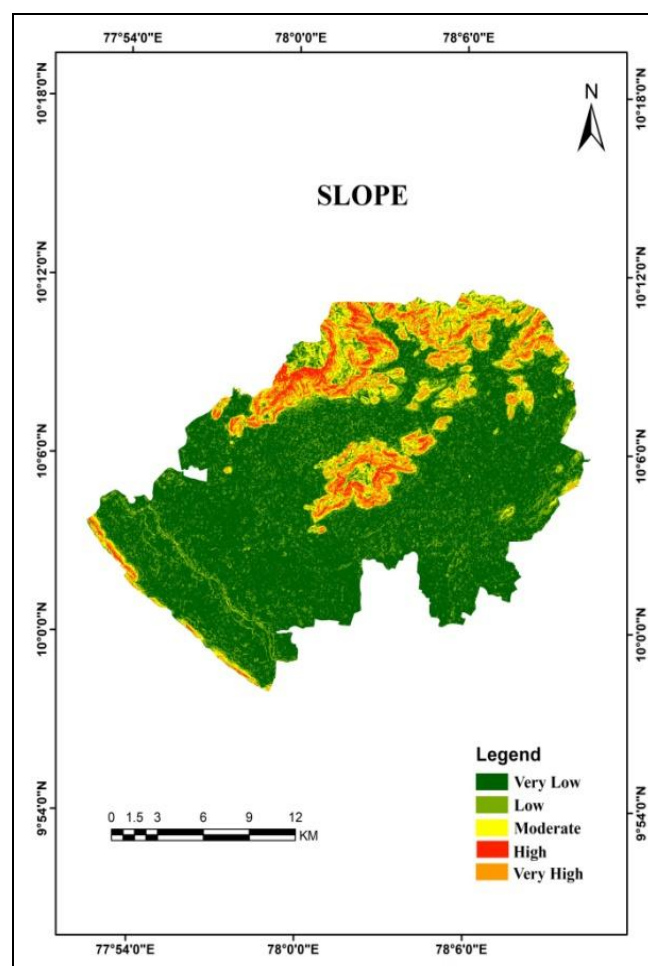
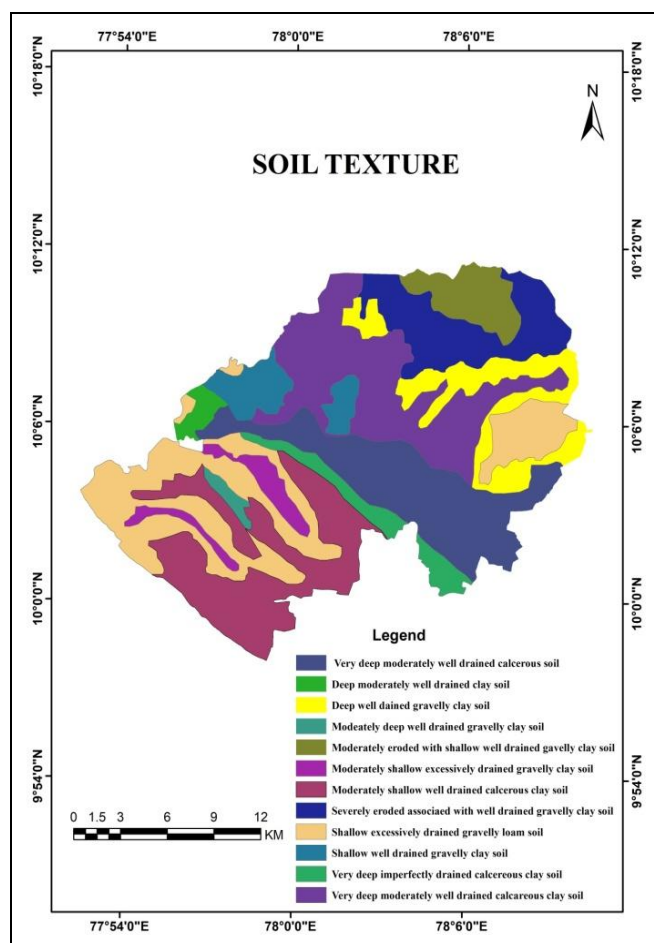


