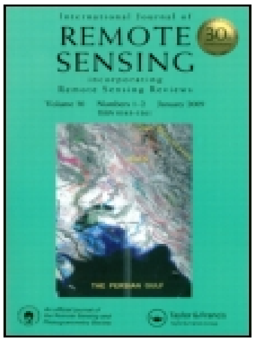

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# Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites

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**Abstract.** IRS-LISS-II data along with other data sets have been utilized to extract information on the hydrogeomorphic features of a hard rock terrain in the Sironj area of Vidisha district of Madhya Pradesh, India. The study exhibits reservoir induced artificial groundwater recharge downstream of surface water reservoirs. IRS-LISS-II data have been supported by information derived from DEM, drainage and groundwater data analysed in a GIS framework. The present study attempts to select suitable sites for groundwater recharge in a hard rock area through recharge basins or reservoirs, using an integrated approach of remote sensing and GIS. Criteria for GIS analysis have been defined on the basis of groundwater conditions in the area and appropriate weightage has been assigned to each information layer according to its relative contribution towards the desired output. The integrated study helps in designing a suitable groundwater management plan for a hard rock terrain.

## 1. Introduction

Application of remote sensing technology in groundwater resources evaluation has been practised for about three decades. In groundwater studies much use has been made of aerospace imagery, chiefly through visual interpretations requiring photogeological experience. It is the general experience that satellite data must be used in conjunction with available ancillary information in application of remote sensing to groundwater hydrology. Apart from updating or refining geological maps, vegetation cover can be mapped and such information can be utilized to estimate water budgets. In particular, the clear response of crops to irrigation from groundwater forms a valuable means of rapidly assessing the location and extent of areas with groundwater usage (Meijerink *et al.* 1994).

The concept of integrating remote sensing and GIS is comparatively new. Probably, the fullest utilization of the potential of the two technologies can be realized only when an integrated approach is adopted. Blending of the two technologies has proved to be an efficient tool in groundwater studies (Gustafsson 1993, Saraf and Jain 1994, Saraf *et al.* 1994, Krishnamurthy and Srinivas 1995, Krishnamurthy *et al.* 1996). Groundwater is a dynamic and replenishable natural resource but in hard rock terrains availability of groundwater is of limited extent. Occurrence of groundwater in such rocks is essentially confined to fractured and weathered horizons. In India, 65 per cent of the total geographical area is covered by hard rock formations. Therefore, efficient management planning of groundwater in these areas is of the utmost importance. An extensive hydrogeological investigation is required for thorough understanding of the groundwater conditions. Remote sensing data provide most accurate spatial information and it can be economically

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utilized over conventional methods of hydrogeological surveys. Digital enhancement of satellite data results in extraction of maximum information and an increased interpretability. GIS techniques facilitate integrated and conjunctive analysis of large volumes of multi-disciplinary data, both spatial and non-spatial, within the same georeferencing scheme. Thus, by integrating these two spatial data management technologies, groundwater development strategies for a hard rock area can be designed.

The present study demonstrates the capabilities of IRS-LISS-II (Linear Imaging Self-scanning Sensor) in groundwater exploration and for preparing hydrogeomorphological maps (Sahai *et al.* 1991, Krishnamurthy and Srinivas 1995). IRS-LISS-II operates in the visible-NIR spectral range of the electromagnetic spectrum and has a spatial resolution of 36·25 m (table 1). It gives repetitive coverage on a cycle of 22 days (IRS-Data Users Handbook 1989).

The objective of the present study has two main components. The first is the identification of reservoir induced groundwater recharge in hard rock areas using IRS-LISS-II data. The second aspect is to suggest suitable locations for surface water reservoirs/basins to augment groundwater recharge where the groundwater conditions are poor.

## 2. The study area

The study area has been chosen as it represents a typical hard rock area, comprising mostly Deccan Trap basic volcanic rocks. It is situated in a part of Vidisha district of Madhya Pradesh state, India, bounded by longitudes 77° 38′ E and 77° 55′ E and latitudes 24° 00′ N and 24° 15′ N (figure 1). The major rivers draining the 740 km$^2$ area are the Kethan and the Naren, which are tributaries of the Betwa river.

The surficial geology of the area consists of Deccan basalt which is weathered over all but a narrow N–S strip in the western margin of the area (figure 2). Bundelkhand Granite which forms the basement of the area (CGWB, 1984) was overlain by Vindhyan sediments during Cambrian time. Neither granite nor Vindhyans are exposed in the area today. After the end of Vindhyan sedimentation, a thick series of successive lava flows were erupted covering the whole area. The

Table 1. Spectral range and application of IRS-LISS-II.

| Band | Spectral range ($\mu$m) | Applications |
|---|---|---|
| 1 | 0·45–0·52 | (a) Coastal environmental studies<br>(b) Soil/vegetation differentiation<br>(c) Coniferous/deciduous vegetation differentiation |
| 2 | 0·52–0·59 | (a) Vegetation vigour<br>(b) Rock/soil discrimination<br>(c) Turbidity and bathymetry in shallow waters |
| 3 | 0·62–0·68 | (a) Strong chlorophyll absorption leading to discrimination of plant species |
| 4 | 0·77–0·86 | (a) Delineation of water features<br>(b) Landform/geomorphic studies |

