



Identification of Groundwater Potential Zones Using GIS and Remote Sensing Techniques Combined with Analytical Hierarchy Process (AHP), in Telangana State

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Abstract: Geographic information system (GIS), remote sensing (RS), and multi-criteria decision analysis (MCDA) techniques were integrated to delineate groundwater potential zones in Telangana State, India. Ten thematic layers; slope, elevation, geology, lineament density, line density, land use/land cover (LULC), soil, drainage density, rainfall, and topographic wetness index (TWI) were generated and analysed. The analytic hierarchy process (AHP) was employed to assign appropriate weights to each thematic layer based on their relative influence on groundwater occurrence. These weighted layers were overlaid using a GIS-based weighted overlay analysis to produce a groundwater potential zone (GWPZ) map. The final output was classified into five categories: poor (56.63%, 65,095 km²), fair (20.64%, 23,692.18 km²), good (5.32%, 6,096.20 km²), very good (4.71%, 5,409.16 km²), and excellent (12.70%, 14,546.77 km²). The results demonstrate the effectiveness of combining geospatial technologies with AHP for identifying groundwater potential zones. The AHP-derived weights assigned to each thematic layer are rainfall (22.83), Geology (16.49), slope (10.36), drainage density (7.47), LULC (8.53), lineament density (5.59), soil (5.60), line density (7.55), elevation (7.03), and TWI (8.53). This approach provides valuable insights for sustainable groundwater resource management and site selection for new bore well development in the region.

Keywords: Groundwater potential zone, Geographic information system (GIS), Remote sensing, Weighted overlay, AHP

Groundwater is a vital yet concealed natural resource, and its exploration poses considerable challenges, especially in regions like Telangana. Traditional methods such as drilling and geophysical surveys, while effective, are often time-consuming and costly. In this context, geospatial technologies offer a more efficient and systematic approach. The integration of geographic information systems (GIS) and remote sensing (RS) with the analytical hierarchy process (AHP) provides a powerful framework for delineating groundwater potential zones. GIS enables the spatial analysis of multiple thematic layers such as land use/land cover, geology, slope, soil type, and distance from water bodies. Remote sensing data, particularly from multispectral satellite sensors, allows the derivation of indices like the normalized difference vegetation index (NDVI) and normalized difference water index (NDWI), which are critical for understanding land surface characteristics influencing groundwater recharge. These indices help identify zones with favorable infiltration potential, vegetation cover, and surface water availability. The AHP technique further enhances this analysis by assigning relative weights to each thematic factor based on expert judgment through a pairwise comparison matrix. This structured decision-making process ensures that each factor's contribution to groundwater potential is quantified objectively. The resulting weighted

overlay analysis provides a groundwater potential map, identifying high, moderate, and low potential zones with greater accuracy. Recent studies have demonstrated the effectiveness of combining GIS, RS, and AHP in groundwater exploration, particularly in semi-arid regions. Kom et al. (2024) successfully applied this methodology in South India, and Upadhyay et al. (2023) highlighted its utility in delineating recharge zones with high spatial precision. Similarly, Ifediegwu et al. (2022) showcased the robustness of AHP-GIS integration in identifying potential zones in data-scarce environments. This integrated approach not only improves the accuracy of groundwater mapping but also supports sustainable water resource planning and management, which is crucial for regions experiencing increasing water stress. The objectives of the study are to integrate GIS and remote sensing techniques with the Analytical Hierarchy Process (AHP) for evaluating multiple thematic factors influencing groundwater potential in Telangana State., to assign weights and ranks to key groundwater indicators and to generate a comprehensive groundwater potential zone map for Telangana State that supports sustainable water resource planning and management.

