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## Groundwater potential index in a crystalline terrain using remote sensing data

Received: 18 October 2005  
Accepted: 20 March 2006  
Published online: 20 April 2006  
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**Abstract** Demand for groundwater for drinking, agricultural and industrial purposes has increased due to uncertainty in the surface water supply. Agriculture is the main occupation of the rural people in Guntur district, Andhra Pradesh, India. Development of groundwater in the district is very less, indicating a lot of scope for further development of groundwater resources. However, assessment of groundwater conditions, particularly in a crystalline terrain, is a complex task because of variations in weathering and fracturing zones from place to place. Systematic studies for evaluation of groundwater potential zones have been carried out in a crystalline terrain of the district. Information on soils, geological formations and groundwater conditions is collected during the hydro-geological survey. Topographical and drainage conditions are derived from the Survey of India topographical maps. Geomorphological units and associated landform features inferred and delineated from the Indian remote sensing satellite imagery (IRS ID LISS III FCC) are moderately buried pediplain (BPM), shallow buried pediplain (BPS), valley fills (VF), structural hill (SH), residual hills (RH), lineaments and

land use/land cover. A groundwater potential index (GPI) is computed for relative evaluation of groundwater potential zones in the study area by integrating all the related factors of occurrence and movement of groundwater resources. Accordingly, the landforms, BPM, BPS, VF, SH and RH, of the area are categorized as very good groundwater potential zone, good to moderate groundwater potential zone, moderate to poor groundwater potential zone, poor to very poor groundwater potential zone and very poor groundwater potential zone, respectively, for development and utilization of both groundwater and surface water resources for eliminating water scarcity. This study could help to improve the agrarian economy for better living conditions of the rural people. Taking the total weight-score of the GPI into account, a generalized classification of groundwater potential zones is evaluated for a quick assessment of the occurrence of groundwater resources on regional scale.

**Keywords** Groundwater potential index · Geomorphological units · Crystalline terrain · Guntur district · Andhra Pradesh · India

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## Introduction

Groundwater plays an important role in drinking, agricultural and industrial needs as a timely assured source due to non-availability of surface water in time. Agriculture is the main occupation of the rural inhabitants (2.92 million) of 729 villages (3,442 km<sup>2</sup>) in Guntur district (11,391 km<sup>2</sup>), Andhra Pradesh, India (Fig. 1). Irrigated land covers about 29% of the total area of the district. Though 88% of the total irrigated land is under canal irrigation, the farmers prefer groundwater for irrigation and drinking water because of uncertainty in the surface water supply (CGWB 1994). Development of groundwater resources in the district is less than 7%, with a net draft of 158 million cubic meters (MCM) out of the utilizable resource of 2,408 MCM/year. There is a lot of scope for further development of groundwater resources. Identification of potential groundwater zones could aid in proper development and utilization of both groundwater and surface water resources for eliminating water scarcity and thereby improving the irrigation practice and agricultural income for standard living conditions of the local people.

However, the occurrence and movement of groundwater, especially in a crystalline terrain, depends on the degree of weathering and extent of fracturing of the rocks. Remote sensing techniques provide a synoptic view of large areas, facilitating better and quicker assessment, development and management of water resources with collateral information. This technique has been employed in the present study to locate groundwater potential zones.

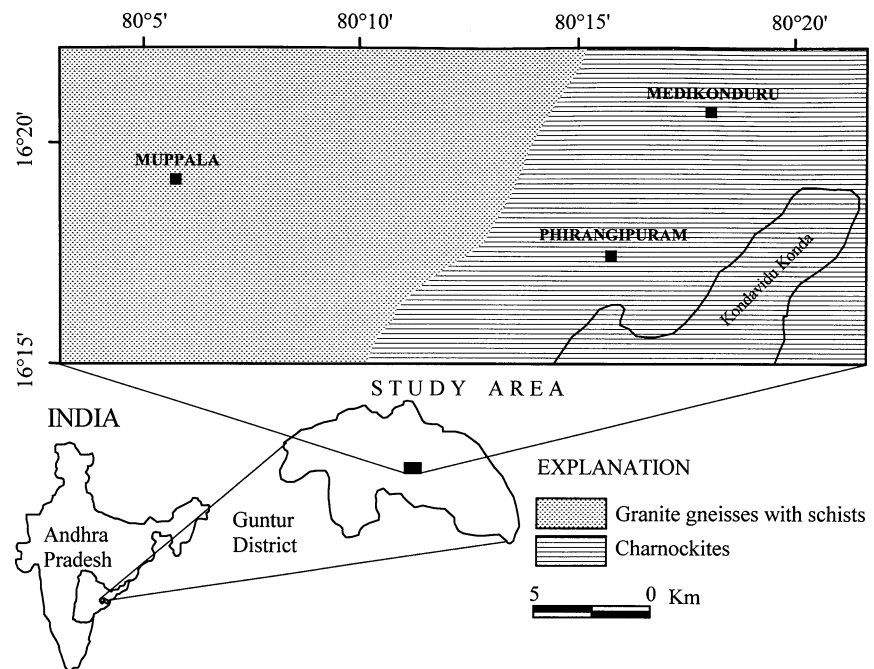
## Methodology

During the hydrogeological survey in the study area, data on soils, geological formations and structural features and weathering and fracturing conditions of the rocks were collected. Groundwater levels were measured from 40 open dugwells in pre-monsoon and post-monsoon periods of 1999–2001.