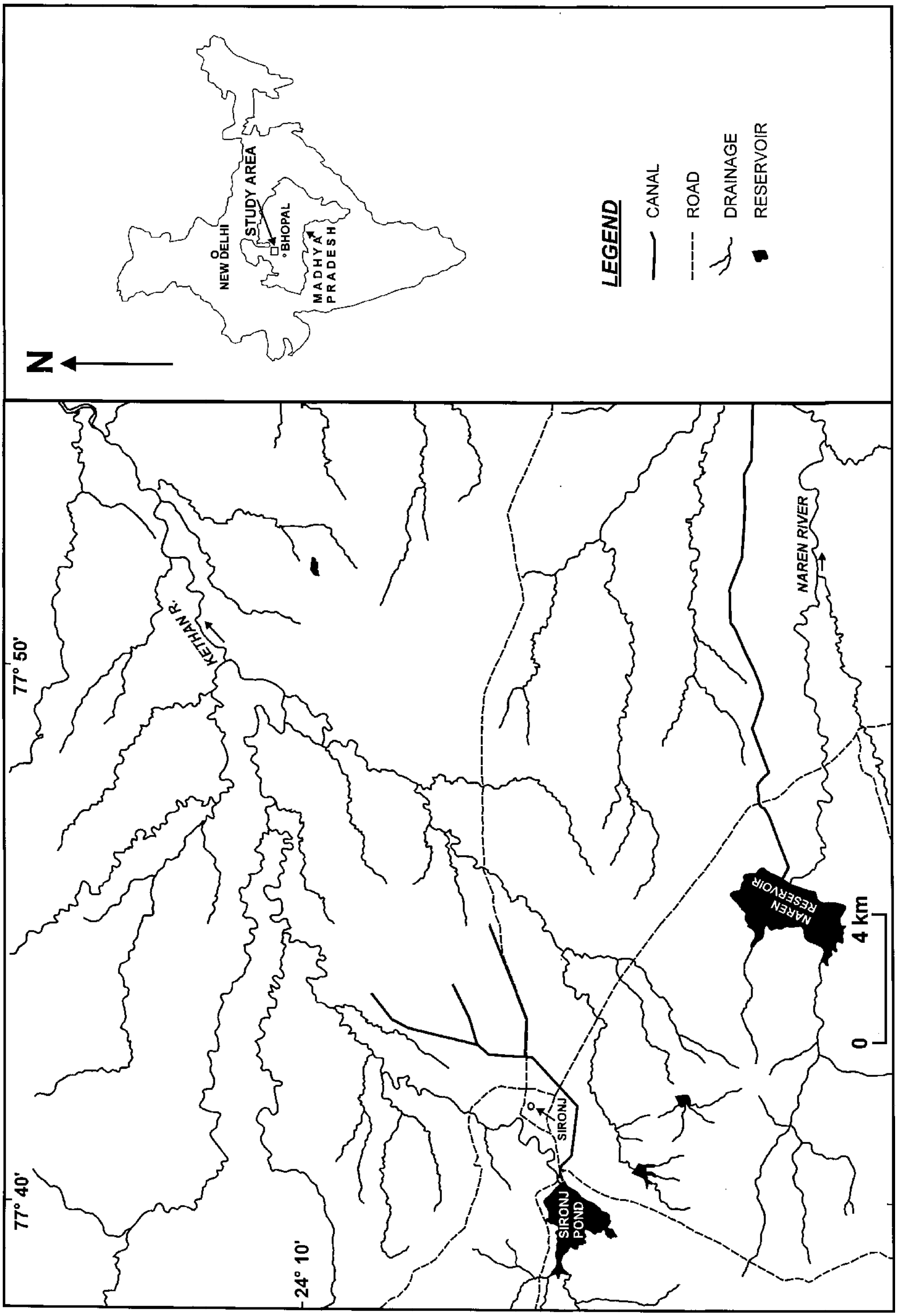



Figure 1. Location map of the study area showing part of the Kethan and the Naren river basins, drainage network and locations of various reservoirs.

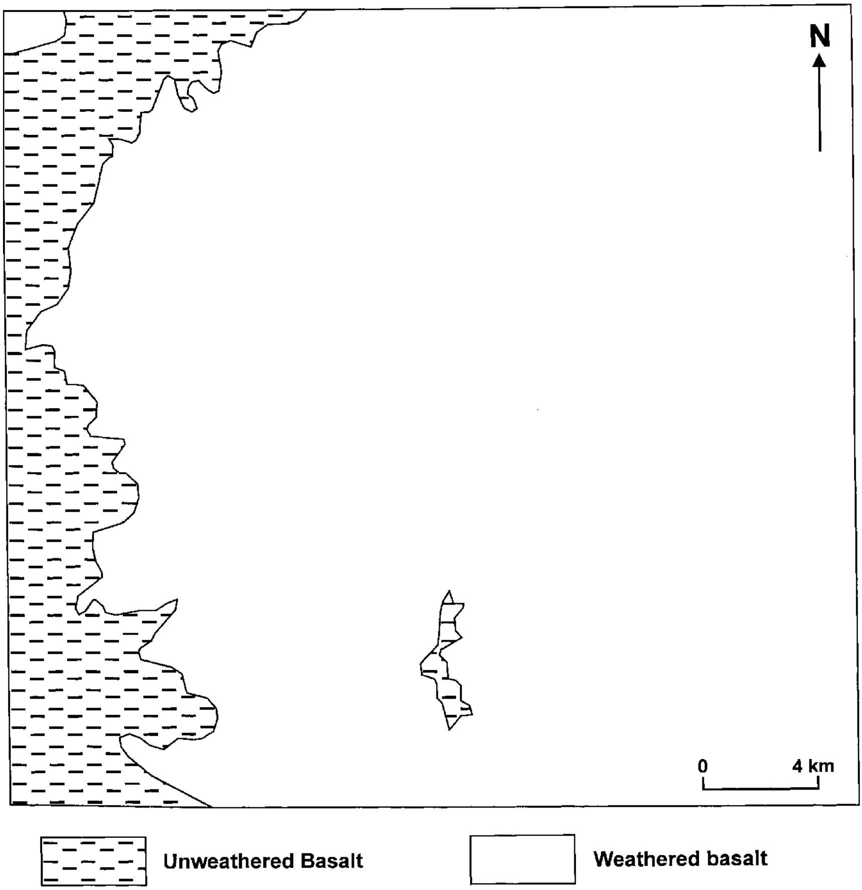



Figure 2. Geological map of the study area.

eruption of basalt took place at the end of the Cretaceous and continued until the early Eocene. Each individual lava flow can be sub-divided into three distinct units:

(*a*) *Red Bole/clay*: Reddish brown clay occurs on the top of each flow. The long time lapse between two successive flows allowed *in situ* weathering to give rise to the red clay which varies in thickness from a few centimetres to a few metres.

(*b*) *Vesicular/Amygdaloidal basalt*: Beneath the red bole, there is a horizon of altered basalt which contain vesicles and amygdales. The vesicles are commonly filled with secondary minerals such as calcite, zeolite and quartz. There is a gradual increase in size and number of vesicles from massive basalt to vesicular zones and finally jointed basalt.

(*c*) *Massive basalt*: The compact, hard, often columnar jointed lava forms the bulk of the flow. It occasionally contains small amygdales.

Physiographically, there are two broad divisions in the area: (*a*) Plateaus and hillocks of basalt, and (*b*) Low lying valley plains. Extensive weathering of basalt has given rise to the formation of a light olive brown silty clay, locally known as 'Muram' (yellow clay) in the valley plain. Black cotton soils develop over weathered basalt, the parent material being yellow clay (Versey and Singh 1982). The combined depth of yellow clay and black cotton soil varies from 3–10 metres. As in other basaltic terrains, there is a multi-aquifer system, the present zone of weathering being the most productive water bearing horizon, which is a shallow aquifer. It is poorly developed over the hilly areas whereas in the valleys, it is up to 20 metres in thickness. Groundwater usually occurs under unconfined conditions but locally it may be semi-confined to confined due to presence of clay overlying jointed basalt (CGWB 1984). The deeper aquifers are beyond the range of present day weathering. The area is fed by south-west monsoon rainfall which starts sometime in July and extends until the end of September. The average annual rainfall is about 1040 mm.

## 3. Data used

Three types of data sets have been used in the present study:

(*a*) Remotely-sensed data, viz. IRS-LISS-II digital data of 27 February 1995. Date of acquisition of remotely-sensed data has been so chosen as this is the peak time of growth of winter crops (Rabi) and dry season vegetation is an indicator of groundwater. It also facilitates better discrimination of lithologic characters than post-monsoon data.