MATERIAL AND METHODS

Study area: The current research was focused on the 33

districts of Telangana, located in southern India between 15° 55' to 19° 55' latitude and 77° 10' to 81° 50' longitude, covering a total area of 1,14,840 km². The region is irrigated by two primary rivers, containing approximately 79% of the Godavari River catchment area and around 69% of the Krishna River catchment area. The state's average annual rainfall is between 900 and 1500 mm in northern Telangana and 700 to 900 mm in southern Telangana, 80% of which comes from the South-West monsoon (June to September). The source of data collected for the study is indicated in Table 1, and the overall flow chart of the study is presented in Figure 1.

Thematic layers

Slope map: The landscape of Telangana state is an undulating terrain, ranging from flat plains to steep hillsides. The slope characteristics of the study area were derived from an ASTER digital elevation model with a resolution of 30 x 30 meters. Slope percentages across the Telangana landscape vary from 2 to 22 degrees. The study area was divided into five slope classes, and the predominant portions of the landscape fall within slope class (very low to very high).

Elevation map: The elevation map for the study area was generated using the ASTER Digital Elevation Model (DEM) and categorized into five groups (very low to very high)

Line density and Drainage density: Line density in hydrology quantifies the length of linear features per unit area, while drainage density represents the total length of

stream segments of all orders per unit area (Andualem et al., 2019).

$$D_d = \frac{\sum L}{A}$$

where drainage density is denoted by D_d, the length of waterways is signified by L, and the total area of the basin is signified with symbol A.

Topographic wetness index (TWI): Mapping flood susceptibility relies significantly on the TWI, a crucial factor in hydrology and geomorphology. Areas with TWI values exceeding the average are more prone to saturation and wetness, correlating directly with flood vulnerability (Lee et al., 2017, Samanta 2018, Swain 2020). High TWI regions face elevated flood risk, whereas low TWI areas are less susceptible. The TWI calculation employed the ASTER DEM with the specified formula.

$$TWI = \ln \frac{AS}{\tan(\beta)}$$

where the upstream contributing area is denoted by AS, and the gradient of the slope is denoted by β. The final TWI map was divided into five classes, showing very low to very high.

Land use land cover: The land use and land cover map was obtained from the Esri land cover map of 10m×10m. Within the study area, six distinct land cover types were identified, namely water, tree, grassland, flooded vegetation, and built-up area.

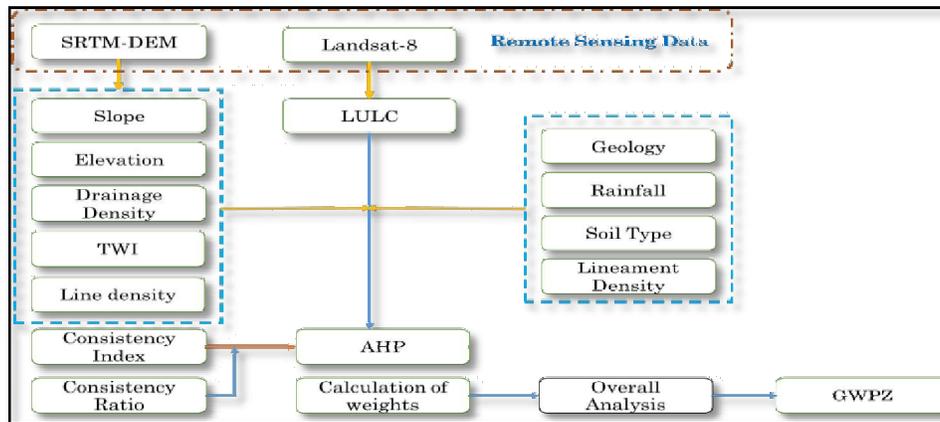


Fig . 1. Flow chart of methodology used in the study

Table 1. Sources of data used for study

Data Type	Sources of data collected	Extracted data
ASTER DEM (Grid) 30 m × 30 m resolution	NASA's official website https://search.earthdata.nasa.gov	Slope, Elevation, Soil type, Drainage Density, geology, and TWI
LULC data (Grid) 10 m× 10 m resolution	ESRI 2020 data, https://livingatlas.arcgis.com/landcover/	Land use/land cover map
Precipitation (TRMM data)	NASA's official website https://giovanni.gsfc.nasa.gov/	Rainfall map

Geology: Groundwater potential is significantly influenced by the occurrence of lithological features. The geology of Telangana, primarily characterized by the presence of the precambrian rocks of the deccan Plateau, dictates the occurrence, distribution, and quality of groundwater in the region. This type of rock predominantly covers the middle and lower courses of the study watershed.

