AIMS Geosciences

AIMS Geosciences, 7(2): 244–267.
DOI: 10.3934/geosci.2021015
Received: 23 March 2021
Accepted: 15 June 2021
Published: 18 June 2021

http://www.aimspress.com/journal/geosciences

Research article

Groundwater exploration in hard rock terrains of East Godavari district, Andhra Pradesh, India using AHP and WIO analyses together with geoelectrical surveys

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Abstract: The need for groundwater exploration in India has been increasing enormously, due to the non-judicial use of available water resources. The present study area is located between longitudes from 81°52′20.293″ to 82°29′32.058″ E and latitudes from 17°01′6.71″ to 17°38′ 12.906″ N in the Eastern Ghats mobile belt region of East Godavari district. The study area is characterized by a wide range of geological settings and high and irregular topographic features. The area is identified by Government as highly backward and Tribal people dwell here. For exploring good aquifer in the study area, the information of ten parameters together with geoelectrical resistivity data has been collected. Analytical Hierarchy Process (AHP) is used as the decision-making technique which uses the weights of different thematic layers (parameters) favorable for groundwater recharge, storage and location. Various thematic layers (parameters) of geology, geomorphology, soil, slope, lineament density, drainage density, groundwater level, Land use/Land cover, rainfall and coefficient of electrical anisotropy were considered in this analysis. A comprehensive groundwater prospect map has been prepared and validated with aquifer thickness map derived from the analysis of geoelectrical data. The entire study area has been classified into different potential zones of good, moderate and poor for groundwater exploration. The good groundwater potential zone is covering an area of 750.91 sqkm (28.4%) with aquifer thickness varying in the range 40–140 m, moderate potential zone encompasses 46.1% of the study area with an areal extent of 1220.33 sqkm and aquifer thickness is about 20–40 m. The remaining area of 24.5% is poor aquifer zone with thickness less than 20 m.

Keywords: geographical information system; remote sensing; thematic layers; analytical hierarchical process; weighted index overlay analysis; groundwater potential zones

1. Introduction

The occurrence of groundwater is constrained with different hydro-geological, geological and geomorphological conditions and tectonic framework of the area. The geoelectrical resistivity surveys are the most economic methods [1–3] for groundwater exploration of all the geophysical methods. However, it may not be that much effective in the case of hard rock terrain since it is difficult to send current into the ground. In such situations, the remote sensing studies would help in identifying the lineaments/fractures. Along lineaments/fractures geoelectrical resistivity sounding surveys could be conducted to know the depth to groundwater layer. When the results of geophysical survey are integrated with the studies like geological, geomorphological, meteorological, and remote sensing, the interpretation results will be more effective to suggest an exact location and depth for drilling a well. The relationship among the surface and subsurface features like geological structures, landforms, geomorphology, lineaments, land use/land cover (LULC), slope, drainage pattern, drainage density, rainfall, soil, depth to water table (DTW), coefficient of anisotropy (CA) and water bodies largely controls the occurrence, storage and distribution of groundwater [4].

The Remote Sensing (RS) and Geographical Information System (GIS) techniques could identify the lineaments and morphological features such as slopes and highs which are favorable environments for storing and movement of groundwater in the area [5]. Land use analysis plays an important role in identifying environmental impact and natural resource management. In recent years, owing to anthropogenic activity, land surface has been modified. The roads, habitation and rocky lands affect the recharge and contribute to increased runoff during rainfall. The structural features such as faults, fractures, shear zones, joints, litho-contacts, cleavages and dykes etc., are reflected in the remote sensing images as lineaments. Geomorphological expressions such as ridges, cliffs, terraces and aligned segments of valleys may also be identified as lineaments in remote sensing imageries [6]. Thus identification of lineaments related to high permeability paths for the movement of underground water is essential for groundwater exploration [7].

Many researchers have studied potential groundwater zones (PGZs) using different sets of thematic layers derived from remote sensing data [8–13]. Field studies are however necessary for validation of the RS and GIS data. The structural features/trends of possible groundwater locations identified from remote sensing imageries can be investigated more efficiently for their exact extension and location through geoelectrical resistivity surveys. For assessment and effective location of groundwater, it is essential to integrate all the available thematic layers (geology, geomorphology, soil, LULC, lineament density, drainage density, rainfall, slope, water level and electrical coefficient of anisotropy) [14–16].

The study area is characteristic of three-fourths hilly terrain (Eastern Ghats mobile belt). The tribal people living in this agency area are still facing water crisis for drinking, domestic and agriculture purposes. They are going miles on foot to fetch a pot of water for drinking. They are economically backward. The identification of groundwater potential zones can help them to exploit good quality of water for their sustenance. If the potential zones can yield sufficient quantities, then the water can be utilized for the small scale solar based agricultural activity. But in such areas, groundwater exploration is not an easy task. Data of as many parameters as possible is important and their integrated interpretation would help in effectively locating the groundwater potential zones of the study area.

The objective of the present paper is to delineate the groundwater potential zones in the study area from an integrated analysis of the geoelectrical, remote sensing, geology, geomorphology, and other hydrogeological inputs. This integrated analysis was carried out using weighted index overlay method combined with Analytical Hierarchy Process. The resistivity data collected at 270 locations in the study area will give the thickness and depth of water bearing zones. The results of both WIO analysis and geoelectrical surveys will be compared for validation.

2. Material and methodology

The study area is situated in East Godavari district of Andhra Pradesh state which is located between longitudes varying from 81°52′ 20.293″ to 82°29′ 32.058″ E and latitudes from 17°01′ 6.71″ to 17°38′ 12.906″ N covered by the Survey of India (SOI) Toposheet no's 65 G/14, 65 G/15, 65 G/16, 65 K/2, 65 K/3, 65 K/4, 65 K/6, 65 K/7 and 65 K/8 on 1:50,000 scale (Figure 1). The study area covers 12 mandals (A local government area, similar to a tehsil, in parts of India) in the district.

The northern region forms a part of Eastern Ghats mobile belt, exposing all the characteristic litho units of this super group such as Khondalite, Charnockite, Migmatite groups. Almost 3/4th of the study area is characterized by these hard rock formations along with a small patch of Deccan traps. The southernmost region is occupied by Sedimentary formations of Rajahmundry sandstones, Tirupathi sandstones and flood plains.

Groundwater in the study area occurs under phreatic and semi-confined conditions and the hydro geological regime of the area is influenced by the Yeleru River which originated in the hilly ranges of Eastern Ghats and drains through the area before it reaches the Bay of Bengal on the east coast of India. The Yeleru River is an ephemeral river and active only during monsoon (June–November) and is characterized by low or no flows during the rest of the period. In addition to Yeleru reservoir, which has an effective storage capacity of 508300 × 10^3 m^3 [17], there are a number of large and medium size tanks in the region which occupy 59.435 sqkm (2.25%) of study area. These tanks provide water resources for irrigation for small and marginal farmers in the region. The people living in the area are still facing water crisis during non monsoon period.

The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) multispectral data of Level 1 precision terrain corrected and registered at-sensor radiance (AST-L1T) and Digital Elevation Model (DEM) of the study area has been downloaded from USGS Earth Explorer portal (https://earthexplorer.usgs.gov). The total study area is covered with three scenes. The ASTER data after processing has been projected on to Survey of India (SOI) toposheets using ERDAS software. Based on the image fusion technique, the digitally rectified images were spectrally merged. The processed image was shown in Figure 1.