(*b*) Existing maps, viz. Survey of India (SOI) Toposheets at 1:50 000 scale, published geological map.

(*c*) Field data, viz. depth to water level data of 18 dug wells (CGWB 1980), of which six are situated within the study area. Pre- and post-monsoon data for three years consecutively from 1976 to 1978 are used to determine the nature of movement of groundwater in the area.

## 4. Methodology

The methodology adopted in the present study consists of four parts as explained schematically in figure 3.

(*a*) In the first step, all the data have been converted to digital format, by digitization of existing maps and well locations. Remote sensing data are already in digital format.

(*b*) The second step involves generation of thematic layers of information from different sources. It involves digital image processing of remote sensing data and further processing of existing maps and field data for extraction of pertinent information.

Various standard digital image processing techniques have been applied to LISS-II data to enhance and extract information on geology, geomorphology, land use, structural features and vegetation cover (Jensen 1986, Drury 1987). Contrast stretching of individual bands is effective in improving interpretability of different features. This is further enhanced by generating False Colour Composite (FCC) from bands-4,-3,-2 coded in red, green and blue colour scheme which highlights the geomorphological features, land use, vegetation cover and soil types (figure 4). Principal component analysis (PCA) on four bands has been performed to reproject highly correlated LISS-II data into statistically independent orthogonal axes and PCA images are generated. FCC of principal component images highlights landform, water bodies and geology. Lineament and structural features are visually interpreted (figure 5) from directional filtered products of contrast stretched band 4 and also the first principal component image which accounts for the maximum spectral

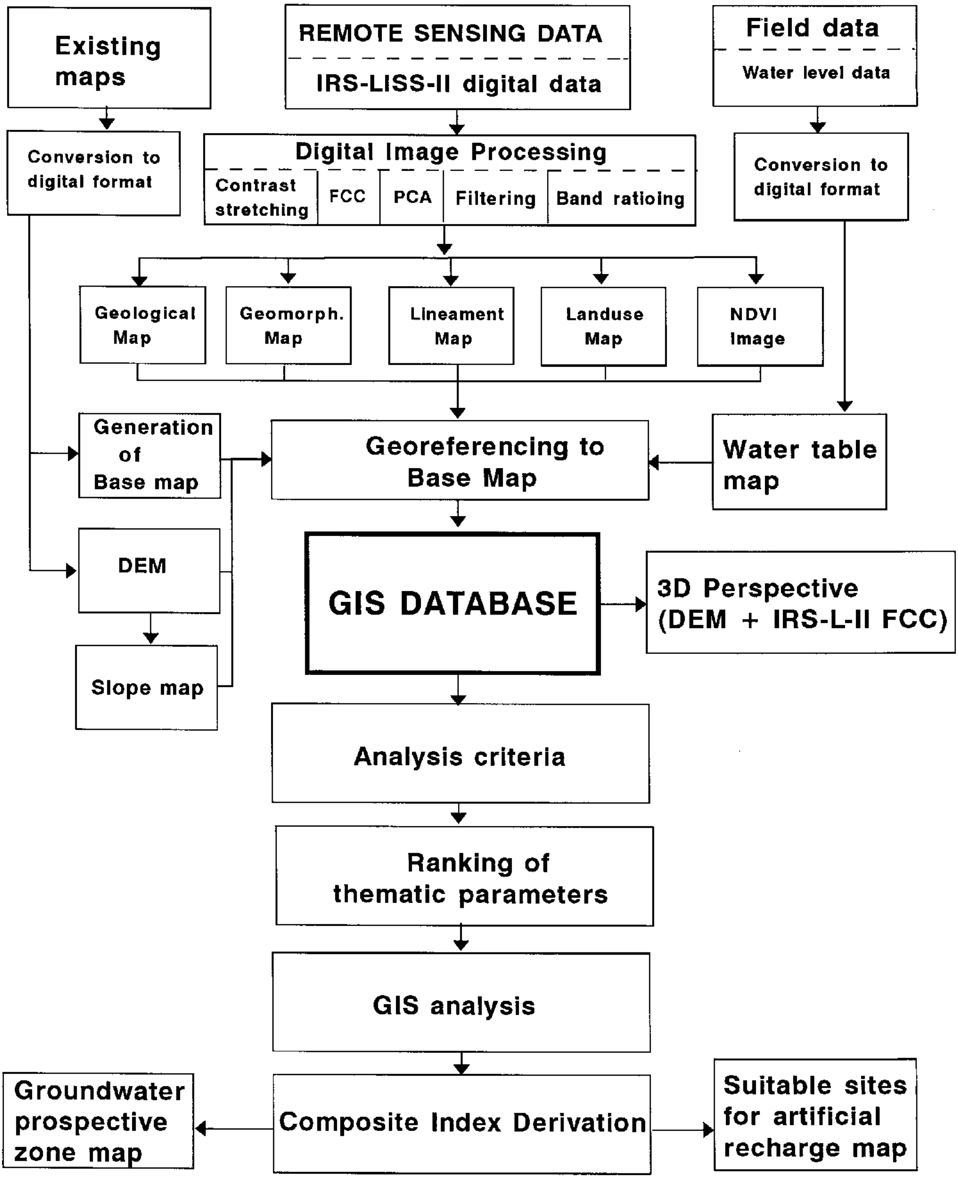



Figure 3. Flow chart showing data flow and different GIS analysis operations followed in the present study.

variance. The normalized difference vegetation index (NDVI) image has been generated to map the abundance or absence of vegetation cover.

An elevation contour map has been digitized from SOI Toposheets at 20 m contour intervals and linear interpolation of these data has led to the generation of a digital elevation model (DEM). The point locations of 18 wells have been digitized and water table data have been interpolated using the Krigging method. Linear interpolation of water table contour map has led to the generation of the ground-water surface.