Soil type: Soil texture is a crucial factor in agricultural production and groundwater recharge. It significantly influences water infiltration into aquifers and surface run-off. The study area has predominantly black, red, and alluvial soil, which is primarily categorized for the study.

Rainfall: Rainfall is an important parameter for delineating groundwater potential and identifying hydrological sources of groundwater storage. Approximately 85% of the rainfall occurs during the rainy season, which starts from June to October. The distribution of rainfall varies across the study area, with the upper part receiving higher amounts of rainfall compared to the southern part. The rainfall map of the study area is divided into five (1-5) categories, from deficient to very high rainfall, respectively.

Lineament density: Lineaments represent the total length of linear geological features per unit area (Andualem et al., 2019).

$$L_d = \frac{\sum_{j=1}^{i=n} Li}{A}$$

Where $\sum_{j=1}^{i=n} Li$ represents the total length of lineaments (L) and A represents a unit area.

Groundwater Potential Zone (GWPZ): The groundwater recharge potential map was generated by evaluating the comparative importance of various thematic layers and their corresponding classes. To delineate groundwater potential zones, the Groundwater Potential Zone (GWPZ), a dimensionless quantitative approach, was adopted. The GWPZ is calculated by integrating all relevant themes and features into a single layer, using the following equation (4):

$$GWPZ = Ge_r Ge_w + Rf_r Rf_w + Sl_r Sl_w + So_r So_w + Ld_r Ld_w + DD_r DD_w + LULC_r LULC_w + LD_r LD_w + TWI_r TWI_w + EI_r EI_w \quad (4)$$

where, Ge_r : Geology rank, Ge_w : Weight assigned to geology; Rf_r : Rainfall rank, Rf_w : Weight assigned to rainfall; Sl_r : Slope rank, Sl_w : Weight assigned to slope; So_r : Soil rank, So_w : Weight assigned to soil type; Ld_r : Line density rank, Ld_w : Weight assigned to lineament density; DD_r : Drainage density rank, DD_w : Weight assigned to drainage density; $LULC_r$: Land use /land cover rank, $LULC_w$: Weight assigned to land use/land cover; LD_r : Lineament density rank, LD_w : Weight assigned to lithology; TWI_r : Topographic index rank, TWI_w : Weight assigned to the topographic wetness index; EI_r : Elevation rank, EI_w : Weight assigned to elevation; GWPZ is the groundwater potential zone, and the suffixes r and w

represent the rank and weight of each layer.

Analytical hierarchical process (AHP): The analytical hierarchical process (AHP) model is a multi-criteria decision-making (MCDM) tool used to solve complex decision-making problems, initially. It is widely accepted for assigning normalized weights to each thematic layer of groundwater prospecting factors. The final weight for each thematic layer is derived from the principal eigenvalue of the generated matrix. The reliability of the output was determined by calculating the consistency index (CI) and consistency ratio (CR) values.

$$CR = \frac{CI}{RI}$$

where CR indicates consistency ratio, RI indicates random consistency index whose values depend on the order of the matrix, and CI indicates consistency index, which can also be calculated.

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

where λ indicates the principal eigenvalue of the matrix and n is the number of groundwater prospecting factors. The value of CR must be < 0.1 .