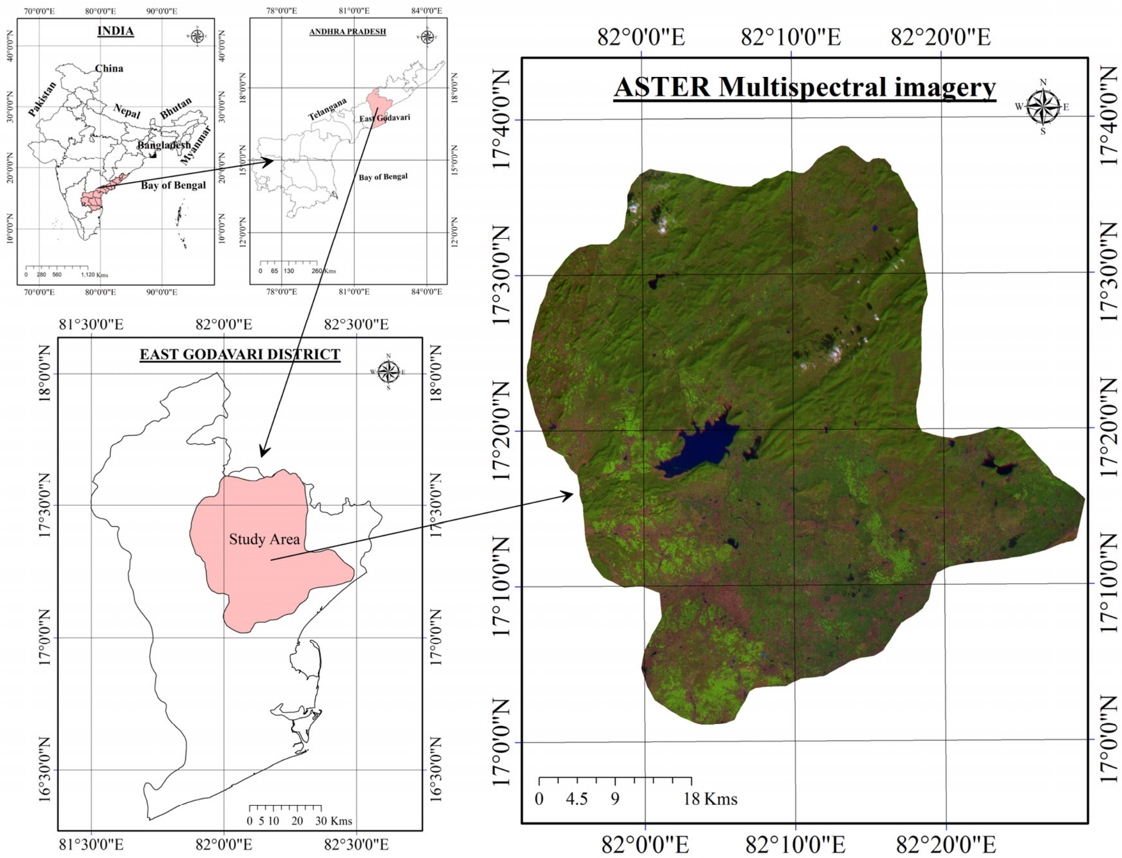


Figure 1. Location map of the study area.

Specific stream pattern (Dendritic) has been noticed from the analysis of ASTER DEM which is a good indicator of underlying rock types (horizontal sedimentary rocks and complex metamorphics), structural features and nature of the terrain [18]. Water tends to store at flat regions rather than the higher topography. Higher the slope greater is the runoff and lesser is the recharge. The topographic elevation is ranging from 3 to 844 meters above mean sea level and higher elevations (from 449 to 844 m) and steep slopes exist in the north and northeast parts of the area allowing the highest runoff and low infiltration rates. The low topographic elevations (from 3–88 m) were observed in the southern portions of the study area of sandstone formations.

Wide range of geological formations and topographic features are characteristics of the study area. The geomorphic features and lineaments have been digitized directly on Bhuvan's (Indian-Geo platform of ISRO, NRSC) thematic layers with Web Map Service (WMS) in Arc GIS across the screen, and the final maps were stored in vector files. All the landforms were grouped into structural, denudational and fluvial origin.

Based on geomorphic units, all the lineaments were classified [19] into three categories namely (1) Ridge parallel lineaments; (2) Drainage parallel lineaments and (3) Structural lineaments (Joints/fractures). The lineaments identified are of varying lengths with different orientations and the length of each lineament was measured. The total number of lineaments identified is 395. These are divided into three groups [20] via medium, minor and micro based on length (Table 1 and Figure 2a). Lineament density map has been prepared by considering drainage parallel and structural lineaments (Figure 2b).

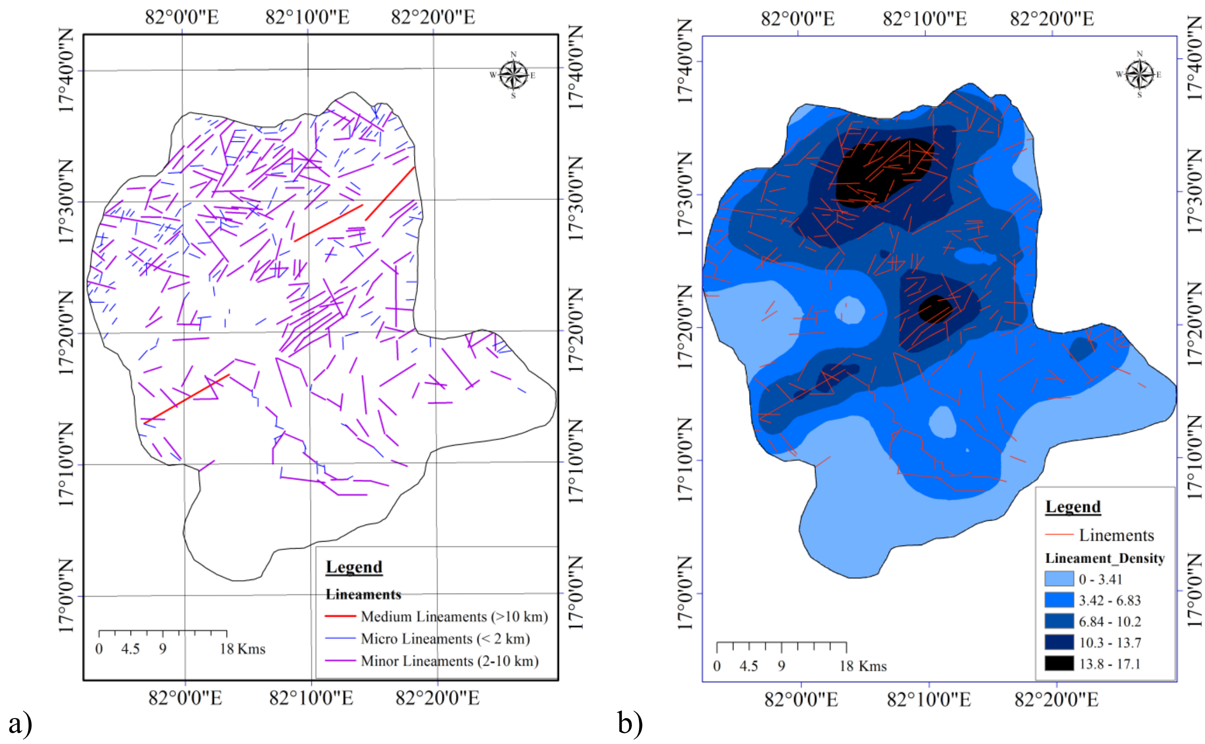


Figure 2. a) Classified lineament map based on length; b) Lineaments density map for total length of lineaments.

Table 1. Number, length and percentage of lineaments based on length.

S. No.	Type of Lineament (by length)	No. lineaments	Percentage (%)
1	Medium (>10 km)	3	0.8
2	Minor (2–10 km)	215	54.4
3	Micro (< 2km)	177	44.8

The land use/land cover map was prepared from the Terra satellite's ASTER Level-1T data using Arc GIS software. The slope map of the study area in degrees has been generated from AST-DEM. The different types of the soil layers in the study area has been extracted using Arc GIS from the district survey report of Department of Mines and Geology [21], Government of Andhra Pradesh and a soil map has been prepared. The drainage density map has been prepared using drainage network derived from aster DEM with sum length of streams in the fishnet of unit area (4 sqkm).

