Integrating Remote Sensing and GIS Derived Mapping Groundwater Potential Zone in Hard Rock Region of Vathalagundu Firka, Tamilnadu, India

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Abstract
Groundwater is a vital resource for meeting domestic and agricultural water requirements in the semiarid region of Vathalagundu Firka, Nilakottai Taluk, Dindigul District, Tamil Nadu, encompassing an area of approximately 64.07 km². This study aims to delineate groundwater potential zones (GWPZs) using an integrated Remote Sensing (RS) and Geographic Information System (GIS) approach. The methodology involved the preparation of thematic layers, including lithology, lineament density, land use/land cover, geomorphology, drainage density, and rainfall, derived from satellite imagery and ancillary data. These layers were assigned weights based on their relative hydrogeological importance and integrated using a Multicriterial Weighted Overlay Index (MWOI) model. Inverse Distance Weighting (IDW) interpolation was applied to generate spatial groundwater potential maps. The resulting groundwater potential zonation classified the study area into high-, moderate-, and low-potential zones. The analysis reveals considerable spatial variation, with moderate groundwater potential zones occupying 70.23% of the area, followed by high potential zones covering 1.56% while low potential zones are limited to 28.09%. High-potential zones are mainly associated with weathered and fractured formations, gentle slopes, low drainage density, and favourable land-use conditions, whereas low-potential zones correspond to areas characterized by steep slopes, high runoff, and relatively impermeable lithological units. The GWPZ map was validated using existing well yield data and field observations, which showed strong agreement between the predicted zones and observed groundwater conditions, confirming the study's findings. This study clearly identified poor

groundwater potential zones for future water recharge domains. The study demonstrates that RS–GIS, integrated with the MWOI model, is an effective tool for assessing groundwater potential. Future research may focus on incorporating time-series groundwater level data, machine learning techniques, and climate variability analyses to improve prediction accuracy and support sustainable groundwater management and artificial recharge planning.

Keywords: Groundwater Potential Map, NDWI, NDDI, NDVI, Land Use and Land Cover, MWOI.

Introduction

The tropical hydrological regime of Thiruvattar Firka, characterised by high rainfall variability, intense weathering, dense drainage networks, and complex lithological controls, has received limited scientific attention in groundwater potential mapping studies. The study area requires attention to examine the demarcation of the groundwater potential zone. Although numerous studies have employed Remote Sensing (RS) and Geographic Information System (GIS) techniques to delineate groundwater potential zones across different hydrogeological settings in India, several critical gaps remain. Most existing studies focus on semiarid or hard-rock terrains and often apply weighted overlay methods without region-specific validation, limiting their applicability to humid tropical coastal settings. Furthermore, many previous investigations rely on subjective weighting schemes with minimal integration of field-based well yield validation, reducing the robustness of their predictions. The present study addresses these gaps by (i) focusing on an understudied tropical region of southern Tamil Nadu, (ii) integrating rainfall as a critical controlling factor alongside terrain, lithological, and land-use parameters, (iii) applying a Multicriterial Weighted Overlay Index (MWOI) supported by spatial interpolation (IDW), and (iv) systematically validating the results using observed well yield and field data. By explicitly linking spatial groundwater potential patterns with local hydro-geomorphic conditions and validation evidence, this study advances existing RS–RS-GIS-based groundwater assessment frameworks. It provides a more reliable scientific basis for groundwater development and sustainable management in tropical coastal environments.

Water covers 71% of the Earth's surface. It is a renewable natural resource. The main source of the water system is precipitation. Water is a vital resource for all living beings. The distribution of water on Earth is 96.5% as oceans, 1.7% as groundwater, 1.7% as glaciers and ice caps, 0.001% as water vapour, clouds (formed of solid, liquid, and suspended particles in air), and precipitation (Boobalan, C et al., 2018). Groundwater (GW) is a critical element of the human life support system and is crucial for various applications (Balasubramaniyan et al., 2025), including drinking water, agriculture, industry, domestic use, and other developmental activities. Groundwater is a significant natural resource crucial for the survival of humans and the growth of aquatic and terrestrial ecosystems. The Earth's crust's water bearings (interconnected fractures, lineaments, etc.) serve as reservoirs and transmission conduits for water storage (Murugesan et al., 2025).