Fig 5: Slope Map

Table 5: Slope values of Vadipatti Taluk

Slope classification	Area(in sq.km)
Very low	289
Low	72
Moderate	39
High	37
Very High	14

Soil Texture: Twelve soil types were mapped. Very deep moderately drained calcareous clay soils (79.29 km²) and moderately well-drained calcerous soils (70.95 km²) provide substantial water-holding capacity. Shallow excessively drained gravelly soils (65.04 km²) have high infiltration but limited water retention. Shallow well drained Gravelly clay soil covers 19.33 sq. km. Severely eroded is associated with well drained gravelly clay soil which covers 43.48 sq. km. Moderately eroded with shallow well drained gravelly clay soil covers 20.76 sq. km. Deep well drained gravelly clay soil covers 38.44 sq.km. Shallow excessively drained Gravelly loam soil covers 17.50 sq.km. Deep moderately well drained clay soil covers 5.48 sqkm. Very deep moderately well drained calcerous soil covers 70.95 sqkm. Very deep imperfectly drained calcerous clay soil covers 15.30sqkm. Moderately shallow excessively drained. Gravelly clay soil covers 12.99 sqkm. Moderately shallow well drained calcerous clay soil 70.96 sq km.



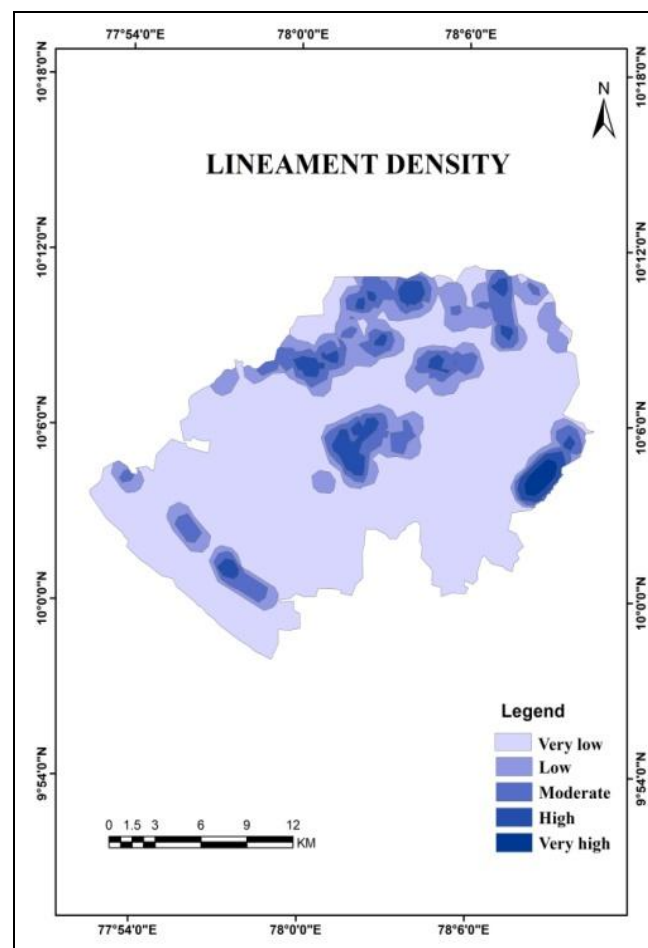
Source: Soil map of Tamilnadu

Fig 6: Soil Texture

Lineament Density

A lineament is defined as a large scale linear feature, which expresses itself in terms of topography of the underlying

structural features. Lineament density map is a measure of significant length of Linear feature expressed in size. The Lineament density map of the study area grouped into five classes like Very low, Low; Moderate, High and very high. Increased lineament density indicates enhanced structural fracturing and groundwater flow potential, receiving correspondingly higher weights.