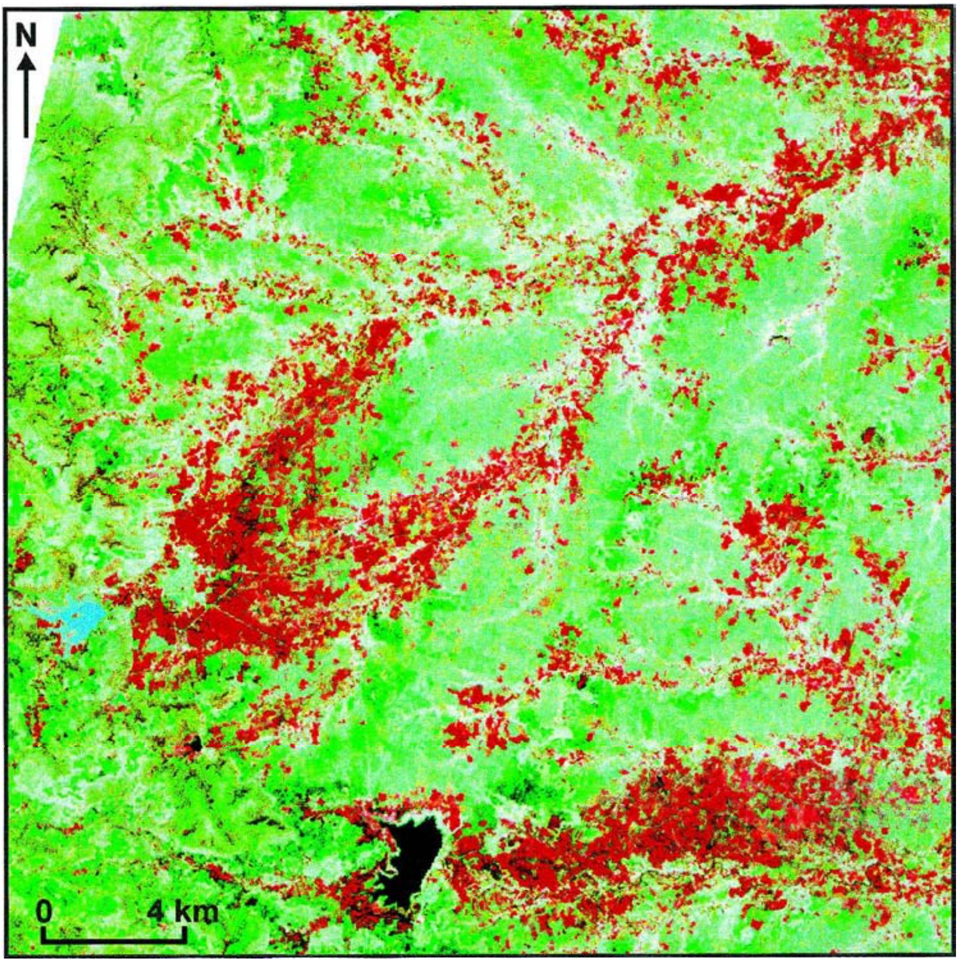



Figure 4. IRS-LISS-II FCC (750 pixels by 750 pixels) (bands 432 in RGB scheme) depicts reservoir induced recharge and better groundwater conditions along valley fills. Anomalous growth of vegetation along valley fills and down stream of reservoirs indicates improved groundwater conditions, the general direction of groundwater flow and the extent of reservoir induced recharge.

(*c*) The third step involves the generation of the GIS database. A base map has been generated from SOI toposheets at 1:50 000 scale comprising surface drainage features, transportation network, canals and location of settlement areas. All data have been georeferenced to the base map. LISS-II data have been georeferenced and resampled using the nearest neighbour interpolation method.

(*d*) The fourth step consists of integration of multi-disciplinary datasets into a composite information set which can answer a broader range of questions in the spatial context. There are two major aspects of integration (ISRO 1994):

(*i*) The criterion defining the logic of the analysis, and

(*ii*) The relative weightage of each parameter.

The criterion for any analysis is dependent on the objective and also the data sets. It is defined by the relative contribution of each parameter towards the desired

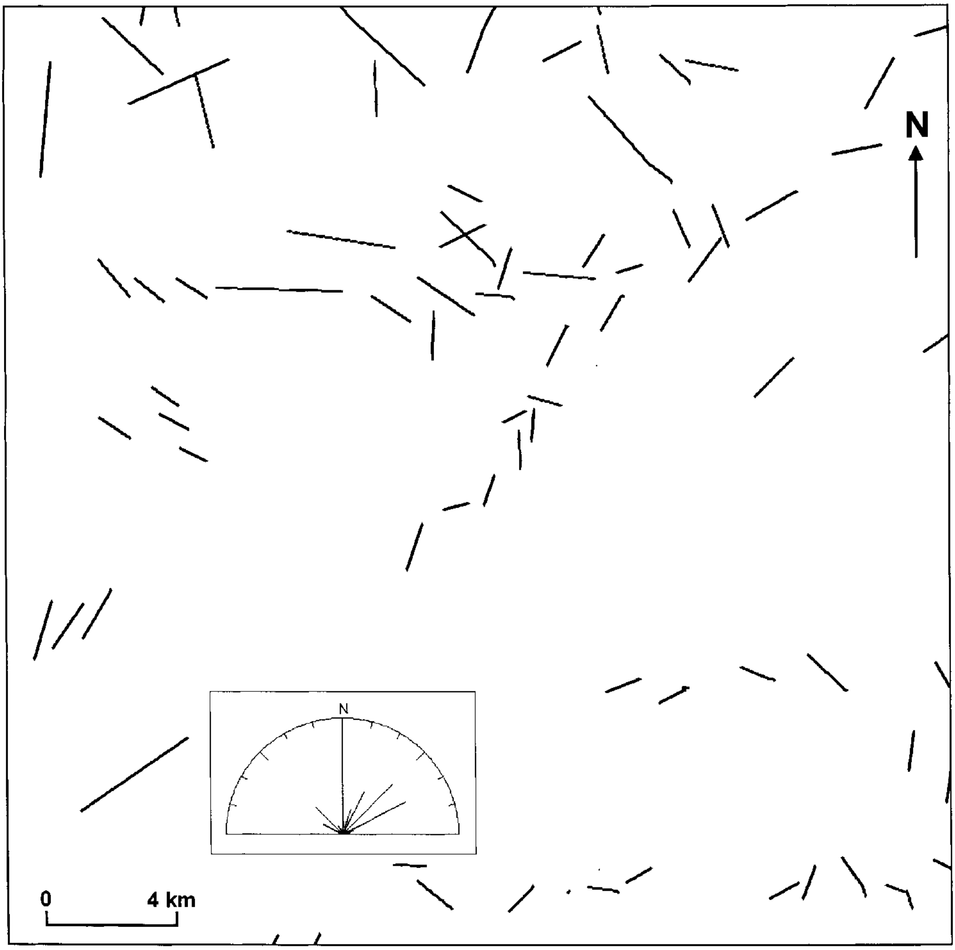



Figure 5. Lineament map of the study area based on IRS-LISS-II data analysis and field information. Rose diagram (Inset) shows the general trend of the lineaments present in the study area.

output phenomenon and is mostly guided by human judgement. On the basis of relative importance, a set of weights have been decided for different information layers and the best suitable condition is derived.

## 5. Analysis and discussion

### 5.1. *Generation of thematic layers*

#### 5.1.1. *Geology*

As described earlier, the area depicts a monotonous lithology of basalt and its weathered products. It can be identified on standard FCC of bands 4, 3, 2 in shades of green (figure 4). Fresh basalt exposures are seen as light green, occupying the high lands in the western margin of the area. Yellow clay developed due to extensive weathering of Deccan basalt. It can be identified by its high DN values in band 3 in contrast to healthy vegetation (figure 11). It is seen as dark green patches, usually over elevated land.