Rainfall observations at 19 locations in the study area were acquired from the database of Andhra Pradesh State Development Planning Society (APSDPS) and Rainfall intensity map of the area has been prepared. Depth to groundwater level (DTW) data at 34 locations was collected from Andhra Pradesh Groundwater and Water Audit Department (APGWAD) and the spatial distribution map of DTW has been prepared.

Transverse (ρ_T) and longitudinal (ρ_L) resistivities have been calculated from 270 Vertical Electrical Soundings (VES) survey data of the study area. Out of these 270 VES points, 146 VES surveys were carried out by the authors in the study area and data of 124 soundings has been taken from APGWAD. The coefficient of electrical anisotropy λ was calculated using equation (1) and a spatial distribution map has been prepared.

$$\lambda = \sqrt{(\rho_{T/}\rho_L)} \tag{1}$$

The Weighted Index Overlay Analysis (WIOA) using spatial analysis tools in Arc GIS was adopted for integrating the thematic layers to generate the groundwater potential map as it is a simple method to analyze multiclass maps based on the relative importance of each thematic layer and a layer's sub class. For this analysis, the weights of each thematic layer have been derived using Analytic Hierarchy Process of Saaty [22].

2.1. Analytic hierarchy process (AHP)

Analytic Hierarchy Process is one of the multi-criteria decision-making methods developed by Saaty [22,23]. AHP is an analysis based on the relative importance of the parameters when compared to one another. The weights are assigned to each parameter and then they are normalized. The consistency index (CI) and consistency ratio (CR) are computed from these weights to check their reliability [22,24–27]. As per Saaty [23], if the computed CR is significantly small (<10%) then the normalized weights are accepted. The diagonal pairwise matrix is generated by filling the upper triangle with a priority of influencing factor of each parameter with other parameters. The lower triangle values are determined by taking the reciprocal of the upper triangle elements. Further, the weights of each parameter are then normalized (weight of each parameter/sum of the weights of all parameters).

The average weight that a parameter carries has been computed by taking an average of the normalized weight of the particular parameter of the row. The consistency vector (λ) is calculated by multiplying the average weight of each parameter in normalized matrix with the sum of weights in a column of the corresponding parameter in the pair wise matrix.

The Consistency Index (CI) and Consistency Ratio (CR) are computed from the pair-wise comparison matrix of all the parameters using the following equations.

$$CI = (\lambda_{max} - n) / (n - 1) \tag{2}$$

$$CR = CI/RI \tag{3}$$

where λ_{max} is the sum of consistency vector (λ) and n is the number of factors considered. The Random Index (RI) is defined as CI expected from a matrix of that order values and are given in Table 2 (If the number of parameters is 10, then RI = 1.49).

Table 2. Random index (RI) values provided by [28].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Nag and Ghosh [29], Etishree et al. [30], Suganthi et al. [31] and Behzad et al. [32] have given different weights to the thematic layers (parameters) depending on their favorability to the groundwater potential. Ten thematic layers have been considered in this study for groundwater exploration. The weights of each thematic layer of this AHP analysis were used to carry out Weighted Index Overlay Analysis (WIOA). The WIOA process computes the groundwater potential zones of the area based on the integrated importance of all the thematic layers and their subdivisions.

The ten thematic layers considered for AHP analysis in this study are Geology, Geomorphology (GM), Lineament Density (LD), Land use/Land cover (LULC), Slope, Soil, Drainage Density (DD), Rainfall (RF), Depth of water table (DTW) and electrical Coefficient of Anisotropy (CA).

In this study, basing on the characteristic properties, geology, geomorphology, lineament density and land use/land cover have higher importance for groundwater storage and movement in comparison to other parameters. Soil and slope have been given higher weightage compared to drainage density, depth to water level, rainfall and coefficient of anisotropy. These thematic layers have been compared to one another for carrying out hierarchy analysis and weights were assigned to them depending on their relative importance for groundwater storage and movement and shown in Table 3.

Table 3. Pairwise comparison matrix.

	Geology	GM	LD	LULC	Slope	Soil	DD	RF	DTW	CA
Geology	1.00	1.00	2.00	3.00	2.00	3.00	2.00	3.00	4.00	3.00
GM	1.00	1.00	2.00	2.00	3.00	1.50	3.00	4.00	4.00	4.00
LD	0.50	0.50	1.00	1.50	2.00	1.50	2.00	3.00	4.00	4.00
LULC	0.33	0.50	0.67	1.00	1.50	2.00	2.00	3.00	4.00	3.00
Slope	0.50	0.33	0.50	0.67	1.00	0.50	2.00	3.00	4.00	4.00
Soil	0.33	0.67	0.67	0.50	2.00	1.00	0.50	2.00	3.00	2.00
DD	0.50	0.33	0.50	0.50	0.50	2.00	1.00	1.50	2.00	3.00
RF	0.33	0.25	0.33	0.33	0.33	0.50	0.67	1.00	3.00	2.00
DTW	0.25	0.25	0.25	0.25	0.25	0.33	0.50	0.33	1.00	3.00
CA	0.33	0.25	0.25	0.33	0.25	0.50	0.33	0.50	0.33	1.00
SUM (W_s)	5.08	5.08	8.17	10.08	12.83	12.83	14.00	21.33	29.33	29.00

Table 4. Normalized comparison matrix.

	Geology	GM	LD	LULC	Slope	Soil	DD	RF	DTW	CA	Weightage (W)	λ
Geology	0.20	0.20	0.25	0.30	0.16	0.23	0.14	0.14	0.14	0.10	0.185	0.94
GM	0.20	0.20	0.25	0.20	0.23	0.12	0.21	0.19	0.14	0.14	0.186	0.95
LD	0.10	0.10	0.12	0.15	0.16	0.12	0.14	0.14	0.14	0.14	0.130	1.06
LULC	0.07	0.10	0.08	0.10	0.12	0.16	0.14	0.14	0.14	0.10	0.114	1.15
Slope	0.10	0.07	0.06	0.07	0.08	0.04	0.14	0.14	0.14	0.14	0.096	1.24
Soil	0.07	0.13	0.08	0.05	0.16	0.08	0.04	0.09	0.10	0.07	0.086	1.11
DD	0.10	0.07	0.06	0.05	0.04	0.16	0.07	0.07	0.07	0.10	0.078	1.10
RF	0.07	0.05	0.04	0.03	0.03	0.04	0.05	0.05	0.10	0.07	0.052	1.11
DTW	0.05	0.05	0.03	0.03	0.02	0.03	0.04	0.02	0.03	0.10	0.039	1.14
CA	0.07	0.05	0.03	0.03	0.02	0.04	0.02	0.02	0.01	0.03	0.033	0.96

Note: GM: Geomorphology; LD: Lineament Density; LULC: Land use/Land cover; DD: Drainage Density; RF: Rainfall; DTW: Depth to groundwater level; CA: Coefficient of anisotropy.

The weights of each thematic layer were then normalized and their average weights were determined (Table 4). The consistency vector has been calculated by multiplying the average weight (W) of each thematic layer in Table 4 with the sum of weights (W_s) in its column of Table 3 and presented in Table 4. Finally, to check the consistency of weights of all the ten thematic layers, consistency index (CI) and consistency ratio (CR) have been calculated using equations (2) and (3). The determined values of CI and CR from this analysis are respectively 8.26% and 5.54%. The consistency ratio (CR) is under 10%, and hence the estimated weights are acceptable as per Saaty [22,23].