RESULTS AND DISCUSSION

The slope of the study area with slope values reclassified into categories: very steep ($> 22^\circ$), steep ($13^\circ - 22^\circ$), moderate ($6^\circ - 13^\circ$), gentle ($2^\circ - 6^\circ$), and flat ($< 2^\circ$). Flat slopes dominate the higher recharge rate, suggesting that most of the region is conducive to water retention (Fig. 3a). Areas with flat and gentle slopes are ideal for effective groundwater recharge, resulting in low runoff and more time for surface water to percolate. Presents the elevation profile of the study area, which is a key topographic factor and serves as a surface indicator for exploring groundwater potential. The study area elevation was classified into five classes: very low (14-188 m), low (188-297 m), moderate (297-416 m), high (416-535 m), and very high (535-949 m) (Fig. 3b).

The map has been reclassified and categorized into five classes: very low, low, moderate, high, and very high. This study found that very high drainage density is found in the eastern, northern, and southern regions. These hilly regions have steep slopes, favoring high runoff and low infiltration, indicating a low GWPZ (Fig. 2c and 2d). TWI values ranged from 10.1 to 20.1 and were reclassified into five categories: very low (10.1 to 12.5), low (12.5 to 15.6), moderate (15.6 to 16.5), high (16.5 to 17.7), and very high (17.7 to 20.1) (Fig. 3e). The low and very low TWI classes are located along river basins and low-lying regions, indicating a higher potential for groundwater availability. Despite the predominance of high and very high TWI classes in the research area, infiltration

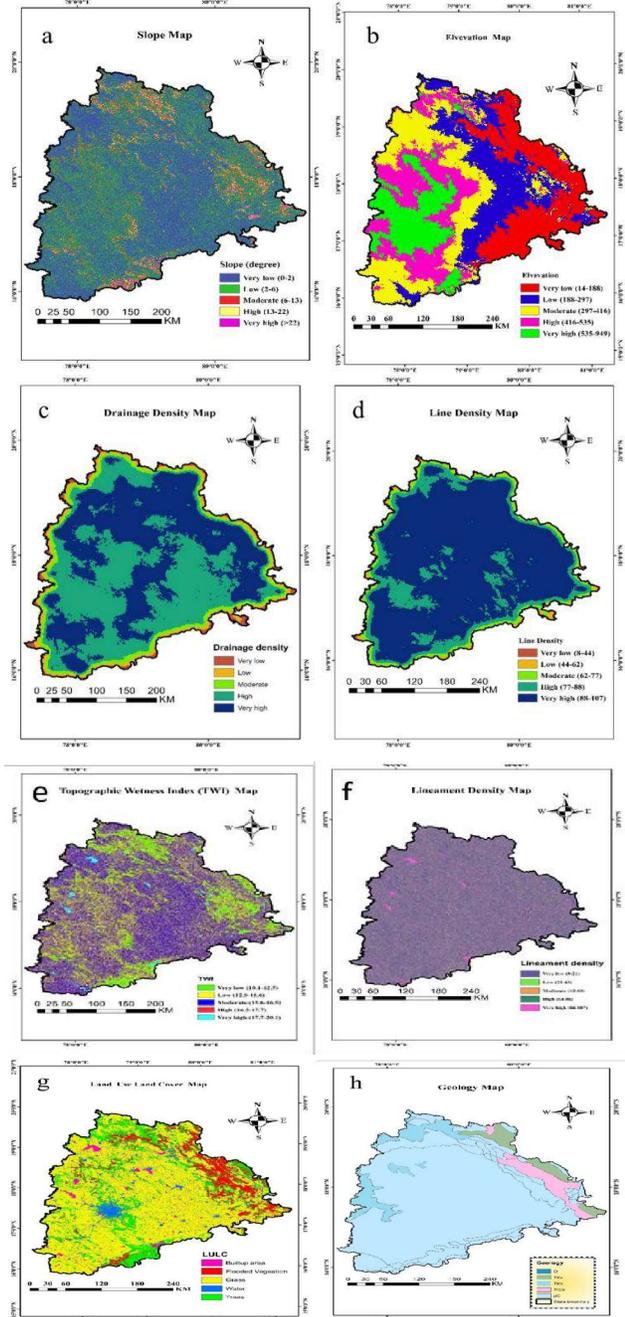


Fig. 2. Generated thematic layers (a) Slope map (b) Elevation map (c) Drainage density map (d) Line density map (e) TWI map (f) Lineament density map (g) LULC map (h) Geology (i) Soil type map (j) Rainfall map of the study area