The Indian remote sensing satellite (IRS) ID, linear image self-scanning (LISS) III of geocoded false color composites (FCC), generated from the bands 2, 3 and 4 on 1:50,000 scale on September 16, 1999, was used in the study area. The Survey of India topographical maps 65 D/3 and 65 D/7 on a scale of 1:50,000 equal to the corresponding imagery were used for the preparation of base maps on topographical and drainage conditions and geomorphological units and associated landform features. The imagery was visually interpreted to delineate geomorphologic units and land use/land cover with the help of the standard characteristic image interpretation elements like tone, texture, shape, size, pattern and association (Table 1). The lineaments were identified from the imagery based on the tonal contrast. The prepared maps were verified from ground truths through field checks and necessary modifications were made before finalizing. As the study area was mostly covered by black cotton soils (98%) and irrigated land (91%), the areal distribution of soil and land use/land cover maps were not shown in the present study.

A groundwater potential index (GPI) was computed for the relative assessment of groundwater potential zones, considering factors such as rainfall, slope, run-off,

**Fig. 1** Location of the study area, Guntur district, Andhra Pradesh, India



**Table 1** Image characteristics of geomorphological units and land use/land cover

Particulars	Image characteristics (photo-elements)					
	Tone	Texture	Size	Shape	Pattern	Association
<b>Geomorphological units</b>						
BPM	Light to dark red	Fine to coarse	Widespread	Irregular	Contiguous	Agricultural land
BPS	Light to dark green	Medium	Small	Irregular	Scattered	Hill and stream course
VF	Light green	Fine to coarse	Small	Regular	Contiguous	Stream course
SH	Brown to dark red	Coarse	Large	Regular	Isolated	Plain land
RH	Brown to dark red	Coarse	Small	Regular	Isolated	Plain land
<b>Land use/land cover</b>						
Built-up land	Light to darkish gray	Coarse	Varying	Varying	Irregular	Agricultural land
Agricultural land						
Crop land	Light to medium red	Fine to medium	Varying	Irregular	Scattered to contiguous	Non-irrigated land
Fallow land	Light yellow	Fine	Varying	Irregular	Contiguous	Non-irrigated land
Plantation	Pinkish	Fine to medium	Varying	Irregular	Contiguous	Uplands
<b>Forest plantation</b>						
Deciduous forest	Light to red with white patches	Fine to medium	Varying	Irregular	Contiguous	Forest plantation
Degraded forest	Light gray to greenish white	Fine to medium	Varying	Irregular	Contiguous	Scattered trees
<b>Wasteland</b>						
Land with scrub	Light to medium pinks gray	Smooth	Varying	Irregular	Scattered	Hill
Land without scrub	Medium to dark green	Smooth	Varying	Irregular	Scattered	Hill
Barren rocky land	Greenish red	Smooth	Varying	Irregular	Scattered	Hill
<b>Water bodies</b>						
Stream	Light to dark blue	Fine	Varying	Definite	Linear	Irrigated land
Tank	Light to dark blue	Smooth	Varying	Varying	Scattered	Irrigated land

infiltration, soil cover, moisture content, lineaments, weathered and fractured rocks, drainage, groundwater levels and vegetation with relation to geomorphological units. In this index, each of the factors was assigned weightages, depending on their influence on the occurrence and movement of groundwater resources. A generalized classification of groundwater potential zones was evaluated on the basis of total weight-score of GPI for a quick assessment of groundwater occurrence on regional scale.

The processing flow chart of the methodology adopted in the present study is shown in Fig. 2.

### Study area

The study area, lying between latitudes 16°15'–16°22'30"N and longitudes 80°3'20"–80°22'13"E, is located in Guntur district, Andhra Pradesh, India (Fig. 1). The area is underlain by crystalline terrain and covers 510 km<sup>2</sup> with a population of 0.16 million. The climate is semi-arid. The average monthly temperature varies from 17°C in winter to 41°C in summer. The average annual rainfall is about 800 mm.