Water resources are an inevitable resource for all sectors. The need for assessing water resources increases every year due to the declining water levels and changes in atmospheric water. Water quality and quantity are declining owing to natural and human-induced interventions (Rajan et al., 2025). Groundwater is essential for domestic and irrigation purposes in arid and semiarid regions (Phaisonreng Kom et al., 2023). Most of the world's inhabitants rely on groundwater for their daily requirements. In arid and semiarid regions, it has become the primary source of water for domestic, agricultural, and industrial purposes (Kom et al., 2021). The use of remote sensing and GIS are highly fruitful and useful for assessing groundwater potential zones (Arulbalaji. P & Gurugnanam. B, 2016);. In recent decades, rising population levels, industrial expansion, and accelerated urbanisation have sharply increased water demand.

GIS is an efficient tool for mapping and analysing spatial datasets (Nijagunappa. R et al., 2007). The feature class weights are easy to use in GIS and useful for overlay analysis (Bagyaraj. M et al., 2014). Identifying potential groundwater zones and integrating thematic maps prepared from remote sensing platforms and GIS will provide more accurate results. In GIS, multiple thematic map overlay analyses were performed (Gurugnanam et al., 2009). The Multi-Criteria Decision Support based on the Weighted Overlay Method (WOM) was very effective in GIS (Murugesan et al., 2025). It was applied to develop a composite Groundwater Potential Index (GWPI). ArcGIS software was used to interpolate the maps (Rajan et al., 2025). Advancements in Geographic Information Systems (GIS) technology have significantly contributed to the growth of research in environmental studies in recent years (Senapathi et al., 2025). Geographic Information Systems (GIS), with spatial interpolation techniques such as Inverse Distance Weighting (IDW), have proven to be powerful tools for mapping (Kannan et al., 2025). Spatial interpolation was performed using Inverse Distance Weighting (IDW) in ArcGIS to estimate values at unsampled locations (Jerin Joe et al., 2025).

In the present study, we attempted to use satellite data-based demarcation of water resources by analysing Lineament and Lineament Density, Land Use/Land Cover, Normalised Difference Vegetation Index, Normalised Difference Water Index, and Normalised Difference Drought Index, which were derived from higher-resolution Landsat satellite data. The surface water resources, including drainage and surface water bodies, are also mapped using the Survey of India Toposheet and cross-checked against Google Map data.

This study aimed to delineate groundwater potential zones by integrating Remote Sensing (RS) and Geographic Information Systems (GIS) using a weighted overlay approach. To achieve this, various thematic layers, including lithology, lineament density, slope, soil type, land use/land cover, geomorphology, drainage density, and rainfall, were compiled and pre-processed. Each factor was assigned an appropriate weight based on its relative influence on groundwater occurrence. Using these weighted layers, a GIS-based overlay analysis was performed to produce a groundwater potential map, which was further classified as having very high to very low potential. Finally, the resulting map is evaluated and validated using field observations or existing hydrogeological data to ensure its reliability and accuracy.

Study Area

The study area, Vathalagundu (officially known as Batlagundu), is a significant town and a firka (a revenue sub-division of a taluk) in the Dindigul district of Tamil Nadu, India (64.07 km²). The study area experiences a tropical climate, generally warm with distinct seasons, benefiting from its proximity to the Kodai hills, which offer cooler weather and fresh produce, with hot, sunny days and moderate humidity. The temperature varies, except in winter, with mild days and cool nights, and the minimum temperature is typically around 19 °C, and the maximum temperature is near 26-27 °C. Rainfall experiences monsoon rains, with occasional showers and cloudy periods, although some periods are predominantly sunny. Winds are generally mild breezes, picking up slightly at night. Bathalagundu (Vathalagundu) Firka features a mix of hard crystalline rocks (Charnockites, Gneisses) in higher areas, with soils primarily being loamy soils over rock outcrops, suitable for agriculture, but also experiencing water stress, necessitating conservation for recharge. (Fig. 1)