Table 2. Groundwater potential zone in the study area

Potential zones	Area (km ²)	Percentage (%)
Fair	23,692.18	20.64
Poor	65,095.69	56.63
Good	6,096.20	5.32
Very good	5,409.16	4.71
Excellent	14,546.77	12.70

and accumulation are less common. Lineaments with densities ranging from low to very high indicating that lineament density is directly proportional to groundwater potential. Areas exhibiting a lineament density between moderate to high were identified as excellent groundwater prospect zones, encompassing major landscapes.

The LULC map of the study area was divided into six categories: water bodies, greens, trees, flooded vegetation, and built area. Among these classes, trees occupy the majority (62%) of the area. Infiltration rates increase as vegetation retains rainwater longer, aiding system recharge. Evergreen forests, cropland, and plantations have moderate runoff and high infiltration rates, contributing to increased groundwater recharge. The area comprises five different types of lithological features, including debré tabor basalts and trachyte, quaternary lacustrine sediment, middle basalt flows, upper basalts and trachyte, and guna tuff (Fig. 2h).

Soil predominantly falls into two categories: clay and sandy loam. In comparison, sandy loam soil predominates across most of the areas (Fig. 2i). Sandy loam soil exhibits superior groundwater potential compared to loam soil. Rainfall is one of the primary factors contributing to floods. The classification of the map was reclassified into five classes: very low (802-1,042), low (1,042-1,195), moderate (1,195-1,347), high (1,347-1,515), and very high (1,515-1,774)(Fig.3h).

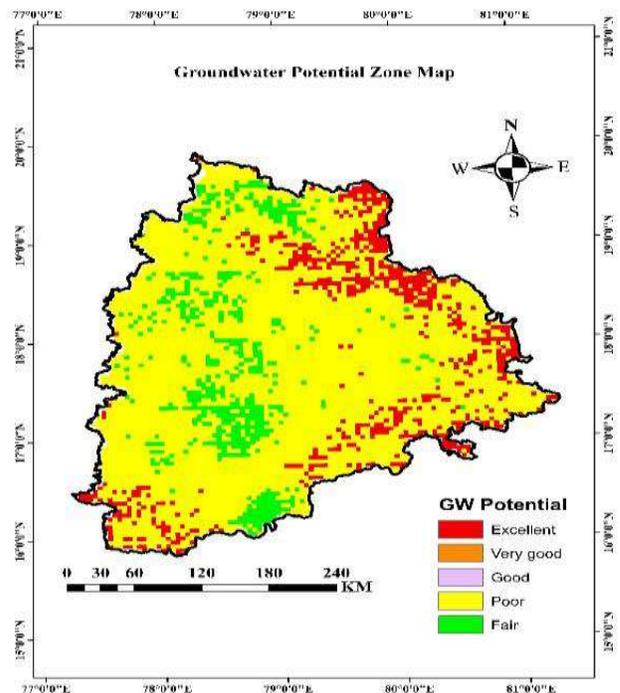


Fig. 3. Groundwater potential zone map of the study area

Table 3. Pair wise comparison matrix for the analytic hierarchy process (AHP) based on ground water potential (GWP) zoning