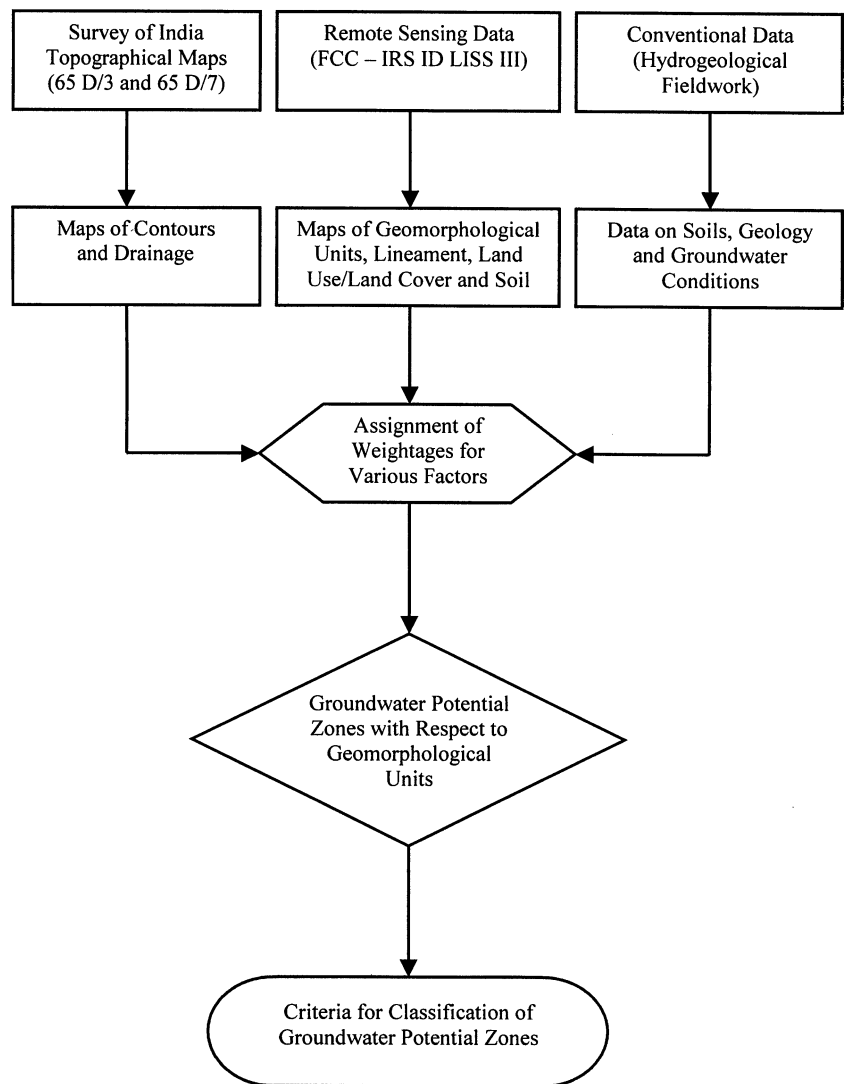
Physiographically, the area is a plain land, sloping gently towards south (Fig. 3). The slope increases towards a hill called Kondavidu Konda to the southeast.

The drainage pattern is sub-dendritic (Fig. 4) and ephemeral in nature. The streams flow towards south, following the topography.

The area rocks, charnockites and granite gneisses with schists, belong to the Precambrian Eastern Ghats (Fig. 1). The charnockites cover almost half of the area towards southeast. The granite gneisses associated with the schists occupy the rest. Basic dykes and pegmatite and quartz veins traverse the rocks. Basement rocks show NE–SW strike with a dip of 70° SE. Black cotton soil is the dominant type. The topsoil layer consists of various proportions of silt, clay, sand, gravel and pebbles with intercalation of kankar and extends its depth from less than 1 to 12 m, with increasing depth towards the hill. The soil zone is underlain by weathered zone and/or fractured zone. The weathered zone extends to a depth of 15 m and the fractured zone 41 m (Subba Rao 2006).

Rainfall is the direct recharge source and irrigation-return-flow is the indirect recharge source of groundwater in the study area. Development of groundwater is through open dugwells and borewells. Groundwater occurs in the weathered zone under unconfined conditions as well as in the fractured zone under semi-confined conditions. The occurrence of intrusive bodies in the area serves as sub-surface barriers to store groundwater. The level of groundwater table ranged from 6–16