Source: Bhuvan Portal

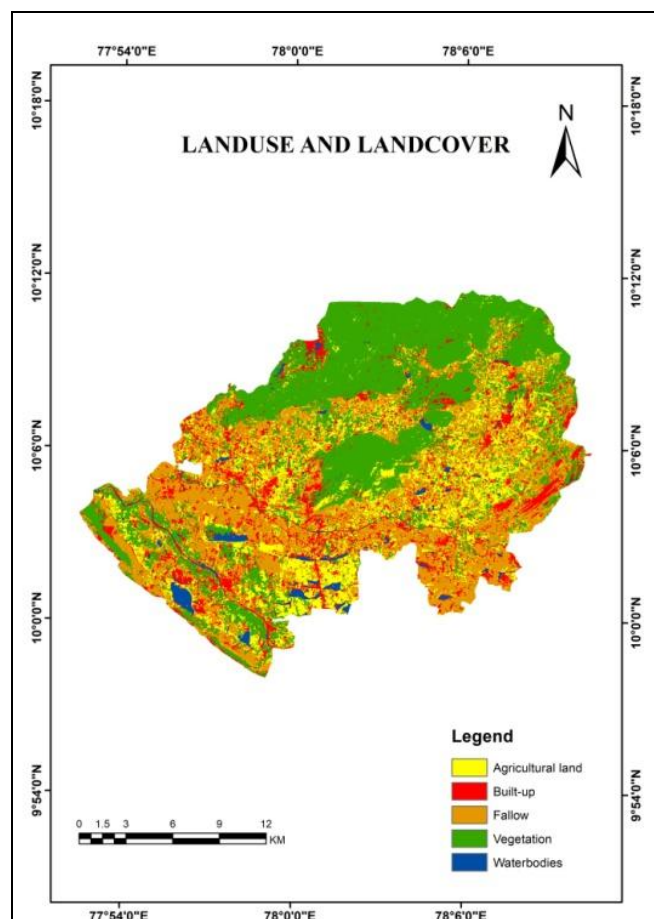
Fig 7: Lineament density**Table 6:** Lineament Density of Vadipatti Taluk

Lineament classification	Area(in sq.km)
Very low	332.53
Low	65.80
Moderate	43.21
High	18.49
Very High	3.13

Land Use/Land Cover

LU/LC is essential for implementing numerous developments, planning, and Land use schemes to fulfil up the increasing demands of basic human needs. The Land use and Land cover maps help to provide base information for further decision making in watershed management. The LULC of Vadipatti in the year 2020 is carried out using Landsat 8 supervised classification says about Build-up, Agricultural land, Fallow land and water bodies. Different Land use and Land cover classified by rank based on its properties. Vegetation dominated 176 Area in sq.km followed by fallow land (150 km², 32.4%), built-up areas (55 km², 11.9%), agricultural land (73 km², 15.8%), and water bodies (10 km², 2.2%). Vegetated areas and water

bodies received highest weights due to enhanced recharge through reduced evaporation and direct infiltration, respectively.