2.2. Weighted index overlay analysis (WIOA)

There are many approaches for performing overlay analysis using Arc GIS processing tools such as fuzzy membership, fuzzy overlay, weighted index overlay and weighted sum. In the present problem, weighted index overlay analysis has been widely used [33–35]. In this analysis, each of the thematic layers considered for the AHP analysis was further divided into different subclasses. Each feature in the sub-classification has been assigned a rank in the range of 1 to 9 depending on their relative merit in the study area with 9 for the highest and 1 for the least. Following the equation (4) of Malczewski [36], the groundwater potential index (GWPI) values are calculated using Weighted Index Overlay Analysis (WIOA).

$$\mathrm{GWPI}=\sum_{j=1}^{m}\sum_{i=1}^{n}(\mathrm{W}_j \times \mathrm{X}_i) \quad (4)$$

Where W_j is the average normalized weight of the j^{th} thematic layer, X_i is the rank of the i^{th} feature (subclass) of the thematic layer; m is the total number of thematic layers and n is the total number of subclasses of given thematic layers.

The GWPI values were used to classify whether the study area is good, moderate or poor with respect to groundwater potential [27,37]. The different stages of methodology adopted for the generation of groundwater potential zone map have been explained in the flow chart (Figure 3). The entire process of WIOA was carried out using Arc GIS.

For carrying out the weighted index overlay analysis, the different thematic layers considered in the region were thoroughly studied and each thematic layer was further divided into subclasses. The subclasses of each layer were given ranks depending on their relative importance for groundwater potential. The detailed discussion of ranking of each sub class in each parameter has been given below.

2.2.1. Geology

Geology is one of the most significant and widely used parameters in identifying groundwater potential zones [39] and Figure 4a shows the geology of the study area. The southern part of the study area is relatively plain whereas the northern part is elevated with its general slope towards south.

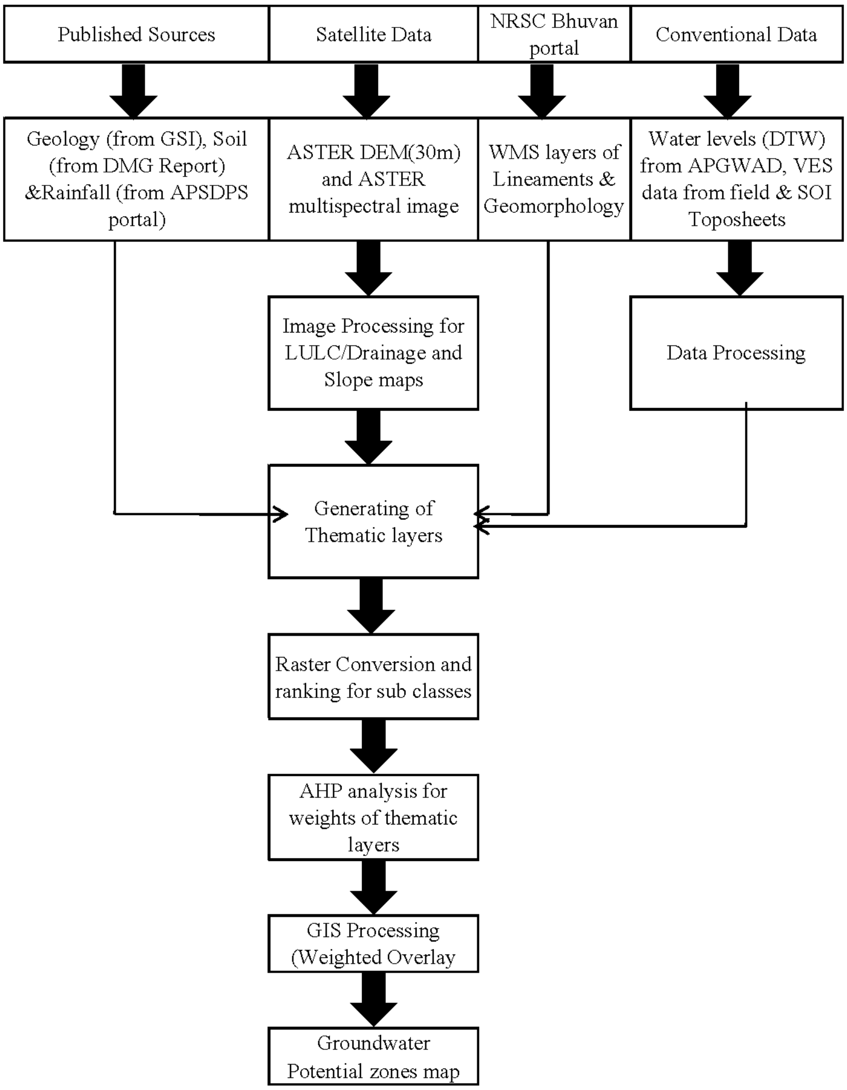


Figure 3. Flow chart for the generation of groundwater potential zones.

The northern region is mainly covered by Khondalite, Charnockite and Migmatite group of rocks. Flood plains, Rajahmundry and Tirupathi sandstones are the dominant formations in the southern part of the study area. Jaggampeta, Tondangi and Gollaprolu mandals fall under Tirupathi sandstones. Peddapuram and Pithapuram are located in Rajahmundry sandstone and flood plain formations. An intrusive body of the Deccan trap separates Tirupathi and Rajahmundry sandstones near Jaggampeta mandal. A small patch of Laterites exists in the north-eastern part of the study area near Rajavommangi mandal.

From the geohydrological point of view, the area is broadly divided into two domains: (1) unconsolidated formations, belonging to Quaternary and Tertiary ages and (2) crystalline metamorphic rocks of Archaean age (Table 5). The groundwater basins in unconsolidated formations have a wide lateral extent and aquifers occur under unconfined conditions. In the crystalline terrain, groundwater is restricted to soil and regolith cover, weathered and fissured zones under unconfined water table conditions.