**Fig. 2** Flow chart of methodology adopted in the study area



**Fig. 3** Physiographical features. Contour lines are expressed in m a.m.s.l

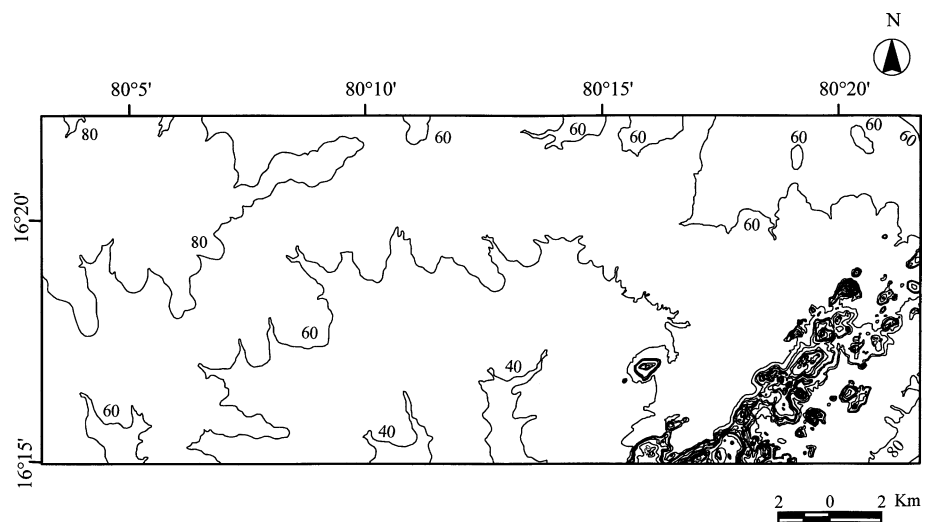
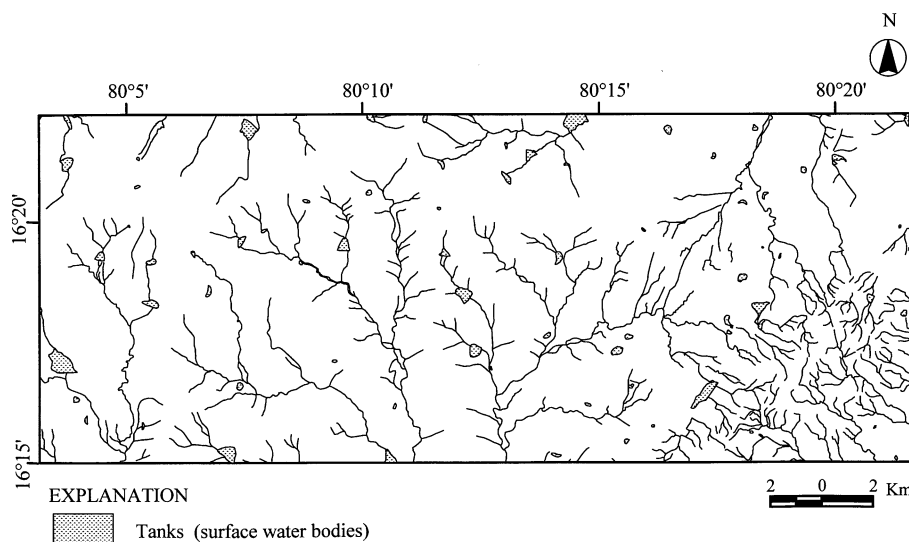


Fig. 4 Drainage pattern



to 2–9 m below ground level (bgl) in pre-monsoon and post-monsoon periods of 1999–2001, respectively (Figs. 5, 6), indicating an annual water-level fluctuation of 4–7 m. The water-level fluctuation is more towards northwest, northeast and west.

### Geomorphological units and associated landform features

#### Geomorphological units

Water is one of the important geological agents in the forming and shaping of landforms. Geomorphology is a study of landforms. Thus, geomorphology can be considered as hydrogeomorphology for planning and execution of groundwater exploration. Geomorphological units identified and delineated from the IRS imagery of the study area are pediplain (PP), valley fills (VF), structural hill (SH) and residual hills (RH). The PP is further divided into buried pediplain (BPM) and shallow buried pediplain (BPS).

#### *Moderately buried pediplain*

The BPM has a gentle slope and occupies most of the area (73.20%; Fig. 7, Table 2). The depth of the BPM varies from 10 to 20 m, but extends to more than 40 m along the fracture zones with a thinner soil cover. The BPM supports a better opportunity for water to infiltrate. A good amount of water circulates within this zone. The greater the thickness of the aquifer material, the higher the scope of potentiality of groundwater. The BPM has dense vegetative cover, suggesting higher moisture retention. Because of the gentle slope of PBM, run-off is generally low.

#### *Shallow buried pediplain*

The BPS, which has a flat surface, covers 14.75% of the total area (Fig. 7, Table 2). The depth of the BPS is from 5 to 10 m; sometimes it goes beyond a depth of 10 m along the fracture zones. The materials of the BPS generally provide a low to moderate rate of infiltration compared to the materials of the BPM. The BPS has sparse vegetative cover, indicating low to moderate moisture content. Run-off is very low in the BPS because of the flat surface.