Source: Landsat

Fig 8: Landuse and Landcover Map

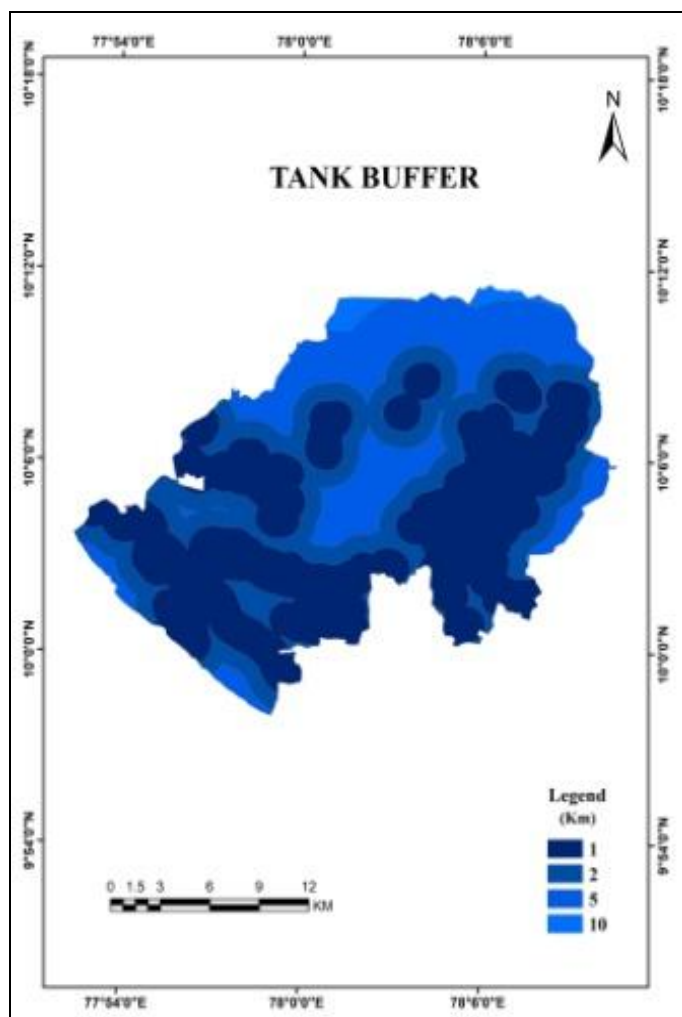
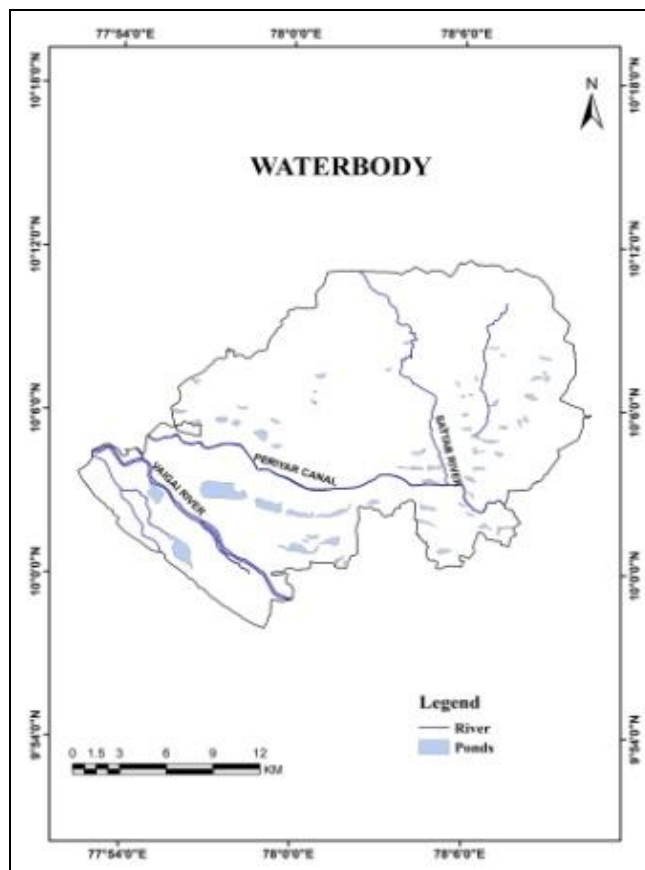
Table 7: Lineament Density of Vadipatti Taluk

Landuse and Landcover Classification Type	Area(in sq.km)
Agricultural Land	73
Built up	55
Fallow	150
Vegetation	176
Waterbody	10

Tank Buffer Analysis

Buffer Analysis: Buffering involves measuring distance outward in directions from an object. Buffering can be done on all three types of vector data: point, line, area. The resulting buffer is a polygon file. Most often buffers in geographic information systems (GIS) and spatial analysis, buffer analysis is the determination of a zone around a geographic feature containing locations that are within a specified distance of that feature, the buffer zone (or just buffer) are measured in uniform distance. In the case of Water body and Tanks continues to store water and Infiltration into the Ground will be higher the water due to rainfall Groundwater recharge will be high due to Geology, surface waterbody, Soil, Geomorphology, Lineament density

Multi-ring buffer analysis demonstrated distance-decay relationships in groundwater potential. Areas within 1 km of water bodies showed maximum recharge potential (weight: 0.38), while zones >10 km distant received minimum weight (0.12).