5.1.2. *Geomorphology*

Visual interpretation of digitally enhanced images enables identification of the following geomorphological features, (*a*) residual/denudational hills, (*b*) pediment, (*c*) alluvial plains, and (*d*) valley fills. Basalt, being rich in mafic minerals, is prone to weathering. However, hard and compact basalt can withstand the effects of weathering and erosion to give rise to residual hills, occupying the higher grounds. These are present as plateaus or mesas along the western margin of the area (figure 4). In places, these are incised by streams to form steep cliffs. Small residual hills are also present in the valley plain, seen as scattered dark green patches on the FCC and these represent the remnant parts of basalt flows. Less resistant and fractured parts of the basalt give way to weathering, resulting in the formation pediments. Alluvial plains are developed along the banks of the Kethan and the Naren rivers. They usually show shades of green but also display red colours due to vegetation growth. Valley fills are developed where there is deposition of alluvial material over the valley, which are identified by characteristic bright spectral signatures. These are seen along the streams, mostly in shades of red as they support luxuriant growth of vegetation. Wherever devoid of vegetation, these are seen as white patches.

5.1.3. *Lineaments*

Lineament analysis for groundwater exploration in basaltic terrain has considerable importance as joints and fractures serve as conduits for movement of groundwater. It is not practical to map lineaments solely on the basis of satellite data, without a thorough knowledge of the structural conditions in an area, as the interpretation may be subjective and may include many artifacts. For extraction of lineaments, the procedure of Moore and Waltz (1986) has been followed. In this study, lineaments derived from satellite data have been carefully matched with previously mapped structural features and a good degree of correlation between the two has been found (figure 5). There are four prominent azimuth directions (*a*) NE–SW, (*b*) NW–SE, (*c*) ENE–WSW, and (*d*) NNE–SSW.

5.1.4. *Topography*

Topographic information has been collected from SOI toposheets at 1:50 000 scale and a digital elevation model (DEM) has been generated from elevation contours at 20 m intervals using a linear interpolation method (figure 6). Most of the area shows more or less flat topography excepting a few hills or plateaus in the western part. The maximum and minimum elevations are 540 m and 414 m respectively. A three-dimensional perspective model of the study area has been prepared using DEM and FCC to understand the role of surface reservoirs and their topographic locations in controlling groundwater conditions (figure 7). Calculating the local first derivative from digital elevation data, a slope map has been prepared and different slope classes are expressed in percentages. Nearly 80 per cent of the total area shows 0–1 per cent slope. Only the bounding cliffs of basalt hills have steep slopes.

5.1.5. *Groundwater recharge*

Depth to water level data of pre- and post-monsoon dates are available for few locations only around the study area which provide insufficient information about groundwater conditions. Moreover, spatial analysis in GIS needs pixel-by-pixel information. In order to generate a water table map, the average depth to water level data of pre- and post-monsoon dates for three years (1976 to 1978) have been

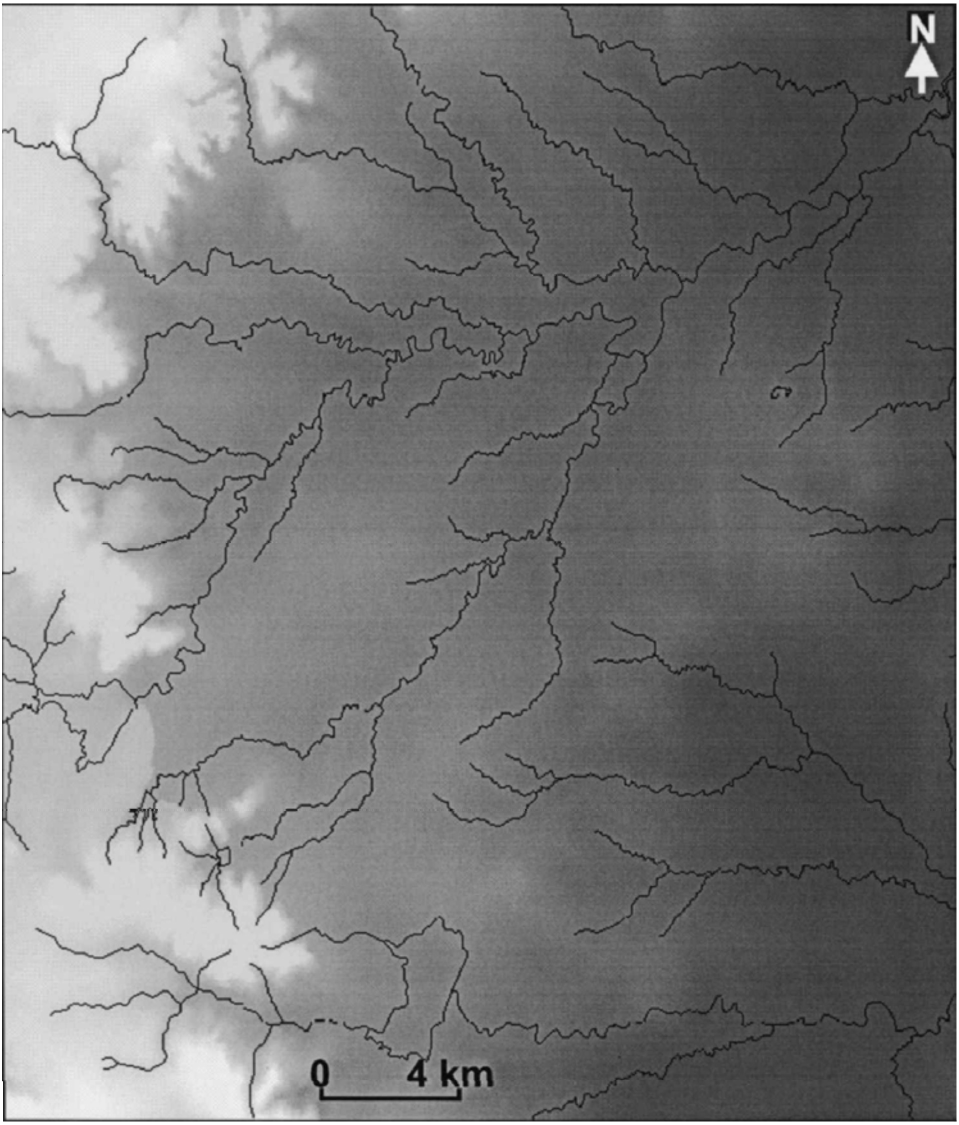



Figure 6. Drainage network superimposed over the DEM of the study area. Lighter tones in the DEM depict higher ground, whereas darker tones indicate lower ground.

interpolated using the Kriging method. The direction of groundwater movement can be inferred from this map at right angles to the water level contours. Further, linear interpolation of the pre- and post-monsoon water table map generates a DEM of the groundwater table, an imaginary groundwater surface which depicts the spatial pattern of the groundwater table.