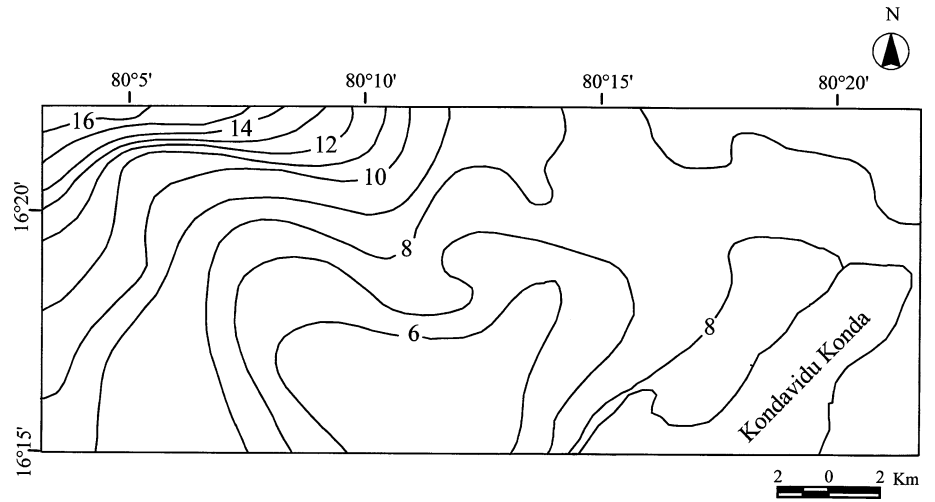
#### *Valley fills*

The VF, linear depressions with very gentle slope, trends mostly north to south and covers 6.91% of the total area (Fig. 7, Table 2). The valley fills are comprised of unconsolidated sediments such as sand, silt and clay with gravel. The depth of VF is less than 3 m. The valley fills are covered by sparse to medium vegetation. They are developed along the lineaments (Fig. 8) and coincidence with stream flow directions (Fig. 4). Valley fills act as recharge and discharge zones for groundwater. Because of the occurrence of sand and gravel, the VF supports rapid infiltration of water. But the occurrence of fine-grained materials like silt and clay in the VF may hinder the infiltration capacity. Run-off is low due to flatter topography in the gentle slopes.

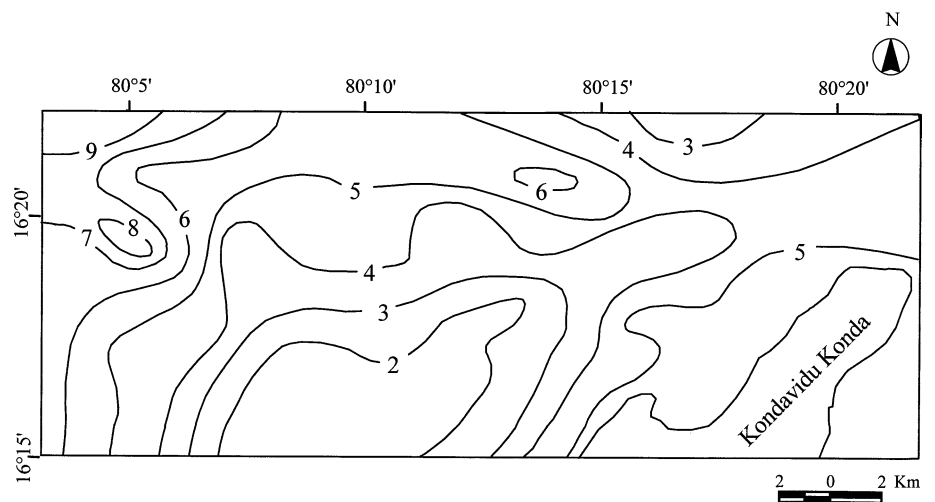
#### *Structural hill*

The SH is the linear hill region, which exhibits definite trend lines and has a height of 510 m a.m.s.l. The SH is observed in the southeastern side of the area (Fig. 7), occupying a relatively small part of the total area (4.62%; Table 2). The structural trend of the hill is NE–

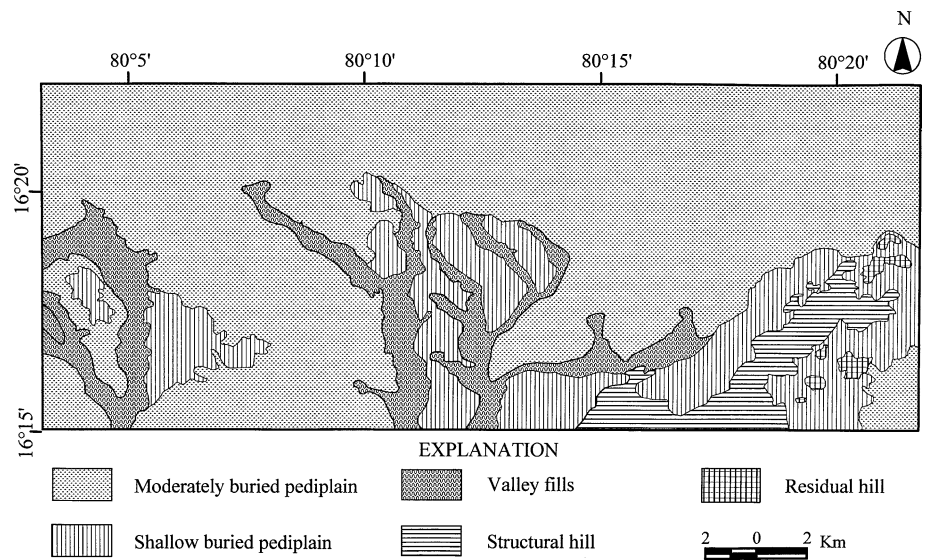
**Fig. 5** Average groundwater levels (m bgl) of pre-monsoon period of 1999–2001