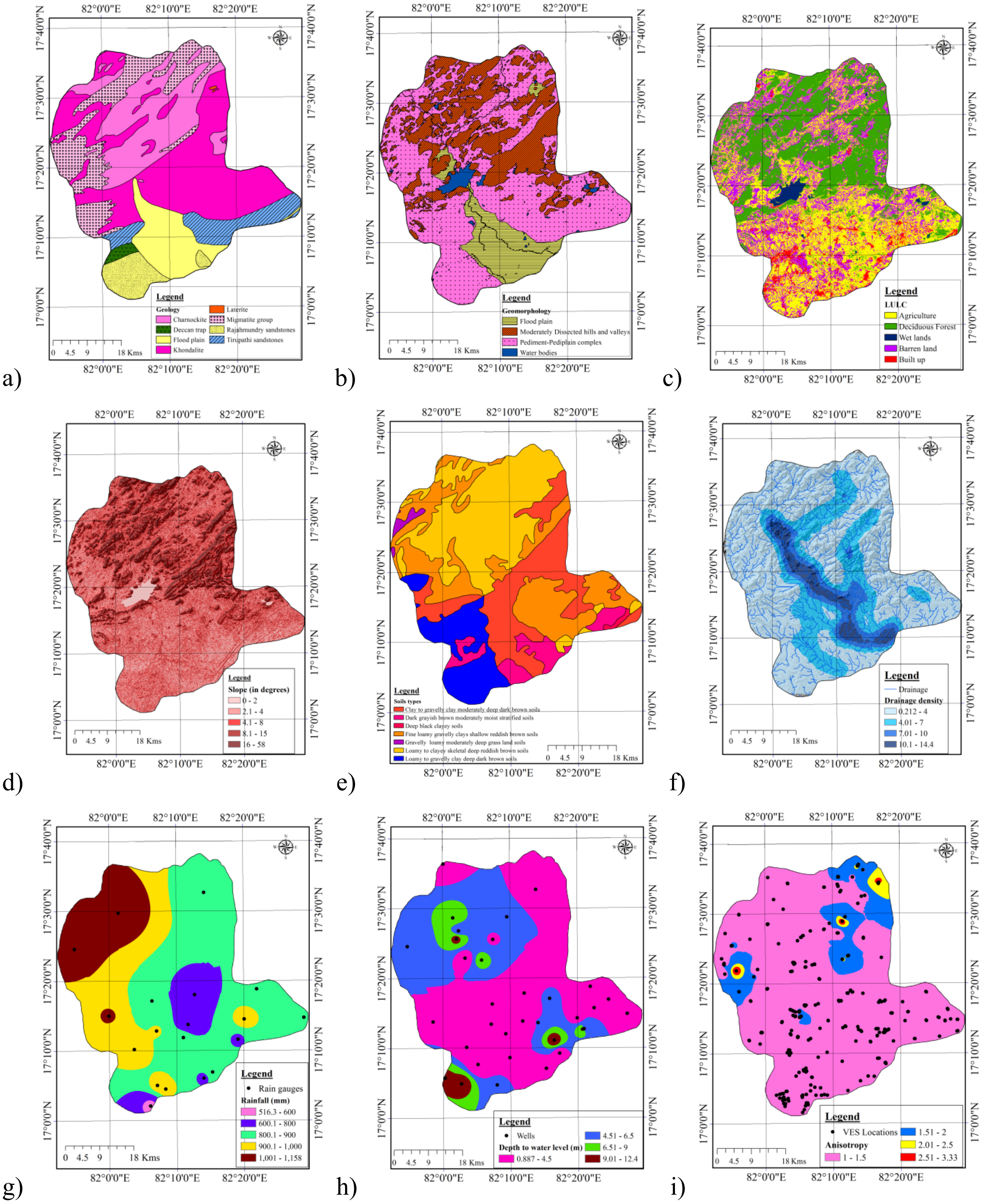


Figure 4. a) Geology [38]; b) Geomorphology; c) Land use/Land cover; d) Slope in degrees; e) Soil; f) Drainage density (km/km^2); g) The average of mean annual cumulative rainfall in mm (2011–15); h) The average of mean annual depth to water level in m (2011–15) and i) Coefficient of anisotropy (λ) map of study area.

Table 5. Stratigraphic succession of geological formations in the study area.

Formation	Geological Time	Characteristics
Flood plain	Quaternary	Unconsolidated to semi-consolidated sand, silt, clay
Laterite	Pleistocene	Moderately dense and porous
Rajahmundry Sandstones	Mio-pliocene	Moderately dense and porous
Deccan Trap	U. Cretaceous to Eocene	Hard and massive
Tirupathi Sandstones	U. Carboniferour to L. Cretaceous	Moderately hard and dense
Khondalite	Archaean	Hard and massive
Charnockite	Archaean	Hard and massive
Migmatite Group	Archaean	Hard and foliated

Basing on the characteristic properties of different geological formation, it is divided into different subclasses and each class was given a rank (Table 6). The Rajahmundry sandstones were assigned with the highest rank (9) due to their porous nature as they belong to sedimentary group whereas Tirupathi sandstones bearing high percentage of clay compared to Rajahmundry sandstones were given slight lesser rank (6).

These sedimentary rocks are the major aquifers in southern region as they can store and transmit water due to their porosity and permeability. The secondary porosity in weathered and fractured zones of hard rocks like Migmatites and Khondalites is generated by tectonic activities. Therefore, they were assigned with good ranks of 5 and 6 respectively based on degree of weathering. Flood plains of semi consolidated sediments were given rank of 5 due to the accumulation of silt and clay. Sands and Laterites were assigned very low rank (3) because of clayey nature. The Charnockites and basaltic Deccan Traps are hard massive rocks and hence they were assigned poor to very poor ranking of 4 and 3 (Table 6) [40].

2.2.2. Geomorphology

The detailed geomorphologic map provides an imperative input for understanding the various geological controls like plateaus which are responsible for the occurrence and flow of groundwater [41]. The study area is characterized by hilly terrain in the north and with low lying plateau in the south. The major geomorphic landforms demarcated in the study area are moderately dissected hills of structural origin, pediment-pediplain complex of denudational origin, flood plain of fluvial origin and water bodies (Figure 4b). Most of the study area (56.78%) is covered under shallow pediment-pediplain complex category and this landform can be classified as moderate to good groundwater accumulation zones.

Table 6. Weightage and ranks of individual thematic layers.

Thematic maps	Weights of thematic layers (%)	Individual features	Ranks for individual class	Area (sqkm)	Percentage of area
Geology	18.488	Rajahmundry sandstone	9	144	5.4
		Tirupathi sandstone	8	195.6	7.5
		Khondalite	6	1003.7	37.9
		Flood plain	5	277.6	10.5
		Migmatite	5	453.7	17.15
		Charnockite	4	545.7	20.6
		Laterite	3	1.6	0.06
		Deccan trap	3	23.4	0.89
Geomorphology	18.634	Water bodies	9	59.4	2.2
		Pediment-Pediplain complex	6	1502	56.8
		Flood plain	5	314.7	12
		Moderately dissected hills and valleys	2	769	29
Lineament density (Km/Km^2)	12.984	0–3	4	625.6	23.65
		3–6	6	756.6	28.6
		6–10	8	836.7	31.6
		10–17	9	426.4	16.15
Land use/Land cover	11.408	Wet lands	9	41.3	1.46
		Agriculture	6	961.6	36.24
		Barren land	3	689	26.04
		Deciduous Forest	3	842.5	31.7
		Built up	2	110.9	4.2
Slope (In degrees)	9.659	0–2	9	377.8	14.31
		2–4	8	638.6	24.1
		4–8	4	817	30.9
		8–15	3	405.7	15.34
		15–58	1	406.2	15.35
Soil	8.624	Dark grayish brown moderately moist stratified soils	8	172.1	6.5
		Clay to gravelly clay moderately deep dark brown soils	7	586.3	22.2
		Gravelly loamy moderately deep grass land soils	7	20.9	0.8
		Fine loamy gravelly clays shallow reddish brown soils	5	679.9	25.6
		Loamy to clayey skeletal deep reddish brown soils	5	851.2	32.2
		Loamy to gravelly clay deep dark brown soils	5	324.8	12.3
		Deep black clayey soils	4	10.1	0.4

Continued on next page

Thematic maps	Weights of thematic layers (%)	Individual features	Ranks for individual class	Area (sqkm)	Percentage of area
Drainage density (Km/Km^2)	7.829	0–4	9	1681.5	63.8
		4–7	8	632.7	24
		7–10	7	184.6	7
		10–15	5	136.5	5.2
Rainfall (mm)	5.193	516–600	5	7	0.26
		600–800	6	265.2	10.02
		800–900	7	1293.6	48.91
		900–1158	8	1079.5	40.81
Groundwater level (m)	3.881	0.9–4.5	9	1507.3	57
		4.5–6.5	8	912.5	34.5
		6.5 –9	7	169.2	6.4
		9–12.5	6	56.3	2.1
Coefficient of anisotropy	3.3	1–1.5	8	2266.7	85.7
		1.5–2	5	328.5	12.4
		2–2.5	1	42.2	1.6
		2.5–3.3	1	7.9	0.3

In general, structural hills represent the geologic structures such as fractures, joints and lineaments etc. These hills are categorized as poor groundwater prospect zones, as they are characterized by high surface runoff. These landforms enclose deep valley gullies with gentle slope developed due to river erosion. These hilly landforms with valleys cover about 29% of the study area (769.157 km^2) mostly in northern region. The alluvial deposits are also observed (12%) close to drainage channels and due to high permeable nature in addition to high porosity; these deposits are characterized as moderate zone for groundwater accumulation in shallow level for dug well construction. Alluvial deposits of the area comprise unconsolidated material of various sizes like gravel, sand, silt or clay. About 59.4 km^2 (2.25%) of the study area is occupied by water bodies. Highest rank (9) has been assigned to water bodies as they are the continuous recharge sources to groundwater and successive ranks (6 & 5) were given to pediment-pediplain complex and flood plain which are characterized by high porosity and permeability. Moderately dissected hills are considered to hold less groundwater as they are un-fractured and have low infiltration capacity and they were assigned with a low rank (3) (Table 6).