Seasonal fluctuation of the water table is directly related to groundwater recharge. Subtraction of the pre-monsoon water table from the post-monsoon water table image yields a water level fluctuation image. The western part of the image shows a low fluctuation zone (0·2–1·4 m). It gradually increases towards the eastern margin and reaches a maximum of 7·3 m in the southeastern corner. As monsoon rainfall is

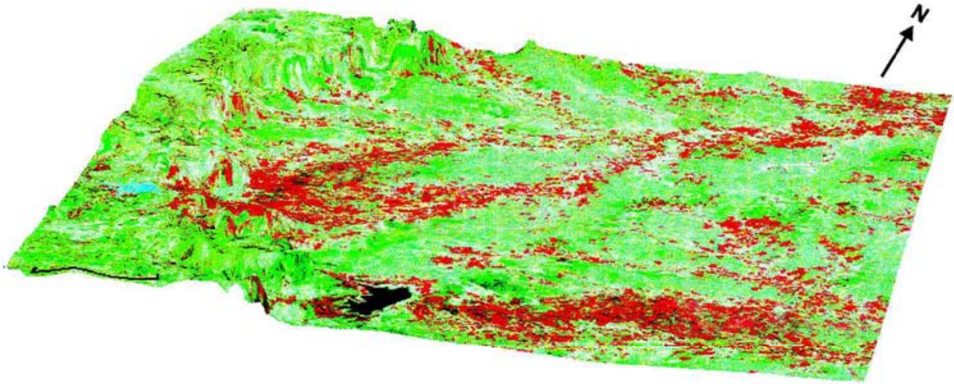



Figure 7. Three-dimensional perspective view of the study area. IRS-LISS-II FCC (as shown in figure 4) has been draped on DEM of the study area. The location of the Sironj reservoir (light blue coloured) on higher ground provides better groundwater recharge conditions, because of a greater hydraulic gradient than of the Naren reservoir. Though the size and extent (i.e., capacity) of the Sironj reservoir is less than that of the Naren reservoir, the extent of reservoir induced recharge area is greater. It suggests that future reservoir sites should be located at higher grounds (as shown in figures 10 (*a*) and (*b*)) in order to fully exploit the available hydraulic gradient and better reservoir induced groundwater recharge conditions.

the major source of recharge in this area, groundwater recharge image (figure 8) has been prepared by multiplying the water level fluctuation image by the specific yield of different formations (Saraf and Jain 1994). Values of specific yield for weathered (3·0) and unweathered basalt (2·0) for the area have been taken from Karanth (1987). This grey scale image displays the spatial distribution of groundwater recharge in the study area, the darker tones indicating poor recharge zones and the brighter tones showing high recharge zones.

5.1.6. *Landuse*

Few landuse classes can be identified in the present area on FCC 432 (RGB). The basalt hills in the western part support open forest. Agricultural lands are developed downstream of the reservoirs and along the valley fills. Most of the land is used for Rabi (winter) crops and only a small area is used for Kharif (monsoon) crops. As a result, most of the area lies fallow during summer. Consequently, land use classes have not been used in the present study.

5.1.7. *Drainage*

A surface drainage map has been prepared from SOI toposheets at 1:50 000 scale. The northern as well as central part of the study area is drained by the Kethan river and its tributaries, whereas the Naren river drains the southern part (figures 1 and 6). The drainage pattern is mainly dendritic but locally exhibits structural control.

5.2. *Evaluation of groundwater conditions in the area*

In basaltic terrains, occurrence of groundwater is controlled by primary features such as vesicles and inter-flow contacts and secondary features like fractures and weathered zones. In order to determine the groundwater prospects in the study area, thematic maps generated from remote sensing data have been interfaced with DEM,

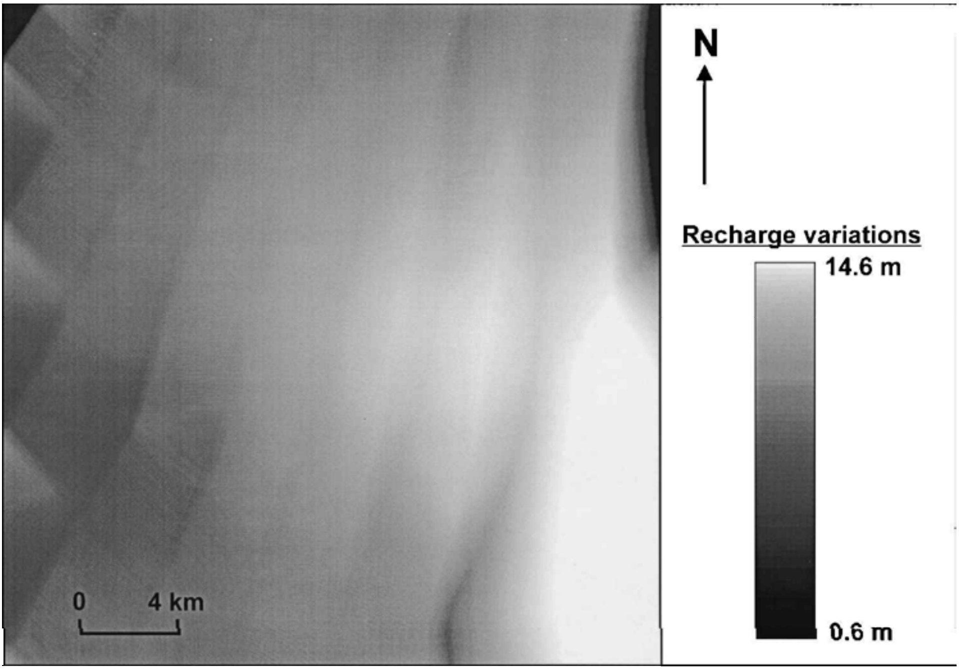



Figure 8. Recharge zones in the study area. This map is the resultant of the water-table fluctuation map multiplied by the specific yield of different geological units of the study area. Lighter tones depict higher groundwater recharge conditions, whereas darker tones reflects low recharge zones.

surface drainage and water table map using GIS. The groundwater flow direction closely follows the direction of river flow indicating that streams in the area are influent. It also matches with the prominent direction of lineaments in the area suggesting that the lineaments act as pathways for groundwater movement.

Evaluation of groundwater conditions in an area needs information on seasonal water level fluctuations and groundwater recharge. The western hilly area is a zone of poor groundwater recharge, whereas the alluvial plains provide better groundwater recharge conditions. The GIS overlay analysis of the recharge image (figure 8) and the geological map reveals that weathered basalt provides better groundwater recharge conditions than unweathered basalt and hence has a better prospect for groundwater. Interfacing of the geomorphological map and NDVI image reveals that valley fills are the most promising sites for groundwater exploration as expressed by the development of dry season vegetation. Thus, integrated analysis of various data sets in GIS enables definition of criteria for groundwater exploration in the study area (table 2) and a groundwater prospective zone map has been generated (figure 9).