**Fig. 6** Average groundwater levels (m bgl) of post-monsoon period of 1999–2001



**Fig. 7** Geomorphological units



**Table 2** Areal extent of geomorphological units

Geomorphological units	Area	
	km <sup>2</sup>	Percentage
BPM	373.32	73.20
BPS	75.23	14.75
VF	35.24	6.91
SH	23.56	4.62
RH	2.65	0.52

SW. The SH has a radial pattern with flat top, indicating a mature topography, and is covered by green foliage. There are numerous fractures, which facilitate some infiltration. The slope of the SH is more than 15°, supporting rapid run-off.

#### *Residual hills*

The residual hills are a group of hills with a height of 196–228 m a.m.s.l. and occupy 0.52% of the total area (Fig. 7, Table 2). These hills are the more resistant rock formations with radial drainage patterns. The RH stands out prominently due to differential erosion and weathering. The RH acts as run-off zones because of its steep slope (> 15°).

#### Associated landform features

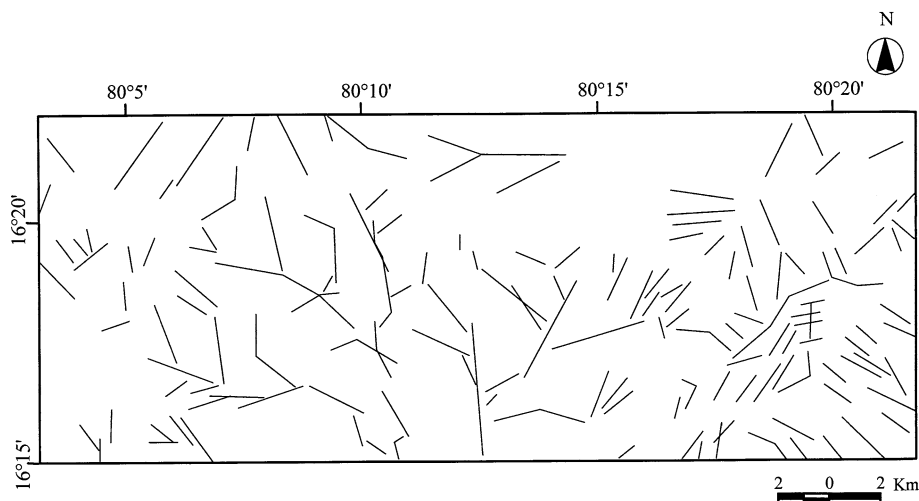
Associated landform features identified from the IRS imagery are lineaments and land use/land cover. These landforms can be considered as surface indicators for identification of water conditions in the sub-surface. This information provides a reliable base for effective planning, development and management of groundwater resources of an area.

#### *Lineaments*

The lineaments, which are the linear features, developed by the tectonic activity, reflect a general surface manifestation of underground fractures, with inherent characteristics of porosity and permeability of the underlying materials. Numerous lineaments identified from the IRS imagery of the study area are illustrated in Fig. 8. These extend over a length of less than 1 km to more than 5 km and orient in the direction of NE–SW and NW–SE, the latter trend being dominant (Fig. 9). Some lineaments, which are fairly straight and do not change with stream courses (Fig. 4), are considered as faults. Other lineaments, which are concentrated mainly in southwest, southeast and south of the study area, follow the topographic depressions of the drainage network (Figs. 3, 4). These lineaments are mostly associated with the BPM, followed by the BPS, VF, SH and RH in decreasing order.

#### *Land use/land cover*

The identified land use/land cover features from the IRS imagery of the study area (Table 1) are agricultural land (cropland, fallow land and plantation), water bodies (stream and tank), forest plantation (deciduous forest and degraded forest), wasteland (land with or without scrub and barren rocky area) and built-up land. They cover about 91, 4, 3, 1 and 1% of the total area, respectively (Fig. 10). The principal crops grown in the area are rice (grains of this plant used as food), chili (capsicum species used as food), tobacco (leaves of this plant used for smoking, chewing or snuff), cotton (soft white fibrous substance covering the seeds of the plants used for preparation of cloths), tomato (glossy red or yellow pulpy edible fruit used as food) and black gram (Indian pulse variety used as food).