Source: Toposheets

Fig 9: Water Body Map and Tank Buffer

Table 8: Global Weightage values for Vadipatti Taluk

Parameters	Class/Ranges	Local Weightage	Global Weightage	WI
Lineament density	0-89.71181641 Low	0.03	0.12	0.0036
	89.71181642-179.4236328	0.09		0.0108
	179.4236329-269.1354492	0.21		0.0252
	269.1354493-358.8472656	0.29		0.0348
	358.8472657-448.559082 High	0.38		0.0456
LULC	Built-up	0.06	0.27	0.0162
	Fallow	0.14		0.0378
	Agriculture	0.21		0.0567
	Vegetation	0.27		0.0729
	Tank	0.32		0.0864
Soil texture	Shallow well drained gravelly clayey soil steeply slope	0.01	0.05	0.0005
	Shallow well drained gravelly clayey soil Undulating	0.02		0.001
	Shallow excessively drained gravelly loam soil moderate slope	0.03		0.0015
	Shallow excessively drained gravelly loam soil Undulating	0.04		0.002
	Moderately shallow well drained clay	0.05		0.0025
	Moderately shallow excessively drained gravelly	0.06		0.003
	Moderately deep well drained clay	0.07		0.0035
	Moderately deep well drained gravelly clay	0.081		0.00405
	Deep moderately well drained clay	0.089		0.00445
	Deep well drained gravelly clay	0.1		0.005
	Very deep imperfectly drained calcarous	0.13		0.0065
	Very deep moderately well drained drained clay	0.14		0.007
	Very deep moderately well drained drainedcalcarous	0.18		0.009
Slope	30.53972986 -74.16791534>High	0.06	0.24	0.0144
	20.94152905-30.53972985	0.14		0.0336
	11.63418281-20.94152904	0.21		0.0504
	4.653673121-11.6341828	0.27		0.0648
	0-4.65367312>Low	0.32		0.0768
Geology	Graphite Gneiss	0.03	0.15	0.0045
	Charnockite	0.06		0.009
	Quartzite	0.11		0.0165
	Pyroxena Granulite	0.21		0.0315
	BiotiteGnesis	0.27		0.0405
	Fluvial	0.32		0.048
Geomorphology	Structural Origin Highly	0.03	0.14	0.0042
	Structural Origin Moderately	0.05		0.007
	Denutational origin pediment pediplain	0.12		0.0168
	Denutational origin Moderately discrete	0.14		0.0196
	Denutational origin Low discrete	0.15		0.021
	Fluvial Origin	0.24		0.0336
	Water bodies	0.27		0.0378
Tank Buffer	10	0.12	0.03	0.0036
	5	0.21		0.0063
	2	0.29		0.0087
	1	0.38		0.0114

Groundwater Potential Zone Map

The resultant map produced by Overlay Analysis shows that Groundwater potential of the Vadipatti Taluk in Madurai District which is related to Geology, Geomorphology, and

Lineament, Soil texture, Water body and Slope. By using various parameters the Groundwater potential zones were identified in the areas of Vadipatti Taluk.

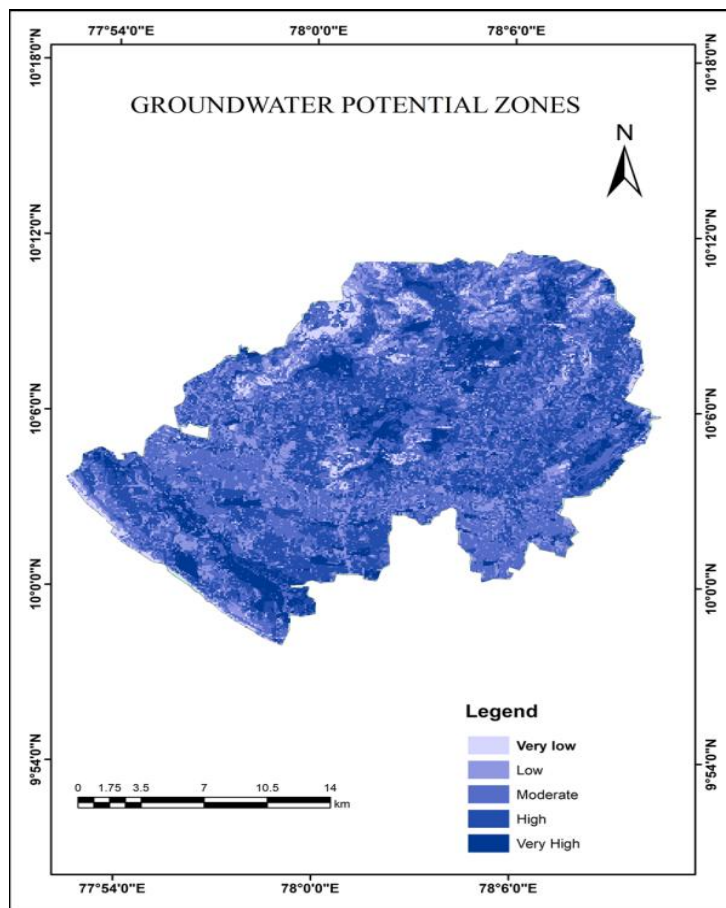


Fig 10: Groundwater Potential Zones

Integration of all weighted thematic layers produced the groundwater potential zone map. Five qualitative categories were delineated:

Table 9: Areal extent of groundwater potential zones in Vadipatti Taluk

GWPZ Category	Area (km ²)	Percentage
Very High	42	9.1
High	153	33.0
Moderate	169	36.5
Low	80	17.3
Very Low	17	3.7
Total	461	100

The resultant map produced by Overlay Analysis shows that Groundwater potential of the Vadipatti Taluk in Madurai District which is related to Geology, Geomorphology, and Lineament, Soil texture, Water body and Slope. By using various parameters the Groundwater potential zones were identified in the areas of Vadipatti Taluk. The Very High Potential Zones (42 km²): Concentrated in Sholavandan region (southeast to southwest) along the Vaigai River valley. These zones coincide with fluvial alluvial plains, low slopes, proximal water bodies, and favorable soil texture. Groundwater is easily accessible and abundant in these areas. Annual groundwater extraction potential is estimated at 0.5-0.8 million cubic meters.

- **High Potential Zones (153 km²):** Distributed in the northeastern regions near Alanganallur and associated areas containing irrigation canals, surface tanks, and ponds. These zones exhibit moderate slopes, pediplains with moderate weathering depth, and variable soil

types. Groundwater is moderately abundant with estimated extraction potential of 0.3-0.5 million cubic meters annually.

- **Moderate Potential Zones (169 km²):** Widely distributed across central and southern regions. These areas present mixed hydrogeological characteristics with moderately weathered gneisses, varied geomorphology, and moderate lineament density. Groundwater availability is variable, estimated at 0.15-0.3 million cubic meters annually. These zones are suitable for localized water supply development.
- **Low Potential Zones (80 km²):** Predominantly in eastern Vadipatti taluk. Limited groundwater availability results from shallow weathering zones, reduced soil depth, moderate slopes, and distance from water bodies. Estimated annual extraction potential: 0.05-0.15 million cubic meters. Recharge structures in these areas require careful site selection.
- **Very Low Potential Zones (17 km²):** Located in mountainous terrain and elevated areas, characterized by structural hills, steep slopes, minimal weathering, and high surface runoff. Groundwater potential is severely limited (<0.05 million cubic meters annually). These zones are unsuitable for conventional groundwater development but may benefit from run-off harvesting structures.

4.3 Spatial Distribution and Hydrogeological Interpretation

Groundwater potential exhibits strong spatial correlation with fluvial geomorphic units, water body proximity, and slope conditions. The highest potential zones align with the

Vaigai River floodplain and alluvial deposits, reflecting both direct infiltration from the river and higher water table levels. Distance from major water bodies progressively reduces groundwater potential, consistent with theoretical expectations regarding recharge distance-decay relationships^[8].

Geological lithology exerts secondary control, with alluvium-dominated areas showing superior potential compared to hard rock zones. However, within hard rocks, zones of high lineament density and deep weathering demonstrate significantly enhanced potential compared to massive unweathered rocks. This observation highlights the importance of structural fracturing in hard rock hydrogeology.

LULC patterns reflect land use-related recharge variations. Vegetated areas exhibit higher potential than built-up zones, likely due to reduced surface sealing and enhanced infiltration. Agricultural areas show intermediate potential, reflecting irrigation-induced recharge processes.

5. Discussion

5.1 Methodological Considerations

The integrated geospatial approach using AHP provides a systematic, reproducible framework for groundwater potential assessment. The methodology accommodates multi-parameter complexity inherent in hard rock hydrogeology while incorporating expert hydrogeological knowledge through the pairwise comparison process. This approach is superior to simple overlay methods because it explicitly weights parameters based on their relative hydrogeological significance^[5].

The weighting scheme employed (Table 1) reflects current understanding of groundwater controls in hard rock settings, emphasizing terrain morphology (slope: 0.24, geomorphology: 0.14) and land surface conditions (LULC: 0.27) as primary controls. Lithological variation (geology: 0.15) and structural fracturing (lineament density: 0.12) exert secondary controls in this study area, consistent with observations in similar granitic and gneissic terrains^[9].