2.2.3. Lineament density

The lineaments in the study area vary in dimensions**.** Only the structural and drainage parallel lineaments which act as conduits for groundwater accumulation and movement have been considered for the generation of density map as they result in increased secondary porosity and permeability.

It is found from the lineament density map (Figure 3b) that the density of lineaments is more in the northern region. It means that the structurally controlled lineaments which resemble the joints/fractures favorable for groundwater storage are more in this region. The complete study area has been divided into four classes. The region covering relatively high-density values (>10 km/km^2) has been given high rank of 9 and lower density regions with low ranks (Table 6).

2.2.4. Land use/Land cover

Land use/Land cover patterns provide information about the nature of surface material which controls infiltration and surface runoff and also the human influence on groundwater [42,43]. Land use patterns such as built-up, forest, agriculture, barren and wetland were identified in the study area (Figure 4c). Deciduous forest is the main (31.8%) occupation in the northern region whereas, in the southern region, agriculture is covering larger area (36.35%). About 26% of the study area is occupied by barren land and built-up land covers 111 km^2 of the area. Only 1.46% of the total study region is under wetlands (Table 6).

Wetlands as high potential (Rank-9) [44] and agriculture fields as good potential zones (Rank-6) were classified for groundwater prospects. Generally the groundwater is not extracted from the forests on hilly terrains [45], low ranking (Rank-3) has been assigned to deciduous forest and barren land whereas buildup area which does not allow water to percolate underground was assigned with very low rank of 2 [46,47]. The ranking division of this thematic layer is shown in Table 6.

2.2.5. Slope

Slope is the rate of change of elevation. The slope map has been classified into five classes according to the percentage of their gradient (Figure 4d) and higher ranks were assigned to lower degrees of slope (Table 6). Topographically, the study area slopes gently from north to south, with the exceptions of hilly region, where the degree of slope is higher (15°–58°).

2.2.6. Soil

The infiltration of water through soils is one of the important hydraulic properties for agriculture and water research. The study of soils is one of the major inputs for identifying groundwater recharge zones due to their ability to penetrate water into subsurface [48]. The rate of infiltration depends on the factors like soil texture, surface topography, intensity of rainfall and vegetation cover [49].

Table 7. Rate of infiltration of different soils.

S. No.	Soil texture	Infiltration rate (mm/hr)
1	Gravelly loamy sand	30
2	Sandy loam	20–30
3	Loamy sand	15–20
4	Sandy clay loam	10–15
5	Silty clay loam	7.5–10
6	Clay loam	5–10
7	Clay	1–5

In the study area, seven types of soils have been identified such as dark grayish brown moderately moist stratified soils (6.5%), clay to gravelly clay moderately deep dark brown soils (22.2%), gravelly loamy moderately deep grassland soils (0.8%), fine loamy gravelly clays shallow reddish-brown soils (25.6%), loamy to clayey skeletal deep reddish-brown soils (32.2%), loamy to gravelly clay deep dark brown soils (12.3%) and deep black clayey soils (0.4%) The soils of the study area have been assigned ranks considering the infiltration rates of Bathis and Ahmed [50] (Table 7). Higher ranks assigned to the soils possess higher rate of infiltration (Table 6).

2.2.7. Drainage density

The runoff of surface water is high if the drainage density is high since it is an inverse function of the permeability of lithological formations, hence; the infiltration of water into the ground would be less [51]. The high density is observed all along the mainstream of highest order in the study area (Yeleru River) where surface runoff is more and the infiltration rate is less. Low drainage density is found mainly in the pediplain-pediment complex region (Figure 4f). The drainage density map has been classified into four classes. The higher ranking has been given to low value of drainage density and vice versa (Table 6).

2.2.8. Rainfall

Rainfall is the major water source and it is directly associated with the availability of groundwater. However, the percolation factor depends on the topography of the area and soil type. It could be seen from Figure 4g that there is a wide variation in rainfall from a minimum of 516 mm at Rayabhupalapatnam station in the southernmost region and a maximum of 1158 mm at Addateegala station in the northwestern region of the area. The higher rainfall in the study area is ranging from 1000 to 1158 mm and was assigned with a higher rank (8) whereas the low rain-fed (516–600 mm) regions were given lower ranks (5) (Table 6).

2.2.9. Groundwater level

It is required to analyze the data of groundwater levels (DTW) which may provide information to estimate essential parameters like groundwater recharge, aquifer depth and thickness etc. [52]. From Figure 4h, it is clear that the annual average DTW is varying from 0.9 to 12.5 meters. Most of the wells in the southern region were showing shallow water levels. Only five wells in the study area show more than 9 m of DTW but not exceeding 12.5 meters. The deeper depths of water level were noticed at Pedda Rayavaram (10.4 m), Yellavaram (10.7 m), Ramesampeta (12.4 m), Durgada (12.5 m) and Thatiparthi (12.3 m). Low and high ranks have been assigned to regions of deeper and shallow DTW values respectively (Table 6).

2.2.10. Coefficient of anisotropy

The coefficient of anisotropy (λ) is a measure of the extent of inhomogeneity caused due to the extent of weathering and fracturing in the basement [53]. The λ is a dimensionless parameter and generally varies between 1 and 2 [54] in most of the geological environments. The hardness or compaction of rocks is represented by the increased values of λ since these formations are characterized by low porosity and low permeability [55].

In the study area, the coefficient of anisotropy is varying from 1.0 to 3.33 with a majority of the area under less than 1.5. Very few locations in the northern region which are closer to hills are showing greater than 2 (Figure 4i). Higher ranks are assigned to formations with λ values in the range 1.0 to 1.5 and low ranks to the regions with λ greater than 2 (Table 6).

The weights and ranks of each thematic layer have been given as input to the Weighted Index Overlay Analysis (WIOA) of the Arc GIS software package. The groundwater potential index (GWPI) values were calculated by the software (using equation 4) from these assigned weights and ranks and the resultant GWPI map was generated.