**Fig. 8** Distribution of lineaments

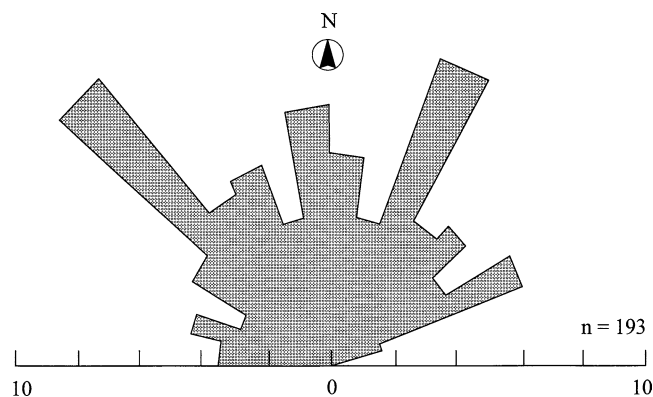


Fig. 9 Orientation of lineaments

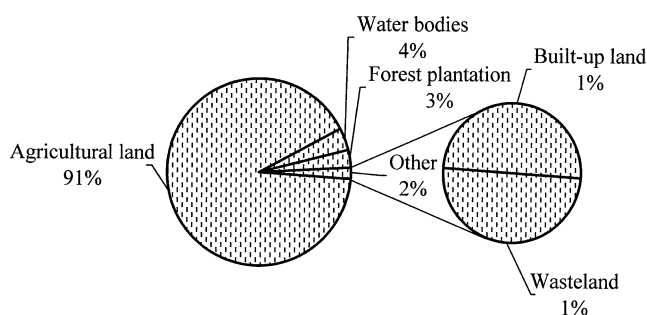


Fig. 10 Percentage of land use/land cover

### Factors controlling groundwater potential zones

For relative evaluation of groundwater potential zones, GPI is proposed and computed by integrating all factors such as rainfall, slope, run-off, infiltration, soil cover, moisture content, lineaments, weathered and fractured rocks, drainage, groundwater levels and vegetation related to occurrence and movement of groundwater resources. In this index, each of the factors is assigned three weightages, 1–3, depending on its influence on the occurrence and movement of groundwater. The weightage factor 1 denotes low groundwater potentiality, 2 moderate groundwater potentiality and 3 high groundwater potentiality (Table 3).

Table 3 Weightage factors for relative groundwater potentiality

Weightage factors	Relative groundwater potentiality
1	Low groundwater potentiality
2	Moderate groundwater potentiality
3	High groundwater potentiality

Rainfall is the main recharge source of groundwater. The entire study area received the same amount of rainfall. So, the weightage factor for rainfall is considered uniform throughout the area.

Soil zone has a significant role on the amount of infiltrating water. Where the soil zone is thin or absent, the rate of infiltration could be more. And also, the rate of infiltration largely depends on the grain size of soils. Fine-grained soils cannot infiltrate water easily into the ground due to their low permeability. If soils contain coarse-grained material, water can infiltrate easily into the ground because of their high permeability. Higher weightage is given to soils, which have more thickness associated with higher permeability.

Generally, flat and gently sloping areas promote infiltration and groundwater recharge, and steeply sloping grounds encourage run-off and little or no infiltration. The area has a gentle slope; it supports low discharge of overland flow and high rate of infiltration. Groundwater potentiality is expected to be greater in the study area.

Lithology characterized by massive rock has little influence compared with topography in the control of availability of groundwater. Though lithology is not an important factor in this particular case, the rocks become aquifers through development of weathering and fracturing by secondary porosity. Therefore, suitable weightages are given to the rocks, which are associated with the weathering and fracturing portions.

Lineaments and their intersections play a significant role in the occurrence and movement of groundwater resources in crystalline rocks. As mentioned earlier, fluctuations of groundwater levels are more towards northwest, northeast and west (Figs. 5, 6); and the lineaments are mostly concentrated towards southwest, southeast and south (Fig. 8). A comparison of the distribution of water-level fluctuations with the lineaments suggests low water-level fluctuations where lineaments are greater and higher water-level fluctuations where lineaments are fewer. Thus, lineaments are the potential aquifer zones. Higher yields occur wherever the lineaments are parallel to the stream courses and/or tanks (surface water bodies) or the lineaments are intersected (Subba Rao and Prathap Reddy 1999; Subba Rao et al. 2001; Sankar 2002; Nag and Surajit 2003; Chakraborty and Paul 2004; Sener et al. 2005; Sreedevi et al. 2005). The combination of fractures (lineaments) with topographically low ground can also serve as the best aquifer horizons (Subba Rao 1992). Higher weightage is assigned to the high density of lineaments, which are closely associated with the shallow groundwater levels, stream courses and tanks.

Vegetative growth depends on the availability of water. If adequate water is available for plants, a thick vegetative cover is expected. This suggests high moisture retention and shallow water-level condition. Accordingly, weightages are given to the vegetative cover.