### 5.3. *Identification of reservoir induced artificial groundwater recharge zones*

One of the most interesting features of the IRS-LISS-II images of the area is the anomalous vegetation growth downstream of surface water reservoirs. There are two large reservoirs in the area (figure 1), and a few small ones. The FCC shows that valley fills support prolific vegetation where there is reservoir across the stream whereas vegetation is only sporadic or even totally absent where there is no recharge

Table 2. Weightage of different parameters for groundwater prospects.

| Sl. no. | Criteria | Classes | Weight |
|---|---|---|---|
| 1 | Geology | Weathered basalt | 1 |
| | | Unweathered basalt | 2 |
| 2 | Geomorphology | Valley fills | 1 |
| | | Alluvial plain | 2 |
| | | Pediment | 3 |
| | | Residual hills | 4 |
| 3 | Lineament | Present | 1 |
| | | Absent | 2 |
| 4 | Slope (%) | 0–0·9 | 1 |
| | | 1–2 | 2 |
| | | 2·1–5 | 3 |
| | | >5 | 4 |

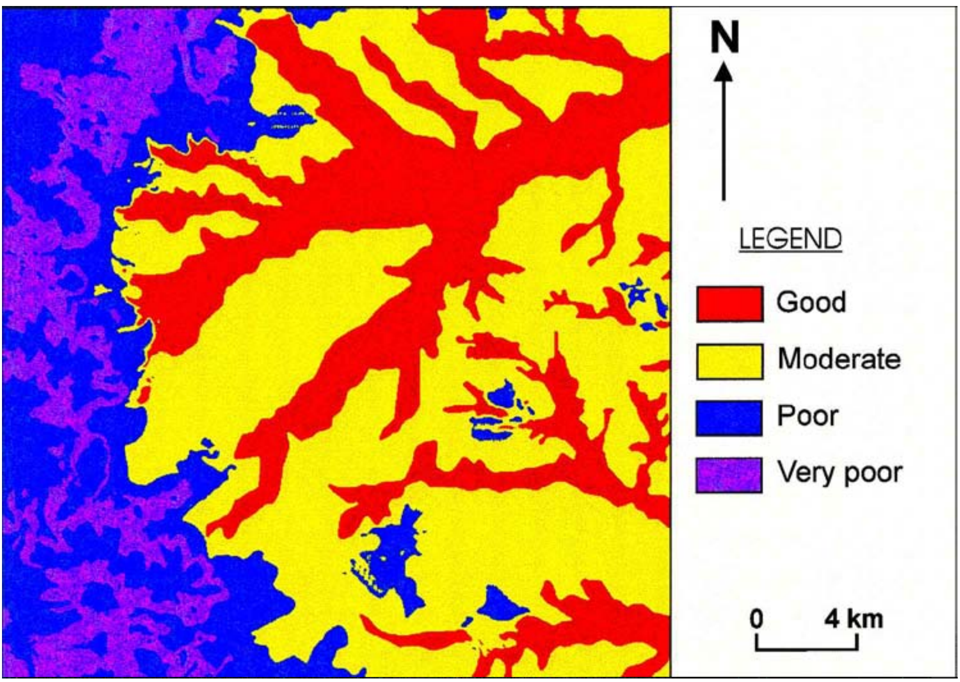
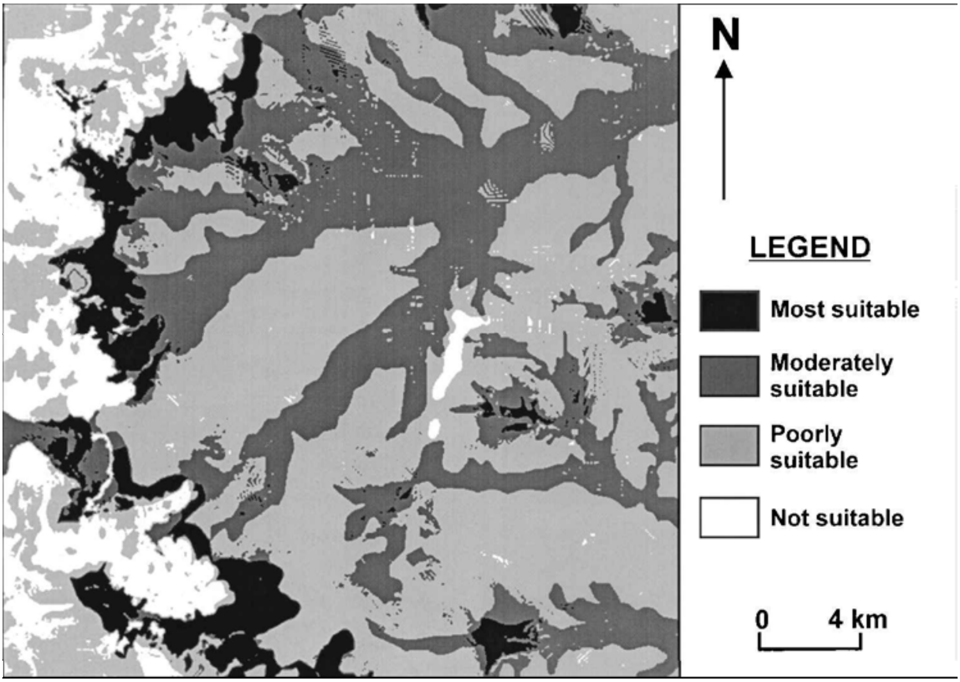
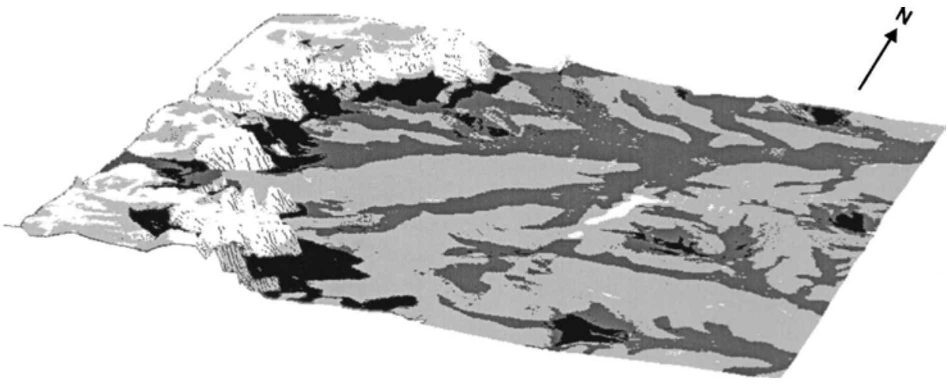



Figure 9. Groundwater prospective zones analysed on the basis of geomorphological, lineaments, vegetation, geological and soils information and their analysis using GIS.