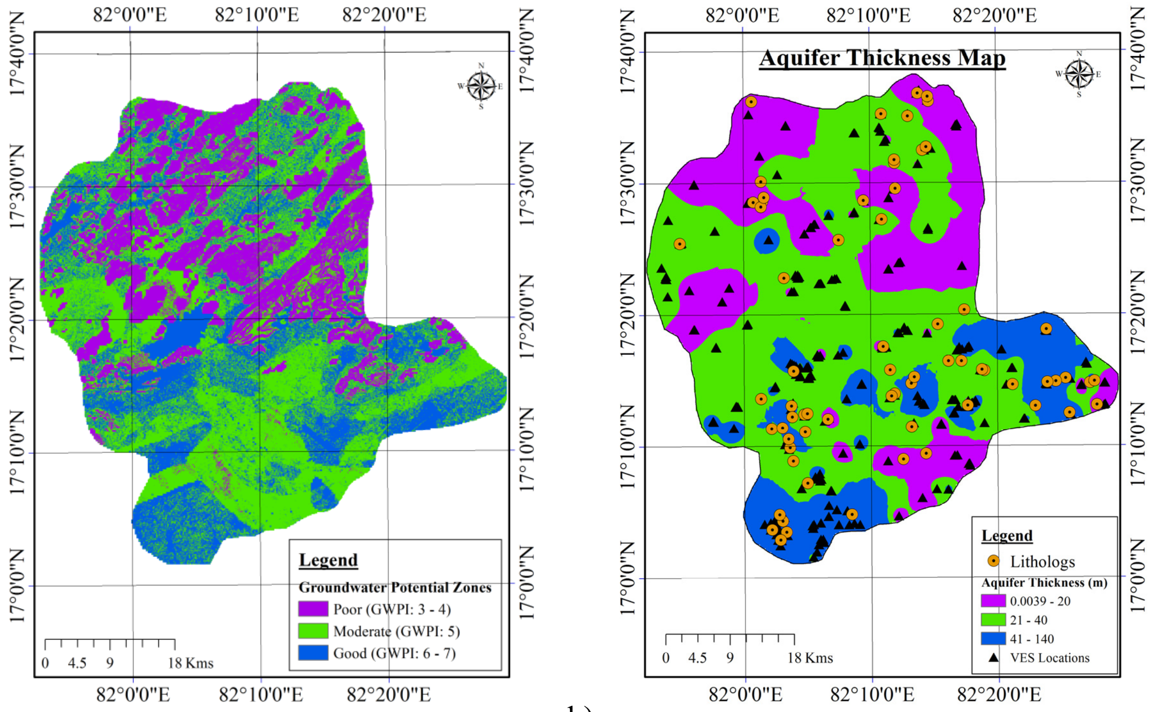
3. Results and discussion

3.1. Groundwater potential zones

The resultant GWPI map was obtained in raster format (Figure 5a). Basing on the GWPI values, the complete study area has been categorized into three classes via (1) GWPI: 6–7; (2) GWPI: 5; (3) GWPI: 3–4 and are referred as good, moderate and poor aquifers respectively. The good groundwater potential zone is covering an area of 750.91 sqkm (28.4%) and this area covers geological units of Khondalites in northern parts (Zone of high rainfall >900 mm; high density of lineaments >7 km/km^2), Rajahmundry and Tirupathi sandstones in southern region, characterized by low drainage density (<4 km/km^2), low slope (<2°), besides agriculture fields. The moderate potential zone encompasses 46.1% of the study area with an areal extent of 1220.33 sqkm that is occupied by Migmatites and Deccan trap formations and slope of the area is 2°–8°. This area is under moderate rainfall (600–900 mm) with lineament density of 3.5–7 km/km^2 and is mostly covered with barren lands with moderate drainage density (4–7 km/km^2). The coefficient of anisotropy is ranging from 1–1.5. The low potential zones of 674.06 sqkm (25.5% of total area) are demarcated in regions covered with moderately dissected hills, deciduous forest, higher slope (>8°), high lineament density and high rainfall. The geological formation is mostly Charnockites.

3.2. Geoelectrical surveys

270 Vertical Electrical Soundings (VES) have been carried out in the study area out of which 184 soundings have been conducted in hard (metamorphic) rock terrains and the remaining 86 were conducted in sedimentary formations. The data has been interpreted with IPI2Win software. At most of the locations in hard rock terrains (Northern part of the study area), three-to-four-layer pattern has been obtained for the maximum (250 m) half current electrode separation except at few locations (14 soundings) where five layers were found. The sequence of layering (from the surface) is as follows: (1) Top wet/dry soil (6–50 Ωm) or Talus material (100–150 Ωm); (2) Highly weathered (5–10 Ωm) or weathered layer with water (10–50 Ωm) or semi weathered/talus material (~200 Ωm); (3) Weathered (10–50 Ωm) or semi weathered/fractured formation (50–150 Ωm); (4) Semi weathered/fractured formation (50–150 Ωm) or hard basement and (5) Hard basement (>150 Ωm).



a) b)

Figure 5. a) Groundwater potential zone map of the study area; b) Aquifer (resistivity range: 10–150 Ωm) thickness map of the study area.

In sedimentary formations (Sandstones/flood plains) in southern region, the results of 10 soundings only have shown 5 layers and all the remaining 76 soundings reported 3 to 4 layers for the maximum spread (250 m) of half current electrode separation. The sequence of layering in the sedimentary formations is: the top wet/ dry soil (5–200 Ωm) followed by clay (<10 Ωm) or saturated sands of medium to coarse-grained sandstone (10–60 Ωm) or gravel (~80 Ωm) which is overlying consolidated sandstone (>150 Ωm).

Litholog data at 67 locations (51 in hard rock terrains and 16 in sedimentary formations) has been collected. The sequence of geoelectrical layers have been compared with the lithologs at 67 wells. It is found that the resistivity values of the subsurface layers are corresponding well to the type of the formation observed from litholog sections. As an example, comparison of lithology with resistivity values at Kindra village (in hard rock terrain) is shown in Figure 6. The subsurface layers with resistivity in the range of 10 to 150 Ωm (both weathered and fractured) in hard rock terrains and 10–60 Ωm in sedimentary formation of the study area has been considered as good aquifers. From the resistivity values of possible water potential layers at the 270 locations, a comprehensive aquifer thickness map has been prepared (Figure 5b). The study area is classified into five zones depending on the aquifer thickness values: (1) less than 10 m; (2) 10–20 m; (3) 20–40 m; (4) 40–70 m and (5) greater than 70 m and less than 140 m.

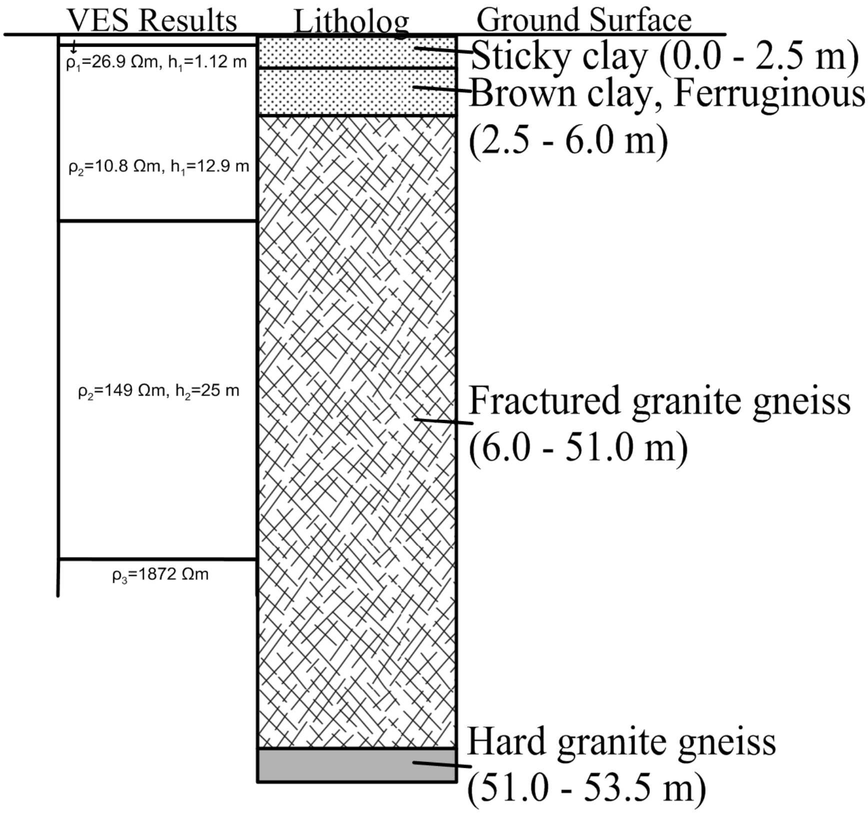


Figure 6. Comparison of resistivity and thickness values (determined with electrical sounding data) with Lithology of the drilled well at Kindra village.