**Table 4** Groundwater potential index (GPI) of various geomorphological units, following the characteristics of the study area

Geomorphological unit	Weightages of individual factors and their influence on occurrence and movement of groundwater resources										Total weight-score of GPI	Classification of groundwater potential zones
	a	b	c	d	e	f	g	h	i	j		
BPM	3	2	2	2	2	3	3	2	3	3	25	Very good groundwater potential zone
BPS	3	2	2	1	1	2	2	2	2	2	19	Good to moderate groundwater potential zone
VF	2	1	1	2	1	1	2	1	1	1	13	Moderate to poor groundwater potential zone
SH	–	1	1	–	–	–	2	1	1	1	7	Poor to very poor groundwater potential zone
RH	–	1	1	–	–	–	–	–	–	1	3	Very poor groundwater potential zone

*1* Low groundwater potentiality, *2* moderate groundwater potentiality, *3* high groundwater potentiality, *a* slope, *b* run-off, *c* vegetation, *d* thickness of soil, *e* moisture content, *f* infiltration capacity, *g* density of lineaments, *h* thickness of weathering, *i* thickness of fracturing, *j* density of stream courses/groundwater levels

### Groundwater potential zones with relation to geomorphological units

Considering the groundwater potentialities of various factors controlling the groundwater potential zones (Table 3), the landforms, BPM, BPS and VF, of the study area (Fig. 7) can be categorized as very good groundwater potential zone, good to moderate groundwater potential zone and moderate to poor groundwater potential zone, respectively (Table 4). The SH and RH are considered as poor to very poor groundwater potential zone and very poor groundwater potential zone, respectively. However, these landforms act as run-off zones because of their steep slope. They may support recharge source of groundwater in the adjacent areas. They also show fractures, which facilitate some infiltration characteristics.

As all important factors responsible for groundwater prospecting are included in the GPI, the index may be applicable to other similar terrains, provided the index is computed dependant upon local variations of the individual factors.

### Criteria for classification of groundwater potential zones

Based on the total weight-score of GPI (Table 4), a generalized classification of groundwater potential zones can be evaluated for a quick assessment of the occurrence of groundwater resources. The zones are classified as very poor groundwater potential zone when the GPI is less than 6; poor to very poor groundwater potential zone when it ranges from 7 to 12; moderate to poor groundwater potential zone when it is between 13 and 18; good to moderate groundwater potential zone when it varies from 19 to 24; and very good groundwater potential zone when it is more than 25 (Table 5).

**Table 5** Classification of groundwater potential zones with respect to total weight-score of GPI

Range of total weight-score of GPI	Classification of groundwater potential zones
> 25	Very good groundwater potential zone
19–24	Good to moderate groundwater potential zone
13–18	Moderate to poor groundwater potential zone
7–12	Poor to very poor groundwater potential zone
< 6	Very poor groundwater potential zone

As the GPI is the total weightage of all the factors in an area and the classification of groundwater potential zones represents the relative availability of groundwater potential conditions, the greater the weight-score, the higher the groundwater potential. The current classification can be applied only for regional studies for an overall scenario of groundwater occurrence. Individual site selections should be based upon conventional methods.

### Conclusions

The following conclusions are drawn:

- Information on soil, geological and groundwater conditions are collected during the hydrogeological fieldwork. Topographical and drainage conditions are derived from the Survey of India topographical maps. Geomorphological units inferred and delineated from the IRS imagery are BPM, BPS, VF, SH and RH. The other associated landform features observed from the imagery are lineaments and land use/land cover.
- A GPI is computed for relative assessment of groundwater potential zones by integrating all the related factors of occurrence and movement of groundwater resources.
- The GPI classifies the BPM as a very good groundwater potential zone, the BPS as good to moderate

groundwater potential zone, the VF as moderate to poor groundwater potential zone, the SH as poor to very poor groundwater potential zone and the RH as very poor groundwater potential zone for development and utilization of both groundwater and surface water resources for eliminating water scarcity, and thereby improving the agrarian economy.

- A GPI can be applied to other similar terrains elsewhere for groundwater prospecting.
- Considering the total weight-score of GPI, a generalized classification of groundwater potential zones is evaluated for a quick assessment of an overall scenario of occurrence of groundwater resources on regional scale.

**Acknowledgements** The author is grateful to the Department of Science and Technology, Government of India, New Delhi 110 016, India, for providing financial assistance under Major Research Project (ESS/72/023/98) entitled "Assessment and Management of Groundwater Resources in a Part of Crystalline Terrain of Guntur District, Andhra Pradesh, India" during 1999–2002. The author is also thankful to Mr. D. John Devadas, DST-Research Scholar (1999–2002), Department of Geology, Andhra University, Visakhapatnam 530 003, India, for his assistance in the field as well as in the laboratory work. The author is also thankful to Mr. I. Bangaru Raju, Research Scholar, Department of Geology, Andhra University, Visakhapatnam 530 003, India, for his help during the preparation of high-quality computer graphics. The valuable comments made by the anonymous referees were useful for improving this manuscript.

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