to the valley fills. The reservoirs of all sizes are augmenting lateral groundwater recharge to the shallow aquifers. The effective area receiving recharge from the larger reservoirs is 8–10 $km^2$, depending on the catchment area of the streams, whereas smaller reservoirs recharge 1–2 $km^2$. Although the reservoir near Sironj is smaller in size (2·8 $km^2$) than the Naren reservoir which covers an area of 5·3 $km^2$, the areal extent of its recharge is greater. This contrasting recharge capability can be explained by the fact that the former is situated on a narrow valley between two hillocks over a gentle slope (figure 8), which provides sufficient hydraulic gradient for groundwater




(*a*)




(*b*)

Figure 10. (*a*) Potential zones for future reservoir sites to provide better reservoir induced groundwater recharge conditions. This map is prepared using the slope map derived from DEM (figure 8) together with the geology, geomorphology and groundwater recharge maps (figure 8) and the lineament map (figure 5). (*b*) Three-dimensional view of the map shown in figure 10 (*a*), clearly indicates zones for the most suitable/favourable sites of future reservoirs to provide best groundwater recharge conditions. The legend for this image is same as shown in figure 10 (*a*).

movement, whereas, the gradient is much less in the flat areas, near the Naren reservoir. Thus, topography plays a major role. GIS facilitates superimposition of geological and lineament maps over FCC and leads to a better understanding of the

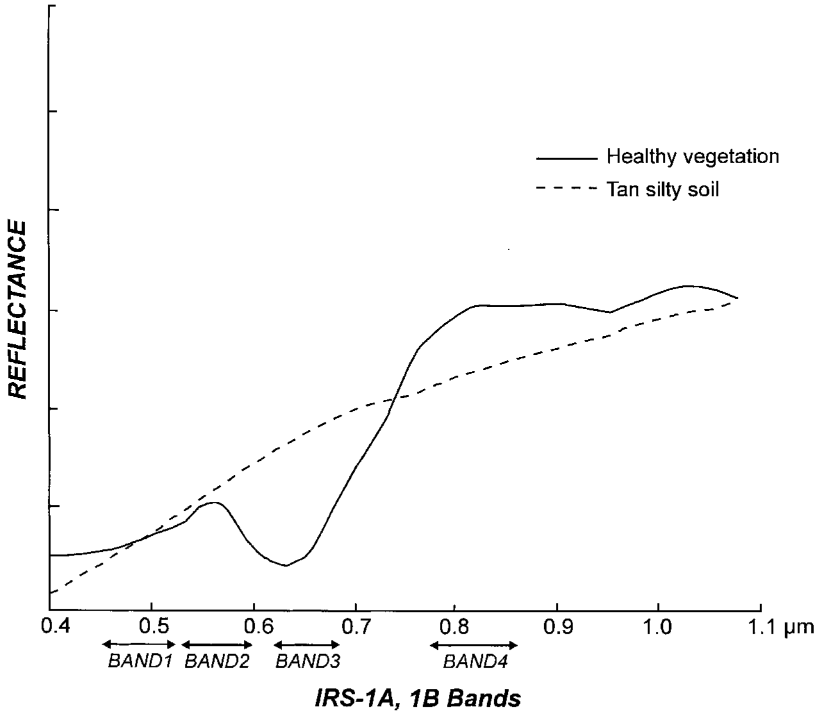



Figure 11. Spectral curves for average spectral responses from IRS-1A and 1B and reflectance from vegetation and soil, unscaled vertical axis (after Holz 1984).

factors affecting artificial recharge. All the reservoirs are constructed over weathered and fractured basalt which permits a high intake of water. The moderate permeability of the basalt helps to maintain the required rate of recharge. The vesicular parts of the basalt provide storage space for groundwater. Careful observation reveals that growth of dense vegetation associated with the reservoirs follows the predominant direction of lineaments suggesting that the lineaments provide routeways for the movement of groundwater.

### 5.4. *Selection of suitable sites for artificial recharge*

Recharge ponds and check dams provide a good measure of artificial recharge in hard rock terrains by collecting surface run-off and increasing the surface area of infiltration. Suitability of these structures depends on various factors which can be identified using GIS techniques (Novaline Jaga *et al.* 1993). Considering the hydrogeomorphic conditions of the area, weighted indexing has been adopted (table 3) to suggest the ideal locations for artificial recharge by basins/ponds using four parameters namely geology, geomorphology, lineaments and topography. This suitability analysis has been performed purely from a groundwater point of view and does not include geotechnical considerations.

(*a*) *Geology*. The area is geologically very simple as mentioned earlier. Fractured and weathered basalt has been given the highest priority as it provides the necessary permeability and storage space. Massive basalt is not favourable as it is impermeable and cannot provide storage space.

Table 3. Weightage of different parameters for suitable sites for artificial recharge.

| | Criteria | Classes | Weight |
|---|---|---|---|
| 1 | Geology | Weathered and fractured basalt | 1 |
| | | Unweathered basalt | 2 |
| 2 | Geomorphology | Pediment | 1 |
| | | Valley fill | 2 |
| | | Alluvial Plain | 3 |
| | | Hillocks/plateau | 4 |
| 3 | Slope(%) | 1–5 | 1 |
| | | 0·1–0·9 | 2 |
| | | >0·9 | 3 |
| | | 0 | 4 |
| | | >5 | 5 |
| 4 | Lineament | Present | 1 |
| | | Absent | 2 |

(*b*) *Geomorphology*. Pediment follows steep slopes in this area and is considered as the most suitable geomorphic class because it checks the velocity of surface run-off and thus provides more chance of water accumulation. Valley fills are given the next priority followed by alluvial plains and basalt plateaus are the least favoured.

(*c*) *Topography*. Gentle slopes (1–5 per cent) serve to build up the hydraulic gradient and are thus considered as the most suitable condition. Areas having very low or steep slope are considered unfavourable.

(*d*) *Lineament*. As discussed earlier, lineaments in this area facilitate groundwater movement and the presence of lineaments is considered as a suitable condition for recharge basins.

A resultant image has been generated by overlaying the thematic layers in GIS and suitable locations for artificial recharge are identified based on the weightages given to each parameter (figure 10 (*a*)). A perspective view of this map has been generated (figure 10 (*b*)) to enhance the understanding of the role of topography in reservoir site selection.

## 6. Conclusions

This study has enabled an evaluation of the capabilities of IRS-LISS-II data for comprehensive understanding of the groundwater conditions of a hard rock area. Digital analysis of LISS-II data has permitted identification of groundwater recharge due to reservoirs in the study area. This is further augmented by analysis of thematic information derived from DEM and groundwater data in a GIS environment. Integrated analysis provides a further insight into the hydrogeological regime of the area which can be utilized for site selection for artificial recharge. GIS facilitates conjunctive analysis of multi-parameter thematic data and decision making for efficient planning for groundwater management. The spatial database developed during this study is being improved by adding further information layers and a modelling approach may be adopted in future using integrated GIS.

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