5.2 Comparison with Previous Studies

The spatial distribution of groundwater potential zones in Vadipatti Taluk is consistent with findings from comparable hard rock studies in South India. Ramalingam and Shantha Kumar^[10] delineated groundwater recharge zones in Tamil Nadu, identifying pediplains and alluvial plains as high-potential areas, consistent with this study. Magesh *et al.*^[11] similarly demonstrated that gentle slopes and fluvial geomorphic units are critical indicators of groundwater potential in hard rock regions.

The proportion of high-to-very-high potential zones (42.1% of the taluk) is comparable to published studies of similar geological settings^[12]. The concentration of very high potential zones along river valleys reflects recognized principles of fluvial aquifer development^[13].

5.3 Hydrogeological Implications

The groundwater potential zones delineated in this study have significant implications for water resource management:

1. **Groundwater Development Prioritization:** Very High and High potential zones (195 km²; 42.1% of taluk) should be prioritized for groundwater development through systematic well drilling. These

zones can sustainably support expanded agricultural irrigation and domestic water supply.

2. **Recharge Structure Placement:** Moderate potential zones (169 km²) are suitable for artificial recharge structures (check dams, percolation tanks, recharge pits, subsurface dykes) designed to enhance infiltration and groundwater recharge during monsoon periods.
3. **Groundwater Management:** Low and Very Low potential zones require conservative management approaches, limiting extraction rates to prevent long-term depletion. These areas should prioritize surface water harvesting and supplementary supplies from higher-potential zones.
4. **Irrigation Planning:** Groundwater-dependent agriculture should be concentrated in High and Very High potential zones where sustainable extraction rates (0.3-0.8 Mm³ annually) can support irrigation expansion. Other zones should rely on supplementary irrigation or rainwater harvesting.

5.4 Study Limitations and Future Work

This study has several limitations meriting discussion:

1. **Validation:** The groundwater potential map was not validated against bore well yield data or water table measurements due to limited available field data. Independent validation using existing bore well inventory or hydrogeochemical surveys would strengthen confidence in zone delineations.
2. **Temporal Variability:** The static map approach does not capture seasonal groundwater fluctuations or long-term trends in water table elevation. Time-series analysis incorporating multi-year groundwater level data would provide improved characterization of groundwater dynamics.
3. **Parameter Uncertainty:** While the AHP approach accommodates expert judgment, uncertainty in parameter weight assignments influences map accuracy. Sensitivity analysis quantifying the effect of weight variations on zone boundaries would improve robustness.

Future studies should incorporate:

- Hydrogeochemical analysis to characterize groundwater quality and recharge mechanisms
- Time-series groundwater level monitoring to quantify recharge rates and seasonal dynamics
- Groundwater modeling to predict sustainable extraction rates
- Ground-based geophysical surveys (electrical resistivity tomography) to characterize aquifer geometry

6. Conclusion

This study successfully delineated groundwater potential zones in Vadipatti Taluk, Madurai District, using integrated geospatial analysis and analytical hierarchy process. Key findings include:

1. Groundwater potential exhibits strong spatial heterogeneity, with Very High and High potential zones (195 km²; 42.1%) concentrated in fluvial alluvial plains and near major water bodies, while Low and Very Low potential zones (97 km²; 21.0%) occur in structurally controlled uplands.
2. Slope and LULC emerge as primary controls on groundwater potential, accounting for 51% of total

weight, while geological lithology and structural features provide secondary controls.

3. The Vaigai River valley and associated alluvial deposits represent priority zones for groundwater development, with estimated sustainable extraction potential exceeding 0.5 Mm³ annually.
4. Moderate potential zones (36.5% of area) are well-suited for artificial recharge structure implementation, potentially augmenting groundwater supplies during drought periods.
5. The systematic geospatial methodology provides a reproducible, scalable framework applicable to groundwater assessment in other hard rock terrains of semi-arid India.

These findings provide critical information for water resource planners, enabling science-based groundwater development decisions that balance immediate water supply needs with long-term aquifer sustainability. Implementation of the recommended zoning-based management strategies will enhance groundwater security in Vadipatti Taluk while supporting agricultural development and rural livelihoods.

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