Criteria	Rainfall	Geology	Slope	Drainage density	LULC	Lineament density	Line density	Weight (%)
Rainfall	1	3	3	5	5	7	7	22.83
Geology	1/3	1	3	3	5	5	3	16.49
Slope	1/3	1/3	1	3	3	5	1	10.36
Drainage density	1/5	1/3	1/3	1	3	2	1	7.47
LULC	1/5	1/5	1/3	1/3	1	2	2	8.53
Lineament density	1/7	1/5	1/5	1/2	1/2	1	1	5.59
Soil	1	1	1	1	1	1	1	5.60
Line density	1/7	1/3	1	1	1/2	1	1	7.55
Elevation	1	1	1	1	1	1	1	7.03
TWI	1	1	1	1	1	1	1	8.53

Soil, Elevation, and TWI Criteria value is equal to 1

The analytic hierarchy process (AHP) was employed to assign weights to ten thematic layers; rainfall, geology, slope, drainage density, land use/land cover (LULC), lineament density, soil, line density, elevation, and topographic wetness index (TWI) based on their relative importance in influencing the target phenomenon. A pairwise comparison matrix was constructed using Saaty's 1–9 scale, where each criterion was compared against others based on expert judgment. The matrix was then normalized, and the average of each row was calculated to derive the final weights. The resulting weights revealed that rainfall (22.83%), geology (16.49%), and slope (10.36%) were the most influential factors, while lineament density (5.59%) and soil (5.60%) contributed less. The consistency check was also performed to ensure the reliability of the judgments used in the comparison matrix.

The principal eigenvalue of the matrix was 10.39 for the ten criteria considered. $CI=0.0433$, and the random index (RI) of 1.49. Consistency ratio was computed was 0.029. Since the CR well below the acceptable threshold of 10%, the pairwise comparisons are considered consistent, validating the reliability of the weight assignment in the AHP process. The groundwater potential of the study area has been categorized into five distinct zones: poor, fair, good, very good, and excellent (Fig. 3 and Table 2). The poor groundwater potential zone occupies the largest portion of the study area, covering approximately 56.63%, which corresponds to 65,095.69 km². This indicates that more than half of the region has limited groundwater availability, possibly due to unfavourable geological conditions, low infiltration capacity, or reduced recharge rates. The fair groundwater potential zone is the next most extensive, accounting for 20.64% of the area (23,692.18 km²). This zone represents areas with moderate groundwater availability, where aquifer characteristics may support limited extraction depending on local hydrological conditions. In contrast, the

excellent groundwater potential zone covers about 12.70% of the total area (14,546.77 km²), indicating regions with highly favourable conditions for groundwater recharge and storage. These zones are predominantly located in the northern and southern parts of the study area. The high groundwater potential in these regions can be attributed to dense forest cover, open land surfaces, and the presence of coarse-grained sediments, all of which enhance infiltration and aquifer recharge. The good and very good groundwater potential zones occupy relatively smaller portions of the study area, covering 5.31% (6,096.20 km²) and 4.71% (5,409.16 km²) respectively. Despite their limited spatial extent, these zones are still important, as they indicate areas with reasonably favorable hydrogeological conditions that can support sustainable groundwater development with proper management. Overall, while a significant portion of the study area exhibits low to moderate groundwater potential, the presence of excellent and very good zones in specific regions offers opportunities for targeted groundwater resource planning and sustainable water management practices.

CONCLUSION

The study delineated groundwater potential zones (GWPZ) in Telangana state using an integrated GIS, remote sensing, and AHP-based approach. Ten hydrologically relevant thematic layers were weighted using Saaty's AHP method and integrated through weighted overlay analysis in a GIS environment. The resulting GWPZ map classified the area into five categories excellent, very good, good, fair, and poor of the total area, respectively. High groundwater potential zones were mainly located in the northern and southern regions, associated with forest cover, open land, sandy loam soils, high rainfall, and dense lineament networks. Low potential zones were linked to rugged terrain, hard rock

geology, steep slopes, urbanization, and high drainage density. Validation with observed groundwater fluctuation data showed good agreement with the classified zones. Despite potential subjectivity in AHP, the approach maintained consistency and demonstrated strong applicability for groundwater resource planning and well site selection.

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