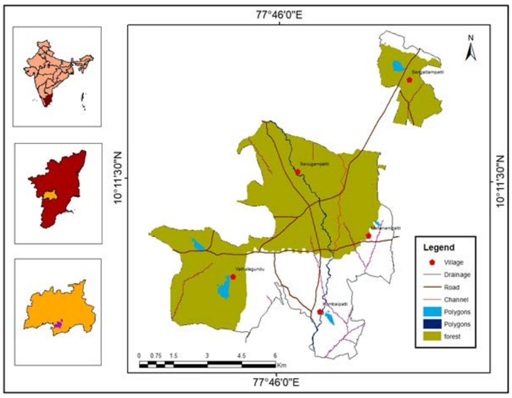

Figure 1 Study Area Map of Vathalagundu Firka

Methodology

The methodology employed for delineating groundwater potential zones integrates Survey of India topographical sheets, remote sensing data, and GIS-based spatial analysis. Initially, the toposheets were georeferenced and interpreted to extract the drainage network and major water bodies, which are critical for understanding groundwater recharge processes and surface–subsurface hydrological interactions. Concurrently, multispectral satellite imagery was processed to generate key thematic layers, including land use/land cover, lineaments and lineament density, and spectral indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Drought Index (NDDI). The land use/land cover layer was utilized to evaluate infiltration characteristics, whereas lineament mapping provided insights into the structural controls governing groundwater movement. The derived spectral indices were used to assess the vegetation condition, moisture availability, and drought stress, which indirectly indicated the groundwater status. All thematic layers were subsequently standardised, reclassified, and integrated within a GIS environment using a weighted overlay analysis to delineate the groundwater potential zones. The resulting synthesis produced a spatially explicit groundwater potential map, facilitating the systematic identification of areas with varying recharge potential and groundwater availability. The methodological workflow is shown in Fig. 2.

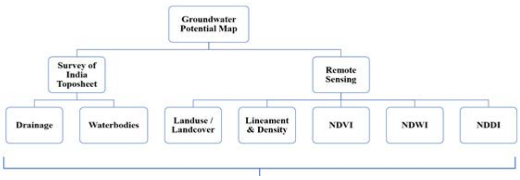

Figure 2 Detailed Methodology Flow Chart

Results and Discussion

Surface Water Body

Surface water bodies, including lakes and ponds, were delineated using Survey of India topographical sheets and satellite imagery, as they directly influence regional water resources. A 20 m buffer was applied around the mapped water bodies to account for their contributions to groundwater recharge. Accordingly, a higher weight was assigned to the water body layer in the analysis. In total, surface water bodies occupy an area of 5.38 km² within the study region (Fig. 1). The results are summarised in Table 1.

Table 1 Table Spatial Distribution Results of Surface Water bodies of Vathalagundu Firka

Surface water bodies	Weightage	Area in Km^2
River	3	0.13
Canal	2	5
Tank	1	0.25

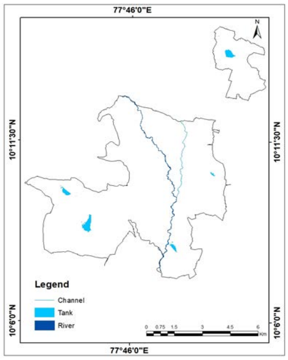

Figure 1 Spatial Distribution Map of Surface Waterbodies of Vathalagundu Firka

Drainage and Drainage density

Drainage represents the surface flow pathways of rainfall, which generally follow the direction of decreasing slope and play a significant role in facilitating groundwater recharge. In the present study, the drainage network was delineated from Survey of India topographical sheets, as illustrated in Fig. 2. The key results of the drainage analysis are summarised in Table 2.

Table 2 Spatial Distribution Results of Drainage Density of Vathalagundu Firka

Drainage density	Weightage	Area (Km^2)
Low	4	46
Moderate	3	5
High	2	7
Very High	1	1

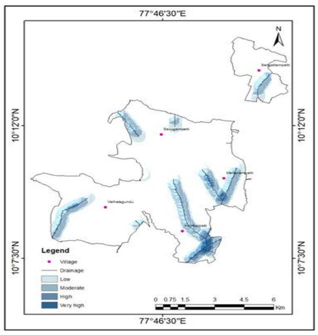

Figure 2 Spatial Distribution Map of the Drainage Density of Vathalagundu Firka

Remote Sensing

Lineament and Lineament Density

Lineaments are natural linear features that represent zones of structural weakness and significantly influence the occurrence and movement of groundwater. In the present study, a lineament map was generated using satellite imagery (Fig. 3), which exhibited a direct relationship with regional water resources. The lineament density was subsequently derived from the extracted lineaments to assess the spatial variation in the structural controls on the groundwater potential. Areas characterised by higher lineament density are generally associated with enhanced groundwater prospects because of increased secondary porosity and permeability. Accordingly, lineament density zones were classified and assigned relative weights based on their influence on groundwater potential. The results of the spatial distribution are given in Table 3.