3.3. Validation of GWPI and resistivity results

Comparing the maps of GWPI (Figure 5a) and aquifer thickness (Figure 5b), it is inferred that good ground water potential zones (GWPI: 6–7) are correlating well with zones of aquifer thickness greater than 40 m and moderate ground water potential zones (GWPI: 5) are agreeing well with zones of aquifer thickness in the range 20–40 m. The low ground water potential zones (GWPI: 3–4) are comparable with the zones of less aquifer thickness (<20 m). An interesting inference may be drawn by a close observation of these two maps (Figure 5a & 5b), that though the northern part of the study area mostly shows low potential (Figure 5a), but the aquifer thickness is considerable (20–40 m) (Figure 5b). The GWPI map (Figure 5a) was drawn based on the characteristics of all the thematic layers whereas; the aquifer thickness map has been prepared based on the measured resistivity data and compared with lithologs. Some northern parts are characterized by higher lineament density, major lineaments, higher rainfall and more weathering (litholog and resistivity values) and also, the numerous E-W ridges may act as barriers to the movement of water and for storing. Hence the common areas of low potential as marked by GWPI map and are showing the aquifer thickness of 20–40 m (Figure 5b) may also be good sources of groundwater for needs of those habitants. This is an advantage of the combined analysis of WIOA and resistivity methods.

The field data acquisition covering large area for groundwater-resource mapping is difficult and tedious in developing countries like India. In such cases, integrated RS and GIS techniques have proved to be efficient tools to tackle the difficult issues associated with groundwater management in terms of time and labor.

In this study, groundwater potential zones have been extracted in parts of the hard rock regions of East Godavari district using Weighted Index Overlay Analysis (WIOA) and Analytical Hierarchical Process (AHP). In this process, detailed information of ten thematic parameters (Geology, Geomorphology, Lineament density, Land use/Land cover, slope, soil, Drainage density, Rainfall, Groundwater level and Coefficient of anisotropy) have been combinedly studied and validated with the more authentic geoelectrical resistivity data together with lithology of the drilled wells.

Though the study area is receiving abundant rainfall, most of water is drained as surface runoff as three-fourths is occupied by hilly terrain (Eastern Ghats mobile belt). The sources of groundwater recharge in hard rocks are joints and fractures. The remaining area is occupied by sedimentary formations including flood plains along with Rajahmundry and Tirupathi sandstones. Among these formations, flood plains and Tirupathi sandstone formations are characterized by good thickness of clay. The presence of impervious hard rocks and thick clay layers in the subsurface are acting as barriers for groundwater accumulation and movement. The source of groundwater is fracturing and faulting of these hard rocks.

It is observed from the Figures 5a and 5b, the aquifer thickness in good potential zones (GWPI value: 6–7) is varying from 41 to 140 m and the aquifer extends 28% of total area. In the regions of moderate potential (GWPI value: 5), it is ranging from 20 to 40 m whereas the aquifers in the poor potential zones are having thickness less than 20 meters. The zones marked with blue colour in Figure 5a and zones of aquifer thickness greater than 40 m in Figure 5b indicating good aquifer may be used for drilling new wells. Groundwater potential map (Figure 5a) provides an insight about the hidden groundwater resource in complex aquifer systems here. Groundwater in moderate and low potential zones of hard rock terrains may also be explored where aquifer thickness (Figure 5b) is more than 20 m.

The study proves that WIO analysis is very useful in identifying groundwater potential zones. This analysis when supported by geoelectrical resistivity survey, would more effectively and authentically explore groundwater potential zones even in complex rock formations. Similar studies for exploring groundwater in hard rock terrains/complex rock formations in India or abroad using WIOA and AHP [15,16,56,57] proved successful rather than depending on the data of single method. Harini et al. [15] carried out integrated analysis of different thematic layers (parameters) such as geology, geomorphology, soil, slope, land use/land cover, drainage density, lineament density and annual rainfall over Krishna river basin and successfully discovered groundwater pockets. We also have used remote sensing images to investigate lineaments and gathered information on geology, geomorphology, slope, soils, land use/land cover, rainfall, depth to water table, drainage density, anisotropy and integrated all the information using AHP and computed Groundwater Potential Index (GWPI) values using WIO analysis. We have also validated these GWPI values with resistivity data.

Shailaja et al. [16] have done similar analysis to explore groundwater in hard rock and semi hard rock areas of Maharashtra, India. They used the parameters like aquifer resistivity, aquifer thickness, transverse resistance, electrical anisotropy, drainage density, lineament density, rainfall, slope, geology, land use/land cover and integrated them using Analytical Hierarchy Process (AHP) of Saaty [22]. They also identified groundwater potential zones in that area. These results were validated by operating characteristic techniques. Here, aquifer thickness and aquifer resistivity must have been got from the geoelectrical resistivity surveys. But in our study, we have used the interpreted results of geoelectrical surveys to validate the results of the GWPI values obtained from WIO analysis (Figure 5a and 5b). Further geoelectrical resistivity results obtained in our study were validated with the lithology of 67 wells. Thus the groundwater potential zones discovered in our study have more validation. Murthy and Mamo [56] have done similar analysis to identify the groundwater potential zones in Moyale-Teltele sub-basin, South Ethiopia. They considered six thematic layers (Parameters) only of lithology, structural features, geomorphology, slope, land cover and drainage in the integrated analysis to determine the groundwater potential zones whereas we used ten thematic layers in our study to delineate the groundwater zones. Demirkesen et al. [57] investigated the groundwater potential zones and risk areas using multi-criteria method with ten parameters such as normalized difference vegetation index, modified normalized difference water index, land use/land cover, lineaments, topography, slope, drainage, lithology, hydraulic conductivity and soil types in semi arid regions of Alasehir sub-basin, Western Turkey. Though they have used ten parameters, there is no validation of this analysis by any other independent method.

In this study, we have used lithology data of 67 wells, data of ten thematic layers (parameters) and more importantly geoelectrical resistivity sounding data from 270 locations. The groundwater potential zones determined from the WIOA and AHP using ten parameters were validated with aquifer thickness map prepared using resistivity results. There is good agreement between the two (Figure 5a and 5b). Further, the good aquifer thickness zones identified (Figure 5b) are correlating well with the high lineament density zones (Figure 2b). These high lineament density zones in hard rock areas could be the sources for recharge.

4. **Conclusions**

Three-fourth of the study area is occupied by hilly terrains (Eastern Ghats mobile belt). In these agency areas, the tribal people are facing acute water shortage and random drilling of wells proved futile. It is very difficult to have current penetration into the ground in resistivity surveys except along the structural features of lineaments/fractures/fissures. These tectonic features may be sources for groundwater storage. In this study, these tectonic features were identified using remote sensing images. Besides the knowledge of tectonic features, information of geology, geomorphology, and hydrogeological studies would be very much useful in reducing the ambiguity of groundwater location.

From the analysis, it can be inferred that the northern part of the study area where hard rocks are present have good groundwater zones with aquifer thickness in the range 20–40 m. Sedimentary formations in the southern region are also good sources for groundwater. A few pockets, though small in areal extent with aquifer thickness in the range 40–140 m (Figure 5b) and GWPI values 6–7 (Figure 5a) indicative of very good sources for groundwater exploration. This map (Figure 5) is more useful to the farmers as it is marked with resistivity sounding (VES) locations. The geographic locations of these VES sounding data can be had from the authors for the needy.

Overall, it is estimated that an area of 750.9 sqkm (28.4%) with aquifer thickness of 40–140 m comes under good groundwater potential zone and moderate groundwater potential zone with aquifer thickness varying 20–40 m occupies an area of 1220 sqkm (46.1%). The remaining part is very poor aquifer.

After carrying out all these analyses, the first author has under taken field study and encouraged the people to go for drilling wells in selected areas. It is brought to our notice that the wells drilled in the recommended zones have yielded copious amount of water to their satisfaction.

Acknowledgement

We are grateful to the Editor for waiving the publication and processing charges. We express our sincere thanks to Andhra Pradesh Groundwater and Water Audit Department for providing a few Vertical Electrical Soundings resistivity data of the study area. The first author acknowledges the financial support from UGC through Rajiv Gandhi National Fellowship, New Delhi. The authors express their sincere thanks to the anonymous reviewers for critically going through the manuscript and for making very useful suggestions.

Conflict of interest

The authors declare no conflict of interest.

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