Table 3 Spatial Distribution Results of Lineament Density of Vathalagundu Firka

Lineament Density	Weightage	Area (Km^2)
Very high	4	1
High	3	17
Medium	2	15
Low	1	31

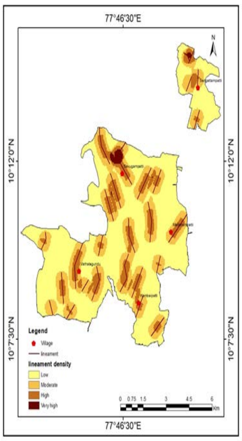

Figure 3 Spatial Distribution Map of Lineament Density of Vathalagundu Firka

Land use/Land Cover

The land use/land cover (LULC) map was generated using satellite data obtained from the USGS portal. The dataset was processed in the ArcGIS environment, where a false colour composite (FCC) was created to enhance feature discrimination. Multispectral sensors provide high-resolution imagery, enabling detailed LULC classification of the catchment area using landsat data (Alemu et al., 2025). Supervised classification, supported by ground control information, was subsequently applied to delineate the different LULC classes within the study area. The spatial distribution and extent of these classes are described below. Due to urbanization and industrial growth, there is a loss of agricultural land, vegetation land, forest land, water bodies, and mineral wealth (Arulbalaji. P & Gurugnanam. B, 2014b).

The relative weightage is assigned to the maps for groundwater potential mapping. The results of the LULC map are presented in Fig.4 and Table 4

Table 4 Spatial Distribution Results of Land use and Land Cover of Vathalagundu Firka

LULC	Weightage	Area (Km^2)
Road	7	4
Vegetation	5	30
Waterbodies	6	4
Fallowlands	4	12
Settlements	2	3
Barrenlands	1	8
Solar pan	3	3

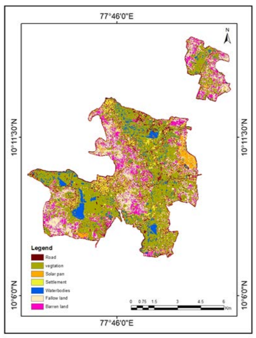

Figure 4 Spatial Distribution of Land Use / Land Cover of Vathalagundu Firka

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a widely used remote sensing indicator for assessing vegetation vigour and density. It is computed from the differential reflectance of vegetation in the red and near-infrared (NIR) spectral bands, exploiting the fact that healthy vegetation strongly absorbs red light for photosynthesis while reflecting a substantial proportion of NIR radiation due to leaf cellular structure. Consequently, NDVI serves as an effective proxy for evaluating vegetation condition and indirectly inferring moisture availability and groundwater-related zones. The integration of geospatial techniques and vegetation indices facilitates the identification and delineation of water-influenced zones within a GIS framework (Arulbalaji.P & Gurugnanam. B, 2014a). NDVI values typically range from −1 to +1, with higher positive values indicating denser and healthier vegetation cover.

Formula: NDVI = (NIR - Red) / (NIR + Red).

Higher values indicate dense, healthy green vegetation (e.g., values between 0.5 and 1.0).

Lower values: Indicate areas with little to no vegetation, such as barren land, water, or snow (e.g., values close to 0 or negative). The results of the NDVI map are presented in Fig. 5 and Table 5.

Table 5 Spatial Distribution Results of NDVI of Vathalagundu Firka

NDVI	Weightage for Water Resources	Suitability	Area (Km²)
Water body	3	High	17
0.5-1	2	Moderate	35
Close to 0 and a negative value	1	Low	12
Fallowlands	4	12	
Settlements	2	3	
Barrenlands	1	8	
Solar pan	3	3	

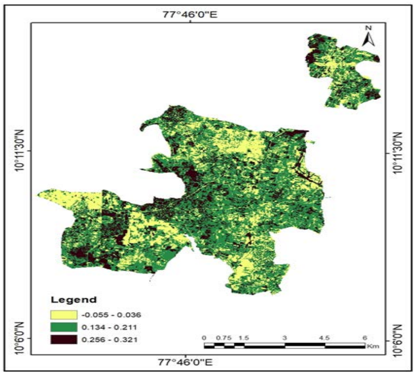

Figure 5 Spatial Distribution Map of NDVI of Vathalagundu Firka

Normalized Difference Water Index (NDWI)

The Normalized Difference Water Index (NDWI) is a satellite-derived spectral index widely employed to delineate open water bodies and to assess moisture content in vegetation and surface soils. It is calculated using the normalized difference between the green and near-infrared (NIR) spectral bands, expressed as the ratio of their difference to their sum. Higher NDWI values generally correspond to increased surface water presence and moisture conditions. It is useful for,

Water body mapping: Delineates open water features, such as lakes, rivers, and oceans, from land.

Vegetation water content: Monitors the amount of water in plant leaves, which is useful for tracking plant health and stress

Agriculture: Enhances irrigation management by identifying areas that require water and minimising waste.

Drought monitoring: Supports monitoring of drought conditions and soil moisture.

Calculation and interpretation

Formula: $NDWI = (Green - NIR) / (Green + NIR)$

Bands: The formula uses the green and near-infrared bands from satellite imagery.

Value range: Values range from -1 to +1.

Interpretation

Water bodies: Typically have values greater than 0.5.

Vegetation: Has lower values, which helps differentiate it from water.

Built-up areas: Show positive values between 0 and 0.2

The results of NDWI are given in Figure 6 and Table 6

Table 6 Spatial Distribution Results of NDWI of Vathalagundu Firka

NDVI	Weightage for Water Resources	Suitability	Area (Km²)
Water body	3	High	15
0.5-1	2	Moderate	37
Close to 0 and a negative value	1	Low	12

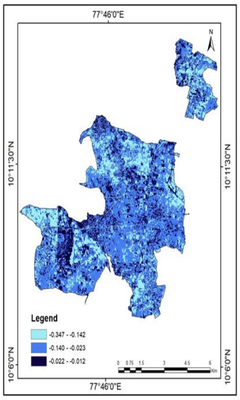

Figure 6 Spatial Distribution Map of NDWI of Vathalagundu Firka

Normalized Difference Drought Index (NDDI)

The Normalized Difference Drought Index (NDDI) is a satellite-based remote sensing indicator used to evaluate and monitor drought severity. It assesses drought conditions by integrating spectral information from the near-infrared (NIR) and shortwave infrared (SWIR) bands and is derived through the combined utilization of the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI). As such, NDDI provides an effective measure of vegetation stress and surface moisture deficits associated with drought conditions. Values range from -1 to 1, where more negative values indicate more severe drought stress. It helps in monitoring water stress in vegetation and is crucial for drought-related challenges in agriculture and water management.

The NDDI map is prepared using satellite data and is given in Fig. 7. The results of the NDDI are given in Table 7. Accordingly, the relative weightage of water is given in the attribute

Table 7 Spatial Distribution Results of NDDI of Vathalagundu Firka

NDWI	Weightage for Water Resources	Suitability	Area (Km²)
Water body	3	High	15
0.5-1	2	Moderate	37
Close to 0 and a negative value	1	Low	12

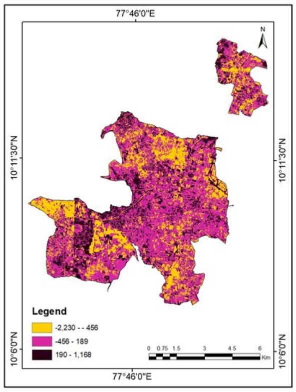

Figure 7 Spatial Distribution Map of NDDI of Vathalagundu Firka

Groundwater Potential Zone Using Overlay Analysis

The Groundwater Potential Map (GPM) was generated through the integrated overlay analysis of multiple thematic layers, including land use/land cover (LULC), drainage density, lineament density, NDVI, NDWI, and NDDI, to spatially classify the study area into zones of varying groundwater potential. The map was produced using a Geographic Information System (GIS)–based weighted sum approach, wherein the relative contribution of each thematic layer was quantitatively incorporated. Similar studies were conducted to generate a groundwater potential map for the Coimbatore district by integrating all the thematic layers in an

ArcGIS environment using a weighted sum overlay analysis tool (Kom et al., 2024). Areas classified as high or excellent groundwater potential exhibit a favourable combination of controlling factors, such as high lineament density, low drainage density, and the presence of surface water bodies or moisture-rich vegetation, and are therefore considered suitable locations for groundwater development. Moderate potential zones represent regions where the influencing parameters are moderately favourable, while low or very poor potential zones are characterised by adverse conditions, including dense drainage networks, built-up land, dry, barren surfaces, or limited recharge capacity. Weighted overlay analysis was employed in GIS to delineate the groundwater potential zone (Balasubramaniyan et al., 2025). The final groundwater potential score at any given location reflects the cumulative influence of all selected parameters. In the weighted overlay analysis, each thematic layer was assigned a specific weight, and individual classes within each layer were ranked according to their relative impact on groundwater occurrence, storage, and movement (Table 8).

Table 8 Overall Weightage Table For Each Layer

Thematic layer	Layer weight	Class	Rank
Surface waterbody	20	River	3
		Canal	2
		Tank	1
Drainage Density	25	Low	4
		Moderate	3
		High	2
		Very high	1
Lineament Density	12	Low	1
		Moderate	2
		High	3
		Very high	4
Land use/ Land cover	18	River	7
		Vegetation	5
			6
		Fallow lands	4
		Settlements	2
		Barren lands	1
		Roadways	3
NDVI	10	Water body	3
		Vegetation	2
		Barren land	1
NDWI	8	Water body	3
		Vegetation	2
		Barren land	1
NDDI	7	Low	3
		Moderate	2
		High	1

Weighted Overlay Index Map for Groundwater Potential Zones

Within the GIS framework, relative weights were assigned to the thematic layers based on their significance to groundwater occurrence and availability. GIS serves as an effective platform for integrating multi-source spatial datasets to delineate groundwater potential zones (Gurugnanam. B et al., 2008). The highest overall weightage was given for lithology and followed by geological structures, soil, rainfall, elevation, LULC, drainage density, slope, and lineament (Jerin Joe et al., 2025). Using the Union analytical tool, the thematic maps generated in the methodology were overlaid and integrated to produce a composite map of groundwater potential. All water-related thematic layers were systematically prepared and combined to derive this comprehensive representation. The integrated output was subsequently classified into three categories of groundwater potential: high, moderate, and low. The results highlight the effectiveness of remote sensing and GIS techniques in groundwater potential assessment (Arulbalaji and Gurugnanam, 2016). The spatial distribution of the groundwater potential zones is illustrated in Fig. 8, and the corresponding results are summarized in Table 9.

Table 9 Spatial Distribution Results of Groundwater Potential Zones of Vathalagundu Firka

Groundwater potential	Weightage for Water Resources	Area (Km²)	Area%
High	3	1	1.56
Moderate	2	45	70.31
Low	1	18	28.12

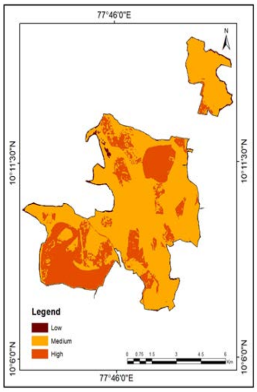

Figure 8 Spatial Distribution Map of Groundwater Potential Zones of Vathalagundu Firka

Suggestions and Future Research Directions

The findings of this study provide a scientific basis for groundwater resource planning in Vathalagundu firka; however, several aspects warrant further investigation to enhance the robustness and applicability of groundwater potential assessments. Future studies should incorporate long-term, time-series groundwater level and well yield data to capture seasonal and interannual variability in aquifer response, particularly under changing monsoonal rainfall patterns. The integration of advanced data-driven approaches, such as machine learning and hybrid models (e.g., Random Forest, Support Vector Machine, and ensemble techniques), could further improve prediction accuracy and reduce subjectivity associated with conventional weighting schemes.

Additionally, the use of higher-resolution satellite datasets, geophysical surveys, and detailed subsurface information would enable a better characterisation of fracture networks and aquifer geometry in weathered and hard-rock terrains. Climate change scenarios and land-use dynamics should also be incorporated to evaluate their long-term impacts on groundwater recharge and sustainability. From a management perspective, the delineated high- and moderate-potential groundwater zones can be prioritised for artificial recharge structures, rainwater harvesting, and regulated groundwater extraction. Future research may also focus on developing a decision-support system by integrating groundwater quality parameters with quantity-based potential maps to support holistic and sustainable groundwater management in tropical coastal environments.

Conclusion

The conclusion synthesises the findings on groundwater occurrence, availability, and potential yield within the study area based on an integrated analysis of multiple controlling factors. The area was classified into distinct groundwater potential zones, namely, low, moderate, and high, which constituted the primary quantitative outcome of the investigation. Overall, the results delineate the spatial extent and distribution of zones suitable for groundwater development, providing a robust scientific basis for informed water resource planning and management.

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